

Quantum Optics and Photonics Division Fachverband Quantenoptik und Photonik (Q)

Vahid Sandoghdar
Max Planck Institute for the Science of Light and
Department of Physics, University of Erlangen-Nürnberg (FAU)
Günther-Scharowsky-Str. 1
91058 Erlangen
vahid.sandoghdar@mpl.mpg.de

Overview of Invited Talks and Sessions

(Lecture rooms a310, e001, e214, f342, and f442; Poster Empore Lichthof)

Invited talks of the joint symposium SYAD

See SYAD for the full program of the symposium.

SYAD 1.1	Tue	11:00–11:30	e415	Artificial gauge fields and topology with ultracold atoms in optical lattices — ●MONIKA AIDELSBURGER
SYAD 1.2	Tue	11:30–12:00	e415	Many-body physics with impurities in ultracold quantum gases — ●FABIAN GRUSDITZ
SYAD 1.3	Tue	12:00–12:30	e415	How to determine the handedness of single molecules — ●MARTIN PITZER
SYAD 1.4	Tue	12:30–13:00	e415	Quantum systems under gravitational time dilation — ●MAGDALENA ZYCH

Invited talks of the joint symposium SYBO

See SYBO for the full program of the symposium.

SYBO 1.1	Thu	11:00–11:30	e415	Recent advances of Optical Coherence Tomography — ●WOLFGANG DREXLER
SYBO 1.2	Thu	11:30–12:00	e415	Vortex-beams for precise and gentle dissection in refractive corneal surgery — ●ALFRED VOGEL, SEBASTIAN FREIDANK, NORBERT LINZ
SYBO 1.3	Thu	12:00–12:30	e415	Structured Illumination and the Analysis of Single Molecules in Cells — ●RAINER HEINTZMANN
SYBO 1.4	Thu	12:30–13:00	e415	Biophotonics - a potential solution to unmet medical needs!? — ●JUERGEN POPP
SYBO 2.1	Thu	14:30–15:00	e415	Smart and multimodal light sheet microscopy — ●JAN HUISKEN
SYBO 2.2	Thu	15:00–15:30	e415	Laser Applications at the Cochlea: Imaging and Stimulation — ●ALEXANDER HEISTERKAMP, NICOLE KALLWEIT, PETER BAUMHOFF, ALEXANDER KRUEGER, NADINE TINNE, HEIKO MEYER, ANDREJ KRAL, HANNES MAIER, TAMMO RIPKEN
SYBO 2.3	Thu	15:30–16:00	e415	Sculpted light landscapes for optical micro-manipulation — CHRISTINA ALPMANN, ALVARO BARROSO PENA, EILEEN OTTE, KATHRIN DIECKMANN, ●CORNELIA DENZ
SYBO 2.4	Thu	16:00–16:30	e415	Optogenetics: Lighting Up the Brain — ●GERO MIESENBOECK

Invited talks of the joint symposium SYUL

See SYUL for the full program of the symposium.

SYUL 1.1	Fri	11:00–11:50	e415	Exawatt laser concepts for extreme field science — ●CHRIS BARTY
SYUL 1.2	Fri	11:50–12:20	e415	Generation of short pulses with ultra-high temporal contrast at the PHELIX petawatt facility — ●VINCENT BAGNOUD
SYUL 1.3	Fri	12:20–12:50	e415	Petawatt lasers for particle acceleration at HZDR Dresden — ●ULRICH SCHRAMM

SYUL 1.4	Fri	12:50–13:20	e415	High-intensity few-cycle pulses with ultrahigh temporal contrast — ●STEFAN KARSCH, ALEXANDER KESSEL, CHRISTOPH SKROBOL, MATHIAS KRÜGER, CHRISTOPH WANDT, SANDRO KLINGEBIEL, OLGA LYSOV, IZHAR AHMAD, SERGEI TRUSHIN, VYACHESLAV LESHCHENKO, ZSUZSANNA MAJOR, FERENC KRAUSZ
SYUL 2.1	Fri	14:00–14:30	e415	Coherent Combination of Ultrafast Fiber Lasers — ●JENS LIMPERT
SYUL 2.2	Fri	14:30–15:00	e415	Cryogenic multipass amplifiers for high peak and average power ultrafast lasers — ●LUIS E. ZAPATA
SYUL 2.3	Fri	15:00–15:30	e415	Multi-TW infrared laser using Frequency domain Optical Parametric Amplification — ●BRUNO E. SCHMIDT, PHILIPPE LASSONDE, GUILMOT ERNOTTE, MATHIEU GIGUERE, NICOLAS THIRE, ANTOINE LARAMEE, HEIDE IBRAHIM, FRANCOIS LEGARE

Sessions

Q 1.1–1.7	Mon	11:00–12:45	a310	Precision Measurements and Metrology I (with A)
Q 2.1–2.8	Mon	11:00–13:00	e001	Ultracold Atoms, Ions and Molecules I (with A)
Q 3.1–3.8	Mon	11:00–13:00	e214	Quantum Information: Concepts and Methods I
Q 4.1–4.7	Mon	11:00–12:45	f342	Photonics I
Q 5.1–5.8	Mon	11:00–13:00	f442	Quantum Optics I
Q 6.1–6.7	Mon	14:30–16:15	a310	Precision Measurements and Metrology II (with A)
Q 7.1–7.8	Mon	14:30–16:30	e001	Ultracold Atoms, Ions and Molecules II (with A)
Q 8.1–8.8	Mon	14:30–16:30	e214	Quantum Information: Concepts and Methods II
Q 9.1–9.7	Mon	14:30–16:15	f342	Photonics II
Q 10.1–10.8	Mon	14:30–16:30	f442	Quantum Optics II
Q 11.1–11.42	Mon	16:30–19:00	Empore Lichthof	Poster: Quantum Optics and Photonics I
Q 12.1–12.51	Mon	16:30–19:00	Empore Lichthof	Ultra-cold atoms, ions and BEC (with A)
Q 13.1–13.5	Mon	17:00–18:15	a310	Precision Measurements and Metrology III (with A)
Q 14.1–14.7	Mon	17:00–18:45	f303	Ultracold plasmas and Rydberg systems I (with A)
Q 15.1–15.5	Mon	17:00–18:15	f442	Quantum Effects: Disorder
Q 16.1–16.8	Tue	11:00–13:00	a310	Precision Measurements and Metrology IV (with A)
Q 17.1–17.7	Tue	11:00–13:00	e001	Quantum Gases: Bosons I
Q 18.1–18.8	Tue	11:00–13:00	e214	Quantum Information: Concepts and Methods III
Q 19.1–19.9	Tue	11:00–13:15	f342	Ultracold Atoms, Ions and Molecules III (with A)
Q 20.1–20.8	Tue	11:00–13:00	f442	Quantum Optics III
Q 21.1–21.8	Tue	14:30–16:30	a310	Matter Wave Optics
Q 22.1–22.8	Tue	14:30–16:30	e001	Quantum Gases: Bosons II
Q 23.1–23.8	Tue	14:30–16:30	e214	Quantum Information: Concepts and Methods IV
Q 24.1–24.8	Tue	14:30–16:30	f303	Ultracold plasmas and Rydberg systems II (with A)
Q 25.1–25.9	Tue	14:30–16:45	f342	Nano-Optics I
Q 26.1–26.6	Tue	14:30–16:00	f442	Quantum Optics IV
Q 27.1–27.64	Tue	16:30–19:00	Empore Lichthof	Poster: Quantum Optics and Photonics II
Q 28.1–28.8	Wed	11:00–13:00	a310	Laser Development I
Q 29.1–29.7	Wed	11:00–13:00	e001	Quantum Gases: Bosons III
Q 30.1–30.8	Wed	11:00–13:00	e214	Quantum Information: Concepts and Methods V
Q 31.1–31.8	Wed	11:00–13:00	f107	Ultra-cold atoms, ions and BEC I (with A)
Q 32.1–32.8	Wed	11:00–13:00	f342	Biophotonics
Q 33.1–33.8	Wed	11:00–13:00	f442	Quantum Effects: Entanglement and Decoherence I
Q 34	Wed	13:15–14:15	a310	Annual General Meeting: Quantum Optics and Photonics
Q 35.1–35.6	Wed	14:30–16:00	a310	Laser Development II
Q 36.1–36.7	Wed	14:30–16:15	e001	Quantum Gases: Bosons IV
Q 37.1–37.8	Wed	14:30–16:30	e214	Quantum Information: Concepts and Methods VI
Q 38.1–38.8	Wed	14:30–16:30	f303	Ultra-cold atoms, ions and BEC II (with A)
Q 39.1–39.8	Wed	14:30–16:30	f342	Nano-Optics II
Q 40.1–40.7	Wed	14:30–16:30	f428	Precision spectroscopy of atoms and ions I (with A)
Q 41.1–41.7	Wed	14:30–16:30	f442	Quantum Effects: Entanglement and Decoherence II
Q 42.1–42.64	Wed	16:30–19:00	Empore Lichthof	Poster: Quantum Optics and Photonics III
Q 43.1–43.10	Wed	16:30–19:00	Empore Lichthof	Ultracold plasmas and Rydberg systems (with A)
Q 44.1–44.24	Wed	16:30–19:00	Empore Lichthof	Precision spectroscopy of atoms and ions (with A)

Q 45.1–45.8	Thu	11:00–13:00	a310	Ultrashort Laser Pulses I
Q 46.1–46.7	Thu	11:00–12:45	e001	Quantum Gases: Bosons V
Q 47.1–47.8	Thu	11:00–13:00	e214	Quantum Information: Quantum Computing and Communication I
Q 48.1–48.8	Thu	11:00–13:00	f107	Ultra-cold atoms, ions and BEC III (with A)
Q 49.1–49.8	Thu	11:00–13:00	f342	Optomechanics I
Q 50.1–50.7	Thu	11:00–13:00	f428	Precision spectroscopy of atoms and ions II (with A)
Q 51.1–51.8	Thu	11:00–13:00	f442	Quantum Effects: QED I
Q 52.1–52.8	Thu	14:30–16:30	a310	Ultrashort Laser Pulses II
Q 53.1–53.9	Thu	14:30–16:45	e001	Quantum Gases: Fermions I
Q 54.1–54.8	Thu	14:30–16:30	e214	Quantum Information: Quantum Computing and Communication II
Q 55.1–55.8	Thu	14:30–16:30	f303	Ultra-cold atoms, ions and BEC IV (with A)
Q 56.1–56.5	Thu	14:30–15:45	f342	Optomechanics II
Q 57.1–57.7	Thu	14:30–16:30	f442	Quantum Effects: QED II
Q 58.1–58.89	Thu	16:30–19:00	Empore Lichthof	Poster: Quantum Optics and Photonics IV
Q 59.1–59.4	Thu	16:30–19:00	Empore Lichthof	Poster: Symposium Biomedical Optics (SYBO)
Q 60.1–60.8	Fri	11:00–13:00	a310	Laser Applications I
Q 61.1–61.9	Fri	11:00–13:15	e001	Quantum Gases: Fermions II
Q 62.1–62.7	Fri	11:00–12:45	e214	Quantum Information: Quantum Computing and Communication III
Q 63.1–63.8	Fri	11:00–13:00	f107	Ultra-cold atoms, ions and BEC V (with A)
Q 64.1–64.6	Fri	11:00–12:30	f342	Nano-Optics III
Q 65.1–65.7	Fri	11:00–12:45	f428	Precision spectroscopy of atoms and ions III (with A)
Q 66.1–66.6	Fri	11:00–12:45	f442	Quantum Effects: QED III
Q 67.1–67.3	Fri	14:30–15:15	a310	Laser Applications II
Q 68.1–68.8	Fri	14:30–16:30	e001	Quantum Gases: Fermions III
Q 69.1–69.6	Fri	14:30–16:00	e214	Quantum Information: Quantum Computing and Communication IV
Q 70.1–70.6	Fri	14:30–16:00	f342	Quantum Gases: Bosons VI
Q 71.1–71.7	Fri	14:30–16:30	f442	Quantum Effects: QED IV
Q 72.1–72.4	Fri	15:30–16:30	a310	Ultrashort Laser Pulses III

Annual General Meeting of the Quantum Optics and Photonics Division

Wednesday 13:15–14:15 a310

Q 1: Precision Measurements and Metrology I (with A)

Time: Monday 11:00–12:45

Location: a310

Q 1.1 Mon 11:00 a310

Femtosecond frequency comb-based heterodyne many-wavelength interferometer — ●JUTTA MILDNER, KARL MEINERS-HAGEN, and FLORIAN POLLINGER — Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig

Direct traceability to the SI definition of the meter and the capability to generate synthetic wavelengths from the optical to the microwave regime make broadband optical frequency combs highly promising sources for future length metrology with high precision as required in engineering, geodesy and surveying.

In this contribution we want to present the development of a novel comb-based many-wavelength interferometer in which a direct heterodyne phase detection of individual comb lines is aimed at. To this end a single fiber-based optical frequency comb with CEO-stabilization and 250 MHz repetition rate is used as a seed laser. By cavity filtering two coherent combs of different mode spacings in the GHz band are generated and subsequently used as local oscillator and measurement beam. The deployed filtering duplet with tunable spacing and Pound-Drever-Hall stabilization scheme will be presented as well as the electronic filtering unit for phase detection. Furthermore, we want to discuss the current progress on the interferometer head setup and show preliminary results of first length measurements.

This project is performed within the joint research project SIB60 'Surveying' of the European Metrology Research Programme (EMRP). The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

Q 1.2 Mon 11:15 a310

Squeezed light and self-induced transparency in mercury-filled hollow core photonic crystal fibers — ●ULRICH VOGL^{1,2}, NICOLAS Y. JOLY^{1,2}, PHILIP ST.J. RUSSELL^{1,2}, CHRISTOPH MARQUARDT^{1,2}, and GERD LEUCHS^{1,2} — ¹Max Planck Institute for the Science of Light, 91058 Erlangen, Germany — ²University Erlangen-Nuremberg, Erlangen, Germany

We recently demonstrated that the use of atomic mercury vapour allows greatly improved loading of an atomic gas into hollow core photonic crystal fibres (PCFs), leading to high and constant vapour pressure in the fibre core [1]. The kagomé-PCFs used guide light not by the photonic band gap effect, but by a two-dimensional version of anti-resonant reflection, and offer much broader windows of transmission, typically over 1000 nm. The generation of squeezed states of light, using pulses that fulfil the self-induced transparency (SIT) condition, was proposed in 1989 [2]. We successfully demonstrate SIT of optical pulses in the mercury-filled PCF system and its use in the generation of squeezed states of light. In the first experiments we observed squeezing below the shot noise limit upon launching short nanosecond pulses into the fibre and using a measurement in direct difference detection. Future prospects include phase-sensitive detection of SIT solitons with temporally shaped local oscillator forms to investigate the phase and number uncertainty of the generated states.

[1] U. Vogl, Ch. Peuntinger, N. Y. Joly, P. St.J. Russell, Ch. Marquardt, and G. Leuchs. *Optics Express* **22**, 29375 (2014).

[2] K. Watanabe, et. al. *Phys. Rev. Lett.* **62**, 2257 (1989).

Q 1.3 Mon 11:30 a310

Dilatometer Setup to Characterize Dimensionally Stable Materials by the Coefficient of Thermal Expansion at a Temperature Range from 100 K to 325 K — ●INES HAMANN¹, RUVEN SPANNAGEL¹, THILO SCHULDT¹, JOSE SANJUAN¹, MARTIN GOHLKE¹, ULRICH JOHANN², DENNIS WEISE², and CLAUS BRAXMAIER^{1,3} — ¹DLR German Aerospace Center, Institute of Space Systems, 28359 Bremen, Germany — ²Airbus Defence & Space, 88039 Friedrichshafen, Germany — ³University of Bremen, ZARM Center of Applied Space Technology and Microgravity, 28359 Bremen, Germany

Space missions with the aim of high precision optical measurements are often limited by the dimensional stability of the instrument which can be exposed to high temperature fluctuations, due to the environment of the space probe. To minimize the change of the geometric dimension due to temperature changes, highly dimensionally stable materials are needed at the specific environmental temperatures. Materials like glass ceramics offer a minimal coefficient of thermal expansion (CTE) but they are also very heavy. Composite materials like CFRP or SiC

offer also a very low CTE but with a lower weight and are more and more used for such applications. To characterize such low expansion materials we use a laser dilatometer with a heterodyne interferometer to measure length variations of the sample caused by an applied temperature variation. Using a cryocooler in combination with a heating system, we are able to determine CTEs at the 10 ppb/K level within a temperature range from 100 K to 325 K. In this talk, we present improvements of our setup and recent sample measurements.

Q 1.4 Mon 11:45 a310

Precision rubidium spectroscopy in space — ●VLADIMIR SCHKOLNIK¹, MARKUS KRUTZIK¹, ACHIM PETERS^{1,2}, and THE FOKUS TEAM^{1,2,3,4,5} — ¹Institut für Physik, Humboldt- Universität zu Berlin — ²Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik, Berlin — ³ILP, Universität Hamburg — ⁴Institut für Physik, JGU Mainz — ⁵Menlo Systems, Martinsried

Frequency stabilized lasers are one of the key elements in high precision instruments such as atom interferometers and atomic clocks. Accordingly, future space missions for tests of the equivalence principle require robust and compact lasers with high mechanical and frequency stability.

In this talk, we present the first Doppler free spectroscopy on rubidium in space, performed during the flight of the sounding rocket mission TEXUS 51. We present the spectroscopy payload, the autonomous stabilization scheme and the experimental results of the flight. The frequency of the stabilized laser was compared to a microwave reference using a fiber based frequency comb during launch and microgravity phase. This frequency measurement can be interpreted as a test of the local position invariance and paves the way for future high precision experiments in space.

This work is supported by the German Space Agency DLR with funds provided by the Federal Ministry for Economic Affairs and Energy under grant numbers DLR 50WM 1237-1240, and 1345.

Q 1.5 Mon 12:00 a310

Coating Thermal Noise Interferometer — ●JANIS WÖHLER FOR THE AEI 10M PROTOTYPE TEAM — MPG for Gravitational Physics Hannover

Thermal noise in the coatings of highly reflective mirrors is becoming a limiting noise source in interferometers used for the detection of gravitational waves. It is caused by mechanical losses of the thin films used in the coatings. A way to reduce the noise is to use crystalline coatings due to their inherently lower mechanical losses. Crystalline AlGaAs-coatings are a promising candidate and their noise properties will be measured before using them in a quantum limited Michelson interferometer. For the measurement, all other noise sources, especially seismic noise and acoustic disturbances, have to be reduced below the thermal noise level. The AEI 10 m Prototype facility is probably the best suited environment for this kind of experiment.

In this talk the setup of the Thermal Noise Interferometer will be presented, which can measure thermal noise in a frequency band from 10Hz to 50kHz, limited from below by seismic noise and from above by photon shot noise. Furthermore prospects of using crystalline coatings in large scale gravitational wave detectors will be discussed.

Q 1.6 Mon 12:15 a310

Enhancing quantum sensing sensitivity and spectral resolution by a quantum memory — ●SEBASTIAN ZAISER, TORSTEN RENDLER, INGMAR JAKOBI, SAMUEL WAGNER, PHILIPP NEUMANN, and JÖRG WRACHTRUP — 3. Physikalisches Institut, Universität Stuttgart, Deutschland

Measurement of the phase accumulation of a quantum state is central to quantum sensing. Typically, the sensor coherence time (here 400 μ s) limits the timescale for this phase accumulation and hence the energy resolution. Processes occurring on larger timescales can indeed be observed[1]. We employ a small nuclear spin quantum register to store quantum information on timescales of the sensors longitudinal relaxation time (here 5ms). This allows us an increase in frequency resolution by more than one order of magnitude while keeping the full measurement signal. We show that the measurement signal is strongly correlated to the amount of quantum information on the memory qubit by gradually disentangling sensing and memory qubit before the sens-

ing step. We further apply our quantum sensor-memory couple for high resolution NMR spectroscopy of single ^{13}C nuclear spins.

[1] A. Laraoui et al., Nature Communications 4, 1651 (2013), arXiv: 1305.1536

Q 1.7 Mon 12:30 a310

Spectroscopic tests of Lorentz and CPT invariance — ●RALF LEHNERT — Indiana University Center for Spacetime Symmetries,

Bloomington, USA — Leibniz Universität Hannover, Hannover, Germany

Various approaches to new physics allow for the possibility of small departures from Lorentz and CPT symmetry. This talk provides a brief discussion of the identification of suitable experimental tests for these ideas. Emphasis is placed on low-energy high-precision spectroscopic measurements.

Q 2: Ultracold Atoms, Ions and Molecules I (with A)

Time: Monday 11:00–13:00

Location: e001

Q 2.1 Mon 11:00 e001

3D Printed Atom Traps — ●REECE SAINT¹, WILL EVANS¹, YIJIA ZHOU¹, MARK FROMHOLD¹, EHAB SALEH², CHRISTOPHER TUCK², RICKY WILDMANN², MARK HARDY², IAN MASKERY², FEDJIA ORUČEVIĆ¹, and PETER KRÜGER¹ — ¹School of Physics and Astronomy, University of Nottingham, United Kingdom — ²Additive Manufacturing, University of Nottingham, United Kingdom

Atom chip technologies have shown excellent promise as a base in order to probe the physics of quantum gases, but also for the implementation of quantum based sensors in gravimetry [e.g. EU-funded iSense project], nanoTesla sensitive magnetic devices with micrometer resolution and optical cloud based microscopy. Such chips are inherently ultra-high vacuum (UHV) compatible, necessary for long lifetime atom traps. Further these traps rely on highly power consuming and planar "under-structures", required to form and cool the magneto-optical traps (MOT) on which atom-chip based experiments depend; not to mention often cumbersome experimental baggage.

We introduce a different approach, addressing the challenges started above: additive manufacturing (3D Printing). Using an additive process where successive layers of material are laid down allows for almost arbitrary structures to be created; coupling this with modern optimization algorithms to optimize magnetic trapping in terms of power consumption, heat generation, structure robustness and size would substantially improve overall device performance. 3D Printing offers the possibility of integrating electronic, optical or vacuum components, potentially allowing the formation of a fully integrated atom chip device.

Q 2.2 Mon 11:15 e001

A 3d micro-structured trap with low axial micromotion and high field gradients — ●DELIA KAUFMANN, TIMM F. GLOGER, PETER KAUFMANN, MICHAEL JOHANNING, and CHRISTOF WUNDERLICH — Department Physik, Universität Siegen, 57068 Siegen, Germany

We present the status of a second generation 3d micro-structured segmented ion trap with built in solenoids for the creation of inhomogeneous magnetic fields. The new design is based on a trap, which, among other things, was used to demonstrate rf single ion addressing [1] and fault tolerant Hahn-Ramsey-spectroscopy [2]. To overcome the present limitations in terms of finite gradient size and axial micromotion and make it better suitable for the application of MAGnetic Gradient Induced Coupling (MAGIC) [3], and the formation of tailored entangled states [4], the new trap features a redesigned middle layer for lower axial micromotion and improved connectivity for higher solenoid current damage threshold. We discuss the design, simulations and the status of the experimental setup.

[1] D. Kaufmann et al., Appl. Phys. B 107, 935 (2012); D. Kaufmann, PhD thesis, Siegen, 2011.

[2] N. Vitanov et al., Phys. Rev. A 91, 033406 (2015)

[3] Ch. Piltz et al., arXiv:1509.01478 (2015)

[4] S. Zipilli et al., Phys. Rev. A 89, 042308 (2014)

Q 2.3 Mon 11:30 e001

Investigation of hyperfine qubit dephasing in trapped ions — ●THEERAPHOT SRIARUNOTHAI, CHRISTIAN PILTZ, GOURI GIRI, and CHRISTOF WUNDERLICH — Department Physik, Universität Siegen, 57068 Siegen, Germany

Magnetic sensitive hyperfine states of trapped ions that serve as qubits can be protected against decoherence by use of continuous or pulsed dynamical decoupling (e.g., [1]). Nevertheless it is desirable to experimentally identify noise sources and characterize them to enhance the basic stability of experiments in quantum information science. We report on investigations into the dephasing of hyperfine qubits exposed

to a magnetic gradient using trapped $^{171}\text{Yb}^+$ ions confined in a macroscopic linear Paul trap. Effective magnetic field noise caused by the ions' motion in varying electric fields is reduced by minimizing the ions' micromotion and by passively filtering the DC potentials applied to trap electrodes. An active magnetic field compensation system counteracts ambient magnetic noise. The dependence of the fidelity of conditional quantum gates (e.g., CNOT) is investigated as a function of the thermal excitation of the ions' motion in the range between the Doppler cooling limit and close to the motional ground state employing microwave sideband cooling [2-4].

[1] N. Timoney et al., Nature 476, 185 (2011).

[2] C. Ospelkaus et al., Nature 476, 181 (2011).

[3] A. Khromova et al., Phys. Rev. Lett. 108, 220502 (2012).

[4] S. Weidt et al., Phys. Rev. Lett. 115, 013002 (2015).

Q 2.4 Mon 11:45 e001

Feedback-based position stabilisation of microparticles — ●SARAVANAN SENGOTTUVEL, MICHAEL JOHANNING, and CHRISTOPH WUNDERLICH — University of Siegen, Germany

We report on the status of an experiment utilizing feedback for the three-dimensional position stabilization of a charged micro particle. Laser light scattered by the particle illuminates position sensitive detectors and generates an error signal upon displacement of the particle. This error signal is then used to generate a compensating field using correction electrodes. For a particle that is initially trapped in a linear segmented Paul trap, this allows to ramp down and finally switch off the trap and end up with a well localized quasi-free particle. We discuss the approach, potential applications and limitations for sensitivity, position confinement and particle size.

Q 2.5 Mon 12:00 e001

All-optical Atom Trap Trace Analysis for Rare Krypton Isotopes — ●PABLO WOELK¹, MARKUS KOHLER¹, CARSTEN SIEVEKE¹, SIMON HEBEL¹, PETER SAHLING¹, CHRISTOPH BECKER², and KLAUS SENGSTOCK² — ¹Carl Friedrich von Weizsäcker Centre for Science and Peace Research, University of Hamburg, Beim Schlump 83, 20144 Hamburg — ²Institut für Laser-Physik, University of Hamburg, 22761 Hamburg

The isotope Krypton-85 is an excellent indicator for the detection of nuclear reprocessing activities. However, for the analysis of atmospheric air samples, sensitive measuring methods down to the single atom level are required because of the small concentrations. Furthermore, for a practical and effective detection of clandestine reprocessing, small sample sizes and a high sample throughput rate are desirable.

Established methods using Atom Trap Trace Analysis (ATTA) allow high sensitivity but have a limited throughput of about 200 samples per year, since the vacuum chambers have to be flushed for several hours after each measurement to avoid cross contamination due to the RF-driven excitation of metastable states.

Here we present an enhanced ATTA apparatus, which in contrast to the established methods, produces metastable Kr all-optically. This avoids cross contamination, therefore allowing a much higher throughput rate. The apparatus is based on a self-made VUV-lamp and a 2D-3D magneto-optical trap setup. In the 2D trap metastable krypton is produced and a beam of atoms is formed by Doppler-cooling simultaneously.

Q 2.6 Mon 12:15 e001

Quantum simulation of the dynamical Casimir effect with trapped ions — ●NILS TRAUTMANN¹ and PHILIPP HAUKE^{2,3} — ¹Institut für Angewandte Physik, Technische Universität Darmstadt — ²Institut für Quantenoptik und Quanteninformation, Österreichis-

che Akademie der Wissenschaften — ³Institut für Theoretische Physik, Universität Innsbruck

Quantum vacuum fluctuations are a direct manifestation of Heisenberg's uncertainty principle. The dynamical Casimir effect allows for the observation of these vacuum fluctuations by turning them into real, observable photons. However, the observation of this effect in a cavity QED experiment would require the rapid variation of the length of a cavity with relativistic velocities, a daunting challenge. Here, we propose a quantum simulation of the dynamical Casimir effect using an ion chain confined in a segmented ion trap. We derive a discrete model that enables us to map the dynamics of the multimode radiation field inside a variable-length cavity to radial phonons of the ion crystal. We perform a numerical study comparing the ion-chain quantum simulation under realistic experimental parameters to an ideal Fabry–Perot cavity, demonstrating the viability of the mapping. The proposed quantum simulator, therefore, allows for probing the photon (respectively phonon) production caused by the dynamical Casimir effect on the single photon level.

Q 2.7 Mon 12:30 e001

Experimental realization of a single-ion heat engine — •KILIAN SINGER^{1,2}, JOHANNES ROSSNAGEL^{1,2}, SAMUEL THOMAS DAWKINS^{1,2}, FERDINAND SCHMIDT-KALER¹, GEORG JACOB¹, and DAWID CRIWELLI^{1,2} — ¹Quantum, Institut für Physik, Universität Mainz, D-55128 Mainz, Germany — ²Experimentalphysik I, Universität Kassel, Heinrich-Plett-Str. 40, D-34132 Kassel, Germany

Thermodynamic machines can be reduced to the ultimate atomic limit [1], using a single ion as a working agent. The confinement in a linear Paul trap with tapered geometry allows for coupling axial and radial modes of oscillation.

The heat-engine is driven thermally by coupling it alternately to hot

and cold reservoirs, using the output power of the engine to drive a harmonic oscillation [2].

From direct measurements of the ion dynamics, the thermodynamic cycles for various temperature differences of the reservoirs can be determined [3] and the efficiency compared with analytical estimates.

[1] J. Rossnagel et al., "A single-atom heat engine", arXiv:1510.03681

[2] O. Abah et al., Phys. Rev. Lett. 109, 203006 (2012).

[3] J. Rossnagel et al., New J. Phys. 17, 045004 (2015)

Q 2.8 Mon 12:45 e001

Single-ion heat pump — •DAWID CRIWELLI^{1,2}, JOHANNES ROSSNAGEL^{1,2}, SAMUEL THOMAS DAWKINS^{1,2}, FERDINAND SCHMIDT-KALER¹, GEORG JACOB^{1,2}, and KILIAN SINGER^{1,2} — ¹Quantum, Institut für Physik, Universität Mainz, D-55128 Mainz, Germany — ²Experimentalphysik I, Universität Kassel, Heinrich-Plett-Str. 40, D-34132 Kassel, Germany

We will present new concepts of implementing a heat pump with a single atom. Analytical and numerical predictions employing realistic experimental conditions are reviewed together with a new trap design for the implementation. We include a detailed description of the experimental procedure. We build on the results of our previous implementation of a single ion heat engine [1,2,3], inverting the mechanism to realize a heat-pump, transferring heat from the cold to the hot reservoir, induced by an external electric field.

[1] J. Rossnagel et al., "A single-atom heat engine", arXiv:1510.03681.

[2] O. Abah et al., Phys. Rev. Lett. 109, 203006 (2012).

[3] J. Rossnagel et al., New J. Phys. 17, 045004 (2015).

Q 3: Quantum Information: Concepts and Methods I

Time: Monday 11:00–13:00

Location: e214

Q 3.1 Mon 11:00 e214

Testing Bell's inequality with atoms entangled over a distance of 400m — •DANIEL BURCHARDT¹, ROBERT GARTHOFF¹, NORBERT ORTEGEL¹, KAI REDEKER¹, MARKUS RAU¹, WENJAMIN ROSENFELD^{1,2}, and HARALD WEINFURTER^{1,2} — ¹Ludwig-Maximilians-Universität, Munich, Germany — ²Max-Planck-Institut für Quantenoptik, Garching, Germany

Bell's inequality allows to exclude local hidden variable theories and forms the basis for certified generation of random numbers and device-independent quantum key distribution. Experimentally it requires highly efficient and spacelike separated measurements on entangled particles.

We present our approach using heralded entanglement of two neutral ⁸⁷Rb-atoms [1]. Based on state selective ionization and detection of the ionization fragments, we implemented a sub- μ s atomic state readout with very high detection efficiency [2]. To close the locality loophole the two setups were separated by a distance of 400m. We will discuss the critical experimental details, namely the control of the coherence properties of the atoms and the synchronisation of both setups and present first results of a test of Bell's inequality.

[1] J. Hofmann et al., Science 337, 72 (2012).

[2] F. Henkel et al., Phys. Rev. Lett. 105, 253001 (2010).

Q 3.2 Mon 11:15 e214

Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres — •ANDREAS REISERER^{1,2}, BAS HENSEN^{1,2}, HANNES BERNIEN^{1,2}, ANAIS DREAU^{1,2}, NORBERT KALB^{1,2}, MACHIEL BLOK^{1,2}, JUIST RUITENBERG^{1,2}, DAVID ELKOUSS², STEPHANIE WEHNER², TIM TAMINIAU^{1,2}, and RONALD HANSON^{1,2} — ¹Kavli Institute of Nanoscience, TU Delft, The Netherlands — ²QuTech, TU Delft, The Netherlands

More than 50 years ago, John Bell proved that no theory of nature that obeys locality and realism can reproduce all the predictions of quantum theory. Meanwhile, many experiments that violate Bell's inequality have been reported. However, all of these experiments relied on additional assumptions, most prominently the absence of signaling between the entangled particles, and fair-sampling of the full dataset when using inefficient detectors. Closing the *loopholes* that arise from

these assumptions has been one of the major research goals of experimental quantum physics, with applications ranging from device independent quantum key distribution to the certification of random numbers.

In our experiment, we entangle two Nitrogen-vacancy (NV) centers in diamond that are located in independent setups at a distance of 1.3km. Efficient spin read-out avoids the fair-sampling assumption, while the use of fast random-basis selection and spin read-out ensure the required locality conditions. This has enabled us to perform a loophole-free test of Bell's inequality.

Q 3.3 Mon 11:30 e214

Quantum non-demolition measurement enables macroscopic Leggett-Garg tests — •COSTANTINO BUDRONI¹, GIUSEPPE VITAGLIANO², GIORGIO COLANGELO³, ROBERT J. SEWELL³, OTFRIED GÜHNE¹, GEZA TÓTH², and MORGAN W. MITCHELL³ — ¹Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Str. 3, D-57068 Siegen, Germany — ²Department of Theoretical Physics, University of the Basque Country UPV/EHU, P.O. Box 644, E-48080 Bilbao, Spain — ³ICFO – Institut de Ciències Fòtoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels, Barcelona, Spain

We show how a test of macroscopic realism based on Leggett-Garg inequalities (LGIs) can be performed in a macroscopic system. Using a continuous-variable approach, we consider quantum non-demolition (QND) measurements applied to atomic ensembles undergoing magnetically-driven coherent oscillation. We identify measurement schemes requiring only Gaussian states as inputs and giving a significant LGI violation with realistic experimental parameters and imperfections. The predicted violation is shown to be due to true quantum effects rather than to a classical invasivity of the measurement. Using QND measurements to tighten the “clumsiness loophole” forces the stubborn macrorealist to re-create quantum back action in his or her account of measurement.

References

C. Budroni, G. Vitagliano, G. Colangelo, R.J. Sewell, O. Gühne, G. Tóth, and M.W. Mitchell Phys. Rev. Lett. **115**, 200403 (2015)

Q 3.4 Mon 11:45 e214

Quantifying the clumsiness in a Leggett-Garg test — ●GIUSEPPE VITAGLIANO¹, COSTANTINO BUDRONI², GIORGIO COLANGELO³, and MORGAN W. MITCHELL^{3,4} — ¹Department of Theoretical Physics, University of the Basque Country UPV/EHU, P.O. Box 644, E-48080 Bilbao, Spain — ²Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Str. 3, D-57068 Siegen, Germany — ³ICFO – Institut de Ciències Fotoniques, Av. Carl Friedrich Gauss, 3, 08860 Castelldefels, Barcelona, Spain — ⁴ICREA – Institutio Catalana de Recerca i Estudis Avancats, 08015 Barcelona, Spain

Leggett-Garg tests aim to witness macroscopic quantum coherence effects through the violation of an inequality involving correlations among measurements, at different instants of time, of a macroscopic quantity. However, clumsy measurements are able to violate a Leggett-Garg inequality even in absence of genuine quantum effects. We formalise the notion of clumsiness in a Leggett-Garg test and, starting from the simplest examples, we provide a general recipe for computing the clumsiness parameter in any LG test. Finally, we analyse in detail the clumsiness parameter of a recent proposal for a Leggett-Garg test on atomic ensembles via simulations with realistic experimental parameters.

Q 3.5 Mon 12:00 e214

Information Inequalities for Classical and Quantum Networks — ●NIKOLAI MIKLIN¹, RAFAEL CHAVES², and COSTANTINO BUDRONI¹ — ¹Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Str. 3, 57068 Siegen, Germany — ²Institute for Theoretical Physics, University of Cologne, 50937 Cologne, Germany

Causal dependencies among random variables can be investigated via information-theoretic quantities (e.g. Shannon entropy, mutual information, etc.): for unconstrained variables, their entropies form a convex cone and causal dependencies can be added as linear constraints [1]. However, such a method is computationally demanding in the case of restrictions on the observable variables (e.g., latent variables, marginal scenarios), since it involves the projection of the entropy cone via the Fourier-Motzkin method, which has a double exponential complexity [2]. Actual computation has been performed in case of few variables.

To overcome such problems, we develop alternative techniques (e.g. based on adhesivity of entropies [3]) able to completely characterize scenarios with higher number of variables. Finally, we apply these techniques to investigated several new causal structures associated both with classical and quantum scenarios such as Bell scenarios, classical and quantum networks.

[1] R. Chaves, et al. Proc UAI 2014, pp. 112 - 121, AUAI Press, 2014

[2] A. Schrijver, Theory of Linear and Integer Programming, John Wiley & sons, 1998

[3] F. Matúš, Discrete Mathematics 307.21, 2007

Q 3.6 Mon 12:15 e214

Measurement uncertainty is larger than preparation uncer-

tainty — ●REINHARD F. WERNER, KAIS ABDELKHALEK, DAVID REEB, and RENÉ SCHWONNEK — Inst. für Theoret. Physik, Leibniz Universität Hannover

Measurement uncertainty is the quantitative expression of the non-existence of a joint measurement of two observables A and B. It relates the minimal errors one incurs in any attempt at approximate joint measurement and, in particular, in successive measurements like Heisenberg's microscope. This is conceptually different from the usual preparation uncertainty which expresses that there are no states in which both observables have a sharp distribution. Nevertheless, as the new result reported here shows, under very general circumstances preparation uncertainty bounds also give a lower bound on measurement uncertainty. We establish a chain of inequalities involving in decreasing order (1) the errors in a joint measurement based on an approximate quantum cloner (2) the lower bounds on measurement uncertainty, when devices are tested with arbitrary input state (3) the same when the tests are of calibration type, i.e., involve only states with known sharp results for the reference observable and (4) preparation uncertainty. For the standard case of position and momentum (and more generally for observables linked by the Fourier transform on an abelian group) all these inequalities are equalities, but we also give examples showing that each of them may be a proper inequality.

Q 3.7 Mon 12:30 e214

Uncertainty relations for angular momentum — ●LARS DAMMEIER, RENÉ SCHWONNEK, and REINHARD F. WERNER — Institut für Theoretische Physik, Leibniz Universität Hannover

In this talk we present various notions of uncertainty for angular momentum in the spin-s representation of SU(2). This is a natural example of how the concept of uncertainty applies to more than two non-commuting observables. For preparation uncertainty we present a method for computing the trade-off regions, and show results for various values of s. Concerning measurement uncertainty, we optimize a joint measurement of all three components such that the distribution of the projection of the output vector in any direction approximates the distribution of the corresponding angular momentum component.

Q 3.8 Mon 12:45 e214

Measurement uncertainty relations in discrete metric — ●RENÉ SCHWONNEK, LOUIS FRAATZ, KAIS ABDELKHALEK, DAVID REEB, and REINHARD F. WERNER — Institut für Theoretische Physik, Leibniz Universität Hannover

Given two non-commuting sharp observables what is the best joint measurement approximating them? A quantitative answer to such a question is given by a measurement uncertainty relation. In this talk we consider observables with finite outcome spaces and employ the Wasserstein metric to quantify the distance between an approximate observable and a sharp one. We will show how this optimization problem can be solved exactly for arbitrary observables by semi-definite programming. Furthermore, we provide analytic lower bounds on the measurement uncertainty in terms of the norms of certain commutators.

Q 4: Photonics I

Time: Monday 11:00–12:45

Location: f342

Q 4.1 Mon 11:00 f342

High-power mid-infrared high repetition-rate supercontinuum source based on a chalcogenide step-index fiber — ●STEFAN KEDENBURG, TOBIAS STEINLE, FLORIAN MÖRZ, ANDY STEINMANN, and HARALD GIESSEN — 4th Physics Institute and Research Center SCoPE, University of Stuttgart, Germany

We demonstrate a tunable and robust femtosecond supercontinuum source with a maximum output power of 550 mW and a maximum spectral width of up to 2.0 μm which can cover the mid-infrared region from 2.3 μm up to 4.9 μm by tuning the pump wavelength. As light source we use a synchronously pumped fiber-feedback OPO and a subsequent OPA which delivers femtosecond, Watt-level idler pulses tunable between 2.5 μm and 4.1 μm . These pulses are launched into As₂S₃ chalcogenide step-index fibers with core diameters of 7 and 9 μm . The spectral behavior of the supercontinuum is investigated by changing the pump wavelength, core diameter, fiber length, and pump power. Self-phase modulation is identified as the main broadening

mechanism in the normal dispersion regime. This source promises to be an excellent laboratory tool for infrared spectroscopy owing to its high brilliance as demonstrated for the CS₂-absorption bands around 3.5 μm .

Q 4.2 Mon 11:15 f342

Ultrafast all-optical mode conversion in graded-index fibers — ●MARTIN SCHNACK, TIM HELLWIG, and CARSTEN FALLNICH — Institute of Applied Physics, University of Münster, Corrensstraße 2, 48149 Münster

We present experimental results on all-optical transverse mode conversion in graded-index multi-mode fibers. Ultrashort probe pulses are converted from the fundamental mode to the next higher-order modes by optically induced transient long-period gratings¹. Temporally synchronized, high-power subpicosecond control pulses are used to excite a combination of transverse modes in the fiber. By exploiting the Kerr-effect the periodic spatial intensity pattern emerging from

multi-mode interference is translated into a spatial refractive index modulation, transiently inducing the necessary long period grating.

The graded refractive index profile of the fiber allows for the first time to achieve efficient mode conversion using control and probe pulses at separate wavelengths². The probe pulses are thus easily distinguishable by spectral filtering and can be directly visualized. Furthermore, numerical simulations are presented, exhibiting excellent agreement with the experimental results.

¹ Walbaum T., Fallnich C., *Appl. Phys. B* **115**, 225 (2014)

² Schnack M., et. al., *Opt. Lett.* **40**, 4675 (2015)

Q 4.3 Mon 11:30 f342

Investigation of higher-order mode content in Si₃N₄ integrated optical waveguides via spatially and spectrally resolved imaging — ●NIKLAS M. LÜPKEN¹, TIM HELLWIG¹, MARTIN SCHNACK¹, KLAUS-J. BOLLER², and CARSTEN FALLNICH^{1,2} — ¹Institute of Applied Physics, University of Münster — ²MESA+ Institute for Nanotechnology, University of Twente

High-confinement Si₃N₄ integrated optical waveguides have been shown to be highly suitable for ultra-broadband supercontinuum generation¹. Thick waveguides (800 nm × 1000 nm), which are inherently multi-mode, have been identified to feature suitable dispersion for efficient supercontinuum generation. We present a detailed experimental investigation of the excitation of transverse modes in these integrated optical waveguides by characterizing the modal distribution at the output of the waveguide. In our experiment a lensed fiber is scanned transversally over the input facet of the waveguide, giving a position-dependent higher-order mode excitation. The modal content was measured by spatially and spectrally resolved imaging (S² imaging)², being an interferometrically based method and, therefore, sensitive enough to detect even very weak higher-order modes.

The presented measurement system can be used for modal decomposition and optimization of fundamental mode content in integrated optical waveguides. Furthermore, our results show that the higher-order mode content is negligible in the studied waveguides.

¹ Epping JP, et al., *Opt. Express* **23**, 19596 (2015).

² Nicholson JW, et al., *Opt. Express* **16**, 7233 (2008).

Q 4.4 Mon 11:45 f342

A hybrid photonic crystal fibre suitable for photon triplet generation — ●ANDREA CAVANNA¹, FELIX JUST¹, XIN JIANG¹, MARIA V. CHEKHOVA^{1,2,3}, GERD LEUCHS^{1,2}, NICOLAS Y. JOLY^{2,1}, and PHILIP ST.J. RUSSELL^{1,2} — ¹Max Planck Institute for the Science of Light Günther-Scharowsky-Str. 1 Building 24, 91058 Erlangen, Germany — ²University of Erlangen-Nürnberg, Staudtstr. 7/B2, 91058 Erlangen, Germany — ³Department of Physics, M.V.Lomonosov Moscow State University, Leninskie Gory, 119991 Moscow, Russia

Here we present a hybrid photonic crystal fibre that allows phase-matching for third-harmonic generation, and therefore for triplet photon generation, between fundamental modes only. The fibre features an inner all-solid band-gap microstructure made of high refractive-index glass rod (SF6) embedded in a lower refractive index host (LLF1). This microstructure is part of a larger step-index PCF, where the longer wavelength radiation propagates by total internal reflection, without being perturbed by the all-solid microstructure. Combined with the difference in modal diameters, phase-matching is achieved between fundamental modes. Experimentally, we have observed third harmonic generation between 1521 nm and 507 nm.

Q 4.5 Mon 12:00 f342

Characterising linear optical circuits via phaseless estimation techniques — ●DANIEL SUESS¹, RICHARD KUENG¹, CHRIS SPARROW², CHRISTOPHER HAROLD², JACQUES CAROLAN², ANTHONY LAING², and DAVID GROSS¹ — ¹Institute for Theoretical Physics, University of Cologne, Germany — ²Centre for Quantum Photonics, University of Bristol

Linear-optical circuits may become important elementary building blocks of quantum computers in the future. Especially integrated photonics has the prospect of being scaleable by using technology from chip manufacturing. Here, we present an efficient, robust, and conceptually simple technique for characterising such a chip based on recent advances in low-rank matrix recovery. We also report on a successful experimental implementation using a universal six-mode linear optics chip.

Q 4.6 Mon 12:15 f342

Coherent single photon frequency conversion for long distance quantum networks — ●TIM KROH¹, ANDREAS AHLRICHS¹, OTTO DIETZ¹, ANDREAS W. SCHELL², BENJAMIN SPRENGER¹, and OLIVER BENSON¹ — ¹Department of Physics, Humboldt-Universität zu Berlin, Germany — ²Department of Electronic Science and Engineering, Kyoto University, Japan

For long-distance quantum cryptographic communication it is convenient to use the existing fiber optical network to transmit single flying quantum bits - that are photons. The concept of a quantum repeater enables the establishment of a quantum communication channel even beyond the absorption limit of less than 100 km for single photon transmission by the successive transfer of entanglement over the whole distance while the participating photons will only travel a small fraction.

To set up a quantum information network using quantum repeaters different building blocks such as quantum gates, memories and sources of entangled photons are required. Bright sources of high quality indistinguishable photons only exist so far at shorter wavelengths, e.g. single quantum dots or a spontaneous parametric process in a nonlinear crystal. We tackle that problem by coherently converting the frequency of single photons emitted by these two sources into the telecom band. Recent results will be presented that demonstrate the preservation of non-classical temporal properties of quantum correlated photon pairs.

Q 4.7 Mon 12:30 f342

Nonlinear metamaterials with amplification and absorption — ●SEBASTIAN ERFORT, SASCHA BÖHRKIRCHER, HOLGER CARTARIUS, and GÜNTER WUNNER — 1. Institut für Theoretische Physik, Universität Stuttgart, 70550 Stuttgart, Germany

Although originally discussed in the context of non-Hermitian quantum mechanics, \mathcal{PT} symmetry has been demonstrated experimentally in optics and other areas. Recently, \mathcal{PT} symmetry has also entered the experimental field of metamaterials [1]. The investigation of polarization eigenstates of metasurfaces with anisotropic absorption has revealed \mathcal{PT} symmetry breaking at a critical coupling strength of the two orthogonal orientations of the dipoles. Investigations so far have been restricted to linear wave propagation in metasurfaces. In our work we extend this to nonlinear metamaterials and investigate this extension with examples composed of split ring resonators or optical breather setups. We will study the influence of the nonlinearity in both cases.

[1] M. Lawrence, et al., *Phys. Rev. Lett.* **113**, 093901 (2014)

Q 5: Quantum Optics I

Time: Monday 11:00–13:00

Location: f442

Q 5.1 Mon 11:00 f442

Towards the Realization of a Vacuum-Ultraviolet Photon Bose-Einstein Condensate — ●CHRISTIAN WAHL, RUDOLF BRAUSEMANN, JOHANNES KOCH, STAVROS CHRISTOPOULOS, and MARTIN WEITZ — University of Bonn, Germany

We propose a new approach for photon Bose-Einstein condensation, based on thermalisation of photons in a noble gas filled optical microcavity, suitable for the vacuum-ultraviolet spectral regime, i.e. in the 100-200nm wavelength regime. While current experiments on photon Bose-Einstein condensation use thermalisation of photons in a dye so-

lution filled optical microcavity in the visible spectral regime [1], we plan to use absorption re-emission cycles on the transition from the ground to the lowest electronically excited state of noble gases, e.g. xenon, for thermalisation. In order to achieve a sufficient spectral overlap between the lowest atomic absorption and the di-atomic excimer emission, centered at 147nm and 170nm respectively [2], a noble gas pressure of up to 60 bar will be created inside the cavity. We are currently in the process of setting up an experiment to study absorption and emission spectra at the relevant noble gas pressures in the vacuum-ultraviolet regime. Current experimental progress will be

reported.

References:

- [1]: J. Klaers et al. *Nature* 468, 545-548 (2010)
 [2]: M. Kink et al. *Physica Scripta* 45, 79-82 (1992)

Q 5.2 Mon 11:15 f442

Dissipative Two-Mode Tavis-Cummings Model with Time-Delayed Feedback Control — ●WASSILIJ KOPYLOV¹, MILAN RADONJIĆ^{2,3}, TOBIAS BRANDES¹, ANTUN BALAZ³, and AXEL PELSTER⁴ — ¹Institut für Theoretische Physik, TU Berlin — ²Faculty of Physics, University of Vienna, Austria — ³Institute of Physics Belgrade, University of Belgrade, Serbia — ⁴Physics Department and Research Center OPTIMAS, TU Kaiserslautern

We investigate the dynamics of a two-mode laser system by extending the two-mode Tavis-Cummings model [1] with dissipative channels and incoherent pumping and by applying the mean-field approximation in the thermodynamic limit [2]. To this end we analytically calculate up to four possible non-equilibrium steady states (fixed points) and determine the corresponding complex phase diagram. Various possible phases are distinguished by the actual number of fixed points and their stability. In addition, we apply three time-delayed Pyragas feedback control schemes [3,4]. Depending on the time delay and the strength of the control term this can lead to the stabilization of unstable fixed points or to the selection of a particular cavity mode that is macroscopically occupied.

- [1] W. Kopylov, M. Radonjić, T. Brandes, A. Balaz, and A. Pelster, *Phys. Rev. A* (in press), arXiv:1507.01811
 [2] M. Tavis and F.W. Cummings, *Phys. Rev.* 170, 379 (1968)
 [3] K. Pyragas, *Phys. Lett. A* 170, 421 (1992)
 [4] W. Just, A. Pelster, M. Schanz, and E. Schöll, *Phil. Trans. Roy. Soc. A* 368, 303 (2010)

Q 5.3 Mon 11:30 f442

Quantum phase transition and universal dynamics in the Rabi model — ●RICARDO PUEBLA, MYUNG-JOONG HWANG, and MARTIN B. PLENIO — Institut für Theoretische Physik und IQST, Albert-Einstein-Allee 11, Universität Ulm, D-89069 Ulm, Germany

We consider the Rabi Hamiltonian, which undergoes a quantum phase transition (QPT) despite consisting only of a single-mode cavity field and a two-level atom. We prove QPT by deriving an exact solution in the limit where the atomic transition frequency in the unit of the cavity frequency tends to infinity. The effect of a finite transition frequency is studied by analytically calculating finite-frequency scaling exponents as well as performing a numerically exact diagonalization. Going beyond this equilibrium QPT setting, we prove that the dynamics under slow quenches in the vicinity of the critical point is universal; that is, the dynamics is completely characterized by critical exponents. Our analysis demonstrates that the Kibble-Zurek mechanism can precisely predict the universal scaling of residual energy for a model without spatial degrees of freedom. Moreover, we find that the onset of the universal dynamics can be observed even with a finite transition frequency.

Q 5.4 Mon 11:45 f442

The Quantum Pulse Gate - A versatile non-linear platform for quantum optics — MARKUS ALLGAIER¹, ●VAHID ANSARI¹, VIKTOR QUIRING¹, RAIMUND RICKEN¹, LINDA SANSONI¹, BENJAMIN BRECHT^{2,1}, and CHRISTINE SILBERHORN¹ — ¹Universität Paderborn, Integrierte Quantenoptik, Warburger Str. 100, D-33098 Paderborn — ²Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, UK

We present experimental results and methods on the Quantum Pulse Gate (QPG) recently introduced [1]. The QPG relies on group-velocity matched, dispersion-engineered sum-frequency generation in Lithium-Niobate waveguides. By being able to select a single Schmidt mode from a multimode quantum state in the telecom regime and convert it into the visible range it offers operation on time-frequency modes recently established as a framework for Quantum Information Processing [2]. Moreover, the QPG allows efficient real-time temporal characterization of single photons with a resolution as short as 150 femtoseconds.

- [1] B. Brecht, et al., *Phys. Rev. A* 90, 030302(R) (2014)
 [2] B. Brecht, et al., *Phys. Rev. X* 5, 041017 (2015)

Q 5.5 Mon 12:00 f442

A Source for Mesoscopic Quantum Optics — ●JOHANNES TIEDAU¹, GEORG HARDER¹, ADRIANA E. LITA², SAE W. NAM², THOMAS GERRITS², TIM J. BARTLEY^{1,2}, and CHRISTINE

SILBERHORN¹ — ¹Universität Paderborn, Integrierte Quantenoptik, Warburger Str. 100, D-33098 Paderborn — ²National Institute of Standards and Technology, Boulder, CO 80305, USA

Parametric down-conversion (PDC) is an established process to generate non-classical states. We present the generation of large, two-mode states in a single spatio-spectral mode from pulsed, single-pass (type II) PDC. Using transition edge sensors, we measure photon number correlations up to 80 photons in each of the two modes, allowing us to calculate correlation functions up to 40th order and herald non-classical distributions with 50 photons per pulse. We achieve these results with 64% detection efficiency in the telecom regime. The mode definition of this source is ideal for non-Gaussian measurements without requiring additional filtering.

Q 5.6 Mon 12:15 f442

Quantum State Tomography for Optical Soliton Molecules — ●OSKAR SCHLETTWEIN, KAI BARNSCHIEDT, JAKOB STUDER, and BORIS HAGE — Arbeitsgruppe Experimentelle Quantenoptik, Institut für Physik, Universität Rostock, D-18059 Rostock, Germany

Bright pulses in optical fibers mainly experience dispersion, the Kerr-effect as well as (stimulated) Brillouin and Raman scattering. The scattering processes introduce phase noise which becomes important for applications at or below the shot noise limit. In contrast to Brillouin scattering the impact of the Raman effect on quantum states is not clear. Numerical simulation as well as a quantum state tomographic setup for bright pulsed signals will be presented to provide deeper insight about it. The setup allows a full quantum state reconstruction of Kerr squeezed states.

Utilizing dispersion managed (DM) fibres the quantum state of DM-solitons can be studied. Extending our system to a two mode quantum state tomograph will lead the way to probe quantum correlations in soliton molecules. This stable configuration of two or more DM-solitons could provide a fruitful source for new fiber based quantum communication application.

Q 5.7 Mon 12:30 f442

Low-noise quantum frequency down-conversion of indistinguishable photons — ●BENJAMIN KAMBS¹, JAN KETTLER², MATTHIAS BOCK¹, JONAS BECKER¹, CARSTEN AREND¹, MICHAEL JETTER², PETER MICHLER², and CHRISTOPH BECHER¹ — ¹Fachrichtung 7.2 (Experimentalphysik), Universität des Saarlandes, Campus E 2.6, 66123 Saarbrücken, Germany — ²Institut für Halbleitertechnik und Funktionelle Grenzflächen, Research Centers SCoPE and IQST, University of Stuttgart, Allmandring 3, 70569 Stuttgart, Germany

Single-photon sources based on quantum dots have been shown to exhibit almost ideal properties such as high brightness and purity in terms of clear anti-bunching and high two-photon interference visibilities of the emitted photons. In order to prepare them for quantum communication applications including long-haul photon transmission via optical fibers, quantum frequency down-conversion (QFDC) has been used to alter the wavelength of single photons to the telecom wavelength range while conserving their nonclassical properties. Here we present experimental results on QFDC of single photons emitted by a p-shell excited InAs/GaAs quantum dot at 903.6 nm. The fluorescence photons were down-converted to 1557 nm with an efficiency >25%. An indistinguishability measurement revealed two-photon interference contrasts of more than 40% prior to and after the down-conversion. As a result, we demonstrate that our scheme preserves photon indistinguishability and can be used to establish a versatile source of indistinguishable single photons at the telecom C-Band.

Q 5.8 Mon 12:45 f442

Quantum imaging via frustrated two photon generation — ●AXEL HEUER and FLORIAN KRAUSE — Experimentelle Quantenphysik, Institut für Physik und Astronomie, Universität Potsdam, D-14469 Potsdam, Germany

Recently, G. B. Lemos et al. [1] presented a quantum imaging setup which allows for image reconstruction using single photons which do not interact with the object. The basic concept of this imaging setup is induced coherence without stimulated emission between two separately pumped nonlinear down-conversion crystals. Here we introduce a related quantum imaging scheme based on frustrated two photon generation [2]. Our setup uses a single down-conversion crystal in conjunction with mirrors. The down converted signal and idler photons as well as the pump light are back-reflected into the crystal by

three different mirrors, one for each beam. The arrangement allows for two indistinguishable paths, forwards and reflected beam, by which a photon pair can be created. If both paths are overlapped and the time delays are equal, the interference between these alternative ways produces suppression or enhancement of the pair creation. This interference can be detected in coincidence as well as a single photon signal

with one detector only. Imaging is achieved by placing an object in the return path of either the signal or the idler photons.

[1] G. B. Lemos, V. Borish, G. D. Cole, S. Ramelow, R. Lapkiewicz and A. Zeilinger, *Nature* (London) 512, 409 (2014).

[2] T. J. Herzog, J.G. Rarity, H. Weinfurter and A. Zeilinger, *PRL* 72, 629 (1994)

Q 6: Precision Measurements and Metrology II (with A)

Time: Monday 14:30–16:15

Location: a310

Q 6.1 Mon 14:30 a310

Atom-chip fountain gravimeter — ●SVEN ABEND¹, MARTINA GEBBE², MATTHIAS GERSEMANN¹, HAUKE MÜNTINGA², HOLGER AHLERS¹, CLAUS LÄMMERZAHL², WOLFGANG ERTMER¹, ERNST M. RASEL¹, and QUANTUS TEAM^{1,2,3,4,5,6,7} — ¹Institut für Quantenoptik, LU Hannover — ²Zarm, U Bremen — ³Institut für Physik, HU Berlin — ⁴Institut für Laser-Physik, Hamburg — ⁵Institut für Quantenphysik, U Ulm — ⁶Institut für angewandte Physik, TU Darmstadt — ⁷Institut für Physik, JGU Mainz

We developed a simple but effective method to coherently relaunch atoms by a combination of double Bragg diffraction and Bloch oscillations in a single retro-reflected light field. This method provides a novel tool for atomic quantum sensors extending the free fall time without increasing their complexity. We demonstrate an atom-chip fountain gravimeter utilizing ultracold atoms, where all necessary atom-optics operations are realized by the atom-chip, including condensation, magnetic transfer and delta-kick cooling. The atom-chip itself even acts as a retro-reflector in vacuum for the beam splitter as inertial reference for gravity. This implementation allows for high contrast interferometry over tens of milliseconds in a volume as little as one centimeter cube, paving the way for measurements with sub- μ Gal accuracies in miniaturized devices.

This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry for Economic Affairs and Energy (BMWi) due to an enactment of the German Bundestag under grant numbers DLR 50WM1552-1557 (QUANTUS-IV-Fallturm).

Q 6.2 Mon 14:45 a310

Atom interferometry with Bose-Einstein condensates on sounding rockets — ●DENNIS BECKER, MAIKE LACHMANN, STEPHAN SEIDEL, and ERNST RASEL — Institut für Quantenoptik, Leibniz Universität Hannover

The universality of free fall is one of the fundamental postulates of our description of nature. The comparison of the free fall of two ultra-cold clouds of different atomic species via atom interferometry comprises a method to precisely test this assumption. By performing the experiments in a microgravity environment the sensitivity of such an atom interferometric measurement can be increased. In order to fully utilize the potential of these experiments the usage of a Bose-Einstein condensate as the initial state of the atom interferometer is necessary.

As a step towards the transfer of such a system in space an atom optical experiment is currently being prepared as the scientific payload for a sounding rocket mission. This mission is aiming at the first demonstration of a Bose-Einstein condensate in space and using this quantum degenerate matter as a source for atom interferometry. The launch of the rocket is planned for 2016 from ESRANGE. This first mission will be followed by two more that extend the scientific goals to the creation of degenerate mixtures in space and simultaneous atom interferometry with two atomic species. Their success would mark a major advancement towards a precise measurement of the universality of free fall with a space-born atom interferometer.

Q 6.3 Mon 15:00 a310

Advances towards a T^3 -interferometer — ●MATTHIAS ZIMMERMANN¹, MAXIM A. EFREMOV¹, WOLFGANG P. SCHLEICH¹, SARA A. DESAVAGE², JON P. DAVIS², FRANK A. NARDUCCI², and ERNST M. RASEL³ — ¹Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQST), Universität Ulm, 89081 Ulm, Germany — ²EO Sensors Division, Naval Air Systems Command, Patuxent River, MD 20670, USA — ³Institut für Quantenoptik, Leibniz Universität Hannover, 30167 Hannover, Germany

We present the theoretical background for and the progress on a novel atom interferometer with a phase shift scaling as T^3 in contrast to

conventional atom interferometers with a scaling of T^2 [1]. Here T denotes the travelling time of the atoms in-between two Raman pulses. These pulses prepare a superposition of two magnetic sublevels while an external magnetic field is applied to imprint two different effective accelerations g_1 and g_2 for these two states [2]. A sequence consisting of four Raman pulses is used to close the interferometer and to obtain the T^3 -scaling. Due to the position-dependent Zeeman shift the atomic resonance frequency changes throughout the experiment and the laser frequency has to be chirped in order to stay in resonance.

[1] W.P. SCHLEICH, D.M. GREENBERGER, and E.M. RASEL, *New J. Phys.* **15**, 013007 (2013)

[2] J.P. DAVIS and F. A. NARDUCCI, *J. Mod. Opt.*, **55**, 3173 (2008)

Q 6.4 Mon 15:15 a310

Quantum Test of the Universality of Free Fall with a Dual Species Atom Interferometer — ●LOGAN RICHARDSON, HENNING ALBERS, DIPANKAR NATH, DENNIS SCHLIPPERT, CHRISTIAN SCHUBERT, WOLFGANG ERTMER, and ERNST RASEL — Institut für Quantenoptik and

Centre for Quantum Engineering and Space-Time Research - QUEST, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany

To understand gravity's role within the standard model, we can test for violations of the universality of free fall with dual-species atom interferometers [1]. To constrain possible violations we require accurate local gravitational acceleration measurements of both test masses. Vibrations can however corrupt these measurements by inducing phase shifts, masking any possible violation signal and fundamentally limiting the sensitivity of the experiment. Correlation of atomic interferometers with a classical sensor can provide a phase shift correction for vibrationally induced noise[2]. We discuss the experimental results of the application of this method into our dual species $^{87}\text{Rb} - ^{39}\text{K}$ interferometer, as well as the strategy for the upcoming large scale $^{87}\text{Rb} - ^{170}\text{Yb}$ interferometer[3]

[1] D. Schlippert et al., *Phys. Rev. Lett.* **112**, 203002 (2014)

[2] B. Barrett et al., *New Journal of Physics*, **17**, 085010 (2015)

[3] J. Hartwig et al., *New J. Phys.* **17**, 035011 (2015)

Q 6.5 Mon 15:30 a310

Quantum Test of the Universality of Free Fall in small and large scale devices — ●HENNING ALBERS, CHRISTIAN MEINERS, DIPANKAR NATH, LOGAN L. RICHARDSON, DENNIS SCHLIPPERT, CHRISTIAN SCHUBERT, ETIENNE WODEY, WOLFGANG ERTMER, and ERNST M. RASEL — Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover

The foundation of general relativity is constituted by Einstein's equivalence principle, which is based on three postulates. One of them is the Universality of Free Fall (UFF), which can be tested by observing the free fall motion of a pair of test masses. Those tests have reached high precision with macroscopic objects [1].

The development of atom optics gives access to new types of inertial sensors to test fundamental physics. By comparing the differential acceleration measured by a simultaneous dual species Mach-Zehnder type atom interferometer we perform a quantum test of the UFF employing the two chemical elements, ^{39}K and ^{87}Rb [2]. We show the latest results as well as the improvements of the experiment aiming towards a test at a ppb uncertainty. To reach this level we will increase the stability and accuracy of the apparatus by using a dipole trap. Another step towards higher sensitivity will be the upscaling towards the 10 m Very Long Baseline Atom Interferometer (VLBAI) apparatus working with Rb and Yb[3].

[1] J. Müller et al., *Class. Quantum Grav.* **29** 184006 (2012)

[2] D. Schlippert et al., *Phys. Rev. Lett.* **112**, 203002 (2014)

[3] J. Hartwig et al., *New J. Phys.* 17, 035011 (2015)

Q 6.6 Mon 15:45 a310

Towards a new generation of high-performance operational quantum sensors — ●JEAN LAUTIER-GAUD, VINCENT MÉNORET, PIERRE VERMEULEN, JEAN-FRANÇOIS SCHAFF, GUILLAUME STERN, CÉDRIC MAJEK, MATHIEU GUÉRIDON, and BRUNO DESRUELLE — Muquans, SAS, rue François Mitterrand 33400 Talence France

After 30 years of academic research in cold atom sciences, intensive developments are being conducted to improve the compactness and the reliability of experimental set-ups. One of the main objectives is to transfer such high-sensitivity experiments from laboratory-based research to an operational utilization outside of the laboratory. This will allow non-specialists and other areas of research to benefit from the outstanding advantages and the measurement capabilities that cold atoms offer. We will present the long-lasting developments that we have been carrying to provide the first industrial cold-atom absolute gravimeter and the first industrial cold-atom atomic clock. We will present the principles of operation and the main features of our instruments. Their performances in terms of sensitivity, stability, and accuracy, as well as the latest results they achieved will be reviewed. High-performance frequency-stabilized laser systems are one of the key technological elements to manipulate cold atoms, and they set the quality of the measurements. Muquans now turned these into benchtop reliable turnkey solutions dedicated to scientists eager to reach faster

their scientific objectives. Such laser systems have been qualified on our own cold atom instruments, and a specific focus on our latest developments in this area in terms of performances will be proposed.

Q 6.7 Mon 16:00 a310

Dark energy search using atom interferometry — ●PHILIPP HASLINGER¹, MATT JAFFE¹, PAUL HAMILTON², JUSTIN KHOURY³, and HOLGER MÜLLER¹ — ¹University of California, Berkeley, CA 94720, USA — ²University of California, Los Angeles, CA 90095, USA — ³University of Pennsylvania, Philadelphia, PA 19104, USA

If dark energy, which drives the accelerated expansion of the universe, consists of a light scalar field it might be detectable as a "fifth force" between normal-matter objects. In order to be consistent with cosmological observation and laboratory experiments, some leading theories use a screening mechanism to suppress this interaction. However, atom-interferometry presents a tool to reduce this screening [1] and has allowed us to place tight constraints on a certain class of these theories, the so-called chameleon models [2]. Recent modifications to our cavity-enhanced atom interferometer have improved the sensitivity by a hundredfold and we expect new results soon.

[1] C. Burrage, E. J. Copeland, E. A. Hinds, Probing dark energy with atom interferometry. *J. Cosmol. Astropart. Phys.* 2015, 042 (2015). [2] P. Hamilton, M. Jaffe, P. Haslinger, Q. Simmons, H. Müller, and J. Khoury, Atom-interferometry constraints on dark energy. *Science* 349, 849 (2015).

Q 7: Ultracold Atoms, Ions and Molecules II (with A)

Time: Monday 14:30–16:30

Location: e001

Q 7.1 Mon 14:30 e001

Non-Equilibrium Thermodynamics of Harmonically Trapped Bosons — ●THOMAS FOGARTY^{1,4}, MIGUEL ANGEL GARCIA-MARCH², STEVE CAMPBELL³, THOMAS BUSCH⁴, and MAURO PATERNOSTRO³ — ¹Theoretische Physik, Universität des Saarlandes, Saarbrücken, Germany — ²ICFO Institut de Ciències Fotòniques, Spain — ³CTAMOP, School of Mathematics and Physics, Queen's University Belfast, United Kingdom — ⁴Quantum Systems Unit, Okinawa Institute of Science and Technology Graduate University, Okinawa, Japan

Trapped ensembles of bosonic atoms represent an ideal candidate to simulate some of the most interesting aspects in the phenomenology of out-of-equilibrium quantum systems. In this talk I will focus on harmonically trapped bosons and use the framework of non-equilibrium thermodynamics to study the role quantum features play in setting the dynamic and static properties of the systems when the Hamiltonian parameters are suddenly quenched. Through a combination of analytical and numerical approaches I explore the non-trivial dynamics that arise from the interplay between the quenched trap frequency and an induced quench of the inter-particle interactions. Interesting quantum phenomena such as Anderson's Orthogonality catastrophe will be explored in this framework. I will further show some qualitative evidence for the relationship between the creation of entanglement and the (irreversible) work performed on the system. This highlights interesting connections between the degree of inter-particle entanglement and their non-equilibrium thermodynamics.

Q 7.2 Mon 14:45 e001

Probing reflectionless potentials via atomic dynamics — ●MARTIN LAHRZ and LUDWIG MATHEY — University of Hamburg, Hamburg, Germany

We explore how reflectionless potentials can be probed via atomic dynamics. If a quantum mechanical wave package passes through a potential, ordinarily, a finite fraction of it gets reflected. However, in special cases, e.g. for specific Pöschl-Teller potentials, the reflection is zero and the full object is transmitted. We investigate the influence of the reflectionless potential on the outgoing wave function and compare it with the propagation of the free particle. This scenario might be realized in an ultra-cold atom system where the potential is represented by an optical trap.

Q 7.3 Mon 15:00 e001

Two-dimensional Quantum Walks of Neutral Atoms in Spin-dependent Optical Lattices — ●GEOL MOON, STEFAN BRAKHANE, VOLKER SCHILLING, CARSTEN ROBENS, WOLFGANG ALT, DIETER

MESCHÉDE, and ANDREA ALBERTI — IAP institute - Wegelerstr. 8 - D-53115 Bonn

We report on the experimental realization of a two-dimensional spin-dependent optical lattice, which we will use to implement discrete-time quantum walks of Cs atoms in a two-dimensional geometry. We demonstrate high-resolution images of single atoms, which we detect through an objective lens with very high numerical aperture ($NA \sim 0.92$), which we designed and installed inside the home-built ultra-low-birefringence dodecagonal vacuum glass cell [1]. Our system provides an ideal platform to study the topological features of 2D quantum walk as the simulator of topological phases [2], which can be realized by suitable choice of the coin operation. We expect to observe exotic matter wave flow at the boundary between different topological domains. Furthermore, controlling the phase accumulated when atoms move from site to site on the 2D lattice permits to realize artificial gauge fields and to study the effect of magnetic fields on the 2D quantum walk [3].

[1] S. Brakhane, et al., *Ultra-low birefringence dodecagonal vacuum glass cell*, Submitted to *Rev. Sci. Instrum.* (2015)

[2] T. Kitagawa, et al., *Exploring topological phases with quantum walks*, *Phys. Rev. A* **82**, 033429 (2010)

[3] P. Arnault and F. Debbasch, *Quantum Walks and discrete Gauge Theories*, arXiv:1508.00038 (2015)

Q 7.4 Mon 15:15 e001

Quantum Walks with Neutral Atoms: A look into the motion of a quantum particle — CARSTEN ROBENS, STEFAN BRAKHANE, WOLFGANG ALT, DIETER MESCHÉDE, and ●ANDREA ALBERTI — Institut für Angewandte Physik, Universität Bonn – Wegelerstr. 8, 53115 Bonn

I will present quantum walk experiments performed with neutral atoms in spin-dependent optical lattices. A cesium atom with two long-lived internal states behaves like a pseudo spin-1/2 particle. Depending on its spin state, the atom moves at regular time steps either one site to the left or to the right, delocalizing over multiple quantum paths. In the limit of vanishing lattice constant, its quantum behavior is described by the one-dimensional Dirac equation. We have recently developed a new spin-dependent transport system, which allows us to spin-selectively shift only one spin species at a time by an arbitrary number of lattice sites. The new atom transport system allows us to carry out interaction-free measurements of the atom's position, which we used to exclude (i.e., falsify) any explanation of quantum transport based on classical, well-defined trajectories [1]. To put it into perspective, our experiment represents the most massive test of quantum superposition states that has been hitherto performed based on the

stringent, objective criteria provided by the Leggett-Garg inequality.

[1] C. Robens et al. *Ideal Negative Measurements in Quantum Walks Disprove Theories Based on Classical Trajectories*, Phys. Rev. X **5**, 011003 (2015).

Q 7.5 Mon 15:30 e001

Half-life times of topological modes of a Bose-Einstein condensate in a gravito optical surface trap — ●ZELIMIR MAROJEVIC, ERTAN GÖKLÜ, and CLAUS LÄMMERZAHN — ZARM, Am Fallturm, 28359 Bremen

We have numerically estimated the half-life times of six topological modes in an axially symmetric gravito optical surface trap $V(\rho, z) = \nu^2 \rho^2 + \beta z$. The topological modes are solutions to the stationary Gross-Pitaevskii equation, which correspond to min-max saddle points of the functional, and these solutions are dynamically unstable. Due to the non linear nature of the problem the time evolution of a small perturbation is very complicated and shows different phases.

Q 7.6 Mon 15:45 e001

News from the Garching $^{23}\text{Na}^{40}\text{K}$ mixture experiment — ●FRAUKE SEESSELBERG¹, NIKOLAUS BUCHHEIM¹, ZHENKAI LU¹, ROMAN BAUSE¹, TOBIAS SCHNEIDER¹, IMMANUEL BLOCH^{1,2}, and CHRISTOPH GOHLE¹ — ¹Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching, Germany — ²Ludwig-Maximilians-Universität, Schellingstraße 4, 80799 München, Germany

Ultracold quantum gases with long-range dipolar interactions promise exciting new possibilities for quantum simulation of strongly interacting many-body systems. Our experimental apparatus is capable of creating ultracold sodium and potassium mixtures aiming towards ultracold groundstate $^{23}\text{Na}^{40}\text{K}$ molecules.

To obtain molecules in their absolute vibrational, rotational and hyperfine ground state, stimulated Raman adiabatic passage (STIRAP) has to be implemented. This is a two photon process capable of transferring weakly bound Feshbach molecules via an intermediate, excited molecular state to the molecular ground state with high efficiency.

With our apparatus we are also capable of analyzing the properties of a small number of potassium atoms immersed into a degenerate Bose gas of sodium atoms. Under these conditions signatures of the Bose polaron can be observed.

Q 7.7 Mon 16:00 e001

Inelastic collisions of strongly confined triplet Rb₂ molecules

— ●MARKUS DEISS¹, BJÖRN DREWS¹, KRZYSZTOF JACHYMSKI^{2,3}, ZBIGNIEW IDZIASZEK², and JOHANNES HECKER DENSCHLAG¹ — ¹Institut für Quantenmaterie, Universität Ulm, 89069 Ulm, Germany — ²Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland — ³Institut für Theoretische Physik III, Universität Stuttgart, 70550 Stuttgart, Germany

We present experimental studies of inelastic collisions of metastable ultracold triplet molecules in the vibrational ground state. The measurements are performed with nonpolar Rb₂ dimers which are trapped in an array of quasi-1D potentials and prepared in precisely-defined quantum states. Using a simple model we can understand the molecular decay dynamics and extract reaction rate coefficients. We will show results both for nonrotating molecules that are prepared in the energetically absolutely lowest triplet hyperfine level and molecules with two quanta of rotational angular momentum. These results are compared to those obtained for vibrationally highly excited Feshbach molecules.

Q 7.8 Mon 16:15 e001

Non-destructive rotational state detection for molecular ions — ●FABIAN WOLF¹, YONG WAN¹, JAN C. HEIP¹, FLORIAN GEBERT¹, CHUNYAN SHI¹, and PIET O. SCHMIDT^{1,2} — ¹Physikalisch-Technische Bundesanstalt, Braunschweig, Germany — ²Leibniz Universität Hannover, Germany

High precision spectroscopy of molecular ions is a promising tool for the investigation of fundamental physics, e.g. the search for variation of fundamental constants, an electron electric dipole moment or parity violation in chiral molecules. However, the practical implementation has remained illusive due to the lack of efficient state preparation and detection schemes. Here, we present the first demonstration of a non-destructive rotational state detection for a single molecular ion trapped in a linear Paul trap [1]. For this purpose, we implement a quantum logic operation between the molecular $^{24}\text{MgH}^+$ ion and a co-trapped atomic $^{25}\text{Mg}^+$ logic ion.

The experimental sequence consists of sympathetic ground state cooling with the logic ion [2] and a state dependent optical dipole force that transfers the molecule's internal state to the shared state of motion. Afterwards, the motional state is mapped onto the atomic qubit state, that can be detected efficiently by state dependent fluorescence. We use this technique to perform a variant of quantum logic spectroscopy on a molecular transition.

[1] Wolf et al. arXiv:1507.07511 (2015)

[2] Wan et al. Phys. Rev. A **91**, 043425 (2015)

Q 8: Quantum Information: Concepts and Methods II

Time: Monday 14:30–16:30

Location: e214

Q 8.1 Mon 14:30 e214

Quantum Complexity Classes with Disturbed Witnesses — ●FRIEDRIKE ANNA DZIEMBA and TOBIAS OSBORNE — Institut für Theoretische Physik, Leibniz Universität Hannover, Germany

Quantum complexity theory categorizes computational problems into complexity classes characterized by a specific type of quantum protocol. The most famous classes are formed by the problems that can be solved efficiently by a quantum computer (class BQP) and the problems that can be verified efficiently by a quantum computer provided with a so-called witness which can either be a quantum or a classical state (classes QMA or QCMA).

We consider these three classes as variants of a complexity class defined by an efficient quantum protocol and a witness that is sent through a parametrized quantum channel. Depending on the noise the channel introduces into the witness we reobtain either the class QMA, QCMA or BQP. Thresholds for the channel parameter guaranteeing one of these cases allow for new characterizations of the standard complexity classes.

Q 8.2 Mon 14:45 e214

Practical applications of compressed sensing in quantum state tomography — ●CARLOS RIOFRIO, ADRIAN STEFFENS, and JENS EISERT — Dahlem center for complex quantum systems, Freie Universität Berlin, 14195 Berlin, Germany.

As quantum systems get closer to technological applications, the problem of identifying, certifying, and characterizing them becomes more daunting. In fact, a complete characterization of a quantum system

requires determining a number of parameters that grow exponentially with the system size. New paradigms that allow for efficient signal processing must be developed and tested to overcome this roadblock. In this talk, we present an overview of the most recent developments in quantum state tomography via compressed sensing. We show a complete analysis based on experimental data from two different systems: First, a photonic circuit that prepares highly entangled photons corresponding to 4-qubit states, which we use as a testbed to showcase our tomographic procedure in a variety of scenarios; Second, a 7-qubit system of trapped ions which encodes a single logical qubit via a color code, in which highly incomplete data is observed. We show how compressed sensing and model selection ideas can be combined, which is necessary in practice when little information is available.

Q 8.3 Mon 15:00 e214

Heisenberg-Weyl basis observables and related applications — ●ALI ASADIAN¹, PAULI ERKER², OTFRIED GUEHNE¹, MARCUS HUBER², and CLAUDIO KLOECKL² — ¹Naturwissenschaftlich-Technische Fakultät, Walter-Flex-Straße 3, Siegen, Germany — ²Universitat Autònoma de Barcelona, 08193 Bellaterra, Barcelona, Spain

The Bloch vector provides a very useful geometrical representation of quantum states for characterizing their properties. We establish a new basis of observables constructed by a suitable combination of the non-Hermitian generalization of the Pauli matrices, the Heisenberg-Weyl operators. This allows us to identify a (Hermitian) Bloch representation for an arbitrary density operator of finite, as well as infinite

dimensional systems in terms of complete set of Heisenberg-Weyl observables. Compared to the canonical basis of Gell-Mann operators, the Heisenberg-Weyl based observables exhibit number of advantageous properties which we highlight in the context of entanglement detection.

Q 8.4 Mon 15:15 e214

Testing an axiom of quantum theory: Which measurements are admissible? — ●MATTHIAS KLEINMANN¹ and ADÁN CABELLO² — ¹University of the Basque Country, Bilbao, Spain — ²Universidad de Sevilla, Sevilla, Spain

Quantum theory is not particularly complicated when it comes to the question of admissible measurements: A measurement is admissible as long as it does not contradict the rules of probability. We confront this assumption with an alternative, minimalistic construction, where quantum measurements with any number of outcomes are generated from quantum measurements with only two outcomes. The predictions of this alternative are vastly identical to quantum theory, except for specialized high-precision Bell-like scenarios. In fact, experimental data of such experiments already provide evidence that correlations in nature are not emerging from measurements with only two or three outcomes. In addition, it is also possible to confront quantum theory with another challenge. A large class of generalized models makes predictions that are in conflict with quantum theory and allows for experiments on quantum systems that would rule out such “post-quantum” models.

Q 8.5 Mon 15:30 e214

How long does it take to obtain a physical density matrix? — ●LUKAS KNIPS^{1,2}, CHRISTIAN SCHWEMMER^{1,2}, NICO KLEIN^{1,2}, JONAS REUTER³, GÉZA TÓTH^{4,5,6}, and HARALD WEINFURTER^{1,2} — ¹Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748 Garching — ²Department für Physik, Ludwig-Maximilians-Universität, D-80797 München — ³Bethe Center for Theoretical Physics, Universität Bonn, D-53115 Bonn — ⁴Department of Theoretical Physics, University of the Basque Country UPV/EHU, P.O. Box 644, E-48080 Bilbao, Spanien — ⁵IKERBASQUE, Basque Foundation for Science, E-48013 Bilbao, Spanien — ⁶Wigner Research Centre for Physics, Hungarian Academy of Sciences, P.O. Box 49, H-1525 Budapest, Ungarn

The statistical nature of measurements easily causes unphysical estimates in quantum state tomography. We show that multinomial or Poissonian noise results in eigenvalue distributions converging to the Wigner semicircle distribution for already a modest number of qubits. In this talk, I will show that this fact can be used to specify the number of measurements necessary to avoid unphysical solutions as well as a new approach to convert unphysical estimates into physical ones.

Q 8.6 Mon 15:45 e214

Quantum-enabled measurement of the electric field using Rydberg atoms — ●EVA-KATHARINA DIETSCHKE, ADRIEN FACON, DORIAN GROSSO, SERGE HAROCHE, JEAN-MICHEL RAIMOND, MICHEL BRUNE, and SEBASTIEN GLEYZES — Laboratoire Kastler Brossel, Collège de France, ENS-PSL, UPMC-Sorbonne Université, CNRS, 11 Place Marcelin Berthelot 75005 Paris, France

In the classical world there is no fundamental limit to the precision of a measurement. In quantum mechanics, however, the precision of a measurement is ultimately limited by quantum fluctuations. For instance, the direction of a large angular momentum J prepared in a

coherent spin state cannot be determined with a precision better than $1/\sqrt{J}$, the standard quantum limit (SQL) for this system. A measurement uncertainty below the SQL can only be attained by the use of quantum-enabled metrology techniques. It is then possible to reach the ultimate limit, the Heisenberg limit, which scales as $1/J$.

Here, we present a quantum-enhanced measurement of the electric field using mesoscopic Schrödinger-cat-like superpositions of Rydberg states. The atom behaves like a large angular momentum J whose precession frequency depends on the electric field. Instead of performing a standard Ramsey experiment using a coherent spin state, we prepare the atom in a cat-like state and measure the quantum phase accumulated by the spin during its Ramsey evolution. With this single-atom-electrometer we succeed in measuring field variations in the order of 1mV/cm in 100ns , beating the SQL. The extreme sensitivity of this measurement could pave the way to many practical applications.

Q 8.7 Mon 16:00 e214

Beyond Conventional Photon Counting — ●JOHANNES KRÖGER¹, THOMAS AHRENS¹, JAN SPERLING², BORIS HAGE³, WERNER VOGEL², and HEINRICH STOLZ¹ — ¹Semiconductor Optics Group, University of Rostock, Rostock, Germany — ²Theoretical Quantum Optics Group, University of Rostock, Rostock, Germany — ³Experimental Quantum Optics Group, University of Rostock, Rostock, Germany

Quantum information sciences are heavily depending on photon number resolving measurements. Advancing demands on detector performances go beyond the abilities of state-of-the-art devices. The established high sensitivity detectors operate in a binary detection mode, creating only a click for any number of absorbed photons.

Systems of click detectors, such as APD-arrays, superconducting nanowires or time multiplexed setups, proved convenient and reliable in many recent experiments. We demonstrate, with experimental evidence, that neither is the statistical information acquired with these devices insufficient for discriminating quantum states, nor is the nonlinear detection mode a disadvantage towards true photon counters.

We developed a model for detector characteristics, enabling us to extract vital information about the light field with intensities ranging from few photons to photon numbers higher than the number of detector elements (or time bins). Exposing our 10×10 APD-array to fs-Ti:Sapphire laser pulses, we measured a parameter for indication of quantum light (similar to the Mandel Q parameter) and higher quantum correlations.

Q 8.8 Mon 16:15 e214

Device-Independent Bounding of Detector Efficiencies — ●JOCHEN SZANGOLIES, HERMANN KAMPERMANN, and DAGMAR BRUSS — Institut für Theoretische Physik III, Heinrich-Heine Universität Düsseldorf

In many quantum information applications, a minimum detection efficiency must be exceeded to ensure success. Protocols depending on the violation of a Bell inequality, for instance, may be subject to the so-called detection loophole: imperfect detectors may yield spurious violations, which consequently cannot be used to ensure, say, quantum cryptographic security. Hence, we investigate the possibility of giving lower bounds on detector efficiency even if an adversary has full control over both the source and the detectors. To this end, we present a technique, based on characterizing the polytope of local correlations, to systematically derive Bell inequalities free from the detection loophole whose violation certifies that the detectors used exceed a certain minimal efficiency.

Q 9: Photonics II

Time: Monday 14:30–16:15

Location: f342

Q 9.1 Mon 14:30 f342

Polymer based optics for sensing applications — ●AXEL GÜNTHER, MAHER REZEM, MAIK RAHLVES, and BERNHARD ROTH — Hannover Centre for Optical Technologies, Leibniz Universität Hannover, Nienburger Str. 17, 30167 Hannover

Integrated polymer photonics is highly relevant to various fields in optical technologies ranging from optical communication to integrated sensor networks. Key components for such devices are optical waveguides with propagation losses lower than 1dB/cm as well as highly

efficient coupling structures for light coupling.

We developed a process which allows the realization of fully polymer based low-loss optical waveguides and relies on a hot embossing step to create a micro-structured substrate and cladding layer. In a subsequent doctor blading step, the core material is introduced into the structure. Using a similar process, we also realized integrated grating coupler elements. In addition, to establish rigid and low-loss connections between two optical waveguides or waveguides and laser diodes, we realize all-polymer self-written waveguides (SWW). Here, we use UV curable monomer which is applied to a gap between two optical

components such as fibers, waveguides or light sources. Launching UV light through the fiber or the waveguide leads to local polymerization of the monomer at the end facet, which also increases the refractive index locally and acts as a seed point for the SWW.

In the talk we discuss various application scenarios where our process can be utilized to create highly integrated sensing structures for detection of physical quantities or chemical analytes.

Q 9.2 Mon 14:45 f342

All-polymer optical WGM sensor approach — ●ANN BRITT PETERMANN¹, UWE MORGNER², and MERVE MEINHARDT-WOLLWEBER¹ — ¹Hannover Centre for Optical Technologies (HOT), Leibniz University Hannover, Nienburger Strasse 17, D-30167 Hannover, Germany — ²Institute of Quantum Optics, Leibniz University Hannover, Welfengarten 1, D-30167 Hannover, Germany

Microcavities, which support whispering gallery modes (WGMs) are resonant optical sensors providing high quality factors. In recent years WGM sensors are continuously enhanced with respect to sensitivity and detection limit which is a highly promising feature in molecular analytics. One of the next steps is the implementation of WGM sensors for real-world applications, such as measurement of force and temperature or sensing of biomolecules. To this end, an all polymer WGM-sensor is being realized. For this purpose various polymer specific issues need to be addressed. Among others, the investigation of a suitable geometry of the resonator and a possible supporting structure is important. In an all-polymer device the commonly used excitation of the sensor with a tapered fiber is not possible. One aim is the design of a new coupling structure with high coupling efficiency. The performance of the polymer sensor compared to silica devices is crucial to determine the sensitivity range and the possible applications. Due to the fabrication, the Q-factor of polymer sensors will be smaller than that of silica sensors, which in turn leads to a smaller sensitivity. However, polymer based systems are attractive because of their diversity in refractive index and hydrophobicity and prospective mass fabrication.

Q 9.3 Mon 15:00 f342

Laser-induced volume phase gratings in lithium niobate for noncollinear frequency conversion — ●HAISSAM HANAFI, DENNIS NIEMEIER, SEBASTIAN KROESEN, MOUSA AYOUB, JÖRG IMBROCK, and CORNELIA DENZ — Westfälische Wilhelms-Universität Münster, Institute of Applied Physics, Corrensstr. 2, 48149 Münster, Germany

We demonstrate the fabrication and characterization of direct femtosecond laser written volume diffraction gratings (VDG) for efficient second-harmonic generation (SHG) in x-cut lithium niobate (LiNbO₃). The designed integrated nonlinear beam splitter device allows due to its hybrid architecture to satisfy the noncollinear phase matching condition between the transmitted and diffracted fundamental wave within the crystal. To determine the grating period, grating thickness and refractive index change, we have measured the linear diffraction efficiency of 532 nm cw laser light depending on the incident angle and input-polarization. The nonlinear properties are analyzed by measuring noncollinear phase-matched SHG using femtosecond laser pulses with a wavelength between 1200 nm and 1400 nm. The linear as well as the nonlinear properties are investigated for a large variety of fabrication parameters of the grating, like writing speed, pulse energy, polarization, and writing direction in order to characterize the diffraction properties. Using a laser scanning SHG microscope, the structural modifications are visualized in three dimensions with high spatial resolution. Furthermore, these permanent femtosecond laser-induced gratings were systematically compared with optical erasable gratings, induced by cw laser light using the photorefractive effect in LiNbO₃:Fe.

Q 9.4 Mon 15:15 f342

Theoretical description of all-optically induced, transient long period gratings — ●TIM HELMWIG, KAI SPARENBERG, and CARSTEN FALLNICH — Institute of Applied Physics, University of Münster, Corrensstrasse 2, 48149 Münster, Germany

A theoretical model is developed for transverse mode conversion at all-optical long-period gratings¹ transiently induced via multimode interference of a control beam and the optical Kerr-effect. An analytic expression for the resulting directed energy exchange of two transverse probe beam modes is derived in a material representation, in analogy to coupled mode theory, as well as in a four-wave mixing representation. The developed continuous-wave model gives insight into the all-optical mode conversion process and shows excellent agreement to existing numerical simulations. Even for pulsed probe and control

beams very good agreement to a corresponding numerical simulation² is found, when the occurring group-walk offs are negligible in comparison to the conversion length of the process.

¹ Hellwig T, et al., *Opt. Express* **22**, 24951 (2014).

² Hellwig T, et al., *Opt. Express* **23**, 19189 (2015).

Q 9.5 Mon 15:30 f342

Characterisation of nanostructured multifocal lenses for use in ophthalmology — ●JÜRGEN OTTEN^{1,2,3}, ULF HINZE¹, BORIS CHICHKOV¹, and ULRICH TEUBNER^{2,3} — ¹Laser Zentrum Hannover e.V., D-30419 Hannover — ²Institut für Laser und Optik, Hochschule Emden/Leer, D-26723 Emden — ³Institut für Physik, Universität Oldenburg, D-26129 Oldenburg

Cataract surgery is one of the most performed surgeries in industrial nations, leading to many advancements of intraocular lens (IOL) implants. Several lens designs are available. One of them uses a monofocal lens combined with a micron-sized Fresnel Zone Plate, yielding a multifocal lens. The zone plate at hand has been constructed using two-photon-polymerisation (2PP). The optical properties of this lens are characterized. Therefore, an experimental setup is built and automated. The lens is placed in a water filled cuvette and illuminated by a collimated laser beam. Using a camera mounted to a positioning system, the beam profile after passing through the lens is recorded in an image series. This series can be evaluated in regard to the beam profile and the distance of the focal points to the zone plate. Using light with a vacuum wavelength of 532nm, the focal points are expected at distances of 28.9mm, 32mm and 35.8mm. Actual measured distances are 28.8mm, 31.95mm and 35.61mm. The deviations from theoretical and measured results are minor, showing that the fabrication of a multifocal lens employing 2PP poses a reliable production process.

Q 9.6 Mon 15:45 f342

3D SLM-based STED-lithography — ●JULIAN HERING, ERIK H. WALLER, and GEORG VON FREYMAN — Department of Physics and Research Center OPTIMAS, University of Kaiserslautern

3D direct laser writing (DLW) is a commonly used technology for the fabrication of almost arbitrarily polymer structures in a single processing step. As the achievable resolution in standard DLW is diffraction limited, several proposals using superresolution technology have been presented in recent years. One of the most promising is stimulated emission depletion (STED) inspired lithography. Here, using especially shaped phase masks, a second laser beam suppresses the polymerization reaction via stimulated emission. Using spatial light modulators (SLMs) for the writing as well as the depletion laser beam allows for (i) automatically aligning the setup, (ii) correcting aberrations present in the setup, and (iii) varying the phase masks used for the depletion laser to find optimal conditions. We compare doughnut- and bottlebeam-modes realized with the SLMs to theoretical expectations. In writing experiments we observe a reduction of the lateral polymerization linewidth of 50% for the doughnut- mode. The bottlebeam-mode results in a reduction of the axial feature size by 56%. Furthermore, we use a numerical algorithm to calculate corresponding phase- and amplitude-patterns for alternative mode patterns: We compare the writing performance of so called multifoci-modes with the results achieved for doughnut and bottlebeam phase masks. Experimentally, the multifoci-modes show at least comparable performance while being conceptually much simpler to realize.

Q 9.7 Mon 16:00 f342

Realization of Photonic Quantum Simulators with Direct Laser Writing — ●CHRISTINA JÖRG¹, FABIAN LETSCHER^{1,2}, MICHAEL RENNER¹, MICHAEL FLEISCHHAUER¹, and GEORG VON FREYMAN^{1,3} — ¹Department of Physics and State Research Center OPTIMAS, University of Kaiserslautern, Germany — ²Graduate School Materials Science in Mainz, Kaiserslautern, Germany — ³Fraunhofer-Institute for Physical Measurement Techniques IPM, Kaiserslautern, Germany

We present a new technique of manufacturing low-loss 3D waveguide arrays on a μm -scale, based on direct laser writing in negative photoresist. As hopping between atom sites corresponds to coupling of light between waveguides, these systems act as simulators for the electronic properties of solids. A hollow waveguide array is fabricated via 3D laserlithography. The structure is then infiltrated with a higher index material, creating waveguides of about $1\ \mu\text{m}$ in diameter and spacing of $1.5\ \mu\text{m}$. By choosing appropriate infiltration materials the coupling constant between waveguides can be tuned. Coupling lengths of about $50\ \mu\text{m}$ at propagation lengths of up to $500\ \mu\text{m}$ could be obtained so

far.

For straight waveguides arranged on a honeycomb-lattice the bulk modes as well as the static edge modes are observed. Using helical waveguides as in [1], a Floquet topological insulator with chiral edge

modes can be realized.

[1] Rechtsman, M. C. et al. Photonic Floquet topological insulators. *Nature* 496, 196-200 (2013).

Q 10: Quantum Optics II

Time: Monday 14:30–16:30

Location: f442

Q 10.1 Mon 14:30 f442

Topological classification of one-dimensional symmetric quantum walks — ●CHRISTOPHER CEDZICH¹, TOBIAS GEIB¹, FRANCISCO ALBERTO GRÜNBAUM², CHRISTOPH STAHL¹, LUIS VELAZQUEZ³, ALBERT WERNER⁴, and REINHARD WERNER¹ — ¹Institut für Theoretische Physik, Leibniz Universität Hannover, Appelstr. 2, 30167 Hannover, Germany — ²Department of Mathematics, University of California, Berkeley CA 94720 — ³Departamento de Matemática Aplicada & IUMA, Universidad de Zaragoza, María de Luna 3, 50018 Zaragoza, Spain — ⁴Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, 14195 Berlin, Germany

We study symmetry protected topological phases for one-dimensional quantum walks. Topological phases play an important role in the classification of quantum matter. An analogous phase classification of quantum walks encounters the problem that walks are given by a unitary operator rather than a Hamiltonian. As a consequence, walks allow local perturbations which cannot be continuously contracted to the identity without violating unitarity, symmetry or a gap condition. This leads to an additional invariant in the homotopy classification which is, however, not invariant under local but not contractible perturbations.

(See also the related talk by T. Geib)

Q 10.2 Mon 14:45 f442

Decoupling and invariants of one-dimensional symmetric quantum walks — CHRISTOPHER CEDZICH¹, ●TOBIAS GEIB¹, FRANCISCO ALBERTO GRÜNBAUM², CHRISTOPH STAHL¹, LUIS VELAZQUEZ³, ALBERT WERNER⁴, and REINHARD WERNER¹ — ¹Institut für Theoretische Physik, Leibniz Universität Hannover, Appelstr. 2, 30167 Hannover — ²Department of Mathematics, University of California, Berkeley CA 94720 — ³Departamento de Matemática Aplicada & IUMA, Universidad de Zaragoza, María de Luna 3, 50018 Zaragoza, Spain — ⁴Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, 14195 Berlin

We study one-dimensional quantum walks satisfying a set of discrete symmetries and a gap condition. For most of the usual symmetry types, a classification can be built on decoupling, i.e., an arbitrary walk can be deformed continuously and while respecting symmetry and gap conditions into one consisting of two non-interacting half chains. The additional eigenvalues appearing after such decoupling are the basis of the classification. One symmetry type (namely DIII in the Cartan classification) does not seem to allow decoupling in general. For this type an alternative approach presented in a related talk by C. Cedzich can be applied.

Q 10.3 Mon 15:00 f442

Measuring topological invariants in photonic quantum walks — ●THOMAS NITSCHKE¹, FABIAN ELSTER¹, SONJA BARKHOFEN¹, AURÉL GÁBRIS², IGOR JEX², and CHRISTINE SILBERHORN¹ — ¹Universität Paderborn, Integrierte Quantenoptik, Warburger Str. 100, D-33098 Paderborn — ²Department of Physics, Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Břehova 7, 11519 Praha, Czech Republic

Concepts such as topological insulators have sparked interest in the investigation of topological material properties. Here, we present the simulation of topological phenomena in a discrete-time quantum walk experiment.

In our implementation of a photonic quantum walk system, we are able to dynamically control the quantum-coin, making it feasible to implement a split-step quantum walk protocol simulating the interfacing of bulks with different topological properties.

Being able to read-out the external as well as the internal state of the walker, we measure reflection amplitudes directly corresponding to topological invariants. We show that by tuning the coin operation, we alter topological phases in our model system.

Q 10.4 Mon 15:15 f442

Multipath correlation interference with a thermal source and quantum logic simulations: a fundamental effect in quantum optics — ●JOHANNES SEILER and VINCENZO TAMMA — Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQST), Universität Ulm, D-89069 Ulm, Germany

We theoretically demonstrate [1] a novel fundamental effect in quantum optics: the emergence of multipath correlation interference with a thermal source and its ability to simulate the operation of a quantum logic gate known as controlled-NOT gate. In particular, 100%-visibility correlations typical of any Bell state are demonstrated by performing polarization correlation measurements in the fluctuation of the number of photons at the interferometer output. The physics of multiboson interference at the very heart of this proposal can be readily used to simulate on-demand higher-order entanglement correlations in higher-dimension bosonic networks.

[1] V. Tamma, J. Seiler, arXiv:1503.07369 (2015)

Q 10.5 Mon 15:30 f442

Lichtstreuung an Ionenkristallen: Sichtbarkeit der Young'schen Interferenzstreifen — ●SEBASTIAN WOLF¹, JULIAN WECHS², JOACHIM VON ZANTHIER² und FERDINAND SCHMIDT-KALER¹ — ¹QUANTUM, Institut für Physik, Universität Mainz, Staudingerweg 7, 55128 Mainz, Germany — ²Institut für Optik, Information und Photonik, Universität Erlangen-Nürnberg, Stadtstr. 1, 91058 Erlangen, Germany

Das Young'sche Doppelspaltexperiment ist ein grundlegendes Experiment der Quantenmechanik. Bei Vorliegen eines Interferenzmusters sind die dazu beitragenden Lichtfelder zueinander kohärent. Es wurden Kalzium-Ionenkristalle beleuchtet und das gestreute Licht im Fernfeld beobachtet [1]. Den Grad der Kohärenz der gestreuten Lichtfelder untersuchen wir, indem wir den Kontrast des Interferenzmusters bestimmen [2]. Dabei steigt mit der Intensität des anregenden Lasers der Anteil der inelastischen Streuung und der Kontrast sinkt. Andererseits verändern sich bei erhöhter Laserintensität auch die Laserkühlparameter und damit die Ionentemperatur, was ebenfalls zu einem reduzierten Kontrast führt. Durch ein gepulstes Kühl- und Nachweisverfahren gelingt es uns, beide Effekte voneinander zu trennen. Wir haben ebenfalls Interferenzmuster von Kristallen mit drei und vier Ionen gemessen. Durch Anpassen der Fallenspannungen lässt sich ein äquidistanter Vier-Ionen-Kristall erzeugen. Das gemessene Muster stimmt hier sehr gut mit der Verteilung eines kohärent beleuchteten Gitters überein.

[1] Eichmann et al., PRL 70 2359 (1993).

[2] S. Wolf et al., arXiv:1511.08697 (2015).

Q 10.6 Mon 15:45 f442

Programming quantum interference in 10^3 channels in multiple-scattering materials — ●TOM A.W. WOLTERINK, RAVITEJ UPPU, GEORGIOS CTISTIS, WILLEM L. VOS, KLAUS-J. BOLLER, and PEPIJN W.H. PINKSE — MESA+ Institute for Nanotechnology, University of Twente, Enschede, The Netherlands

We demonstrate quantum interference in multiple-scattering materials. Starting with on the order of 10^3 coupled channels we create the equivalent of a 2×2 linear optical circuit with programmable correlations by adaptive phase modulation of incident wavefronts. This results in fully programmable Hong-Ou-Mandel interference, showing bunching as well as antibunching of output photons. Our results establish multiple-scattering materials as a platform for adaptive high-dimensional quantum interference experiments, as required, e.g., for boson sampling. Moreover, since multiple-scattering materials are excellent physical unclonable functions for use as optical keys in quantum-secure authentication, our results show the feasibility of including optical keys in other quantum-information protocols.

Q 10.7 Mon 16:00 f442

The 3D inverse optoacoustic source problem on the beam axis — ●O. MELCHERT, J. STRITZEL, M. WOLLWEBER, M. RAHLVES, and B. ROTH — Hannover Centre for Optical Technologies, Leibniz Universität Hannover, Hannover, Germany

Today, optoacoustics is widely used in the life sciences, e.g. for imaging of biological tissue. A yet unsolved problem is to determine optical properties from the experimental signals. While the *direct* problem of absorption of light in biological media consists of solving the optoacoustic wave equation for an initial pressure distribution $p_0(\mathbf{r})$, the mathematically challenging *inverse* problem requires the reconstruction of $p_0(\mathbf{r})$ from a proper set of observed signals.

For the particular case of a Gaussian transverse beam profile, the signal $p(z, \tau, \mathbf{r}_\perp = 0)$ at a point z along the beam axis (i.e. $\mathbf{r}_\perp = 0$), at the (retarded) time τ , is given by an integral equation, linear in the initial pressure profile $p_0(\tau)$ on the boundary of the absorbing medium. This integral equation can be interpreted as a Volterra equation of the second kind with known kernel, where $p(z, \tau, \mathbf{r}_\perp)$ is given and $p_0(\tau)$ is an unknown function to be solved for. For this integral equation, technically feasible inversion schemes exist. We study the inversion of *synthetic* signals that correspond to different initial pressure distributions, compare the inversion in the far-field to an approximate method based on the solution of a simple differential equation and consider the effect of noise on the quality of the reconstructed profile.

Q 10.8 Mon 16:15 f442

Mirror-like effect in correlated atoms — ●QURRAT-UL-AIN GULFAM¹ and ZBIGNIEW FICEK² — ¹Department of Physics, Jazan University, Jazan, Saudi Arabia — ²The National Center for Mathematics and Physics, KACST, Riyadh, Saudi Arabia

Reflection of light off correlated two-level identical atoms has been investigated. To ensure a one-dimensional emission from the system, normally the atoms have to be coupled with external media [1]. Contrarily, here, we have considered a real 3-dimensional dipole-dipole interaction among free space atoms. The directionality in the collective spontaneous emission is induced by the vacuum-mediated interaction based effects. Clear evidence of mirror-like effect in a one-dimensional cavity can be observed in atomic position configurations as simple as a 3-atom linear chain. We first consider the transient behavior when an initial excitation is contained in the system and later also study the steady state evolution of a weakly-driven system. Correlations among the atoms strongly affect the angular distribution of the first order correlation function detected in the far-field. This way suitable directions for enhanced (reduced) reflectivity are determined [2].

[1] D. E. Chang, et al, Phys. Rev. Lett., **110**, 113606 (2013).

[2] V. E. Lembessis, et al, Phys. Rev. A., **92**, 023850 (2015).

Q 11: Poster: Quantum Optics and Photonics I

Time: Monday 16:30–19:00

Location: Empore Lichthof

Q 11.1 Mon 16:30 Empore Lichthof

Towards an atomic erbium Bose-Einstein condensate generated in a quasistatic dipole trap — ●DANIEL BABIK, JENS ULITZSCH, HENNING BRAMMER, ROBERTO RÖLL, and MARTIN WEITZ — Institut für Angewandte Physik, Wegelerstraße 8, 53115 Bonn

We report on progress in an ongoing experiment directed at the generation of an atomic Bose-Einstein condensate of erbium atoms in a quasistatic optical dipole trap. In alkali atoms with their S-ground state configuration in far detuned laser fields with detuning above the upper state fine structure splitting the trapping potential is determined by the scalar electronic polarizability. In contrast for an erbium atomic quantum gas with its $L > 0$ electronic ground state, the trapping potential for inner-shell transitions also for far detuned dissipation-less trapping laser fields becomes dependent on the internal atomic state (i.e. spin). Therefore it is expected to reach much longer coherence times with atomic erbium in spin-dependent optical lattice experiments and for far detuned Raman manipulation in comparison with alkali atoms.

In our Bonn experiment an erbium atomic beam is decelerated by a Zeeman-slower using radiation tuned to the strong 400.91 nm transition of atomic erbium. Following work by the Innsbruck group, we then trap erbium atoms in a narrow-line magneto-optical trap using the atomic transition at 582.84 nm. In the next experimental step, we plan to load erbium atoms into the quasistatic dipole potential generated by a focused beam near 10.6 μm wavelength and here cool atoms evaporatively to quantum degeneracy.

Q 11.2 Mon 16:30 Empore Lichthof

Implementation of lambda-enhanced gray molasses cooling of 87Rb — ●MATTHIAS TARNOWSKI, BENNO REM, NICK FLÄSCHNER, DOMINIK VOGEL, CHRISTOF WEITENBERG, and KLAUS SENGSTOCK — Institut für Laserphysik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany

Efficient laser cooling is an important step in all quantum gas machines. Recently, lambda-enhanced gray molasses cooling on the D1 lines was established for various alkali atoms, leading to substantially lower temperatures compared to the common bright molasses on the D2-line. While gray molasses was first explored with Cs and Rb, the efficiency of lambda-enhancement has so far not been demonstrated for these species. Here, we implement this technique for the first time on the $F=2$ to $F'=2$ transition of the 87Rb D2 line and find a pronounced temperature decrease around the two-photon resonance with the repumper, which is produced as a sideband by an EOM. We reach significantly lower temperatures than with the bright molasses. Our results show that the efficiency of laser cooling of rubidium can be substantially increased with little expenses.

Q 11.3 Mon 16:30 Empore Lichthof

Gray-molasses cooling of ⁶Li towards a double degenerate Bose-Fermi mixture of ¹³³Cs and ⁶Li atoms — ●MANUEL GERKEN, STEPHAN HÄFNER, JURIS ULMANIS, EVA D. KUHNLE, and MATTHIAS WEIDEMÜLLER — Physikalisches Institut, Ruprecht-Karls Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany

An ultracold Bose-Fermi mixture of ¹³³Cs and ⁶Li atoms is an ideal system for the study of the heteronuclear Efimov scenario [1,2] as well as the emergence of polarons due to its large mass imbalance and the tunability of atomic interactions via Feshbach resonances [3]. Here we present our approach to gray-molasses cooling on the D1 line of Li which will be newly implemented in our experiment as a further step after doppler-cooling in the MOT. The process will lead to lower temperatures and higher phase space densities and therefore yield better starting conditions for evaporative cooling of Li. By sympathetically cooling the Cs with Li the generation of a double degenerate Bose-Fermi mixture will be possible.

[1] J. Ulmanis et al., arXiv:1509.05585 (2015)

[2] R. Pires et al., Phys. Rev. Lett. **112**, 250404 (2014)

[3] R. Pires et al., Phys. Rev. A **90**, 012710 (2014)

Q 11.4 Mon 16:30 Empore Lichthof

Integrated cold atom traps based on additive manufacturing — ●WILLIAM EVANS, REECE SAINT, YIJIA ZHOU, MARK FROMHOLD, EHAB SALEH, CHRISTOPHER TUCK, RICKY WILDMAN, MARK HARDY, IAN MASKERY, FEDJA ORUCEVIC, and PETER KRUGER — The University of Nottingham, University Park, Nottingham, NG7 2RD, United Kingdom

Research into atom chip based sensors is focused on producing highly sensitive portable instruments that harness and exploit the properties of ultra-cold atoms. These quantum systems can be employed in high precision accelerometers and gyroscopes or within nanoscale sensitive magnetic devices with micrometer resolution. For use in these systems atom chips often require a current carrying 'under-structure' to produce the magnetic fields necessary to trap atoms.

Current systems typically rely on milled or bent wire structures to complete this task but with recent developments in the application of 3D-printing techniques a wide range of possible designs has opened up. With emphasis on reducing power consumption, optimizing the shape of the magnetic field and reducing size we are developing 3D printed structures utilizing additive manufacturing. For this poster we will present the current advances in our approach and our ambitions for the next generation of structures.

Q 11.5 Mon 16:30 Empore Lichthof

Imaging of Single Atoms in a Two-Dimensional State-Dependent Optical Lattice — ●VOLKER SCHILLING, STEFAN BRAKHANE, GEOL MOON, CARSTEN ROBENS, WOLFGANG ALT, ANDREA ALBERTI, and DIETER MESCHKE — Institute of Applied Physics, Bonn, Germany

Detecting photons in a large solid angle is crucial for fast imaging in ultra-cold atom experiments. In the quantum technologies group in Bonn, we are currently building up a new experiment containing our in-house built high numerical aperture (NA = 0.92) in-vacuum objective which enables single site resolution of neutral caesium atoms in a two-dimensional state-dependent optical lattice. We prepare single caesium atoms in the lattice at a working distance of 150 μ m in front of the high-NA objective inside a dodecagonal ultra-low birefringence vacuum glass cell [1]. The high-NA objective is characterised by analysing the fluorescence signal coming from single caesium atoms. The experimental configuration and the state-dependent transport in two independent dimensions is presented. The high-NA imaging system in combination with the two-dimensional state-dependent optical lattice will provide fast image acquisition after simulation of complex physical phenomena, for instance, artificial magnetic fields by means of discrete-time quantum walks in two dimensions.

[1] Stefan Brakhane et. al., *Ultra-low birefringence dodecagonal vacuum glass cell*, Submitted (2015)

Q 11.6 Mon 16:30 Empore Lichthof

Two-dimensional quantum walks in artificial magnetic fields — ●MUHAMMAD SAJID, STEFAN BRAKHANE, WOLFGANG ALT, DIETER MESCHKE, and ANDREA ALBERTI — Institute for Applied Physics, wegelerstr. 8, D-53115, Bonn University

Quantum walks hold the prospect to simulate quantum transport and topological effects in solid-state systems and have been realized in various experiments including ultra-cold neutral atoms in optical lattices [1]. For example, the behavior of charged particles in a periodic neutral subject to an external electric field has been simulated with neutral atoms in one-dimensional spin-dependent optical lattices where acceleration of the lattice corresponds to an electric field acting on charged particles [2].

Here we report on a theoretical study of discrete-time quantum walks subject to a magnetic field on a square lattice, which simulates the dynamics of a two-dimensional electronic system in a magnetic field [3]. In particular, I discuss the topological properties of magnetic quantum walks by identifying Chern topological invariants and by demonstrating the existence of topologically protected edge states carrying quantized current at spatial boundaries [4]. In addition, I present an experimental proposal how to realize artificial magnetic fields using neutral atoms in a two-dimensional spin-dependent optical lattice.

[1] M. Karski et al. *Science* 325, 174 (2009).

[2] M. Genske et al. *PRL* 110, 190601 (2013).

[3] Pablo Arnault and Fabrice Debbaesch, arXiv:1508.00038v3

[4] J. K. Asboth and J. M. Edge, *PRA* 91, p. 022324 (2015)

Q 11.7 Mon 16:30 Empore Lichthof

Diffusion of Single Atoms in a Bath — ●DANIEL ADAM¹, FARINA KINDERMANN¹, ANDREAS DECHANT², MICHAEL HOHMANN¹, TOBIAS LAUSCH¹, DANIEL MAYER¹, FELIX SCHMIDT¹, ERIC LUTZ², and ARTUR WIDERA¹ — ¹TU Kaiserslautern, Department of Physics, Kaiserslautern, Germany — ²Friedrich-Alexander-Universität, Department of Theoretical Physics, Erlangen, Germany

Diffusion processes are a central phenomenon in almost all natural sciences ranging from cell transport in biology over traffic modelling to financial market theory. The typical measured quantity to evaluate the random walk process is the mean squared displacement (MSD). If the MSD increases linearly with the evolution time of the system one assumes normal diffusion and hence implies three well known properties: First the underlying single step distribution is Gaussian, second the system is ergodic, and third the auto correlation function is stationary. Here we engineer a system of a single atom in a periodic potential, which is coupled to a photon bath. The MSD shows normal diffusion for almost all times, but a closer look at the microscopic properties reveals an exponential single step distribution and ergodicity is not reached within timescales large compared to the characteristic timescale of the system. In addition the autocorrelation function shows ageing typically known from glassy materials. A continuous time random walk (CTRW) model with exponential step distribution perfectly fits to our data. Our results may shed light on the microscopic behavior of related biological systems.

Q 11.8 Mon 16:30 Empore Lichthof

Influence of particle distinguishability on coherence phenomena in optical lattices — ●TOBIAS BRÜNNER, ALBERTO RODRIGUEZ, and ANDREAS BUCHLEITNER — Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Strasse 3, D-79104 Freiburg, Deutschland

Cold, interacting atoms in tilted optical lattices exhibit coherent dynamics, for instance Bloch oscillations in position and momentum space. The influence of interactions between the particles was studied and can generally be associated with a suppression of the coherence phenomena. However, the role of the particle-indistinguishability on this dynamics has not been investigated systematically yet. From many-photon interference experiments we know that the degree of distinguishability has a non-trivial influence on the evolution of the underlying many-particle state, and manifests itself in the outcomes of coincidence measurements. In a similar fashion, we want to identify how and where the indistinguishability can be observed in the dynamics of cold, interacting atoms in tilted optical lattices. As our first step, we compare the spectrum of a Bose-Hubbard Hamiltonian for identical atoms with that of a Hamiltonian describing two distinguishable species. Tuning the degree of distinguishability between the two species allows for an assessment of the ‘quantum-to-classical’ transition, i.e. the transition from identical bosons to distinguishable particles.

Q 11.9 Mon 16:30 Empore Lichthof

Simulation of magnetic chip traps — ●JOHANNES BATTENBERG and REINHOLD WALSER — TU Darmstadt, Deutschland

Trapping magnetizable atoms with magnetic traps is the basic tool to experiments with ultracold atomic gases [1, 2, 3]. In the QUANTUS experiment, which is performed in the drop tower in Bremen (ZARM), the required magnetic field is created by a multi-layer microchip. These multiple current conducting layers provide a multitude of current combinations and offer a variety of different magnetic traps of different shapes, minimum locations and spatial alignments. From the experimental point of view, it is desirable to choose the general trap parameters and look up the required current. Therefore, one needs a simulation to provide this reverse map.

A modular framework was developed in Python to calculate the static magnetic field of the chip. We employ a finite element method using the Biot-Savart-Law. With this tool we can characterize the trap potential and identify key properties like trap frequencies and anharmonicities.

[1] W. Hänsel *et al.*, Bose-einstein condensation on a microelectronic chip, *Nature* 413, 498–501 (2001)

[2] J. Fortágh and C. Zimmermann, Magnetic microtraps for ultracold atoms, *Rev. Mod. Phys.* 79, 235–289 (2007)

[3] R. Folman *et al.*, Microscopic atom optics: From wires to an atom chip, *Adv. At. Mol. Opt. Phys.* 48, 263–356 (2002)

Q 11.10 Mon 16:30 Empore Lichthof

Creation of a superposition of opposite circular states in Rydberg atoms using optimal control theory and quantum Zeno dynamics — ●SABRINA PATSCH¹, DANIEL M. REICH², JEAN-MICHEL RAIMOND³, and CHRISTIANE P. KOCH¹ — ¹Universität Kassel — ²Aarhus University — ³Collège de France

An alkali Rydberg atom in a circular state has a single valence electron excited to the maximum value of the magnetic quantum number m . Its electronic orbital which is very sensitive to magnetic fields forms a torus similar to the orbit in the classical Bohr model. We attempt to create a superposition of two circular Rydberg states with opposite values of m , a so-called cat state. The creation of such a superposition opens the possibility to build highly precise sensors for measuring magnetic fields.

The central issue is to prevent decoherence during the preparation of the superposition state, given experimental limitations such as those in the setup for quantum Zeno dynamics at the Collège de France [1]. We employ optimal control theory [2] for resonant driving using rf fields combined with microwave fields inducing Zeno dynamics to minimize the time needed to circularise an atom without significant loss of efficiency.

[1] Signoles, A. et al. Confined quantum Zeno dynamics of a watched atomic arrow. *Nature Phys.* 10, 715 (2014).

[2] Reich, D.M. et al. Monotonically convergent optimization in quantum control using Krotov’s method. *J. Chem. Phys.* 136, 104103 (2012).

Q 11.11 Mon 16:30 Empore Lichthof

Rydberg quantum optics in ultracold gases — HANNES GORNIACZYK, CHRISTOPH TRESP, IVAN MIRGORODSKIY, CHRISTIAN ZIMMER, •ASAF PARIS-MANDOKI, and SEBASTIAN HOFFERBERTH — 5. Physikalisches Institut, Universität Stuttgart, Germany

Mapping the strong interaction between Rydberg excitations in ultracold atomic ensembles onto single photons via electromagnetically induced transparency enables the realization of optical nonlinearities which can modify light on the level of individual photons.

Following previous work [1] in which a single-photon transistor was realized, we investigate the use of an electrically tuned Förster-resonance to improve the transistor performance. The strong amplification of this transistor allows performing fine-structure-resolving spectroscopy of the Förster resonance.

We also present our investigation of anisotropic interaction between individual polaritons coupled to Rydberg D-states. The anisotropy breaks the one-dimensionality of the system even when the propagating light is focussed more tightly than the Rydberg blockade volume. This effect provides an additional tool for engineering photon-photon interaction in a Rydberg system [2].

[1] H. Gorniaczyk, C. Tresp, J. Schmidt, H. Fedder, and S. Hofferberth, “Single Photon Transistor Mediated by Inter-State Rydberg Interaction”, *Phys. Rev. Lett.* 113, 053601 (2014).

[2] C. Tresp, P. Bienias, S. Weber, H. Gorniaczyk, I. Mirgorodskiy, H. P. Büchler, S. Hofferberth, “Dipolar Dephasing of Rydberg D-state polaritons”, *Phys. Rev. Lett.* 115, 083602 (2015).

Q 11.12 Mon 16:30 Empore Lichthof

Large bandwidth excitation of rydberg atoms in thermal vapor cells — •ANDY RICO, ALBAN URVOY, ROBERT LÖW, HARALD KÜBLER, and TILMAN PFAU — 5. Physikalisches Institut, University of Stuttgart, Germany

Over the past years, significant experimental effort has been made towards studying Rydberg atoms in vapor cells. It has given new insight into the fundamental physics of ensemble of Rydberg atoms, as well as opened the door for technical applications, such as MW electric field sensing among others. In most previous studies of Rydberg atoms in vapor cells, attaining a high enough excitation bandwidth was critical to obtain both fast enough excitation dynamics and high Rydberg population. Here we first present new results on the observation of electric field modulation up to several GHz in a cesium vapor cell through Rydberg excitation. The large excitation bandwidth allows here the system to follow the fast modulation. We also discuss the potential and limitations of this scheme as a light modulator. Second, we examine the recently observed optical bistability in a vapor cell [1], which is obtained for high Rydberg population, for different orbital angular momentum states. We investigate this effect in our system and discuss the possible nature of the underlying mechanism.

[1] C. Carr et al., *PRL* 111, 113901 (2013)

Q 11.13 Mon 16:30 Empore Lichthof

Dynamics of ultracold Rydberg macrodimers — HEINER SASSMANNSHAUSEN, FRÉDÉRIC MERKT, and •JOHANNES DEIGLMAYR — ETH Zurich, Laboratory of Physical Chemistry, Switzerland

We report on a study of pairwise interactions between Cs atoms excited to $n p_{3/2}$ Rydberg states of principal quantum numbers in the range $n = 22 - 36$ [1]. Molecular resonances arising from dipole-dipole and higher long-range-interaction terms between the Rydberg atoms are identified on the basis of their spectral positions, their response to static and pulsed electric fields, and millimeter-wave spectra between pair states. The Rydberg-atom-pair states are found to spontaneously decay by Penning ionization and the dynamics of the ionization process are investigated. To interpret the experimental observations, a potential model was derived that is based on the numerical determination of the eigenvalues and eigenfunctions of the long-range interaction Hamiltonian. With this potential model, which does not include adjustable parameters, all experimental observations could be accounted for, and the results demonstrate that long-range-interaction models provide a global and accurate description of interactions in ultracold Rydberg gases which accounts for phenomena as diverse as the formation of Rydberg macrodimers, Penning ionization in dense Rydberg gases, and Rydberg-excitation blockade effects.

[1] H. Saßmannshausen, F. Merkt, and J. Deiglmayr, *Phys. Rev. A* 92, 032505 (2015)

Q 11.14 Mon 16:30 Empore Lichthof

Rydberg-dressed interactions in trap loss spectroscopy of ul-

tracold potassium — •STEPHAN HELMRICH, ALDA ARIAS, NILS PEHOVIK, EMIL PAVLOV, TOBIAS WINTERMANTEL, and SHANNON M WHITLOCK — Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg

The introduction of long-range interactions between particles in ultracold atomic gases can give rise to new and exotic phases of matter. Weakly admixing a Rydberg state to ground state atoms (Rydberg dressing) presents one avenue towards realizing such interactions. We aim to perform Rydberg dressing of ultracold potassium atoms, utilising a two-photon ladder-transition close to two-photon resonance. A strong cooperative enhancement in interaction strength due to multiphoton and multiatom excitations is theoretically predicted. It allows to externally control both interaction strength and dressed-state lifetime by the Rabi frequencies and the detunings of both laser fields. Furthermore, we will present spectroscopy measurements of trap loss due to interaction effects, which allow us to directly compare theoretical predictions with experimental observations. We will show first signatures of interactions induced through Rydberg dressing, which are the first step towards simulating quantum systems with strong and long-range correlations. This would enable the study of novel pairing mechanisms, supersolidity or new types of superfluidity.

Q 11.15 Mon 16:30 Empore Lichthof

Longitudinally homogeneous medium of tunable length for Rydberg EIT — •STEFFEN SCHMIDT, DANIEL TIARKS, GIOVANNI GIRELLI, STEPHAN DÜRR, and GERHARD REMPE — MPI für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching

In electromagnetically induced transparency (EIT), an initially opaque medium is made transparent for probe light by applying a strong control beam. As this is a quantum interference effect, it relies on the coherence of the system. In Rydberg EIT, the energy of a Rydberg state depends on the density of the surrounding ground state atoms. If the density of ground state atoms is position dependent, then the density dependent resonance shift causes dephasing which deteriorates the performance of EIT [1]. The transverse inhomogeneity can be made irrelevant by tightly focusing the light. To avoid problems from a longitudinal inhomogeneity, we prepare a longitudinally homogeneous medium by an appropriate design of an optical dipole trap. The trap has the additional feature that the length of the medium is tunable between 20 and 300 μm . A long medium makes it possible to remain at low atomic density, so that the dephasing rate is low, and simultaneously to reach high optical depth, so that the effects of Rydberg blockade can be large.

[1] S. Baur et al. *Phys. Rev. Lett.* 112, 073901 (2014).

Q 11.16 Mon 16:30 Empore Lichthof

Simulating many-body spin-dynamics with Rydberg atoms — •RENATO FERRACINI ALVES, MIGUEL FERREIRA-CAO, VLADISLAV GAVRYUSEV, ADRIEN SIGNOLES, GERHARD ZUERN, SHANNON WHITLOCK, and MATTHIAS WEIDEMÜLLER — Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany

Simulating many-body spin-dynamics is of great interest both for its connection to practical systems, such as quantum magnetism, spintronics, and polar molecules [1], as well as for getting a deeper insight in systems driven by a many-body Hamiltonian. In our experiment we realize a Heisenberg XX-model by mapping two dipolar-interacting Rydberg states to two spins states ($|nS\rangle \rightarrow |\downarrow\rangle$ and $|nP\rangle \rightarrow |\uparrow\rangle$). This scheme allows us to explore the dynamics of spin systems with long range interactions [2].

We will present preliminary results of the measurement of microwave-driven Rabi oscillations between the spin-states, in which interactions lead to damping of the contrast for high Rydberg densities [3]. Also, we describe advanced techniques, such as Ramsey spectroscopy, that will be implemented to investigate further the spin-dynamics.

[1] B. Yan et al., *Nature* 501, 521-525 (2013)

[2] D. Barredo et al., *Phys. Rev. Lett.* 114, 113002 (2015)

[3] D. Maxwell et al., *Phys. Rev. Lett.* 110, 103001 (2013)

Q 11.17 Mon 16:30 Empore Lichthof

Precision two-color spectroscopy of long-range ground-state vibrational levels in ultracold ^{40}Ca — VEIT P. DAHLKE¹, •EVGENIJ PACHOMOV¹, EBERHARD TIEMANN², FRITZ RIEHLE¹, and UWE STERR¹ — ¹Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig — ²Institut für Quantenoptik, Leibniz-Universität Hannover, Welfengarten 1, 30167 Hannover

We have measured the three most weakly bound ground state vibrational levels in the $X^1\Sigma_g^+$ potential of $^{40}\text{Ca}_2$, using two-colour photoassociation with different intermediate levels in the $a^3\Sigma_u^+$, $c^3\Pi_g$ excited state potential. We have interrogated cold ensembles of about 10^5 calcium atoms trapped in a crossed dipole trap at temperatures of approximately $1\ \mu\text{K}$. The unperturbed binding energies have been measured with kHz accuracy benefiting from few Hertz linewidth offset-locked tunable lasers and detailed lineshape analysis.

The interaction potential at typical internuclear separations for these weakly bound levels is dominated by the long range coefficients C_6 , C_8 which have been derived using a full quantum computation including information of the inner potential range. Our data also give a precise value for the s-wave scattering length $a = 308(10)a_0$ and is an important step in the implementation of low loss optical Feshbach resonances for alkaline earth metals.

Q 11.18 Mon 16:30 Empore Lichthof

Molecular Beam Setup for Quantum Logic Spectroscopy of single Molecular Ions — ●JAN CHRISTOPH HEIP¹, FABIAN WOLF¹, CHUNYAN SHI¹, and PIET O. SCHMIDT^{1,2} — ¹Physikalisch-Technische Bundesanstalt, Braunschweig, Germany — ²Institut für Quantenoptik, Leibniz Universität Hannover, Germany

Molecular ions have a rich level structure and therefore are useful for applications ranging from precision measurements to quantum information processing. Besides the motional degrees of freedom, they exhibit also vibrational and rotational degrees of freedom, rendering direct laser cooling a challenge. We have demonstrated non-destructive rotational state detection and quantum logic spectroscopy in MgH^+ using a co-trapped Mg^+ logic ion [1]. Furthermore, we will present the design of an improved experimental setup including a molecular beam and an RF-Paul-trap with segmented blades. The molecular beam will enable the investigation of a large variety of molecular ions and significantly shorten the time required for preparing a single cold molecular ion.

[1] F. Wolf et al., *Non-destructive state detection for quantum logic spectroscopy of molecular ions*, arXiv:1507.07511 (2015).

Q 11.19 Mon 16:30 Empore Lichthof

Towards ultracold LiK ground-state molecules — ●MARKUS DEBATIN^{1,2}, SAMBIT PAL², MARK LAM², and KAI DIECKMANN² — ¹Atom-, Molekül- und optische Physik, Physikalisches Institut, Universität Freiburg, Hermann-Herder-Str. 3, 79104 Freiburg — ²Center for Quantum Technologies (CQT), National University of Singapore, Block S15, 3 Science Drive 2, Singapore 117543

Ultracold heteronuclear molecules have seen increasing interest in the scientific community over the last few years [1]. Due to their large electric dipole moment of 3.6 Debye LiK ground-state molecules are particularly suited to investigate the physics of strongly-interacting dipolar quantum gases.

In our experiment [2] we perform spectroscopy on ultracold $^6\text{Li}^{40}\text{K}$ Feshbach molecules with the aim to create ground-state molecules. Starting with samples of about $3 \cdot 10^4$ ultracold Feshbach molecules we currently investigate transitions mainly to levels close to the asymptote of the $B^1\Pi$ electronic potential. For these levels a good coupling efficiency to the ground state of the $X^1\Sigma^+$ potential is predicted. This will be investigated in the next steps in order to develop a scheme to transfer the Feshbach molecules to the absolute ground state via a simulated Raman adiabatic passage (STIRAP). Our spectroscopy results as well as an update on the current experimental status will be presented.

[1] M. A. Baranov et al. Chem. Rev. 112, 5012-5061, 2012 [2] A.-C. Voigt et al. Phys. Rev. Lett. 102, 020405, 2009

Q 11.20 Mon 16:30 Empore Lichthof

High resolution imaging system for experiments on degenerate NaK — ●ROMAN BAUSE^{1,2}, FRAUKE SEESSELBERG¹, NIKOLAUS BUCHHEIM¹, ZHENKAI LU¹, IMMANUEL BLOCH^{1,2}, and CHRISTOPH GOHLE¹ — ¹Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany — ²Ludwig-Maximilians-Universität, Schellingstraße 4, 80799 München, Germany

Ultracold mixtures of two species of atoms could be used to study a wide range of open problems. To investigate such systems, we have constructed an apparatus that can produce a degenerate Bose-Fermi mixture of ^{23}Na and ^{40}K atoms. Among other things, we are planning to investigate quantum gases with a tunable dipole-dipole interaction, which could be done by producing NaK molecules in their absolute ground state.

A crucial ingredient for such experiments is an imaging system that allows observation of both atomic species with sub-micrometer resolution. We achieve this with a custom objective (NA=0.6), which offers diffraction-limited imaging at wavelengths of 589 and 767nm. It simultaneously supports a near-infrared optical lattice for 2D confinement of the atomic or molecular sample in the object plane of the system. We will present the experiences we have made during the construction and testing of this setup.

Q 11.21 Mon 16:30 Empore Lichthof

News from the Garching NaK mixture — ●NIKOLAUS BUCHHEIM, FRAUKE SEESSELBERG, ZHENKAI LU, ROMAN BAUSE, TOBIAS SCHNEIDER, IMMANUEL BLOCH, and CHRISTOPH GOHLE — Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 85748 Garching

Ultracold quantum gases with long-range dipolar interactions promise exciting new possibilities for quantum simulation of strongly interacting many-body systems like fractional MOT insulators and supersolid phases. Our experimental apparatus is capable of creating ultracold sodium and potassium mixtures with high phase space density, weakly bound feshbach molecules and aims towards generating ultracold polar $^{23}\text{Na}^{40}\text{K}$ molecules in their vibrational, rotational and hyperfine ground state.

To this end, a stimulated Raman adiabatic passage (STIRAP) has to be implemented, which is a two photon process capable of transferring weakly bound Feshbach molecules via an intermediate, excited molecular state to the ground state with high efficiency. We employ a spin-orbit coupled intermediate state in the D/d molecular manifold of the NaK system. With our apparatus we are also capable to analyze the properties of a small number of Potassium atoms immersed into a degenerate Bose gas of Sodium atoms. This setting is known as the Bose polaron.

Q 11.22 Mon 16:30 Empore Lichthof

Optical transport of ultracold atoms for the production of groundstate RbYb — ●TOBIAS FRANZEN, BASTIAN POLKLESENER, SIMONE KIPP, KAPILAN PARAMASIVAM, CHRISTIAN HALTER, and AXEL GÖRLITZ — Institut für Experimentalphysik, Heinrich-Heine-Universität Düsseldorf

Ultracold dipolar molecules constitute a promising system for the investigation of topics like ultracold chemistry, novel interactions in quantum gases, precision measurement and quantum information.

Here we report on a versatile transport apparatus for the production of ultracold RbYb molecules. This setup constitutes an improvement of our old apparatus, where the interactions in RbYb and possible routes to molecule production have already been studied extensively [1,2]. In the new setup a major goal is the efficient production of ground state RbYb molecules.

Separate production chambers allow the parallel production of Yb and Rb samples. Optical tweezers transport both species to a separate science chamber. This chamber provides excellent optical access and room for additional components in- and outside of the vacuum.

[1] F. Münchow et al., PCCP 13(42), 18734 (2011).

[2] M. Borkowski et al., PRA 88, 052708 (2013)

Q 11.23 Mon 16:30 Empore Lichthof

Herstellung angepasster mikro-optischer Strukturen mit einem FIB — ●MARCEL SALZ, ANDREAS PFISTER, MAX HETTRICH und FERDINAND SCHMIDT-KALER — QUANTUM, Institut für Physik, Johannes-Gutenberg-Universität Mainz

Die Verwendung von Focused Ion Beam (FIB) Systemen ist nicht nur fester Bestandteil in der Halbleiterindustrie, sondern hat auch zahlreiche interessante Anwendungen in der Wissenschaft gefunden. Insbesondere lassen sich Glasfasern auf der Nanometerebene kontrolliert bearbeiten, um etwa den Akzeptanzwinkel von Endflächen zu erhöhen [1] oder zur Entwicklung von faserbasierten optischen Pinzetten [2].

Wir berichten über die Herstellung von konkaven Strukturen auf der μm -Skala in den Endflächen von Glasfasern. Um faserbasierte optische Resonatoren zu ermöglichen wurden sphärische konkave Strukturen mit einem Durchmesser von bis zu $100\ \mu\text{m}$ erzeugt, wobei die Abweichungen von der gewünschten Form über den zentralen Bereich von $50\ \mu\text{m}$ kleiner als $20\ \text{nm}$ sind. Nach einer dielektrischen Beschichtung bauen wir aus zwei solcher Spiegelendflächen einen optischen Resonator auf, der eine Finesse von 16 500 bei einem vergleichsweise großen Abstand von $250\ \mu\text{m}$ erreicht. Ein solcher Resonator eignet sich für die Integration in mikrostrukturierte Ionenfallen, wo er als Licht-Ionen-Schnittstelle [3] für CQED-Experimente eingesetzt werden kann [4].

- [1] V. Callegari et al., *J. Micromech. Microeng.* 19, 107003 (2009)
 [2] C. Liberale et al., *Nat. Photon.* 1, 723-727 (2007)
 [3] B. Brandstätter et al., *Rev. Sci. Instrum.* 84, 123104 (2013)
 [4] A. D. Pfister et al., arXiv:1508.05272 (2015)

Q 11.24 Mon 16:30 Empore Lichthof

Characterisation of efficient single-photon sources based on nitrogen-vacancy centres for radiometric applications —

•BEATRICE RODIEK¹, MARCO LÓPEZ¹, HELMUTH HOFER¹, STEFAN KÜCK¹, XIAO-LIU CHU², and STEFAN GÖTZINGER² — ¹Physikalisch Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig — ²Max Planck Institute for the Science of Light, 91058 Erlangen, Germany

Single-photon sources (SPS) play today an important role in quantum metrology. The main aim is to realize a SPS with a high photon rate while the background and the multi-photon emission rates are still low. Such a single-photon source would be a candidate for a standard source for radiometry. One way of a SPS realisation is based on colour centres in nanocrystals. At PTB, we are working on SPS based on nitrogen-vacancy- (NV-) centres in nanodiamonds, for their use in the calibration of single photon detectors. To investigate these sources, we use a confocal microscope setup that allows us to excite the colour centres and also to collect the fluorescent emission of the source. The colour centres are characterized in terms of spectrum, count rate, anti-bunching and stability. A photon rate of approx. 650 kphotons per second at the detector with a high single photon emission purity, indicated by the $g_2(0)$ -value as low as 0.05 was obtained. Further results and details of the setup will be presented at the conference.

Q 11.25 Mon 16:30 Empore Lichthof

A silicon vacancy-based quantum memory in diamond —

•JOHANNES GÖRLITZ¹, JONAS NILS BECKER¹, EILON POEM², JOSHUA NUNN², IAN ALEXANDER WALMSLEY², and CHRISTOPH BECHER¹ — ¹Universität des Saarlandes, Saarbrücken, Germany — ²Clarendon Laboratory, University of Oxford, United Kingdom

Due to its favourable spectral properties, the silicon vacancy center (SiV) in diamond is already a promising candidate for the realization of a spin-photon interface for quantum communication applications. Because of its large ground state splitting of about 48 GHz, we propose that the SiV is also a potential candidate for broadband quantum memory applications. We present preliminary work demonstrating the feasibility of such a device based on a Raman-type memory scheme in a dense, homogenous SiV ensemble fabricated by homoepitaxial CVD growth on top of a low strain, high-pressure-high-temperature (HPHT) diamond substrate. The sample is investigated at 4K in a flow cryostat setup with a transmission geometry specifically build to allow for efficient memory preparation and readout. The ensemble is pre-characterized using photoluminescence excitation (PLE) and coherent population trapping (CPT) experiments. The obtained experimental parameters are used in a theoretical model to calculate memory efficiencies as well as optimized control pulse parameters that can be used in the near future to build a first experimental realization of the memory.

Q 11.26 Mon 16:30 Empore Lichthof

Creating nitrogen-vacancy centers (NVs) in isotopically controlled diamond layers by CVD diamond growth — •CHRISTIAN OSTERKAMP, TAKASHI YAMAMOTO, BORIS NAYDENOV, and FEDOR JELEZKO — Universität Ulm, Institut für Quantenoptik

The negatively charged nitrogen-vacancy center (NV) is amongst the leading solid-state quantum bits. The fluorescence of single NVs can be detected and its electron spin can be polarized, read-out and manipulated at ambient conditions. Creation of NVs on demand is an important task for quantum technology applications like quantum computers or magnetic- and electric field sensors [1]. We engineer NVs by delta doping during a plasma enhanced chemical vapor deposition (PECVD) process [2] and we are able to produce isotopically pure diamonds by changing the ratio of ¹²C/¹³C atoms in the growth chamber.

- [1] C. Müller et al., *Nat. Comm.*, 5 4703 (2014)
 [2] C. Osterkamp et al., *Appl. Phys. Lett.* 106, 113109 (2015)

Q 11.27 Mon 16:30 Empore Lichthof

Closed loop optimal control on NV centers in diamond —

•FLORIAN FRANK¹, THOMAS UNDEN¹, JORGE CASANOVA², ZHENYU WANG², RESSA SAID³, JONATHAN ZOLLER³, MARTIN PLENIO², and FEDOR JELEZKO¹ — ¹Institute for Quantum Optics, Ulm University, Ulm, Germany — ²Institute of Theoretical Physics, Ulm University,

Ulm, Germany — ³Institute for Complex Quantum-systems, Ulm University, Ulm, Germany

The objective of optimal control is to control a given system in a way that its output matches a reference. In closed loop optimal control, the controller gets an active feed back of the experiment to tune the control parameters. We use this technique to optimize the fidelity of quantum operations on the nitrogen vacancy center. Therefore we tune the microwave pulses and sequences to maximize the fidelity of this operations.

Q 11.28 Mon 16:30 Empore Lichthof

Towards a quantum simulator based on nuclear spins in diamond —

•TIMO WEGGLER¹, THOMAS UNDEN¹, NIKOLAS TOMEK¹, FLORIAN FRANK¹, ALEXANDRE LE BOITÉ², JANMING CAI⁵, PAZ LONDON³, ALEX RETZKER⁴, ITHO KOHEI⁶, MARTIN PLENIO², BORIS NAYDENOV¹, and FEDOR JELEZKO¹ — ¹Institute for Quantum Optics, Ulm University, Germany — ²Institute for Theoretical Physics, Ulm University, Germany — ³Department of Physics, Technion, Israel Institute of Technology, Haifa, 32000, Israel — ⁴The Racah Institute of Physics, Hebrew University of Jerusalem, 91904 Jerusalem — ⁵School of Physics, Huazhong University of Science and Technology, Wuhan 430074, China — ⁶Department of Applied Physics and Physico-Informatics, Keio University, Hiyoshi, Yokohama, Japan

Towards a quantum simulator based on nuclear spins in diamond.

Q 11.29 Mon 16:30 Empore Lichthof

Polarization of a C13 nuclear spin bath in diamond in arbitrary aligned fields —

•SAMUEL MÜLLER¹, JOCHEN SCHEUER¹, ILAI SCHWARZ², QIONG CHEN², MARTIN B. PLENIO², BORIS NAYDENOV¹, and FEDOR JELEZKO¹ — ¹Institute of Quantum Optics, Ulm University, Albert Einstein Allee 11, 89081 Ulm, Germany — ²Institute of Theoretical Physics, Ulm University, Albert Einstein Allee 11, 89069 Ulm, Germany

Nuclear magnetic resonance spectroscopy (NMR) and magnetic resonance imaging (MRI) are powerful analysis tools in life science and medicine. The sensitivity of both depends critically on the nuclear spin polarisation. Dynamical nuclear polarization of C13 nuclear spins in diamond via optically pumped Nitrogen-Vacancy centers (NV) allow a high degree of polarization to be reached even at room temperature and low magnetic field.

Here we compare different polarization schemes in terms of their efficiency and robustness against magnetic field misalignment, which is of crucial importance for their application to randomly oriented nanodiamonds. In contrast to ensemble measurements, the single spin approach allows us to investigate the characteristics of a single nuclear spin bath surrounding a NV.

Q 11.30 Mon 16:30 Empore Lichthof

Elementary model of a two-photon double-slit experiment —

•LUCAS HAPP¹, MAXIM A EFREMOV^{1,2}, and WOLFGANG P SCHLEICH^{1,3} — ¹Institut für Quantenphysik und Center for Integrated Quantum Science and Technology (IQST), Universität Ulm, D-89081 Ulm, Germany — ²A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, 119991 Moscow, Russia — ³Institute for Quantum Science and Engineering (IQSE), Department of Physics and Astronomy, Texas A&M University, College Station, TX 77843

The principle of complementarity states that in a double-slit experiment the “which-slit” information cannot be measured at the same time as an interference pattern is observed. A recently performed experiment [1] targeted at the verification of this principle. The TEM₀₁ mode for the pump light has been applied to create entangled photon pairs via SPDC in a nonlinear crystal. In this way, the entanglement can be used to locate the photons in one of the slits, while at the same time the TEM₀₁ mode function, containing two distinct wave vectors, leads to interference in the far field.

We present an elementary model of this experiment by describing the nonlinear crystal by a gas of three-level atoms and the creation of photon pairs by a cascade decay of these atoms. Moreover, to explain the experimental results, we obtain the relevant detection probabilities in terms of the Glauber correlation functions.

[1] Menzel R, Puhlmann D, Heuer A and Schleich W P, *Proc. Natl. Acad. Sci. U.S.A.* 109, 9314 (2012)

Q 11.31 Mon 16:30 Empore Lichthof

Superbunching and Nonclassicality as new Hallmarks of Super-radiance —

•DANIEL BHATTI^{1,3}, JOACHIM VON ZANTHIER^{1,3}, and

GIRISH S. AGARWAL² — ¹Institut für Optik, Information und Photonik, Universität Erlangen-Nürnberg, 91058 Erlangen, Germany — ²Department of Physics, Oklahoma State University, Stillwater, OK, USA — ³Erlangen Graduate School in Advanced Optical Technologies (SAOT), Universität Erlangen-Nürnberg, 91052 Erlangen, Germany

Superradiance, i.e., spontaneous emission of coherent radiation by an ensemble of two-level atoms in collective states introduced by Dicke in 1954 [1], is one of the enigmatic problems of quantum optics. The startling gist is that even though the atoms have no dipole moment they radiate with increased intensity in particular directions [2]. Following the advances in our understanding of superradiant emission by atoms in entangled W-states we examine the quantum statistical properties of superradiance [3]. This requires the investigated system to have at least two excitations. We present results for the spatially resolved photon-photon correlations of systems prepared in doubly excited W-states and give conditions when the atomic system emits nonclassical light. Moreover, we derive conditions for the occurrence of the rare phenomenon of superbunching. Both effects can be witnessed equally in the photon-photon cross correlations of the spontaneously scattered light and highlight the nonclassicality of such correlations.

[1] R. H. Dicke, Phys. Rev. 93, 99 (1954).

[2] R. Wiegner, et al., Phys. Rev. A 84, 023805 (2011).

[3] D. Bhatti, et al., arXiv:1511.00956 (2015).

Q 11.32 Mon 16:30 Empore Lichthof

Detection of quantum correlations of light without quantum discord or entanglement — •TOM ETTRICH¹, SEMJON KÖHNKE¹, MELANIE MRÄZ¹, ELIZABETH AGUDELO OSPINA², JAN SPERLING², WERNER VOGEL², and BORIS HAGE¹ — ¹AG Experimentelle Quantenoptik, Institut für Physik, Universität Rostock, Rostock, Germany — ²AG Theoretische Quantenoptik, Institut für Physik, Universität Rostock, Rostock, Germany

We give a brief overview of the experimental requirements for the preparation and verification by measurement of Einstein-Podolsky-Rosen (EPR) entanglement based on two squeezed vacuum states generated by optical parametric amplifiers (OPA).

By applying carefully generated phase-randomization with a uniform distribution to the mutual phase of the bipartite state both quantum discord and entanglement vanish for a particular range of parameters. However, the method developed by our theoretical colleagues of the group of W. Vogel provides the means to construct a filtered regularised multimode Glauber-Sudarshan P function from measured homodyne data, which contains negativities and therefore does show quantum correlation.

Q 11.33 Mon 16:30 Empore Lichthof

Correlation measurement via unbalanced homodyning with a weak local oscillator — •CHRISTIAN REIHER¹, MELANIE MRÄZ¹, STEVE JÄGER¹, SEMJON KÖHNKE¹, JOHANNES KRÖGER², JAN SPERLING³, HEINRICH STOLZ², WERNER VOGEL³, and BORIS HAGE¹ — ¹AG Experimentelle Quantenoptik, Institut für Physik, Universität Rostock, Germany — ²AG Halbleitertechnik, Institut für Physik, Universität Rostock, Germany — ³AG Theoretische Quantenoptik, Institut für Physik, Universität Rostock, Germany

We present an experiment to evaluate the photostatistics of squeezed states of light by correlation measurements via unbalanced homodyne detection with a weak local oscillator. As squeezer an optical parametric amplifier with a PPKTP-crystal is used. The measurements will be carried out with a τ -SPAD (single-photon avalanche diode) click detector. The main task will be to attenuate the light field to a sufficiently low intensity. Hence the cleanness of the used light field is of special interest, i.e. no other light should trigger our detector, like the light of the pump beam, the seed beam or stray light. The pump beam will be blocked by dichroic mirrors and an edge filter. The seed beam will be blocked by two out of phase rotating choppers. The second one opens the path to the detector only while the first one blocks the seed beam, resulting in a disruption of cavity-length-control. First investigations showed, that there is no negative effect on the resonator length by using this method. This way we make sure that no other event will occur during the deadtime of the detector.

Q 11.34 Mon 16:30 Empore Lichthof

Quantum State Tomography of Kerr-squeezed fs-pulses in optical fibres — •KAI BARNSCHIEDT, OSKAR SCHLETTWEIN, JAKOB STUDER, and BORIS HAGE — Arbeitsgruppe Experimentelle Quantenoptik, Institut für Physik, Universität Rostock, D-18059 Rostock, Germany

Balanced homodyne detection is used for optical state tomography accessing the field quadratures of a signal field with a local oscillator. By tuning the phase between signal and a strong local oscillator information about multiple quadratures is gained and can be used for reconstructing the quantum state of the signal. fs-pulses in optical fibres are affected by linear and nonlinear effects due to high intensities and long travelling distances in fibres, influencing the pulse parameter (e.g. pulse shape, wavelength) and further the quantum state of the light. Balanced homodyne detection is based on interference of a strong local oscillator with the signal, hence a constant phase relation and matching pulse parameters are needed during the measurement time. We propose a method able to extract the local oscillator out of the Kerr-squeezed signal itself. An optical cavity is held on resonance to the repetition frequency of the laser using Pound-Drever-Hall lock-in technique. The cavity is transparent for the main part of the pulse, while the information about the quantum state, present in all sidebands, is mostly reflected by the incoupling mirror of the cavity. The reflected beam (signal) and the transient beam (local oscillator) can then be used for balanced homodyne detection to reconstruct the quantum state via tomographic methods.

Q 11.35 Mon 16:30 Empore Lichthof

Simulation of Kerr-Squeezing in Optical Fibers — •JAKOB STUDER, OSKAR SCHLETTWEIN, KAI BARNSCHIEDT, and BORIS HAGE — Arbeitsgruppe Experimentelle Quantenoptik, Institut für Physik, Universität Rostock, D-18059 Rostock, Germany

Squeezed states of light have many promising applications such as gravitational-wave detectors or optical communications. These states can be created by nonlinear processes in crystals or optical fibres.

One possibility is to utilise the optical Kerr effect, which is especially prominent for short pulses in optical fibres. The Kerr nonlinearity creates an arbitrary squeezed state which can be transformed into an amplitude-squeezed state and detected with various experimental methods. We develop a quasiclassical, probabilistic method to simulate such squeezing processes. For this purpose, the propagation of statistically distributed pulses through the fibre is numerically calculated using the Split-Step-Fourier method. Subsequently, the photon-number distribution after the propagation through the simulated setup is analysed to evaluate the resulting amplitude-squeezing.

This method is demonstrated for two specific experimental setups which use optical fibres to create amplitude-squeezed light. Firstly, the squeezing in an asymmetric Sagnac interferometer and secondly the squeezing by spectral filtering of temporal solitons is investigated and compared to experimental results. At the current state, the simulation results show good qualitative and partial quantitative agreement to the experiments.

Q 11.36 Mon 16:30 Empore Lichthof

Towards creating Rydberg polaritons with cold atoms inside a hollow-core fiber — •MARIA LANGBECKER, MOHAMMAD NOAMAN, and PATRICK WINDPASSINGER — QUANTUM, Institut für Physik, Johannes Gutenberg-Universität Mainz, Staudingerweg 7, 55128 Mainz, Germany

Cold atoms inside hollow-core fibers present a promising candidate to study strongly coupled light-matter systems. Combined with the long range Rydberg interaction which is controlled through an EIT process, a corresponding experimental setup should allow for the generation of a strong and tunable polariton interaction. Using this scheme, novel photonic states can be generated and studied with possible applications in quantum information and simulation.

This poster presents our experimental setup where laser cooled Rubidium atoms are transported into a hollow-core fiber. We show the characterization of a Kagomé-type hollow-core fiber whose properties allow for simultaneous atom guiding and two-photon Rydberg EIT excitation and present the first measurements of Rydberg EIT of the optical molasses in front of the fiber. Finally, we discuss our progress towards Rydberg physics in a quasi-one-dimensional geometry.

Q 11.37 Mon 16:30 Empore Lichthof

Tunable polarons of slow-light polaritons in a BEC — •FABIAN GRUSD^{1,2,3} and MICHAEL FLEISCHHAUER¹ — ¹Department of Physics and Research Center OPTIMAS, University of Kaiserslautern, Germany — ²Graduate School Materials Science in Mainz, Kaiserslautern, Germany — ³Department of Physics, Harvard University, Cambridge, MA 02138, USA

When a mobile impurity atom interacts with a bath of phonons, for example inside a Bose-Einstein condensate (BEC), it forms a polaron.

Here we present a versatile experimental setup that allows to tune both the mass of the impurity and its interactions with the BEC. The impurity is realized as a dark-state polariton, the long-lived quasiparticle of slow light, inside a quasi two-dimensional BEC. We show that its interactions with the Bogoliubov phonons lead to photonic polarons, described by the Bogoliubov-Fröhlich Hamiltonian for sufficiently weak couplings, and make theoretical predictions using an extension of a recently introduced renormalization group approach. Physics beyond the Fröhlich model can also be probed using our scheme. Due to the small impurity mass, the photonic setup is ideally suited to investigate the polaron self-trapping transition in a BEC, which is poorly understood at present.

Q 11.38 Mon 16:30 Empore Lichthof

A modified setup for trapping of neutral mercury — •HOLGER JOHN and THOMAS WALTHER — Technische Universität Darmstadt, Institut für Angewandte Physik, Schlossgartenstraße 7, 64289 Darmstadt

Laser-cooled mercury constitutes an interesting starting point for various experiments, in particular in light of the existence of bosonic and fermionic isotopes. On the one hand the fermionic isotopes could be used to develop a new time standard based on an optical lattice clock. Another interesting venue is the formation of ultra cold Hg-dimers employing photo-association and achieving vibrational cooling by employing a special scheme. The requirements for trapping neutral mercury are given by the cooling transition at 253.7 nm with a linewidth of 1.27 MHz.

We have developed a non-cryogenic Yb-doped fiber amplified ECDL with the fundamental wavelength of 1014.8 nm. It's twice frequency doubled and stabilized at a build-up reference resonator.

In addition to the laser-system our vacuum-system has been modified with a new compact Hg-source. We will report on the status of the experiments.

Q 11.39 Mon 16:30 Empore Lichthof

Optimizing the homodyne detection efficiency of a femtosecond PDC source — •THOMAS DIRMEIER^{1,2}, IMRAN KHAN^{1,2}, GEORG HARDER³, VAHID ANSARI³, NITIN JAIN^{1,2,4}, BIRGIT STILLER^{1,2}, ULRICH VOGL^{1,2}, GERD LEUCHS^{1,2,5}, CHRISTOPH MARQUARDT^{1,2}, and CHRISTINE SILBERHORN^{2,3} — ¹Institute of Optics, Information and Photonics, University of Erlangen-Nuremberg, Germany — ²Max Planck Institute for the Science of Light, Erlangen, Germany — ³Applied Physics, Integrated Quantum Optics Group, University of Paderborn, Germany — ⁴Center for Photonic Communication and Computing, EECS Department, Northwestern University, Evanston, Illinois, USA — ⁵Department of Physics, University of Ottawa, Canada

The realization of quantum networks requires the ability to produce a large number of non-classical states from different sources that are able to easily interfere with each other. Parametric downconversion sources in ppKTP waveguides provide an efficient platform to produce such states in the telecommunication regime with a well-controlled mode structure. At the end of such a network, the receiver efficiency allows for the proper execution of quantum protocols. For a mode-sensitive homodyne detection scheme, this efficiency is mainly governed by the interferometric overlap in space and time between the measured signal and the local oscillator (LO) field. We show the progress on the pulse-to-pulse homodyne detection of different states generated in our engineered ppKTP waveguide source. Specifically, we investigate the influence of different temporal LO pulse shapes.

Q 11.40 Mon 16:30 Empore Lichthof

Towards efficient coupling of light and a single two level atom in free space — •LUCAS ALBER^{1,2}, BHARATH SRIVATHSAN¹, MARTIN FISCHER^{1,2}, MARKUS WEBER¹, MARKUS SONDERMANN^{1,2}, and GERD LEUCHS^{1,2,3} — ¹Max-Planck-Institute for the Science of Light, Erlan-

gen, Germany — ²Friedrich-Alexander University Erlangen- Nürnberg (FAU), Department of Physics, Erlangen, Germany — ³Department of Physics, University of Ottawa, Canada

We report on the efficient free-space interaction between light and a single trapped ion. This is accomplished by transforming a paraxial Gaussian beam into a spherical linear dipole wave using a radial polarization converter and a deep parabolic mirror. We measure the phase shift imprinted on a weak coherent beam by a single ¹⁷⁴Yb⁺ ion trapped in the focus of the parabolic mirror. Our first result matches the best value reported in any free space experiment so far. The achieved phase shift is mainly limited by aberrations of the parabolic mirror, the twofold degeneracy of the ground level, and the spatial spread of the ion's wave function. We will overcome these limitations by using a deformable mirror for aberration correction and by trapping of a ¹⁷⁴Yb²⁺ ion. The latter species comprises a closed two level transition with a comparably small natural linewidth.

Q 11.41 Mon 16:30 Empore Lichthof

A quantum theory of CCD camera photodetection — •VANESSA CHILLE^{1,2,3}, NICOLAS TREPS³, CLAUDE FABRE³, CHRISTOPH MARQUARDT^{1,2}, GERD LEUCHS^{1,2,4}, and ANDREA AIELLO¹ — ¹Max Planck Institute for the Science of Light, Günther-Scharowsky-Str. 1/Bldg. 24, D-91058 Erlangen, Germany — ²Institute of Optics, Information and Photonics, University of Erlangen-Nuremberg, Staudtstr. 7/B2, D-91058 Erlangen, Germany — ³Laboratoire Kastler Brossel, Sorbonne Université - UPMC, ENS, Collège de France, CNRS; 4 place Jussieu, 75252 Paris, France — ⁴Department of Physics, University of Ottawa, 25 Templeton, Ottawa, Ontario, K1N 6N5 Canada

The measurement of a light beam's spatial shape by means of a CCD camera is a standard procedure in optics. Complex spatial modes receive increasing attention, particularly in the context of quantum optics. Thus, the limits of such kind of measurement imposed by quantum physics are of more and more importance.

We present a quantum theory of multi-pixel photodetection, and we use it to determine the quantum noise affecting the measurements of the width and the position of a light beam. An analytic theory is derived and compared to the theory in [1] that investigates the beam width noise independently of the measurement scheme. Numerical simulations are performed. They give realistic and promising predictions for experimental studies. We also study the influence of detector imperfections.

[1] V. Chille et al. arXiv:1506.08588 (2015).

Q 11.42 Mon 16:30 Empore Lichthof

The dynamical Stark effect in the Markovian dynamics of the driven Dicke model — •DANIEL PAGEL, ANDREAS ALVERMANN, and HOLGER FEHSKE — Institut für Physik, Ernst-Moritz-Arndt-Universität, 17487 Greifswald, Germany

The proper description of light-matter interaction in the strong coupling regime is one fundamental topic in quantum optics. Here, we study the Dicke model of driven two-level emitters strongly interacting with a single mode of a cavity beyond the rotating wave approximation. Its dissipative dynamics for weak coupling to an environment can be studied with Markovian master equations. We point out that the usually employed quantum optical master equation is invalid at strong emitter-cavity coupling and describe how exact diagonalization and the Floquet approach can be combined in a solution strategy for the master equation that is applicable also for periodically driven systems. Using this master equation we study the emission of light from the Dicke model and analyze its nonclassical properties. As an indicator of the dynamical Stark effect the peaks in the emission spectra are shifted in dependence on the external driving strength. Depending on the emitter-cavity coupling strength and the bath temperatures we find strong bunching or antibunching and characterize the statistics of the emitted radiation.

Q 12: Ultra-cold atoms, ions and BEC (with A)

Time: Monday 16:30–19:00

Location: Empore Lichthof

Q 12.1 Mon 16:30 Empore Lichthof

Heating and decoherence effects in a hybrid atom-ion system — •TAO YIN, TAO QIN, and WALTER HOFSTETTER — Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität, 60438 Frankfurt/Main, Germany

In this work we study heating and decoherence effects in a hybrid atom-ion system, in which the atom and ion are trapped by a harmonic trap and Paul trap, respectively. We consider the entangled state of one ion strongly coupled to one atom. As a consequence of the time-dependent trapping potential and short-range atom-ion collisions, the ionic micromotion plays an important role in such systems. We investigate the dynamic properties in this system by the Floquet formalism and calculate the effects of heating and decoherence arising from the ionic micromotion. We also study the validity of the secular approximation for different atom-ion mass ratios and trapping geometries. Our results can be used to explain and design experiments on hybrid atom-ion simulators of this type. In addition, we consider adding a second ion to this system, and preliminarily study its possible effects on the atom-ion entangled state due to the long-range coulomb interaction between these two ions.

Q 12.2 Mon 16:30 Empore Lichthof

Towards Ultracold Interaction - Optical trapping of Barium Ions and Rubidium Atoms — •PASCAL WECKESSER, ALEXANDER LAMBRECHT, JULIAN SCHMIDT, LEON KARPA, and TOBIAS SCHAETZ — Albert-Ludwigs-Universität Freiburg

In the last years several experimental groups investigated collisions between laser-cooled atoms and ions, leading to a better understanding of the atom-ion interaction in many aspects [1-4]. Due to the RF-confinement of the ions these systems have been dominated by an intrinsic heating effect [5], limiting collision dynamics on the order of a few milli-Kelvin. A purely optical and electrostatic potential for both ions and atoms should overcome this effect [6] allowing to investigate ultracold interactions, such as cluster formation of an ion binding atoms within the common $1/r^4$ -potential [7]. Here we present our experimental setup combining simultaneously trapped Ba^+ ions and Rb atoms in a far detuned bichromatic dipole trap. We discuss the properties of this novel trap, methods for extending the ion lifetime as well as prospective experiments within reach with the presented setup.

- [1] A.T.Grier et al., Phys.Rev.Lett. 102,223201(2009)
- [2] C.Zipkes et al., Nature 464,388(2010)
- [3] S.Schmid et al. Phys.Rev.Lett. 105.133202 (2010)
- [4] W.G.Rellergert et al., Phys.Rev.Lett. 107,243201 (2011)
- [5] M.Cetina et al., Phys.Rev.Lett. 109,253201 (2012)
- [6] T.Huber et al., Nat. Comm. 5,5587 (2014)
- [7] R.Cote et al. Phys.Rev.Lett. 89.093001 (2002)

Q 12.3 Mon 16:30 Empore Lichthof

Orbital magnetism of ultracold fermionic gases in a lattice: Dynamical Mean-Field Approach — •AGNIESZKA CICHY¹, ANNA GOLUBEVA¹, ANDRII SOTNIKOV², and WALTER HOFSTETTER¹ — ¹Goethe Universität, Frankfurt a. M., Germany — ²Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine

The impressive development of experimental techniques in ultracold quantum degenerate gases of alkaline-earth-like atoms in the last years has allowed investigation of strongly correlated systems. Long-lived metastable electronic states in combination with decoupled nuclear spin give the opportunity to study the Hamiltonians beyond the possibilities of current alkali-based experiments. Ytterbium is particularly convenient due to its large number of bosonic and fermionic (e.g. ¹⁷³Yb) isotopes with a wide range of interaction strengths.

We study finite-temperature properties of the two-band Hubbard model on a simple cubic lattice. Our main goal is to investigate the role of exchange interaction in finite temperature magnetic phases, for the whole range of fillings. We use the Dynamical Mean-Field Theory approach and its extension in real space to obtain finite-temperature phase diagrams including transitions to magnetically-ordered phases. We determine which parameter regimes are most favourable for ferromagnetism, in terms of experimental observation in ultracold atomic gases in a lattice. We also calculate the entropy in the vicinity of magnetically-ordered phases that allows to make important predic-

tions for on-going and future experiments aiming at approaching and studying long-range ordered states in ultracold atomic mixtures.

Q 12.4 Mon 16:30 Empore Lichthof

Dynamical Mean-Field Theory of the SU(4)-symmetric Fermi-Hubbard model and its extensions — •ANNA GOLUBEVA¹, AGNIESZKA CICHY¹, ANDRII SOTNIKOV², and WALTER HOFSTETTER¹ — ¹Goethe Universität, Frankfurt am Main, Germany — ²Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine

Alkaline-earth-like atoms have emerged in the field of ultracold quantum gases as a promising alternative to alkali atoms. Their internal structure includes low-lying metastable electronic states offering the possibility to simulate many-body models with orbital phenomena. Furthermore, certain isotopes (specifically ⁸⁷Sr, ¹⁷³Yb) exhibit a high SU(N) symmetry of interactions which is a result of the decoupling between the nuclear spin and electronic degrees of freedom. Recent experimental advances in this field [1-3] have triggered theoretical interest.

We investigate the SU(4)-symmetric Fermi-Hubbard model in a simple cubic optical lattice at finite temperatures. By means of Dynamical Mean-Field Theory [4] and its real-space extension we study the magnetic phases and entropy characteristics of the system at half- and quarter-filling. We also analyze the influence of different interspecies interactions on possible magnetic orderings.

- [1] Taie et al., Nature Phys. 8, 825–830 (2012)
- [2] Taie et al., Phys. Rev. Lett. 105, 190401 (2010)
- [3] Fukuhara et al., Phys. Rev. A 79, 021601 (2009)
- [4] Georges et al., Rev. Mod. Phys. 68, 13 (1996)

Q 12.5 Mon 16:30 Empore Lichthof

Manipulation of a dipolar Bose-Einstein condensate using an electro-optical deflector system — •MATTHIAS SCHMITT, HOLGER KADAU, MATTHIAS WENZEL, IGOR FERRIER-BARBUT, and TILMAN PFAU — 5. Physikalisches Institut and Center for Integrated Quantum Science and Technology, Universität Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany

Strongly dipolar quantum gases enable the observation of many-body phenomena with anisotropic, long-range interactions. Observing these effects can be enhanced by an initial preparation of the atomic density distribution in multi-well [1] or ring-shaped potentials [2] as well as in-situ imaging.

We present the first results on tailored potentials imprinted on a Bose-Einstein condensate of dysprosium atoms. The potentials are created with a 532 nm laser modulated with an electro-optical deflector system and a Pockels cell. The light is focused on the atomic cloud using a diffraction-limited custom objective with high numerical aperture.

- [1] D. Peter, K. Pawłowski, T. Pfau and K. Rzażewski, J. Phys. B, 45, 225302 (2012)
- [2] M. Abad, M. Guilleumas, R. Mayol, M. Pi and D. M. Jezek, EPL, 94, 10004 (2011)

Q 12.6 Mon 16:30 Empore Lichthof

Controlling Rydberg atoms in dense gases — •KARL MAGNUS WESTPHAL, KATHRIN SOPHIE KLEINBACH, FELIX ENGEL, FABIAN BÖTTCHER, MICHAEL SCHLAGMÜLLER, ROBERT LÖW, TARA CUBEL LIEBISCH, SEBASTIAN HOFFERBERTH, and TILMAN PFAU — 5. Physikalisches Institut and Center for Integrated Quantum Science and Technology, Universität Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany

When a Rydberg atom is excited in a dense gas, there can be tens of thousands of neutral atoms within the Rydberg electron orbit, resulting in a density-dependent frequency shift, as discovered by Amaldi and Segrè in 1934. However, Rydberg excitations in a BEC lead not only to a density shift, but a line shape that changes with the principal quantum number n . The line broadening depends precisely on the interaction potential energy curves of the Rydberg electron with the neutral atom perturbers. In particular, we show the relevance of the triplet p-wave shape resonance in the e^- -Rb(5S) scattering, which significantly modifies the interaction potential [1]. We discuss a variety of results of experiments with a single charged impurity in quantum gases

as well as wavefunction imaging. Spatial control of the excitations allows us to study the density-dependent quantum chemistry between a Rydberg atom and neutral atoms.

1 M. Schlagmüller et al., [arXiv:1510.07003](https://arxiv.org/abs/1510.07003), (2015)

Q 12.7 Mon 16:30 Empore Lichthof

Towards the production of RbCs ground-state molecules from degenerate gases in an optical lattice — ●BEATRIX MAYR¹, LUKAS REICHSÖLLNER², ANDREAS SCHINDEWOLF¹, SILVA MEZINSKA¹, RUDOLF GRIMM^{1,2}, and HANNS-CHRISTOPH NÄGERL¹ — ¹Institut für Experimentalphysik, Universität Innsbruck — ²Institut für Quantenoptik und Quanteninformation IQOQI, Innsbruck

Ultracold dipolar systems are of high interest for quantum chemistry, precision spectroscopy, quantum many-body physics, and quantum simulation. Our goal is the production of a low entropy sample of dipolar RbCs molecules in the rovibronic and hyperfine ground-state. To be able to mix degenerate samples of Rb and Cs, the inter-species scattering length a_{RbCs} has to be tuned close to zero by means of a magnetic Feshbach resonance. Since Cs three-body losses would cause a breakdown of a Cs BEC in the magnetic-field region, in which RbCs Feshbach resonances are available, we initially prepare a Cs Mott insulator with unity filling spatially separated from the Rb sample. The optical lattice wavelength and depth are chosen in a way that Rb is still superfluid and can be overlapped with Cs after switching the magnetic field to achieve $a_{\text{RbCs}} = 0$. Precise control over the relative position of the two degenerate samples and high magnetic field stability will enable the formation of RbCs Feshbach molecules with a high filling factor of the optical lattice followed by the application of the STIRAP transfer to the absolute molecular ground-state, as demonstrated in Ref. [1].

[1] T. Takekoshi et al., *Phys. Rev. Lett.* **113**, 205301 (2014)

Q 12.8 Mon 16:30 Empore Lichthof

Expansion dynamics of an ultracold gas from realistic trap potentials for atom interferometry — ●SRIHARI SRINIVASAN and REINHOLD WALSER — Institut für Angewandte Physik, TU Darmstadt, Hochschulstraße 4a, 64289 Darmstadt

The versatility of Bose-Einstein Condensates (BEC) for use in experiments has enabled an entire genre of topics ranging from quantum optics and condensed matter physics to quantum simulators and sensors. The QUANTUS collaboration [1] aims to use atom interferometry with an ultracold ⁸⁷Rb gas in the vacuum drop tower at ZARM in Bremen [2]. The experiment module can either be catapulted or dropped inside the vacuum drop tower to perform atom interferometry in microgravity under free fall to test Einstein's Equivalence Principle. Expansion dynamics of a BEC is well understood analytically [3]. Interferometric fringe contrast of an expanding BEC released from the trap is strongly influenced trap anharmonicity and thermal component of the gas. We aim to simulate the expansion of a BEC and a thermal cloud from a realistic, anisotropic magnetic trap of the QUANTUS II atom chip. This is done as a part of a comprehensive simulation of a realistic atom interferometer to be used for comparison with experimental data.

[1] QUANTUS Collaboration: www.iqo.uni-hannover.de/quantus.html

[2] T. van Zoest et al., *Science*, **328**, 1540 (2010) and H. Mütting et al., *Phys. Rev. Lett.*, **110**, 093602 (2013).

[3] Yu Kagan et al., *Phys. Rev. A*, **54**(3), R1753 (1996) and Y Castin et al., *Phys. Rev. Lett.*, **77**(27), 5315 (1996).

Q 12.9 Mon 16:30 Empore Lichthof

Regions of tunneling dynamics for few bosons in an optical lattice subjected to a quench of the imposed harmonic trap — ●GEORGIOS KOUTENTAKIS^{1,2}, SIMEON MISTAKIDIS¹, and PETER SCHMELCHER^{1,2} — ¹Zentrum für Optische Quantentechnologien, Universität Hamburg, Luruper Chaussee 149, D-22761 Hamburg, Germany — ²The Hamburg Centre for Ultrafast Imaging, Universität Hamburg, Luruper Chaussee 149, D-22761 Hamburg, Germany

Recent advancements in ultracold atom experiments have introduced an interplay in the trapping length scales of lattice and harmonic confinement. This fact motivates the investigation, whether it is possible to prepare atomic gases at certain quantum states by utilizing a composite atomic trap consisting of a lattice potential that is embedded inside an overlying harmonic trap. In the present work, we examine how frequency modulations of the harmonic trap stimulate the dynamics of an 1D few-boson gas. The gas is initially prepared at a highly confined state, and the subsequent dynamics induced by a quench of the har-

monic trap frequency to a lower value is examined. It is shown that a non-interacting gas always diffuses to the outer sites, whereas the response of the interacting system is more involved and is dominated by a resonance, which is induced by the bifurcation of the low-lying eigenstates. Our study reveals that the position of the resonance depends both on the atom number and the interaction coupling, manifesting its many body nature. A corresponding mean field treatment as well as a single-band approximation have been found to be inadequate for the description of the tunneling dynamics in the interacting case.

Q 12.10 Mon 16:30 Empore Lichthof

Cradle-like processes and mode-coupling of interaction quenched ultracold bosons in periodically driven lattices — ●SIMEON MISTAKIDIS¹ and PETER SCHMELCHER^{1,2} — ¹Zentrum fuer Optische Quantentechnologien, Universitaet Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany — ²The Hamburg Centre for Ultrafast Imaging, Universitaet Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany

The out-of-equilibrium dynamics of ultracold bosons in one-dimensional lattices following an interaction quench upon a periodically driven optical lattice is investigated. It is shown that an interaction quench triggers the inter-well tunneling dynamics, while for the intra-well dynamics breathing and cradle-like processes can be generated. In particular, the occurrence of a resonance between the cradle and tunneling modes is revealed. On the other hand, the employed periodic driving (vibration) enforces the bosons in the mirror wells to oscillate out-of-phase and to exhibit a dipole mode, while in the central well the cloud experiences a breathing mode. The dynamical behaviour of the system is investigated with respect to the driving frequency revealing a resonant-like behaviour of the intrawell dynamics. To drive the system in a highly non-equilibrium situation an interaction quench upon the driving is performed giving rise to admixing of excitations in the mirror wells, an enhanced breathing in the center and an amplification of the tunneling dynamics. As a result of the quench the system experiences multiple resonances between the inter- and intra-well dynamics at different quench amplitudes.

Q 12.11 Mon 16:30 Empore Lichthof

A new apparatus of Bose-Fermi mixture — ●HAOZE CHEN — University of Science and Technology of China Shanghai Branch, Shanghai, China

We will introduce a new apparatus for investigation of lithium6 and potassium41 Bose-Fermi mixture. The whole system contains several novel developed technics. Lithium6 and potassium41 are precooled by a spin-flipped Zeeman slower and 2D plus MOT respectively and captured by 3D-MOT simultaneously. Lithium6 cloud is further cooled by UV-MOT, while potassium41 is further cooled by gray molasses, which enhance the phase-space density from 1e-7 to 1e-4. We then apply D1 optical pumping for both atoms to increase the loading efficiency and purify the spin state. Then both species are loaded in a magnetic trap, and transport from our MOT chamber to science cell, which has a much better vacuum and optical access. We start evaporate cooling of potassium41 in a plugged magnetic trap, while lithium6 is sympathetic cooled by potassium41. After 15s of evaporation, we have generated double degenerate gas with more than 2e5 pure BEC of K41 and 5e5 degenerate fermi gas with 10% Fermi temperature of Li.

Q 12.12 Mon 16:30 Empore Lichthof

Energy and mass transfer between zig-zag chains trapped in a double well potential — ●ANDREA KLUMPP¹, ALEXANDRA ZAMPETAKI¹, and PETER SCHMELCHER^{1,2} — ¹ZOQ Universität Hamburg — ²ILP Universität Hamburg

Ion traps are versatile tools for experiments in various fields, such as spectroscopy, quantum computing, molecular physics and biophysics [1]. The development of micro-fabricated segmented Paul traps opens up new fields for research relating, among others, to the transport of ions [2], the splitting [3] and also the coupling of ion crystals [4].

In our work we investigate the dynamics of two trapped ion crystals in a three dimensional double well potential with a strong confinement perpendicular to the x-z plane as in the case of a planar trap. The initial state of the ions in our setup is given by well separated zig-zag configurations in both wells. The crystals are built of 13 in the first well and 20 in the second. After lowering the barrier between the wells, we observe mass and energy transfer between the crystals as a result of the asymmetry in the initial crystal sizes. In addition, we detect oscillations propagating into the big crystal like a shock wave, while

the small ion crystal melts completely.

- [1] Major et al., Charged particle traps I+II Springer,(2005 + 2009)
- [2] Huber et al., NJP 10, 013004 (2008)
- [3] Ruster et al., Phys. Rev. A 90, 033410 (2014)
- [4] Klumpp et al., arXiv:1508.07979

Q 12.13 Mon 16:30 Empore Lichthof

Magnesium Ion Crystals at SpecTrap — ●MANUEL VOGEL¹, ZORAN ANDELKOVIC¹, GERHARD BIRKL², TOBIAS MURBÖCK², WILFRIED NÖRTERSCHÄUSER³, and STEFAN SCHMIDT³ — ¹ GSI, 64291 Darmstadt — ² Institut für Angewandte Physik, TU Darmstadt, 64289 Darmstadt — ³ Institut für Kernphysik, TU Darmstadt, 64289 Darmstadt

We have investigated laser-cooled magnesium ions stored in a Penning trap. The ions are produced externally and are dynamically captured in the trap. We have combined buffer-gas cooling and laser cooling, thus reducing the ion temperatures from Mega-Kelvin to milli-Kelvin on the timescale of seconds. At this temperature, the ions adopt crystalline structures. For ion numbers of the order of a few thousand, these so-called 'mesoscopic' ion crystals display shell structures depending on experimental parameters, which we have visualized by use of a CCD camera. We have investigated the fluorescence signal depending on laser parameters and characterized the crystal structures. This is part of the sympathetic cooling of highly-charged ions as a next step in the framework of the SpecTrap experiment at the HITRAP facility at GSI/FAIR.

Q 12.14 Mon 16:30 Empore Lichthof

Optimized atomic transport with an atom chip — ●ROBIN CORGIER^{1,2}, ERIC CHARRON², ERNST MARIA RASEL¹, and NACEUR GAALLOUL¹ — ¹ Leibniz University of Hanover, Germany — ² Université Paris-Sud, France

Recent proposals for testing performing a quantum test of Einsteins principle of equivalence assume Bose-Einstein condensates (BEC) as sources of atom interferometry sensors. Atom chip devices have allowed to build transportable BEC machines with high repetition rates as demonstrated in the QUANTUS project [J. Rudolph et al. New J. Phys. 17, 079601 (2015)]. The proximity of the atoms to the chip surface is, however, limiting their optical access and the times the atoms spend in the interferometer necessary for precision measurements. In this context, a fast and perturbation-free transport of the atoms is required. Shortcuts to adiabaticity protocols were proposed and allow in principle to implement such sequences with well defined boundary conditions. In this theoretical study, we engineer suitable protocols to move atomic ensembles trapped at the vicinity of an atom chip by tuning the realistic chip currents and external magnetic fields. We find a realistic protocols for moving the atomic trap optimizing the transport time and reducing detrimental effects due to the offset of atoms positions from the trap center. Further developments generalizing our method to anharmonic traps and spatially extended atomic wave packets are also discussed.

Q 12.15 Mon 16:30 Empore Lichthof

Species and regime trade-off of atomic sources for extended-time atom interferometry — ●SINA LORIANI, DENNIS SCHLIPPERT, CHRISTIAN SCHUBERT, ERNST MARIA RASEL, and NACEUR GAALLOUL — Leibniz University of Hanover, Germany

Recent proposals for space-borne atomic sensors designed to detect gravitational waves or testing the universality of free fall predict unprecedented sensitivity for long interrogation times. These extremely long drift times of several seconds are possible thanks to the collimation technique of delta-kick cooling (DKC) [Müntinga, et al. Phys. Rev. Lett. 110, 093602 (2013), T. Kovachy et al., Phys. Rev. Lett. 114, 143004 (2015)]. These atomic lenses are, however, subject to aberrations depending on the extent of the collimated wave packets and the potentials used. In this theoretical study, we trade-off the performance of the DKC for commonly used alkaline and alkaline-earth-like ensembles of atoms (Rb, Sr, Yb, etc.) in the metrology context. The efficiency of the DKC is evaluated and contrasted for these isotopes in the three possible density regimes (thermal, hydrodynamic and degenerate). The expansion dynamics is followed by solving different scaling law approaches depending on the temperature and density of the considered atomic cloud. The results show a clear advantage when using condensed or hydrodynamic ensembles.

Q 12.16 Mon 16:30 Empore Lichthof

Impurity in a Bose-Einstein condensate using quantum

Monte Carlo methods — ●LUIS ARDILA¹ and STEFANO GIORGINI² — ¹ Max Planck Institute for the Physics of Complex Systems, D-01187 Dresden, Germany — ² INO-CNR BEC Center and Department of Physics, University of Trento - via Sommarive 14 38123 Povo

We investigate the properties of an impurity immersed in a dilute Bose gas at zero temperature using quantum Monte Carlo methods. The interactions between bosons are modeled by a hard-sphere potential with scattering length a , whereas the interactions between the impurity and the bosons are modeled by a short-range, square-well potential where both the sign and the strength of the scattering length b can be varied by adjusting the well depth. We characterize the attractive and the repulsive polaron branch by calculating the binding energy and the effective mass of the impurity. Furthermore, we investigate the structural properties of the bath, such as the impurity-boson contact parameter and the change of the density profile around the impurity. At the unitary limit of the impurity-boson interaction, we find that the effective mass of the impurity remains smaller than twice its bare mass, while the binding energy scales with $\hbar^2 n^{2/3}/m$, where n is the density of the bath and m is the common mass of the impurity and the bosons in the bath. The implications for the phase diagram of binary Bose-Bose mixtures at low concentrations are also discussed.

Q 12.17 Mon 16:30 Empore Lichthof

Interaction-Induced Topological Phases in the Hofstadter-Hubbard Model — ●PRAMOD KUMAR, THOMAS MERTZ, and WALTER HOFSTETTER — Institut für Theoretische Physik, Goethe-Universität, 60438 Frankfurt/Main, Germany

Interaction effects have been the subject of contemporary interest in topological phases of matter. In the presence of interactions, the accurate determination of topological invariant gets cumbersome due to its dependence on multiple integrals containing Green's functions and their derivatives. We employ the recently proposed, "topological Hamiltonian" method (Z. Wang and S.-C. Zhang) to explore interaction-induced topological phases in the time-reversal-invariant Hofstadter-Hubbard model. Within this approach, the zero frequency part of the self-energy is sufficient to determine the correct topological invariant. We combine the topological Hamiltonian approach with the local self-energy approximation within Hartree-Fock and dynamical mean field theory (DMFT), and present the corresponding phase diagram in the presence of many-body interactions. We investigate the presence of quantum spin Hall (QSH) states for different interactions by calculating the \mathbb{Z}_2 invariant.

References:

- 1. Z. Wang and S.-C. Zhang, Phys. Rev. X 2, 031008 (2012).

Q 12.18 Mon 16:30 Empore Lichthof

Atom laser based quantum sensors — ●TOBIAS MENOLD, CAROLA ROGULJ, MALTE REINSCHMIDT, PETER FEDERSEL, ANDREAS GÜNTHER, and JÓZSEF FORTÁGH — Physikalisches Institut, Universität Tübingen, Germany

Developing new quantum sensors is the biggest challenge in today's quantum technology. Thereby, quantum fluctuations play an important role as they provide direct access to the quantum information of a system. Our goal is to develop a new quantum sensor for these quantum fluctuations. Using a quantum state transfer, they are transferred to an atom laser, whose output is measured with single atom sensitivity.

We demonstrate such a sensor, by transferring the dynamics of an ultra-cold atomic cloud onto an atom laser and reconstructing its dynamics using our time resolved, single atom detection scheme. In a second experiment we transfer classical field noise of a multi-mode microwave field onto the atom laser and analyze its statistics. We find that the atom laser output allows for measuring not only the power spectral density of the noise but also the field correlations.

Using our sensor, a quantum galvanometer comes into direct reach. It should allow the investigation of quantum transport phenomena in various solid state systems.

Q 12.19 Mon 16:30 Empore Lichthof

Towards Dysprosium Quantum Gases — ●FLORIAN MÜHLBAUER, NIELS PETERSEN, and PATRICK WINDPASSINGER — QUANTUM, Institut für Physik, Johannes Gutenberg-Universität Mainz, Staudingerweg 7, 55128 Mainz, Germany

Ultra-cold dipolar quantum gases enable the study of many-body physics with long-range, inhomogeneous interaction effects due to the anisotropic character of the dipole-dipole interaction. These systems

are expected to show novel exotic quantum phases and phase transitions which can be studied with dysprosium atoms. Dysprosium is a rare-earth element with one of the largest ground-state magnetic moments (10 Bohr magnetons) in the periodic table. Therefore, the dipole-dipole interaction is not a small perturbation but becomes comparable in strength to the s-wave scattering. This influences significantly the physical properties of the trapped atomic sample, such as its shape and stability.

This poster presents the current status of our experimental setup to generate dysprosium quantum gases. We discuss the relevant properties of dysprosium and present our laser system and vacuum design.

Q 12.20 Mon 16:30 Empore Lichthof

A quantum gas machine for studies of local losses induced by photoionization — •TOBIAS KROKER¹, JANINE FRANZ¹, BERNHARD RUFF^{2,3}, TIM ANLAUF¹, JULIETTE SIMONET¹, PHILIPP WESSELS^{1,3}, MARKUS DRESCHER^{2,3}, and KLAUS SENGSTOCK^{1,3} — ¹Zentrum für Optische Quantentechnologien, Hamburg, Germany — ²Institut für Experimentalphysik, Hamburg, Germany — ³The Hamburg Centre for Ultrafast Imaging, Hamburg, Germany

Local photoionization of ultracold atoms shall offer insight into the coherence properties of a Bose-Einstein condensate (BEC). To access the corresponding quantum effects, we are setting up an experiment which allows resolving correlations among electrons photoionized from a BEC by a femtosecond laser pulse.

Here we report on our progress in setting up a quantum gas machine where the ultracold gases are optically transported into the focus region of the femtosecond laser beam. As photoionization induces local losses in the BEC, a theoretical model of the dissipative system is essential including a quantification of the quantum Zeno effect.

Q 12.21 Mon 16:30 Empore Lichthof

Dynamics of nonlinear excitations of helically confined charges — •ALEXANDRA ZAMPETAKI¹, JAN STOCKHOFE¹, and PETER SCHMELCHER^{1,2} — ¹Zentrum für Optische Quantentechnologien, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany — ²The Hamburg Centre for Ultrafast Imaging, Luruper Chaussee 149, 22761 Hamburg, Germany

The confinement of long-range interacting particles on a curved manifold can modify significantly their effective interactions. In the special case of identical charges trapped on a helical geometry the effective two-body potential acquires an extraordinary oscillatory form [1].

For a closed helical trap the corresponding system of charges was recently found to exhibit an unconventional deformation of the linear spectrum when tuning the helix radius [2]. Here we show that the same geometrical parameter can affect significantly also the dynamical behaviour of an initially broad excitation for long times. In particular, for small values of the radius, the excitation disperses into the whole crystal whereas within a specific narrow regime of larger radii the excitation self-focuses, assuming finally a localized form. Beyond this regime, the excitation defocuses and the dispersion gradually increases again. We analyze this geometrically controlled nonlinear behaviour using an effective discrete nonlinear Schrödinger model, which allows us among others to identify a number of breather-like excitations.

[1] P. Schmelcher, EPL 95 50005 (2011).

[2] A. V. Zampetaki, J. Stockhofe and P. Schmelcher, Phys. Rev. A 91, 023409 (2015).

Q 12.22 Mon 16:30 Empore Lichthof

Three-body recombination in a quasi-two-dimensional quantum gas — •BO HUANG^{1,2}, ALESSANDRO ZENESINI³, and RUDOLF GRIMM^{1,2} — ¹Institut für Experimentalphysik, Universität Innsbruck, 6020 Innsbruck, Austria — ²Institut für Quantenoptik und Quanteninformation (IQOQI), Österreichische Akademie der Wissenschaften, 6020 Innsbruck, Austria — ³Institute of Quantum Optics, Leibniz Universität Hannover, 30167 Hannover, Germany

Quantum three-body recombination in three-dimensional systems is influenced by a series of weakly bound trimers known as Efimov states, which are induced by short-range interactions and exhibit a discrete scaling symmetry. On the other hand, two-dimensional systems with contact interactions are characterized by continuous scale invariance and support no Efimov physics. This raises questions about the behaviour of three-body recombination in the transition from three to two dimensions. We use ultracold caesium atoms trapped in anisotropic potentials formed by a pair of counter-propagating laser beams to experimentally investigate three-body recombination in quasi-two-dimensional systems with tunable confinement and tunable

interactions. In our recent results, we observed a smooth transition of the three-body recombination rate coefficient from a three-dimensional to a deeply quasi-two-dimensional system. A comparison between the results obtained near two Feshbach resonances indicates a universal behaviour of three-body recombination in the quasi-two-dimensional regime.

Q 12.23 Mon 16:30 Empore Lichthof

Local probing of two-dimensional superfluid gases in the BEC-BCS crossover — •KLAUS HUECK, KENO RIECHERS, WOLF WEIMER, KAI MORGENER, JONAS SIEGL, NICLAS LUICK, THOMAS LOMPE, and HENNING MORITZ — Institut für Laserphysik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg

In this poster we present local measurements of the superfluid fraction of a strongly interacting two-dimensional gas of diatomic Li⁶ molecules. Using a high resolution imaging system, we perform a local measurement of the phase fluctuations on a single layer 2D gas. From this we extract the algebraic scaling exponent of the first order correlation function $g^{(1)}(r)$. This exponent is directly proportional to the superfluid density.

We furthermore report on our progress towards the creation of homogeneous two-dimensional Fermi gases in the BEC-BCS crossover.

Q 12.24 Mon 16:30 Empore Lichthof

Nonequilibrium Green functions approach to expansion dynamics in strongly correlated fermionic lattice systems — •JAN-PHILIP JOOST, NICLAS SCHLÜNZEN, SEBASTIAN HERMANS, and MICHAEL BONITZ — CAU Kiel, Germany

Experiments with ultracold atoms in optical lattices gained in importance over the last years and are of high current interest, since they allow to directly measure quantum behaviour and serve as a model for solid state systems [1]. The proper description of transport processes in quantum lattices in the regime of strong coupling is a challenging task, which has been limited, so far, to one-dimensional systems. The nonequilibrium Green functions [2] (NEGF) technique, however, is not restricted with respect to dimension or particle number. Combined with the T -matrix approximation [3], in particular, the NEGF method is well-suited to fill the gap for higher dimensions [4]. Here, we show results for strongly interacting fermions in 2D and 3D. The approach gives access to the short-time dynamics, as well as the long-time limit of the expansion. Beside the density and energy evolution, also the momentum distribution, dispersion relation and the site-resolved build-up of correlations are obtained, the latter of which can be verified experimentally using the recently developed fermionic atom microscopes.

[1] U. Schneider *et al.*, Nat. Phys. **8**, 213 (2012)

[2] K. Balzer and M. Bonitz, *NEGF Approach to Inhomogeneous Systems*, Lecture Notes in Physics (Springer, 2013)

[3] M. P. von Friesen *et al.*, Phys. Rev. B **82**, 155108 (2010)

[4] N. Schlünzen *et al.*, arXiv:1508.02947 (2015)

Q 12.25 Mon 16:30 Empore Lichthof

Variational calculation of ⁴He for Droplets — •CHRISTOPHER BATE, YAROSLAV LUTSYSHYN, and DIETER BAUER — Universität Rostock Institut für Physik

We aim to study droplets of liquid ⁴He at very low temperature with the variational ansatz that was recently proposed for the ground state of strongly correlated Bose liquids [1]. This ansatz goes beyond the traditional Jastrow-Feenberg functional form and when optimized, provides an excellent description of the correlations in the system. Even though this wavefunction is constructed of short-range two-body factors and does not contain one-body surface terms, phase separation and free surface emerge at appropriate densities. This allows to study the inhomogeneous phases such as the droplets of superfluid helium, and the formation of the inhomogeneous phase as well. Due to advances in computational techniques and the fact that we can study the system on a variational level, we are able to consider droplets with up to 10⁴ particles.

[1] Y. Lutsyshyn, “A coordinated wavefunction for the ground state of liquid helium-4”, arXiv 1506.03752 (2015), to be published.

Q 12.26 Mon 16:30 Empore Lichthof

Interactions of Single Cesium Atoms with an Ultracold Rubidium Bath — •DANIEL MAYER^{1,2}, MANUEL STEIN¹, MICHAEL HOHMANN¹, FARINA KINDERMANN¹, TOBIAS LAUSCH¹, FELIX SCHMIDT^{1,2}, and ARTUR WIDERA^{1,2} — ¹Department of Physics and Research Center OPTIMAS, University of Kaiserslautern, Ger-

many — ²Graduate School Materials Science in Mainz, Kaiserslautern, Germany

Our project aims on combining single, tightly controlled particles with a quantum many-body system by immersing single neutral Cesium (¹³³Cs) atoms into a Rubidium (⁸⁷Rb) Bose-Einstein condensate.

We store both species in a common, red detuned dipole trap which gives rise to dynamical interspecies interaction. To capture the dynamics of the Cs distribution interacting with a cold, thermal Rb cloud, a species selective, 1D optical lattice is used for position resolved fluorescence imaging of the single Cs atoms. The temperature for Rb and Cs atoms can be measured by release-recapture thermometry providing an additional, independent view on the interaction process.

We will give the current status on interaction dynamics between single impurities in an ultracold Rb gas.

Q 12.27 Mon 16:30 Empore Lichthof

Lifetime Measurements of Topological Defects in Coulomb Crystals — ●MIRIAM BUJAK¹, JONATHAN BROX¹, PHILIP KIEFER¹, ISABELLE SCHMAGER¹, HAGGAI LANDA², and TOBIAS SCHAEZT¹ — ¹Atom-, Molekül- und optische Physik, Physikalisches Institut, Universität Freiburg, Hermann-Herder-Str. 3, 79104 Freiburg — ²LPTMS, Université Paris Sud, Orsay, France

We study structural defects (kinks) of Mg-Ions in Coulomb crystals. Simulations reveal a strong anharmonicity of the kink's internal mode of vibration, further enhanced by the controlled extension into three dimensions. As a consequence, the discrete kink experiences a self-induced globally confining potential, capable of trapping it at the centre of the crystal.

The formation of kink configurations in dependence of the trapping parameters is investigated and the lifetime of these defects is explored.

[1] M. Mielenz et al., Phys. Rev. Lett. **110**, 133004 (2013)

Q 12.28 Mon 16:30 Empore Lichthof

Spectroscopy of Discrete Solitons in Coulomb Crystals — ●JONATHAN BROX¹, MIRIAM BUJAK¹, PHILIP KIEFER¹, ISABELLE SCHMAGER¹, HAGGAI LANDA², and TOBIAS SCHAEZT¹ — ¹Atom-, Molekül- und optische Physik, Physikalisches Institut, Universität Freiburg, Hermann-Herder-Str. 3, 79104 Freiburg — ²LPTMS, Université Paris Sud, Orsay, France

We study structural defects (kinks) which are formed during the transition from a laser cooled cloud of Mg-Ions to a Coulomb crystal [1]. The occurrence of these structures is investigated in dependence of crystal size and axial as well as radial confinement.

Ion crystals with such structural defects feature localized vibrational modes in the spectrum of phonons [2]. We present first results on the spectroscopy of vibrational modes of the Coulomb crystal.

[1] M. Mielenz et al., Phys. Rev. Lett. **110**, 133004 (2013)

[2] H. Landa et al., New J. Phys. **15**, 093003 (2013)

Q 12.29 Mon 16:30 Empore Lichthof

Characterizing and Controlling the Structure of Topological Defects in Coulomb Crystals — ●ISABELLE SCHMAGER¹, JONATHAN BROX¹, MIRIAM BUJAK¹, PHILIP KIEFER¹, HAGGAI LANDA², and TOBIAS SCHAEZT¹ — ¹Atom-, Molekül- und optische Physik, Physikalisches Institut, Universität Freiburg, Hermann-Herder-Str. 3, 79104 Freiburg — ²LPTMS, Université Paris Sud, Orsay, France

We study structural defects (kinks) in Coulomb crystals of Mg-Ions in dependency on the ratio of radial to axial confinement and cooling conditions [1].

The formation of kink configurations and the transformation of kinks to different structures are investigated. We compare the properties of extended (2D) and blurred (3D) kinks for crystals consisting of 30 ions [2]. Furthermore, different creation and control processes are studied in detail.

[1] M. Mielenz et al., Phys. Rev. Lett. **110**, 133004 (2013)

[2] H. Landa et al., New J. Phys. **15**, 093003 (2013)

Q 12.30 Mon 16:30 Empore Lichthof

Motional Mode Analysis of Trapped Ions — ●FREDERICK HAKELBERG, HENNING KALIS, MATTHIAS WITTEMER, MANUEL MIELENZ, ULRICH WARRING, and TOBIAS SCHAEZT — Physikalisches Institut, Albert-Ludwigs-Universität Freiburg

Trapped ions present a promising system for quantum simulations [1]. However scaling to large systems present a major challenge. Surface-electrode traps with individually controllable potential wells offer a

promising approach by allowing the design of arbitrary patterns of trapped ions [2]. The Coulomb coupling of ions in two distinct traps (separated by $\approx 40 \mu\text{m}$) has been shown [3]. In our experiment we trap ²⁵Mg⁺ ions in a triangular surface-trap array with individual trap sites. The trap features 30 control electrodes which allow us to apply potentials for stray field compensation, and the control of motional-mode frequencies and mode orientations. We present two methods for measuring mode orientations and frequencies. The first is based on motional-sensitive two-photon stimulated-Raman transitions. The second makes use of oscillating control potentials generated by the control electrodes. We compare results with detailed models of both methods.

[1] Ch. Schneider *et al.*, Rep. Prog. Phys. **75**, 024401 (2012)

[2] T. Schaetz *et al.*, New J. Phys. **15**, 085009 (2013)

[3] K. R. Brown *et al.*, Nature **471**, 7337 (2013)

Q 12.31 Mon 16:30 Empore Lichthof

SOC2: Neutral-atom Space Optical Clock — ●SRUTHI VISWAM¹, LYNDIE SMITH¹, WEI HE¹, DARIUSZ SWIERAD¹, JOSHUA HUGHES¹, YESHPAL SINGH¹, KAI BONGS¹, STEFANO ORIGLIA², SOROOSH ALIGHANBARI², STEFAN SCHILLER², SOREN DORSCHER³, STEFAN VOGT³, CHRISTIAN LISDAT³, and UWE STERR³ — ¹University of Birmingham, United Kingdom — ²Heinrich-Heine Universität Düsseldorf, Germany — ³Physikalisch-Technische Bundesanstalt, Germany

Several different atoms and ions are used to build ultra-stable clocks which might find application in time referencing, gravity measurement, data encryption, navigation etc. although it seems that it is strontium that is going to replace the current definition of time. Many groups around the world have already proven reliability and robustness of the strontium optical lattice clock and the next step is to make it more transportable and mobile. In this poster we report our progress and results from the robust transportable Space Optical Clock. So far, the robust preparation of cold Sr-88 atoms in a first stage magneto-optical trap (MOT) with 8E+6 and second-stage red broadband MOT with a transfer efficiency of 40 percent, single frequency MOT with 80 percent transfer efficiency and lattice with 1E+5 atoms is achieved. The compact atomic package is transported from the University of Birmingham, United Kingdom to Physikalisch-Technische Bundesanstalt, Germany. Next step is to lock the clock laser to the atomic transition. Lasers that are frequency stabilized by locking to the resonant mode of ultra low expansion cavities have been used for the cooling purpose.

Q 12.32 Mon 16:30 Empore Lichthof

Experiments and theory of NaK molecules — ●KAI K. VOGES, MATTHIAS W. GEMPEL, TORBEN A. SCHULZE, TORSTEN HARTMANN, ALESSANDRO ZENESINI, and SILKE OSPELKAUS — Institut für Quantenoptik, Universität Hannover

Dipolar collisions between ultracold molecules are characterized by the amazing combination of long-range interaction and strong anisotropy. These properties and their tunability are powerful tools for the investigation of various phenomena, from the many-body dynamics of degenerate gases to the fundamental understanding of collisional physics and chemical processes.

In the experiment we are currently setting up, all these phenomena and many others will be investigated by involving ultracold ground-state NaK molecules. Our set-up has wide optical access, careful design of the electric field and large tunability of the experimental parameters for a wide control of the molecular properties. Here we present the current status of the experiment and an analysis of possible coherent two-photon transfer paths from weakly-bound Feshbach molecules to rovibronic ground state molecules.

Q 12.33 Mon 16:30 Empore Lichthof

Dissipative preparation of antiferromagnetic order in the Fermi-Hubbard model — JAN KACZMARCZYK¹, HENDRIK WEIMER², and ●MIKHAIL LEMESHKO¹ — ¹IST Austria, Klosterneuburg, Austria — ²Leibniz Universität Hannover, Germany

The realization of strongly correlated quantum phases such as the antiferromagnetic phase is one of the longstanding goals of quantum simulations with ultracold fermions in optical lattices. We show that a combination of two Raman-assisted hopping schemes gives rise to dissipative dynamics that exhibits a large amount of antiferromagnetic order in the steady state. We analyze the interplay between the familiar Fermi-Hubbard Hamiltonian and these additional dissipative terms using wave-function Monte-Carlo methods and a novel variational principle for dissipative quantum many-body dynamics [1]. We observe antiferromagnetic correlations appearing within experimentally acces-

sible times on the order of 0.5 s, as well as a substantial reduction in entropy per particle compared to the current experimental setups without additional dissipation. Our considerations are based on the atomic level structure of fermionic 40K and can be implemented into existing experimental setups.

[1] H. Weimer, Phys. Rev. Lett. 114, 040402 (2015).

Q 12.34 Mon 16:30 Empore Lichthof

An analytic model of quantum thermalization — ●GREGORY SZEP¹, MIKHAIL KATSNELSON², and MIKHAIL LEMESHKO¹ — ¹Institute of Science and Technology Austria, Am Campus 1, Klosterneuburg 3400, Austria — ²Radboud University of Nijmegen, Heijendaalseweg 135, 6525AJ Nijmegen, The Netherlands

The thermalisation of a subsystem, contained in a closed dynamical system - in both classical and quantum regimes - is an intuitive phenomenon by which the energy levels of the subsystem irreversibly approach the maximum entropy canonical distribution. Numerical evidence, based on single trajectories of both integrable and non-integrable systems, has been presented [1,2], while no analytic results exist that do not invoke the eigenstate thermalisation hypothesis or artificial thermostats. Here a method is proposed, that treats the eigenstates spanned by the equivalent closed subsystem as the basis set from which measurements are obtained. By considering how do the hybridised subsystem-system states, project onto the closed subsystem eigenstates, an attempt is made to derive a canonical distribution for the subsystem.

[1] F. Jin, et. al., New. J. Phys. 15, 033009 (2013) [2] S. Yuan, H. De Raedt, and M. I. Katsnelson, J. Phys. Soc. Jpn. 78, 094003 (2009).

Q 12.35 Mon 16:30 Empore Lichthof

Geometrical pumping with a Bose-Einstein condensate — ●MAXIMILIAN SCHEMMER¹, LU HSIN-I², LAUREN AYCOCK², DINA GENKINA², SEIJI SUGAWA², and IAN SPIELMAN² — ¹Institut d'Optique Graduate School, Palaiseau, France — ²Joint Quantum Institute, National Institute of Standards and Technology, and University of Maryland, Gaithersburg, Maryland, USA

We realized a quantum "charge" pump for a Bose-Einstein condensate (BEC) in a novel bipartite magnetic lattice, whose bands are characterized by non-trivial topological invariants: the Zak phases. For each band, the Zak phase is determined by that band's integrated Berry curvature, a geometric quantity defined at each crystal momentum. We probed this Berry curvature in a charge pump experiment, by periodically and adiabatically driving the system. Unlike topological charge pumps in filled bands that yield quantized pumping, our BEC occupied just a single crystal momentum state allowing us to access its band's local geometry. Like topological charge pumps, for each pump cycle we observed an overall displacement (here, not quantized) and a temporal modulation of the atomic wavepacket's position in each unit cell, i.e., the polarization. Our magnetic lattice enabled us to observe this modulation by measuring the BEC's magnetization. While our periodic drive shifted the lattice potential by one unit cell per cycle, the displacement of the BEC, solely determined by the underlying Berry curvature, was always less than the lattice's displacement.

Q 12.36 Mon 16:30 Empore Lichthof

Development of a deterministic ion source — ●JENS BENARY, ANDREAS MÜLLERS, CIHAN SAHIN, and HERWIG OTT — Technische Universität Kaiserslautern

We present a deterministic ion source based on an ultracold atom cloud. ⁸⁷Rb atoms are confined in a magneto-optical trap (MOT) and subsequently photo-ionized. The fast electrons are detected with a channel electron multiplier (CEM) and act as a trigger for the ions.

In addition to photoionization, we are implementing a three photon excitation to Rydberg states. Using the mechanism of Rydberg blockade, the source could be adapted to control the number of emitted ions down to a single particle.

Currently, the ions are detected with a second CEM. However, future applications may include ion interferometry or semiconductor doping. These will benefit from the high repetition rate and low energy spread of this type of source.

The three photon excitation via the intermediate 5P_{3/2} and 5D_{5/2} states gives access to nP or nF Rydberg states. This can be realized in a simple manner using IR diode lasers with wavelengths between 776 nm and 1260 nm. In addition, the 5D_{5/2} state has a decay channel to 6P_{3/2}, which can be excited to nS or nD Rydberg states with an additional laser at 1016 nm.

We discuss the status of the experiment and present results obtained so far.

Q 12.37 Mon 16:30 Empore Lichthof

Sympathetic cooling of OH⁻ ions using Rb atoms in a MOT — ●JI LUO¹, BASTIAN HÖLTKEMEIER¹, HENRY LOPEZ¹, PASCAL WECKESSER¹, ANDRE DE OLIVERA^{1,2}, ERIC ENDRES³, ROLAND WESTER³, and MATTHIAS WEIDEMÜLLER¹ — ¹Physikalisches Institut, Universität Heidelberg, INF 226, 69120 Heidelberg — ²Departamento de Física, Universidade do Estado de Santa Catarina-Joinville, SC, Brazil — ³Institut f. Ionenphysik und angewandte Physik, Universität Innsbruck, Technikerstraße 25/3, 6020 Innsbruck

We report on the current status of our experiment employing a hybrid atom-ion trap for investigating the interaction between OH⁻ anions and rubidium atoms. The experimental setup consists of an octupole rf ion trap with thin wires providing sufficient optical access to combine the ion trap with a dark-spontaneous-force optical trap for the atoms. The motional and internal temperature of the anions will be probed by photodetachment spectroscopy.

Q 12.38 Mon 16:30 Empore Lichthof

Mode frequency stability of individually trapped ions in a two-dimensional array — ●YANNICK MINET, MANUEL MIELENZ, HENNING KALIS, FREDERICK HAKELBERG, MATTHIAS WITTEMER, ULRICH WARRING, and TOBIAS SCHAEZT — Physikalisches Institut, Albert-Ludwigs-Universität, Hermann-Herder-Straße 3, 79104 Freiburg, Germany

A promising way to realise quantum simulations is based on trapped ions. Advanced micro-fabrication techniques and geometrical optimisation allows the construction of two-dimensional surface-electrode trap arrays [1] that may be used as large-scale simulators [2]. Prerequisites for such implementations are high-fidelity control of all motional degrees of freedom and a high-level of mode stability.

We present measurements of the stability of mode frequencies of a single ²⁵Mg⁺ ion trapped in one out of three sites, which are arranged in an equilateral triangle and separated by 40 μm. Our results are discussed in the context of future experiments, where we aim to establish inter-ion Coulomb couplings between all three trap sites.

[1] Ch. Schneider et al., Rep. Prog. Phys. **75**, 024401 (2012)

[2] T. Schaetz et al., New J. Phys. **15**, 085009 (2013)

Q 12.39 Mon 16:30 Empore Lichthof

Fast and high-fidelity motional control of trapped ions — ●MATTHIAS WITTEMER, GOVINDA CLOS, FREDERICK HAKELBERG, HENNING KALIS, MANUEL MIELENZ, ULRICH WARRING, and TOBIAS SCHAEZT — Physikalisches Institut, Albert-Ludwigs-Universität, Hermann-Herder-Straße 3, 79104 Freiburg, Germany

Laser-cooled ions, trapped in radio-frequency potentials, are promising candidates for experimental quantum simulations [1]. In addition to the precise manipulation of the electronic states (pseudo spin), control of the motional states of the trapped ions is crucial for adequate quantum simulations.

We report on experiments with Mg⁺ ions in a (conventional) linear Paul trap and a surface-electrode trap with three distinct trapping sites, arranged in an equilateral triangle. The implementation of an arbitrary waveform generator [2] into the experimental setups enables real-time control of the motional degrees of freedom within a few microseconds. This may allow precise studies of tunable spin-spin interactions [3] and phenomena like thermalization [4] or squeezed-state emergence [5] in isolated quantum systems.

[1] T. Schaetz et al., New J. Phys. **15**, 085009 (2013)

[2] R. Bowler et al., Rev. Sci. Instrum. **84**, 033108 (2013)

[3] A.C. Wilson et al., Nature **512**, 57-60 (2014)

[4] G. Clos et al., arXiv:1509.07712 (2015)

[5] R. Schützhold et al., Phys. Rev. Lett. **99**, 201301 (2007)

Q 12.40 Mon 16:30 Empore Lichthof

Fermi-Fermi Mixtures of Dysprosium and Potassium — CORNEE RAVENSBERGEN², SLAVA TZANOVA¹, VINCENT CORRE², ●MARIAN KREYER¹, ALEXANDER WERLBERGER¹, and RUDOLF GRIMM^{1,2} — ¹Intitut für Experimentalphysik, Universität Innsbruck, Austria — ²Institut für Quantenoptik und Quanteninformation IQOQI, Innsbruck, Austria

Ultracold Fermi-Fermi mixtures with tunable interactions represent an intriguing test bed for exploring the physics of strongly interacting many-body quantum systems and few-body quantum states. Two-

species Fermi gases extend the variety of phenomena thanks to mass imbalance. Mixtures of a fermionic isotope of dysprosium (^{161}Dy or ^{163}Dy) and the fermionic ^{40}K provide a mass ratio of about four, which is big enough to experience strong asymmetries while avoiding losses from Efimov states. Furthermore, the large magnetic moment of dysprosium offers an additional feature to study anisotropic effects. In our experimental setup, we have implemented a Zeeman slower for dysprosium and a 2D magneto-optical trap (2D-MOT) for potassium to load a two-species MOT in the main vacuum chamber. It is planned to load both clouds into a dipole trap for evaporative cooling to achieve degeneracy of both species.

Q 12.41 Mon 16:30 Empore Lichthof

Dimensional Phase Transitions of Bosons in Optical Lattices with Tunable Hopping — ●BERNHARD IRSIGLER¹, DENIS MORATH², DOMINIK STRASSEL², SEBASTIAN EGGERT², and AXEL PELSTER² — ¹Physics Department, Freie Universität Berlin, Germany — ²Physics Department and Research Center OPTIMAS, Technische Universität Kaiserslautern, Germany

Here we investigate in detail how the dimensionality affects the critical temperature of Bose-Einstein condensation. Motivated by the recent experiment [1] we consider bosons in an optical lattice, where the hopping along the three spatial dimensions is assumed to be tunable. With this we model all possible continuous transitions between the dimensions $D = 1, 2, 3$ and determine the respective critical temperatures in the vicinity of pure integer dimensions, which turn out to agree with the Mermin-Wagner theorem. In the homogeneous case the critical temperature vanishes in $D = 1, 2$ and therefore also in the dimensional transition $1 \rightarrow 2$. However in $D = 3$ the critical temperature is finite and vanishes for $3 \rightarrow 2$ logarithmically and for $3 \rightarrow 1$ like a power law. For the harmonically trapped case in any dimension $D = 1, 2, 3$ the critical temperature remains finite.

[1] A. Vogler, R. Labouvie, G. Barontini, S. Eggert, V. Guarrera, and H. Ott, *Phys. Rev. Lett.* **113**, 215301 (2014).

Q 12.42 Mon 16:30 Empore Lichthof

Variational calculation of ^4He droplets — ●CHRISTOPHER BATE, YAROSLAV LUTSYSHYN, and DIETER BAUER — Institut für Physik, Universität Rostock, 18051 Rostock

We aim to study droplets of liquid ^4He at very low temperature with the variational ansatz that was recently proposed for the ground state of strongly correlated Bose liquids [1]. This ansatz goes beyond the traditional Jastrow-Feenberg functional form and, when optimized, provides an excellent description of the correlations in the system. Even though this wavefunction is constructed of short-range two-body factors and does not contain one-body surface terms, phase separation emerges and a free surface is formed at appropriate densities. This allows to study the inhomogeneous phases such as the droplets of superfluid helium, and the formation of the inhomogeneous phase as well. Due to advances in computational techniques and the fact that we can study the system on a variational level, we are able to consider droplets with up to 10^4 particles.

[1] Y. Lutsyshyn, “A coordinated wavefunction for the ground state of liquid helium-4”, arXiv 1506.03752 (2015), to be published.

Q 12.43 Mon 16:30 Empore Lichthof

Investigating and Minimizing Surface Effects in Cold Atom magnetic Field Microscopy — ●XIAOKE LI¹, AMRUTA GADGE¹, TIM JAMES¹, BO LU², CHRISTOPHER MELLOR¹, NEPHTALI GARRIDO-GONZALEZ¹, CHRISTIAN KOLLER³, FEDJA ORUCEVIC¹, and PETER KRÜGER¹ — ¹School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD, UK — ²Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong — ³Mirco and Nano systems FH, Wiener Neustadt, Austria

Using cold atom as magnetic field sensor is one of the promising directions towards quantum technology. The advantage is that it can measure the magnetic field (and electric field) with both high spatial resolution and good field sensitivity, compared with magnetic force microscopy and SQUIDS. The limitation of achieved resolution is met while minimizing the distance between atoms and surface, which leads to loss of atoms due to Casimir force and Johnson noise. To reduce the surface effects and achieve submicron trapping, we investigate different surfaces such as silicon nitride membranes. The positioning of atoms over different samples is carried out by an on-chip magnetic transport system, which is generated by a 10-layer printed circuit board containing wires with $10\mu\text{m}$ to 20mm widths. Before loading the ^{87}Rb atoms

into the magnetic trap, we use a novel dual color magneto-optical trap to improve the atom number. We will present the results of simulation and current progress of experiment.

Q 12.44 Mon 16:30 Empore Lichthof

High resolution ion imaging of cold atoms — ●MARKUS STECKER, HANNAH SCHEFZYK, MALTE REINSCHMIDT, ANDREAS GÜNTHER, and JÓZSEF FORTÁGH — Physikalisches Institut, Universität Tübingen, Germany

Spatially resolved optical detection methods of cold atomic clouds are in general diffraction limited. In our novel approach we ionize atoms out of the cloud and image them via an ion optics with variable magnification up to 1000 and a spatial resolution above the optical diffraction limit. This allows the observation of trapped quantum gases with single atom sensitivity and high temporal and spatial resolution. In such a system, local statistic like temporal and spatial correlations can be studied, and global cloud properties or dynamical processes can be investigated.

We present the ion optics setup and the corresponding simulations, which show the theoretical limits of the system in terms of magnification and resolution. We also show the experimental implementation to an ultra-cold atom setup. The current ionization scheme uses a 480nm laser to ionize atoms out of a magneto-optical trap. In order to characterize the imaging quality, we imprint test structures with the ionization laser onto the MOT and analyze the generated ion patterns. Furthermore, we present the first steps to use this system for excitation and spatially resolved detection of Rydberg atoms.

Q 12.45 Mon 16:30 Empore Lichthof

Towards the micromotion energy limit in a hybrid atom-ion experiment — ●JOSCHKA WOLF, ARTJOM KRÜKOW, AMIR MOHAMMADI, AMIR MAHDIAN, and JOHANNES HECKER DENSCHLAG — Universität Ulm, Institut für Quantenmaterie, Albert-Einstein-Allee 45, D-89069 Ulm, Deutschland

In our hybrid atom-ion experiment, we investigate the interaction of a laser-cooled trapped ^{138}Ba ion with an ultracold cloud of ^{87}Rb atoms [1].

Induced by micromotion, in this system there are three main sources of atom-ion collision energy. The excess micromotion caused by static electrical fields, the phase micromotion resulting from a phase delay between the radio frequency blades and a collision induced micromotion energy.

In this poster we show our recent progress in the minimization of phase micromotion and excess micromotion. We are then essentially left with collision induced micromotion and plan to measure this quantity for the first time in the near future.

[1] A. Krüchow et al., arXiv:1510.04938 (2015)

Q 12.46 Mon 16:30 Empore Lichthof

Towards high resolution imaging in a strongly imbalanced Bose Fermi mixture — ●ALEXANDER MIL, FABIAN OLIVARES, ARNO TRAUTMANN, MARCELL GALL, and FRED JENDRZEJEWSKI — Kirchhoff-Institut für Physik, Heidelberg, Deutschland

Strongly imbalanced Bose-Fermi mixtures are an ideal tool for the study of impurity problems, which are of great interest in modern condensed matter physics e.g. the polaron or the Kondo problem. A generic property of such systems is the screening cloud surrounding the impurity. While these screening clouds are central to the properties of most systems with impurities, they still remain hard to detect and to control. The current state of our experiment is well suited to tackle this problem. Using a mixture of bosonic sodium and fermionic lithium, with one of the species tightly trapped, leads to well localized impurities. Recent experiments on this system led to the observation of the phonon-induced lamb shift, which is characteristic for the presence of the screening cloud. Next goal is the direct observation of the screening cloud in real space.

We present our progress towards high resolution imaging in a sodium lithium mixture for direct observation of the screening cloud. Key feature here is a new imaging lens design enabling diffraction limited resolution for both species at a numerical aperture of 0.4. Moreover we elaborate on the imaging algorithm and the experimental setup allowing for high detection efficiencies.

Q 12.47 Mon 16:30 Empore Lichthof

Towards ultracold mixtures of lithium and caesium — ●ELISA DA ROS, PIERRE JOUVE, JONATHAN NUTE, JIZHOU WU, NATHAN

COOPER, and LUCIA HACKERMÜLLER — University of Nottingham, United Kingdom

Ultracold mixtures hold the promise of understanding new phases of matter and collisions at very low energies. We showcase here our experiment capable of producing ultracold clouds of both bosonic caesium-133 and fermionic lithium-6 using a crossed-beam optical dipole trap.

We present the results of in situ optical density measurements of molecular lithium-6 Bose-Einstein condensates, aiming to compare different theoretical models. We also explain the design, construction and characterization of a dual species effusive oven for fast loading of magneto-optical traps integral to our experiments involving ultracold mixtures of both species. Finally, we exhibit our progress towards a quantum integrated light and matter interface (QuLMI) using waveguide chips in collaboration with the University of Jena, University of Vienna and the Max Planck Institute for the Physics of Complex Systems.

Q 12.48 Mon 16:30 Empore Lichthof

A Thouless quantum pump with ultracold bosonic atoms in an optical superlattice — ●CHRISTIAN SCHWEIZER^{1,2}, MICHAEL LOHSE^{1,2}, ODED ZILBERBERG³, MONIKA AIDELSBURGER^{1,2}, and IMMANUEL BLOCH^{1,2} — ¹Fakultät für Physik, LMU München, Germany — ²Max-Planck-Institut für Quantenoptik, Garching, Germany — ³Institut für Theoretische Physik, ETH Zürich, Switzerland

Topological charge pumping enables the transport of charge through an adiabatic cyclic evolution of the underlying Hamiltonian. In contrast to classical transport, the transported charge is quantized and purely determined by the topology of the pump cycle, making it robust to perturbations. Here, we report on the realization of such a pump with ultracold bosonic atoms forming a Mott insulator in a dynamically controlled optical superlattice. By taking in situ images of the cloud, we observe a quantized deflection per pump cycle. We reveal the pump's genuine quantum nature by showing that, in contrast to groundstate particles, a counterintuitive reversed deflection occurs for particles in the first excited band. Furthermore, we directly demonstrate that the system undergoes a controlled topological transition in higher bands when tuning the superlattice parameters. These results open a route to the implementation of more complex pumping schemes, including spin degrees of freedom and higher dimensions.

Q 12.49 Mon 16:30 Empore Lichthof

Coulomb explosion imaging of ⁶Li₂ Feshbach molecules in a reaction microscope — ●NIELS KURZ, ALEXANDER DORN, and THOMAS PFEIFER — Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

A reaction microscope enables the imaging of the spatial structure of complex molecules by instant ionization of all constituent particles using e.g. fs laser pulses, a technique coined "Coulomb Explosion Imaging". The use of ultracold targets in a reaction microscope has been successfully applied to investigate multi-photon ionization of ⁷Li in 800 nm fs pulses or in intense VUV light at the FLASH facility in Hamburg [M. Schuricke, K. Bartschat, A. N. Grum-Grzhimailo, G. Zhu, J. Steinmann, R. Mooshammer, 2009].

Unprecedented is the combination of this technique with an ultracold target of weakly bound di-atomic molecules formed from fermionic

atoms (⁶Li in our case) by the use of Feshbach resonances. In the universal regime the spatial extension of Feshbach molecules can be tuned over a wide range, by using only one experimental parameter, to create molecules with a spatial extent of up to 10.000 Bohr radii.

We present a project aimed at creating firstly a BEC of di-atomic ⁶Li molecules and secondly few-fermion systems as targets in a reaction microscope by the use of the so-called spilling technique [F. Serwane, S. Jochim, 2011]. This will result in the first measurement of interatomic distance in ⁶Li₂ Feshbach molecules with tunable interatomic distance.

Q 12.50 Mon 16:30 Empore Lichthof

Full tomographic reconstruction of a two-mode squeezed state — ●JAN PEISE¹, ILKA KRUSE¹, KARSTEN LANGE¹, BERND LÜCKE¹, LUCA PEZZÈ², JAN ARLT³, WOLFGANG ERTMER¹, KLEMENS HAMMERER⁴, LUIS SANTOS⁴, AUGUSTO SMERZI², and CARSTEN KLEMP¹ — ¹Institut für Quantenoptik, Leibniz Universität Hannover, Germany — ²INO-CNR and LENS, Firenze, Italy — ³Institut for Fysik og Astronomi, Aarhus Universitet, Denmark — ⁴Institut für Theoretische Physik, Leibniz Universität Hannover, Germany

Homodyne detection serves as a standard tool in quantum optics for a wide range of applications including full state reconstruction by tomography. Homodyne detection is not limited to quantum optics with photons but can be similarly employed as a detection tool in atomic systems. Up to now, it was utilized to demonstrate nonseparability or the many-particle realization of interaction-free measurements.

Here we present the full state reconstruction of a two-mode squeezed state which was created by spin dynamics in a Bose-Einstein condensate. By unbalanced homodyning of the created state, we obtain an unbiased, complete density matrix via a Maximum-Likelihood reconstruction. The reconstructed state shows the characteristics expected from the spin-dynamics process. The created state is characterized by a dominant population of twin Fock states compared to other states with the same overall particle number. It resembles an ideal two-mode squeezed state with a fidelity of 78.4%. The created two-mode squeezed state has a large variety of application in the fields of quantum information and metrology.

Q 12.51 Mon 16:30 Empore Lichthof

Motion of a rotating impurity in a Bose-Einstein condensate — ●BIKASHKALI MIDYA¹, RICHARD SCHMIDT², and MIKHAIL LEMESHKO¹ — ¹Institute of Science and Technology (IST) Austria, Am Campus 1, 3400 Klosterneuburg, Austria — ²ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, USA

In this work, we consider the translational motion of a rotating quantum impurity coupled to a Bose-Einstein condensate with boson-boson contact interaction, and boson-impurity anisotropic interaction. The microscopic Hamiltonian to describe such system is derived by first eliminating the dynamical variable of impurity by Lee-Low-Pines transformation, and then approximating the boson system by Bogoliubov method. The effect of the linear momentum of the impurity on the quasiparticle "angulon", a quantum rotor dressed by quantum field [1], spectrum is investigated by the variational technique.

[1] Richard Schimdt and Mikhail Lemeshko, "Rotation of quantum impurities in the presence of a many-body environment", Phys. Rev. Lett. 114, 203001 (2015).

Q 13: Precision Measurements and Metrology III (with A)

Time: Monday 17:00–18:15

Location: a310

Q 13.1 Mon 17:00 a310

Comparison of a ¹⁷¹Yb⁺ single ion clock and a ⁸⁷Sr lattice clock with 2 × 10⁻¹⁷ uncertainty — ●NILS HUNTEMANN, SÖREN DÖRSCHER, ALI AL-MASOUDI, SEBASTIAN HÄFNER, CHRISTIAN GREIBING, BURGHARD LIPPHARDT, CHRISTIAN TAMM, UWE STERR, CHRISTIAN LISDAT, and EKKEHARD PEIK — Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

We report on a comparison of two optical clocks based on the ²S_{1/2} ↔ ²F_{7/2} transition of a single ¹⁷¹Yb⁺ ion stored in a radio-frequency Paul trap and on the ¹S₀ ↔ ³P₀ transition of thousands of ⁸⁷Sr atoms confined in an optical lattice. While the lattice clock achieves frequency instabilities smaller than 2 × 10⁻¹⁶ / √τ/s, a systematic uncertainty of 3 × 10⁻¹⁸ has been reported for the ion clock. From more

than 80 h of acquired data, we determine the frequency ratio of the two clocks with a fractional uncertainty of 2.4 × 10⁻¹⁷. This is the smallest uncertainty achieved between clocks of different types to date and enables consistency tests in other laboratories developing the same combination of optical clocks. Moreover, the experiment is well suited to search for temporal variations of the fine structure constant α due to the large sensitivity of the E3 transition frequency. Data from this measurement and a similar one performed 2.5 years earlier constrain a potential linear drift $\dot{\alpha}/\alpha$ to below 1 × 10⁻¹⁷/yr.

This work is supported by QUEST, the DFG within CRC 1128 (geo-Q) and RTG 1729, and the EMRP within ITOC and QESOCAS. The EMRP is jointly funded by the EMRP-participating countries within EURAMET and the European Union.

Q 13.2 Mon 17:15 a310

The magnesium optical lattice clock at the IQ — ●DOMINIKA FIM, STEFFEN RÜHMANN, KLAUS ZIPFEL, NANDAN JHA, STEFFEN SAUER, ANDRÉ KULOSA, WOLFGANG ERTMER, and ERNST M. RASEL — Leibniz Universität Hannover, Institut für Quantenoptik, Hannover

Optical lattice clocks based on fermionic strontium already reached uncertainties in the low 10^{-18} regime and are studied among others by JILA and NIST. In Hannover at the IQ, we operate an optical lattice clock based on bosonic magnesium atoms. Magnesium has a relatively simple electronic structure and hence allows for the implementation of very precise atomic structure models.

Recent measurements of the magic wavelength, which we could determine to 468.48(21) nm, and the 2nd order Zeeman shift were limited due to tunneling effects which results in a 10 kHz broad clock transition linewidth. In this presentation we will give a status update, where we will report on the optical lattice with a reduced tunneling rate and in this context more accurate measurements on the magic wavelength and the 2nd order Zeeman shift. We also prepare the optical lattice clock for a frequency measurement and will give the first estimations for the frequency accuracy for our apparatus.

Q 13.3 Mon 17:30 a310

A strontium-based atomic breadboard for the Space Optical Clock mission on the ISS — ●STEFANO ORIGLIA¹, STEPHAN SCHILLER¹, LYNSIE SMITH², YESHPAL SINGH², DARIUSZ ŚWIERAD², SRUTHI VISWAM², WEI HE², JOSHUA HUGES², KAI BONGS², UWE STERR³, CHRISTIAN LISDAT³, STEFAN VOGT³, and THE SOC2 TEAM¹ — ¹HHU, Düsseldorf, Germany — ²University of Birmingham, UK — ³PTB, Braunschweig, Germany

The rapid improvement in the performance of optical clocks are opening the door to new technological and scientific applications. Ultra-precise optical clocks in space will allow many experiments, as in the field of fundamental physics (Einstein's gravitational time dilation), time and frequency metrology (comparison between ground clocks using a master clock in space), geophysics (space-assisted relativistic geodesy) and astronomy (local oscillators for radio ranging and interferometry in space). The ESA candidate mission Space Optical Clocks project aims at operating an optical lattice clock on the ISS in approximately 2022.

Within an EU-FP7-funded project, a compact and robust strontium optical lattice clock demonstrator is being developed with a goal instability of $1 \times 10^{-15} \tau^{-1/2}$ and a goal inaccuracy of 5×10^{-17} . For the design of the clock, techniques and approaches suitable for later space application are used, such as modular design, diode lasers, low power consumption, and compact dimensions. The atomic part is operative at the point where atoms are reliably trapped into the optical lattice. The latest results and future perspectives will be presented.

Q 13.4 Mon 17:45 a310

Squeezed vacuum for sub-shot-noise frequency metrology — ●ILKA KRUSE¹, KARSTEN LANGE¹, JAN PEISE¹, BERND LÜCKE¹, LUCA PEZZÈ², JAN ARLT³, WOLFGANG ERTMER¹, LUIS SANTOS⁴, AUGUSTO SMERZI², and CARSTEN KLEMP¹ — ¹Institut für Quantenoptik, Leibniz Universität Hannover, Germany — ²QSTAR, INO-CNR and LENS, Firenze, Italy — ³Institut for Fysik og Astronomi, Aarhus Universitet, Denmark — ⁴Institut für Theoretische Physik, Leibniz Universität Hannover, Germany

All interferometers with classical input states are limited by the shot-noise limit due to the finite particle number. In particular, this effect imposes a limitation for the stability of state-of-the-art atomic microwave clocks. In optics, squeezed vacuum is widely used to overcome this limitation and to operate interferometers beyond the shot-noise limit. Here we create a squeezed vacuum state in an ultracold atomic ensemble by spin-changing collisions. We employ this entangled state to demonstrate a sub-shot-noise frequency measurement in ⁸⁷Rb. Our frequency measurement shows a minimal fractional instability of 6.1×10^{-10} and a sensitivity of 1.5 dB below shot-noise.

Q 13.5 Mon 18:00 a310

Decoherence related limitation of light shift immune Ramsey schemes — ●SERGEY KUZNETSOV^{1,2}, NILS HUNTEMANN¹, CHRISTIAN SANNER¹, BURGHARD LIPPHARDT¹, CHRISTIAN TAMM¹, and EKKHARD PEIK¹ — ¹Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany — ²Institute of Laser Physics SB RAS, Novosibirsk 630090, Russia

Over the last years generalizations of Ramsey's method of separated oscillatory fields were proposed that provide immunity to probe-induced frequency shifts [1-3]. They are of particular importance for optical clocks, based on strongly forbidden transitions, where the probe light field induces a significant light shift via non-resonant coupling to higher lying levels. We apply such a technique for our optical clock based on the $^2S_{1/2} \leftrightarrow ^2F_{7/2}$ transition of a single ¹⁷¹Yb⁺ ion stored in a radio-frequency Paul trap [4]. Heating of the ion's motion during the probe period, however, degrades the cancellation of the light shift. We present a theoretical investigation of the effect and compare it with experimental data. We furthermore present a way to compensate for the effect of motional heating.

S.K. acknowledges the DAAD (German Academic Exchange Service) for financial support.

[1] V.I. Yudin, *et al.*, PRA **82**, 011804 (2010).

[2] R. Hobson, *et al.*, arXiv:1510.08144.

[3] T. Zanon-Willette, E. de Clercq, E. Arimondo arXiv:1511.04847.

[4] N. Huntemann *et al.*, PRL **109**, 213002 (2012).

Q 14: Ultracold plasmas and Rydberg systems I (with A)

Time: Monday 17:00–18:45

Location: f303

Q 14.1 Mon 17:00 f303

Rydberg Spectroscopy in a Bose-Einstein Condensate — ●KATHRIN SOPHIE KLEINBACH¹, MICHAEL SCHLAGMÜLLER¹, TARA CUBEL LIEBISCH¹, FELIX ENGEL¹, FABIAN BÖTTCHER¹, KARL M. WESTPHAL¹, ROBERT LÖW¹, SEBASTIAN HOFFERBERTH¹, TILMAN PFAU¹, JESÚS PÉREZ-RÍOS², and CHRIS H. GREENE² — ¹5. Physikalisches Institut und IQST, Universität Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany — ²Department of Physics and Astronomy, Purdue University, 47907 West Lafayette, IN, USA

Spectroscopy of a single Rydberg atom excited within a Bose-Einstein condensate is presented. Not only a frequency shift proportional to the density is observed, as discovered by Amaldi and Segre in 1934, but an asymmetric broadening, which depends on the principal quantum number n . The line broadening depends on the interaction potential energy curves of the Rydberg electron scatterer with the neutral atom perturber. In Rb there is a shape resonance for the triplet p-wave scattering of e-Rb(5s) at 0.02 eV leading to a potential with a large energy shift, which crosses the lower lying nS, (n-2)D, and (n-1)P states. When a nS + N × 5S1/2 state is photoassociated, neutral atom perturbers near the crossing with the shape resonance potential become relevant, leading to large n-dependent line broadenings. We present a simple microscopic model for the spectroscopic line shape by

treating the atoms overlapped with the Rydberg orbit as zero-velocity, independent, point-like particles, with binding energies associated with their ion-neutral separation, and good agreement is found.

Q 14.2 Mon 17:15 f303

Non adiabatic quantum state preparation with Rydberg atoms — ●JIŘÍ MINÁŘ, MATTEO MARCUZZI, EMANUELE LEVI, and IGOR LESANOVSKY — School of Physics and Astronomy, University of Nottingham, Nottingham, NG7 2RD, United Kingdom

We propose a non-adiabatic protocol to create antiferromagnetic GHZ states in a chain of Rydberg atoms. The proposed implementation relies on the blockade mechanism between atoms in Rydberg states and individual site addressing. The procedure is then generalized in order to create ground states of a many body Rokhsar-Kivelson Hamiltonian, which describes the physics of a one dimensional spin-half chain with repulsive long range interactions. We analyze the performance of the scheme accounting for various effects, such as the interplay between the repulsive interaction strength and the Rabi frequency of the addressing beam, the effect of the tails of the long range interaction or the robustness with respect to the noise in the experimental parameters.

Q 14.3 Mon 17:30 f303

Electron pair formation in He (Cooper pair) — ●HUBERT KLAR — DHBW Lörrach

The empirical shell model for atoms predicts for two-electron atoms an infinity of high double Rydberg states of the form $\text{He}(n'l, n'l')$. A fictitious force presented in this conference elsewhere, however, destroys this oversimplified picture. In $e\text{-He}+(nl)$ scattering we observe a spontaneous time-reversal symmetry breaking. The incoming wavefront is turned towards the top of a potential ridge which leads to an e-e attraction. A Cooper pair is born. After reflection at a centrifugal barrier the outgoing wave diverges from the ridge. Slightly below the threshold for double escape the wave may be reflected at an outer barrier or slightly above threshold the Cooper pair decays immediately. Our quantum mechanical result compares favorably with Wannier's classical ionization theory and with experimental data.

Q 14.4 Mon 17:45 f303

Coherence in a cold atom photon switch — ●WEIBIN LI and IGOR LESANOVSKY — School of Physics and Astronomy, University of Nottingham, Nottingham, UK

We study coherence in a cold atom single photon switch where the gate photon is stored in a Rydberg spinwave. With a combined field theoretical and quantum jump approach and by employing a simple model description we investigate systematically how the coherence of the Rydberg spinwave is affected by scattering of incoming photons. With large-scale numerical calculations we show how coherence becomes increasingly protected with growing interatomic interaction strength. For the strongly interacting limit we derive analytical expressions for the spinwave fidelity as a function of the optical depth and bandwidth of the incoming photon.

Q 14.5 Mon 18:00 f303

Emergent devil's staircase without particle-hole symmetry in Rydberg quantum gases with competing attractive and repulsive interactions — ●ZHIHAO LAN, JIŘÍ MINÁŘ, EMANUELE LEVI, WEIBIN LI, and IGOR LESANOVSKY — School of Physics and Astronomy, University of Nottingham, Nottingham, NG7 2RD, UK

The devil's staircase is a fractal structure that characterizes the ground state of one-dimensional classical lattice gases with long-range repulsive convex interactions. Its plateaus mark regions of stability for specific filling fractions which are controlled by a chemical potential. Typically such staircase has an explicit particle-hole symmetry. Here we introduce a quantum spin chain with competing short-range attractive and long-range repulsive interactions, i.e. a non-convex potential. In the classical limit the ground state features generalized Wigner crystals that - depending on the filling fraction - are either composed of dimer particles or dimer holes which results in an emergent complete devil's staircase without explicit particle-hole symmetry of the underlying microscopic model. In our system the particle-hole symmetry is lifted due to the fact that the staircase is controlled through a two-body interaction rather than a one-body chemical potential. The introduction of quantum fluctuations through a transverse field melts the staircase and ultimately makes the system enter a paramagnetic phase. For

intermediate transverse field strengths, however, we identify a region, where the density-density correlations suggest the emergence of quasi long-range order. We discuss how this physics can be explored with Rydberg-dressed atoms held in a lattice.

Q 14.6 Mon 18:15 f303

Dynamics of cluster formation and non-equilibrium phases of Rydberg excitations in the anti-blockade regime —

●FABIAN LETSCHER^{1,2}, THOMAS NIEDERPRÜM¹, OLIVER THOMAS^{1,2}, TANITA EICHERT¹, HERWIG OTT¹, and MICHAEL FLEISCHHAUER¹ — ¹Department of Physics and Research Center OPTIMAS, University of Kaiserslautern, Germany — ²Graduate School Materials Science in Mainz, Gottlieb-Daimler-Strasse 47, 67663 Kaiserslautern, Germany

Motivated by recent experiments we discuss theoretically the dynamics and temporal correlations of Rydberg excitations in the anti-blockade regime. In this regime spatially extended regions of atoms in the ground state coexist with connected clusters of Rydberg excitations. Measurements performed on an atomic lattice gas show that the non-equilibrium dynamics in the steady state is characterized by strong temporal bunching and large correlation times. The latter arise from two competing intrinsic timescales: In the two-step excitation process, the first Rydberg excitation is highly suppressed, while the second excitation is strongly enhanced. We simulate the dynamics of large lattice systems using a many-body rate equation model which shows good agreement with the experiments. To understand the main features of the two-particle correlations we introduce a simplified cluster model and discuss its many-body dynamics.

Q 14.7 Mon 18:30 f303

Enhancement of a Single-Photon Transistor by Stark-Tuned Förster Resonances — ●CHRISTOPH TRESP¹, HANNES

GORNIA CZYK¹, PRZEMYSLAW BIENIAS², ASAF PARIS-MANDOKI¹, WEIBIN LI³, IVAN MIRGORODSKIY¹, CHRISTIAN ZIMMER¹, HANS PETER BÜCHLER², IGOR LESANOVSKY³, and SEBASTIAN HOFFERBERTH¹ — ¹Physikalisches Institut, Universität Stuttgart, Germany — ²Institut für theoretische Physik III, Universität Stuttgart, Germany — ³School of Physics and Astronomy, University of Nottingham, United Kingdom

We report on the use of Stark-tuned Förster resonances to enhance the gain of a Rydberg mediated single-photon transistor and the non-destructive detection of single Rydberg atoms. We show that our all-optical detection scheme enables high-resolution spectroscopy of Förster resonances, revealing the fine structure splitting of Rydberg states and the splitting of Zeeman-substates. We discuss how excitation hopping between a stored Rydberg excitation and incoming source polaritons can be minimized by choice of the Rydberg states. We then proceed to use a particularly suited two-color resonance to demonstrate scattering of over 100 source photons from a single Rydberg excitation, demonstrating efficient all optical Rydberg detection. Finally, we investigate the Rydberg transistor in coherent operation by reading out the gate photon after scattering source photons. Due to projection of the stored spin wave and phase imprinting, the coherence of the gate excitation is affected by scattered and transmitted source photons.

Q 15: Quantum Effects: Disorder

Time: Monday 17:00–18:15

Location: f442

Q 15.1 Mon 17:00 f442

Perturbative approach to the effective dynamics of disordered quantum systems — ●CHAHAN KROPF, CLEMENS GNEITING, and ANDREAS BUCHLEITNER — Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Str. 3, D-79104, Freiburg, Deutschland

The ensemble average dynamics of disordered quantum systems can be effectively described by quantum master equations [1]. In the cases of spectral disorder and of isotropically disordered eigenvector distributions one can derive master equations which are valid for arbitrary times. Furthermore, in the limit of short-times, an explicit form valid for any disorder distribution can be derived [2]. We will show how this latter result can be expanded to longer time scales by using perturbation theory – which is needed to diagonalize the Hamiltonians of the single realizations of the disorder – prior to the ensemble average. As an example, we will discuss the validity of this approach for a specific

application to the Anderson model.

[1] C. Kropf, C. Gneiting, and A. Buchleitner, arXiv:1511.08764 (2015)

[2] C. Gneiting, F. R. Anger, and A. Buchleitner, arXiv:1508.07187 (2015).

Q 15.2 Mon 17:15 f442

Many-Body Localization and Discrete Spectrum Imply Simple Dynamics — ●DENIZ STIEGEMANN¹, PIETER NAAIKJENS², and

TOBIAS OSBORNE¹ — ¹Institut für Theoretische Physik, Leibniz Universität Hannover, Germany — ²Department of Mathematics, University of California, Davis, USA

In a quantum spin lattice, the time-evolution is usually generated by a local Hamiltonian, e.g. consisting of nearest-neighbour interactions. We prove that if a system exhibits strong dynamical localization and has a discrete and non-degenerate spectrum, then the local Hamilto-

nian can be replaced with a modified Hamiltonian which consists of pairwise commuting terms. This modified Hamiltonian still generates the same dynamics as the original local Hamiltonian, and there is a trade-off between the smallest gap in the spectrum and the degree of locality of the modified Hamiltonian. We discuss the result for both finite and infinite systems.

Q 15.3 Mon 17:30 f442

Analytical description of wave packet expansion in a one dimensional disordered potential — ●JUAN PABLO RAMIREZ VALDES, ANDREAS BUCHLEITNER, and THOMAS WELLENS — Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Str. 3a, 79104 Freiburg, Germany

We present an analytic description of the asymptotic disorder-averaged probability density of an initially strongly confined wave packet in a one-dimensional weak, random potential with finite correlation length. At long times, the expansion of the wave packet comes to a halt due to destructive interferences leading to Anderson localization, the signature of which is the exponential decay of the energy eigenfunctions. But in the case of a wave packet, there is an additional element in the description: the asymptotic state is determined by the superposition of partial waves with different energies E . Using diagrammatic techniques, it is possible to calculate the asymptotic state at fixed energy E [1]. Combining this result with a self-consistent equation for the spectral density of the wave packet [2], we derive an analytical expression for the asymptotic average density, which is compared with the results of numerical simulations.

[1] V. L. Berezinskii, Sov. Phys. JETP 38, 620 (1974).

[2] Bertrand I. Halperin, Phys. Rev. 139, A104 (1965).

Q 15.4 Mon 17:45 f442

Q 16: Precision Measurements and Metrology IV (with A)

Time: Tuesday 11:00–13:00

Location: a310

Q 16.1 Tue 11:00 a310

A micromechanical proof-of-principle experiment for measuring the gravitational force of milligram masses — ●JONAS SCHMÖLE and MARKUS ASPELMEYER — Faculty of Physics, University of Vienna

We address a simple question: how small can one make a gravitational source mass and still detect its gravitational coupling to a nearby test mass? We describe an experimental scheme based on micromechanical sensing that should allow to observe gravity between milligram-scale source masses, thereby improving the current smallest source mass values by three orders of magnitude. We also discuss the implications of such measurements both for improved precision measurements of Newton's constant and for a new generation of experiments at the interface between quantum physics and gravity.

Q 16.2 Tue 11:15 a310

Fundamental uncertainty of the speed of light in vacuum — ●DANIEL BRAUN¹, FABIENNE SCHNEITER¹, and UWE R. FISCHER² — ¹Institute of Theoretical Physics, University Tübingen, 72076 Tübingen, Germany — ²Seoul National University, Department of Physics and Astronomy, Center for Theoretical Physics, 151-747 Seoul, Korea

The speed c of light in vacuum is a natural constant of crucial importance for the foundations of physics and many applications. Advanced theories predict quantum fluctuations of c or even a time-evolution. Combining arguments from quantum parameter-estimation-theory and classical general relativity, we here establish rigorously the existence of lower bounds on the precision to which c can be determined *in principle*. They result in minimal uncertainties of lengths measured through the propagation of light signals that are comparable to predictions from quantum gravity theory. However, the minimal uncertainties depend on the quantum state of light used for the measurement, challenging thus the idea of quantum fluctuations of geometry that exist independently of a measurement prescription. In particular, our novel, measurement-based approach predicts that fluctuations on the length scale of the Planck length are only accessible through quantum-enhanced measurements that use highly non-classical states of light.

Q 16.3 Tue 11:30 a310

Optimal currents of indistinguishable fermions — ●MATTIA WALSCHAERS^{1,2}, ANDREAS BUCHLEITNER², and MARK FANNES¹ — ¹Instituut voor Theoretische Fysica, KU Leuven, Celestijnenlaan 200D, 3001 Leuven, Belgium — ²Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, D-79104 Freiburg, Germany

We study currents of indistinguishable particles, in disordered systems far from equilibrium. Our goal is to identify fundamental bounds to the particle flow, and design principles to saturate these bounds. In the fermionic case, for weak coupling between system and reservoirs, we introduce a symmetry-based mechanism to enhance the flow. This mechanism is broadly applicable provided the inter-particle interactions are small with respect to quantum statistical effects.

Q 15.5 Mon 18:00 f442

Unitary 2-designs and Decoupling with Random Diagonal-Unitary Matrices — YOSHIFUMI NAKATA¹, ●CHRISTOPH HIRCHE¹, CIARA MORGAN², and ANDREAS WINTER¹ — ¹Física Teòrica: Informació i Fenòmens Quàntics, Universitat Autònoma de Barcelona, ES-08193 Bellaterra (Barcelona), Spain — ²School of Mathematics and Statistics, University College Dublin, Belfield, Dublin 4. Ireland

We investigate unitary 2-designs and decoupling, two of the most important primitives in quantum Shannon theory, with random diagonal-unitaries. We first show that the alternate application of random diagonal-unitaries in the Pauli- Z and $-X$ bases constitutes a unitary 2-design after a number of repetitions, implying that the process achieves decoupling. We then go on to show that even fewer repetitions are sufficient for achieving decoupling at the same rate as that with Haar random unitaries. We also provide a simple quantum circuit that implements a unitary 2-design and achieves decoupling, which is partitioned into a constant number of commuting parts.

Laser Interferometer Space Antenna Optical Bench Test Bed — ●MICHAEL TRÖBS¹, GERMÁN FERNANDEZ BARRANCO¹, MICHAEL CHWALLA², EWAN FITZSIMONS², OLIVER GERBERDING¹, GERHARD HEINZEL¹, CHRISTIAN KILLOW³, MAIKE LIESER¹, NEDA MESHKSAR¹, VITALI MÜLLER¹, MICHAEL PERREUR-LLOYD³, DAVID ROBERTSON³, SÖNKE SCHUSTER¹, THOMAS SCHWARZE¹, HENRY WARD¹, MAX ZWETZ¹, and KARSTEN DANZMANN¹ — ¹Albert Einstein Institut — ²Airbus Defense and Space — ³University of Glasgow

The Laser Interferometer Space Antenna (LISA) is a future space-based interferometric gravitational-wave detector consisting of three spacecraft in a triangular configuration in Earth-like orbits around the sun. The interferometric measurements of path length changes between satellites will be performed on so-called optical benches in the satellites. Angular misalignments of the interfering beams will couple into the length measurement and represent a significant noise source (tilt-to-length coupling). Imaging systems are foreseen to reduce this tilt-to-length coupling. We report on an optical bench test bed to investigate imaging systems and the test results. The tilt-to-length coupling requirement of 25 $\mu\text{m}/\text{rad}$ was met with a two-lens imaging system.

Q 16.4 Tue 11:45 a310

The journey to noise reduced and ultra stable interferometers for high-precision metrology — ●KATHARINA-SOPHIE ISLEIF, OLIVER GERBERDING, MORITZ MEHMET, MICHAEL TRÖBS, KARSTEN DANZMANN, and GERHARD HEINZEL — Albert Einstein Institut, Institut für Gravitationsphysik, 30167 Hannover

Laser interferometry achieving $\text{pm}/\sqrt{\text{Hz}}$ sensitivities in the mHz-frequency range is the key technology for satellite missions in the area of gravitational wave detection and geodesy, but it requires sophisticated interferometer layouts that suppress classical interferometer noise sources like scattered light, ghost beams, laser frequency noise and misalignments just by design. We present the recipe for a successful low-noise interferometer construction, starting with a digital design of the interferometer using the C++ library IfoCad, followed by an optimisation in which we are looking at the simulated interferometer data. Different optimisation parameters, like the overall interferometer architecture, the usage of wedged components and the correct positions, are discussed on the basis of two examples: A

Mach-Zehnder interferometer used for the test mass readout in future geodesy missions via deep frequency modulation interferometry, and the 3-Backlink-Setup, an experiment for the laser interferometer space antenna (LISA). The interferometer construction combines the manufacture of a template, a thermally stable quasi-monolithic assembly of the components and a Coordinate Measuring Machine. We compare the simulation with a setup assembled by hand and an optimally designed interferometer.

Q 16.5 Tue 12:00 a310

Initial measurements using the eLISA Phasemeter optical testbed — ●GERMÁN FERNÁNDEZ BARRANCO, DANIEL PENKERT, THOMAS SCHWARZE, OLIVER GERBERDING, and GERHARD HEINZEL — Max Planck Institute for Gravitational Physics, Callinstraße 38 30167 Hannover

The planned spaceborne gravitational wave detector eLISA will allow the detection of gravitational waves at frequencies between 0.1 mHz and 1 Hz. It uses high-precision heterodyne laser interferometry as the main measurement technology. A breadboard model for the phase readout system of these interferometers (Phasemeter) was developed in the scope of an ESA technology development project. This project was completed successfully fulfilling all performance requirements in an electrical two-signal test. Here we present the planning and advances in the implementation of an optical testbed for the Phasemeter as well as initial measurements. The testbed is based on an ultra-stable hexagonal optical bench. This bench allows the generation of three unequal heterodyne beatnotes, thus providing the possibility to probe the Phasemeter for non-linearities in an optical three-signal test. The final goal is to show 1 microcycle/sqrt(Hz) performance in the eLISA band (0.1 mHz - 1 Hz) with a dynamic range of 10 orders of magnitude using beatnotes between 2 and 25 MHz. The initial measurements presented here fulfill the 1 microcycle/sqrt(Hz) requirement down to 100 mHz. Once performance over the full bandwidth is achieved, other components of the eLISA metrology chain (clock noise transfer and removal, inter-satellite ranging and communication) can be tested in this setup.

Q 16.6 Tue 12:15 a310

Deep frequency modulation interferometry — ●OLIVER GERBERDING^{1,2}, KATHARINA-SOPHIE ISLEIF¹, THOMAS SCHWARZE¹, MORITZ MEHMET¹, GERHARD HEINZEL¹, and FELIPE GUZMAN CERVANTES² — ¹Albert Einstein Institut, Institut für Gravitationsphysik, Callinstraße 38, 30167 Hannover — ²Joint Quantum Institute, National Institute of Standards and Technology, Maryland, USA

Laser interferometry with pm/ $\sqrt{\text{Hz}}$ precision and multi-fringe dynamic range at low frequencies is a core technology to measure the motion of

various objects (test masses) in space and ground based experiments for gravitational wave detection and geodesy. Even though available interferometer schemes are well understood, their construction remains complex, often involving the need to build quasi-monolithic optical benches with dozens of components. Here we present a new scheme that uses strong laser frequency modulations in unequal arm-length interferometers in combination with a fit algorithm originally developed for the readout of strong phase modulations, the so-called deep phase modulation interferometry. This combination is the basis for the development of a more elegant interferometric sensing toolset for future missions that requires much smaller and simpler interferometric sensors while using advanced digital signal processing for the phase recovery. We discuss noise influences, both from classic sources and new, technique-specific couplings and we present first results achieved in simulations and experiments.

Q 16.7 Tue 12:30 a310

Seismische Isolationsplattform für den AEI 10m-Prototypen — ●ROBIN KIRCHHOFF — AEI 10m Prototype Team

Im Albert-Einstein-Institut in Hannover wird zur Zeit ein Michelson-Interferometer mit 10m Armlänge aufgebaut, an dem neuartige Techniken für die Gravitationswellendetektion entwickelt und getestet werden. Ein elementarer Bestandteil ist die seismische Isolationsplattform AEI-SAS, welche als Grundlage für die Optiken und weitere Komponenten des Interferometers dient. Das Ziel dieser Plattform ist es, die Störungen durch im Boden vorhandene Seismik bestmöglich zu minimieren. Dies wird einerseits durch passive Mechanismen umgesetzt, welche auf dem Prinzip des Pendels basieren, andererseits wird eine aktive Isolation verwendet, bei der die Bewegung der Plattform ausgelesen, das entstandene Signal bearbeitet und die Bewegung über Aktuatoren minimiert wird. Die Umsetzung dieser passiven und aktiven Techniken am AEI 10m-Prototypen ist Thema dieses Vortrages.

Q 16.8 Tue 12:45 a310

Dreifachpendelaufhängung für das AEI 10m-Prototypinterferometer — ●JOHANNES LEHMANN — AEI 10m Prototype Team

Im AEI in Hannover wird ein Interferometer mit 10m Armlänge aufgebaut, dessen Empfindlichkeit durch das Standard Quanten Limit begrenzt sein soll. Dafür müssen andere Rauschquellen wie die Seismik reduziert werden. Als Vorisolation werden dazu Seismische Isolationsplattformen verwendet, auf denen die Komponenten des Interferometers aufgebaut werden. Für die Spiegel des Interferometers wird eine weitere Isolation benötigt, die durch ein Dreifachpendel als Aufhängung gewährleistet werden soll. Das Design und der Aufbau dieser Aufhängung wird im Vortrag vorgestellt.

Q 17: Quantum Gases: Bosons I

Time: Tuesday 11:00–13:00

Location: e001

Group Report

Q 17.1 Tue 11:00 e001

Rosensweig instability and solitary waves in a dipolar Bose-Einstein condensate — ●MATTHIAS WENZEL, HOLGER KADAU, MATTHIAS SCHMITT, IGOR FERRIER-BARBUT, and TILMAN PFAU — 5. Physikalisches Institut und Center for Integrated Quantum Science and Technology, Universität Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany

Ferrofluids show unusual hydrodynamic effects due to the magnetic nature of their constituents. For increasing magnetization a classical ferrofluid undergoes a Rosensweig instability and creates self-organized ordered surface structures or droplet crystals.

In the experiment we observe a similar behavior in a sample of ultracold dysprosium atoms, a quantum ferrofluid. By controlling the short-range interaction with a Feshbach resonance we can induce a finite-wavelength instability due to the dipolar interaction.

Subsequently, we observe the spontaneous transition from an unstructured superfluid to an ordered arrangement of droplets by in situ imaging. These patterns are surprisingly long-lived and show hysteretic behavior. When transferring the sample to a waveguide we observe mutually interacting solitary waves. Time-of-flight measurements allow us to show the existence of an equilibrium between dipolar attraction and short-range repulsion. In addition we observe interference between droplets.

In conclusion, our system shows both superfluidity and translational

symmetry breaking. This novel state of matter is thus a possible candidate for a supersolid ground state.

Q 17.2 Tue 11:30 e001

Rosensweig instability due to three-body interaction or quantum fluctuations? — VLADIMIR LONČAR¹, DUŠAN VUDRAGOVIĆ¹, ●ANTUN BALAŽ¹, and AXEL PELSTER² — ¹Scientific Computing Laboratory, Institute of Physics Belgrade, University of Belgrade, Serbia — ²Physics Department and Research Center OPTIMAS, Technical University of Kaiserslautern, Germany

In the recent experiment [1], the Rosensweig instability was observed in a ¹⁶⁴Dy Bose-Einstein condensate, which represents a quantum ferrofluid due to the large atomic magnetic dipole moments. After a sudden reduction of the scattering length, which is realized by tuning the external magnetic field far away from a Feshbach resonance, the dipolar quantum gas creates self-ordered surface structures in form of droplet crystals. As the underlying Gross-Pitaevskii equation is not able to explain the emergence of that Rosensweig instability, we extend it by both three-body interactions [2-4] and quantum fluctuations [5]. We then use extensive numerical simulations in order to study the interplay of three-body interactions as well as quantum fluctuations on the emergence of the Rosensweig instability.

[1] H. Kadau, M. Schmitt, et al., [arXiv:1508.05007v2](https://arxiv.org/abs/1508.05007v2) (2015).

[2] H. Al-Jibbouri, I. Vidanović, A. Balaž, and A. Pelster, *J. Phys. B* **46**, 065303 (2013).

- [3] R. N. Bisset and P. B. Blakie, [arXiv:1510.09013](#) (2015).
 [4] K.-T. Xi and H. Saito, [arXiv:1510.07842](#) (2015).
 [5] A. R. P. Lima and A. Pelster, *Phys. Rev. A* **84**, 041604(R) (2011); *Phys. Rev. A* **86**, 063609 (2012).

Q 17.3 Tue 11:45 e001

Phonon to roton crossover and droplet formation in trapped dipolar Bose-Einstein condensates — ●FALK WÄCHTLER and LUIS SANTOS — Institut für Theoretische Physik, Leibniz Universität Hannover, Hannover, Germany

The stability, elementary excitations, and instability dynamics of dipolar Bose-Einstein condensates depend crucially on the trap geometry. In particular, dipolar condensates in a pancake trap with its main plane orthogonal to the dipole orientation are expected to present under proper conditions a roton-like dispersion minimum, which if softening induces the so-called roton instability. On the contrary, cigar-shape traps are expected to present no dispersion minimum, and to undergo phonon (global) instability if destabilized. In this talk we investigate by means of numerical simulations of the non-local non-linear Schrödinger equation and the corresponding Bogoliubov-de Gennes equations the stability threshold as a function of the trap aspect ratio, mapping the crossover between phonon and roton instability. We will discuss in particular how this crossover may be observed in destabilization experiments to reveal rotonization.

In a second part, motivated by recent experiments on droplet formation in Stuttgart, we introduce large conservative three-body interactions, and study how these forces affect the destabilization dynamics. We will discuss the ground-state physics of the individual droplets, and the crucial role that is played by the interplay between internal droplet energy, external center-of mass energy of the droplets, and energy dissipation in the nucleation of droplets observed in experiments.

Q 17.4 Tue 12:00 e001

Lattice Physics with Ultracold Magnetic Erbium — ●SIMON BAIER¹, MANFRED J. MARK^{1,2}, DANIEL PETTER¹, KIYOTAKA AIKAWA¹, LAURIANE CHOMAZ^{1,2}, ZI CAI², MIKHAIL BARANOV², PETER ZOLLER^{2,3}, and FRANCESCA FERLAINO^{1,2} — ¹Institut für Experimentalphysik, Universität Innsbruck, Technikerstraße 25, 6020 Innsbruck, Austria — ²Institut für Quantenoptik und Quanteninformatik, Österreichische Akademie der Wissenschaften, 6020 Innsbruck, Austria — ³Institut für Theoretische Physik, Universität Innsbruck, Technikerstraße 21A, 6020 Innsbruck, Austria

Strongly magnetic atoms are an ideal systems to study many-body quantum phenomena with anisotropic and long-range interactions. Here, we report on the first observation of the manifestation of magnetic dipolar interaction in extended Bose-Hubbard (eBH) dynamics by studying an ultracold gas of Er atoms in a three-dimensional optical lattice. We drive the superfluid-to-Mott-insulator (SF-to-MI) quantum phase transition and demonstrate that the dipolar interaction can favor the SF or the MI phase depending on the orientation of the atomic dipoles. The system is well described by the individual terms of the eBH Hamiltonian. This includes the onsite interaction, which, additional to the isotropic contact interaction, can be tuned with the dipole-dipole interaction by changing the dipole orientation and the shape of the onsite Wannier functions. We find for the first time the presence of the nearest-neighbor interaction between two adjacent particles. Future work will investigate dipolar effects with erbium molecules and fermions as well as spin physics in our lattice system.

Q 17.5 Tue 12:15 e001

Strong-wave-turbulence character of non-thermal fixed

points in Bose gases — ●ISARA CHANTESANA^{1,2,3} and THOMAS GASENZER^{2,3} — ¹Institut für Theoretische Physik, Ruprecht-Karls-Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany — ²Kirchhoff Institut für Physik, INF 227, 69120 Heidelberg, Germany — ³ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstraße 1, 64291 Darmstadt, Germany

Far-from equilibrium dynamics of a dilute Bose gas is studied by means of the two-particle irreducible effective action formalism. We investigate the properties of non-thermal fixed points predicted previously, which are related to non-perturbative strong wave turbulence solutions of the many-body dynamic equations. Instead of using a scaling analysis, we study the Boltzmann equation of the scattering integral by means of direct integration equation for sound waves. In this way we obtain a direct prediction of the scaling behaviour of the possible fixed-point solutions in the context of sound-wave turbulence. Implication for the real-time dynamics of the non-equilibrium system are discussed.

Q 17.6 Tue 12:30 e001

Evidence of Non-Thermal Fixed Points in one-dimensional Bose gases — ●SEBASTIAN ERNE^{1,2,4}, ROBERT BÜCKER⁴, WOLFGANG ROHRINGER⁴, THOMAS GASENZER^{1,2,3}, and JÖRG SCHMIEDMAYER⁴ — ¹Institut für Theoretische Physik, Ruprecht-Karls-Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany — ²ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstraße 1, 64291 Darmstadt, Germany — ³Kirchhoff-Institut für Physik, INF 227, 69120 Heidelberg, Germany — ⁴Vienna Center for Quantum Science and Technology (VCQ), Atominstytut, TU Wien, Vienna, Austria

This work investigates the rapid cooling quench over the dimensional and quasicondensate-crossover. Analyzing experiments performed at the Atominstytut, we study the relaxation of such a far-from equilibrium system. The early stage of condensate formation is dominated by solitonic excitations, leading to a characteristic momentum distribution in agreement with a model of randomly distributed defects. The number of solitons increases with the quenchrate giving rise to an incompressible condensate. The isolated system follows a self-similar evolution governed by a universal time-independent nonthermal fixed point distribution. The dynamic universality classes of these nonequilibrium attractor solutions are relevant for a wide variety of physical systems ranging from relativistic high-energy physics to cold quantum gases. At later times of the evolution the system fully equilibrates leading to deviations from the self-similar evolution. Our results show a new way of condensation in far from equilibrium 1d Bose gases.

Q 17.7 Tue 12:45 e001

Spin phonon dynamics with classical statistical methods — ●ASIER PIÑEIRO ORIOLI^{1,2}, ARGHAVAN SAFAVI-NAINI², MICHAEL WALL², and JOHANNES SCHACHENMAYER² — ¹Institute for Theoretical Physics, Heidelberg, Germany — ²JILA, NIST and University of Colorado, Boulder, Colorado, USA

Systems with both spin and phonon degrees of freedom are ubiquitous in physical fields ranging from condensed matter to biophysics. However, methods to compute the dynamics of such systems are scarce, especially in high dimensions. In this work, we combine the Truncated Wigner Approximation (TWA) for bosons with its recently developed discrete version (dTWA) for spins to describe the dynamics of coupled spin-phonon systems. We benchmark the method by comparing to exact results and discuss applications to trapped-ion and cavity experiments.

Q 18: Quantum Information: Concepts and Methods III

Time: Tuesday 11:00–13:00

Location: e214

Q 18.1 Tue 11:00 e214

Lattice Gauge Tensor Networks — ●SIMONE MONTANGERO — Institute for complex quantum systems & Center for Integrated Quantum Science and Technologies, Ulm university, Albert-Einstein-Allee 11, 89075 Ulm, Germany.

We show that gauge invariant quantum link models, Abelian and non-Abelian, can be exactly described in terms of tensor networks states. Quantum link models represent an ideal bridge between high-energy

and cold atom physics, as they can be used in cold atoms in optical lattices to study lattice gauge theories. In this framework, we characterize the equilibrium and out-of-equilibrium physics of Abelian and non Abelian (1+1)D quantum link lattice gauge theories, such as the phase diagrams of U(1) and SU(2) theories and the real-time dynamics of the string breaking and of the Schwinger mechanisms.

Q 18.2 Tue 11:15 e214

Tree Tensor Network algorithms: Simulating quantum many-body models on lattices in one and two dimensions — ●MATTHIAS GERSTER¹, MATTEO RIZZI², PIETRO SILVI¹, ROSARIO FAZIO³, and SIMONE MONTANGERO¹ — ¹Institute for Complex Quantum Systems, Ulm University, D-89069 Ulm, Germany — ²Johannes Gutenberg-Universität Mainz, Institut für Physik, D-55099 Mainz, Germany — ³NEST, Scuola Normale Superiore & Istituto Nanoscienze CNR, I-56126 Pisa, Italy

We present a tree tensor network algorithm suitable for numerically determining and characterizing ground states of quantum lattice models in one and two spatial dimensions. Our tensor network method has several attractive features, the most prominent one being the treatment of open and periodic boundary conditions on equal footing. Moreover, the loopless network geometry guarantees the existence of a stable and efficient energy minimization algorithm, and a moderate scaling of the computational cost with the refinement parameter (bond dimension). We also comment on strategies for implementing symmetries in the state architecture, allowing to reduce the computational demands and enabling precise targeting of conserved quantities. We demonstrate the usefulness of our technique by some benchmark results for paradigmatic lattice models like an Ising chain.

Q 18.3 Tue 11:30 e214

A positive tensor network approach for simulating open quantum many-body systems — ALBERT H. WERNER¹, DANIEL JASCHKE², PIETRO SILVI³, ●MARTIN KLIESCH¹, TOMMASO CALARCO³, JENS EISERT¹, and SIMONE MONTANGERO³ — ¹Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, 14195 Berlin, Germany — ²Department of Physics, Colorado School of Mines, Golden, Colorado 80401, USA — ³Institute for Complex Quantum systems (ICQ), Universität Ulm, 89069 Ulm, Germany

Open many-body quantum systems play an important role in quantum optics and condensed-matter physics, and capture phenomena like transport, interplay between Hamiltonian and incoherent dynamics, and topological order generated by dissipation.

We introduce a versatile and practical method to numerically simulate one-dimensional open quantum many-body dynamics using tensor networks. It is based on representing mixed quantum states in a locally purified form, which guarantees that positivity is preserved at all times. Moreover, the approximation error is controlled with respect to the trace norm. Hence, this scheme overcomes various obstacles of the known numerical open-system evolution schemes.

Q 18.4 Tue 11:45 e214

Tree Tensor Networks at work: a study of 1D disordered Bose-Hubbard model — MATTHIAS GERSTER¹, ●MATTEO RIZZI², FERDINAND TSCHIRSICH¹, PIETRO SILVI¹, ROSARIO FAZIO^{3,4}, and SIMONE MONTANGERO^{1,5} — ¹Institute for Complex Quantum Systems, Ulm University, Germany — ²Johannes Gutenberg-Universität, Mainz, Germany — ³ICTP, Trieste, Italy — ⁴NEST, Scuola Normale Superiore & Istituto Nanoscienze CNR, Pisa, Italy — ⁵Center for Integrated Quantum Science and Technology (IQST)

We study the equilibrium properties of the one-dimensional disordered Bose-Hubbard model by means of a gauge-adaptive tree tensor network variational method suitable for systems with periodic boundary conditions. We compute the superfluid stiffness and superfluid correlations close to the superfluid to glass transition line, obtaining accurate locations of the critical points. By studying the statistics of the exponent of the power-law decay of the correlation, we determine the boundary between the superfluid region and the Bose glass phase in the regime of strong disorder and in the weakly interacting region, not explored numerically before. In the former case our simulations are in agreement with previous Monte Carlo calculations.

Q 18.5 Tue 12:00 e214

Entanglement in qudit hypergraph states — ●CHRISTINA RITZ¹, FRANK STEINHOFF², NIKOLAI MIKLIN¹, and OTFRIED GÜHNE¹ — ¹Naturwissenschaftlich Technische Fakultät, Universität Siegen, Walter-Flex-Str. 3, D-57068 Siegen, Germany — ²Instituto de Física, Universidade Federal de Goiás, 74001-970, Goiânia, Goiás, Brazil

Hypergraph states form a class of multipartite states, where the free parameters are reduced by restrictions on the initial state and the allowed entangling operations. Within this framework the study of multipartite entanglement regarding SLOCC- and LU-equivalence classes has raised interest in the field of hypergraph states for qubits. In this work, we generalize the class of hypergraph states to multipartite systems of arbitrary dimension by means of discrete phase-space constructions. For uniform hypergraphs a complete SLOCC classification is obtained in terms of the greatest common divisor hierarchy. The special case of tripartite systems is analyzed in detail, resulting in a full classification for prime dimension and dimension four. In addition to the local creation of (hyper)edges from existing ones connecting the same or more vertices, a new feature, namely the creation from less vertices, appears for non-prime dimensions.

Q 18.6 Tue 12:15 e214

Extreme violation of local realism in hypergraph states — ●MARIAMI GACHECHILADZE, COSTANTINO BUDRONI, and OTFRIED GÜHNE — University of Siegen, Siegen, Germany

Hypergraph states form a family of multiparticle quantum states that generalizes the well-known concept of Greenberger-Horne-Zeilinger states, cluster states, and more broadly graph states. We study the nonlocal properties of quantum hypergraph states. We demonstrate that the correlations in hypergraph states can be used to derive various types of nonlocality proofs, including Hardy-type arguments and Bell inequalities for genuine multiparticle nonlocality. Moreover, we show that hypergraph states allow for an exponentially increasing violation of local realism which is robust against loss of particles. Our results suggest that certain classes of hypergraph states are novel resources for quantum metrology and measurement-based quantum computation.

Q 18.7 Tue 12:30 e214

Trace-norm contraction under tensor product channels — ●DAVID REEB¹ and PETER VRANA² — ¹Institut für Theoretische Physik, Leibniz Universität Hannover — ²Budapest University of Technology and Economics

We establish upper bounds on the information storage time in a quantum memory under independent noise in the case where active error correction is allowed. For this, we provide an upper bound on the trace-norm contraction coefficient of a tensor product of quantum channels. Our method yields nontrivial bounds in cases where others fail. Specializing to qubit channels, this solves a conjecture by Ben-Or/Gottesmann/Hassidim concerning the Quantum Refrigerator model of computation (arXiv:1301.1995).

Q 18.8 Tue 12:45 e214

Improving compressed sensing with the diamond norm — ●MARTIN KLIESCH¹, RICHARD KUENG², JENS EISERT¹, and DAVID GROSS² — ¹Freie Universität Berlin — ²Universität zu Köln

In low-rank matrix recovery, one aims to reconstruct a low-rank matrix from a minimal number of linear measurements. Within the paradigm of compressed sensing, this is made computationally efficient by minimizing the nuclear norm as a convex surrogate for rank.

In this work, we identify an improved regularizer based on the so-called diamond norm, a concept imported from quantum information theory. We show that—for a class of matrices saturating a certain norm inequality—the descent cone of the diamond norm is contained in that of the nuclear norm. This suggests superior reconstruction properties for these matrices. We explicitly characterize this set of matrices, which also contains quantum channels. Moreover, we demonstrate numerically that the diamond norm indeed outperforms the nuclear norm in a number of relevant applications: These include not only the task of quantum process tomography but also signal analysis tasks such as blind matrix deconvolution or the retrieval of certain unitary basis changes.

The diamond norm is defined for matrices that can be interpreted as order-4 tensors and it turns out that the above condition depends crucially on that tensorial structure. In this sense, this work touches on an aspect of the notoriously difficult tensor completion problem.

Q 19: Ultracold Atoms, Ions and Molecules III (with A)

Time: Tuesday 11:00–13:15

Location: f342

Q 19.1 Tue 11:00 f342

Towards an optical phase shift based on Rydberg blockade — •DANIEL TIARKS, STEFFEN SCHMIDT, STEPHAN DÜRR, and GERHARD REMPE — Max-Planck-Institut für Quantenoptik, 85748 Garching, Deutschland

Controlling the interaction between single photons is important for many quantum information technologies. Recently we demonstrated [1,2,3] that an opaque medium in which single photons are converted into stationary Rydberg excitations can be used to control the transmission of a subsequent light pulse by using electromagnetically induced transparency. Manipulation of coherent superpositions requires, however, non-dissipative interactions that only affect the phase of the light.

In this work we report on our recent progress towards realizing controlled phase shifts of single photons extending the work of [4,5]. We store photons in highly excited Rydberg states which change the refractive properties of the medium due to Rydberg blockade. A subsequent light pulse will thus experience a significant phase shift.

- [1] S. Baur et al., PRL 112, 073901 (2014)
- [2] D. Tiarks et al., PRL 113, 053602 (2014)
- [3] H. Gorniaczyk et al., PRL 113, 053601 (2014)
- [4] O. Firstenberg et al., Nature 502, 71 (2013)
- [5] A. Feizpour et al., Nature Physics 11, 905 (2015)

Q 19.2 Tue 11:15 f342

Towards a single-photon source based on Rydberg FWM in thermal vapors — •FABIAN RIPKA, YI-HSIN CHEN, ROBERT LÖW, and TILMAN PFAU — 5. Physikalisches Institut, Universität Stuttgart

Photonic quantum devices based on atomic vapors at room temperature combine the advantages of atomic vapors being intrinsically reproducible as well as semiconductor-based concepts being scalable and integrable. One key device in the field of quantum information are on-demand single-photon sources. A promising candidate for realization relies on the combination of two atomic effects, namely four-wave mixing (FWM) and the Rydberg blockade effect.

Coherent dynamics to Rydberg states on ns timescales [1] and sufficient Rydberg interaction strengths [2] have already been demonstrated in thermal vapors. These effects could also be observed in a pulsed FWM scheme [3]. Recently, we investigated a storage-retrieval scheme by means of two pulses. We could determine the collective lifetime of the Rydberg coherence to be 1.1ns, limited by motional dephasing. Additionally, this double-pulsed FWM scheme enables an enhanced generation efficiency of output photons up to tens of photons per pulse. The goal is then to reduce this number of photons by interaction-induced suppression of the Rydberg coherence, in order to obtain non-classical photon states and even single photons per FWM cycle.

- [1] Huber et al., PRL 107, 243001 (2011)
- [2] Baluktsian et al., PRL 110, 123001 (2013)
- [3] Huber et al., PRA 90, 053806 (2014); Chen et al., accepted by Appl. Phys. B

Q 19.3 Tue 11:30 f342

Imaging of Rydberg atoms and light propagation through a non-linear non-local medium — •VLADISLAV GAVRYUSEV, MIGUEL FERREIRA-CAO, ADRIEN SIGNOLES, GERHARD ZUERN, RENATO FERRACINI, SHANNON WHITLOCK, and MATTHIAS WEIDEMÜLLER — Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany

Electronically highly excited (Rydberg) atoms constitute a system with long range interactions which allows to study many intriguing phenomena, ranging from quantum non-linear optics to dipole-mediated energy transport. To optically image Rydberg atoms we use the interaction enhanced imaging technique [1] which exploits interaction-induced shifts on highly polarizable excited states of probe atoms, that can be spatially resolved via an electromagnetically induced transparency resonance. The sensitivity is tunable up to few Rydberg excitations by using strong dipole-dipole interactions, induced via a Förster resonance or by direct dipolar coupling between the involved states. By monitoring the Rydberg distribution we observed the migration of Rydberg electronic excitations, driven by quantum-state changing interactions [2], and we are working towards controlling this dynamic. The strong

interactions also affect the optical properties of the medium and can allow to explore a highly non-linear and non-local regime, where the response will depend both on local light intensity and atom density, leading to pattern formation and effective photon-photon interactions.

- [1] G. Günter et al., Phys. Rev. Lett. 108, 013002 (2012)
- [2] G. Günter et al., Science 342, 954 (2013)

Q 19.4 Tue 11:45 f342

Two-body interactions and decay of three-level Rydberg-dressed atoms — •STEPHAN HELMRICH, ALDA ARIAS, NILS PEHOVIK, EMIL PAVLOV, TOBIAS WINTERMANTEL, and SHANNON M WHITLOCK — Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg

We theoretically analyse the interactions and decay rates for atoms dressed by multiple laser fields to strongly interacting Rydberg states using a quantum master-equation approach. In this framework a comparison of two-level and three-level Rydberg-dressing schemes is presented. We identify a resonant enhancement of the three-level dressed interaction strength which originates from cooperative multiphoton couplings. This feature can be effectively used for Rydberg dressing under electromagnetically-induced-transparency condition combined with small single-photon detunings. The cooperative enhancement in interaction is accompanied by low levels of distance-dependent dissipation. We will present first experimental studies of Rydberg dressing of ultracold potassium atoms with dressing times comparable to the timescales for atomic motion. In the future, near-resonant Rydberg dressing in three-level atomic systems may enable the realization of laser driven quantum fluids with long-range and anisotropic interactions and with controllable dissipation.

Q 19.5 Tue 12:00 f342

Dissipative Preparation of Entangled Many-Body States with Rydberg Atoms — •MARYAM ROGHANI and HENDRIK WEIMER — Institut für Theoretische Physik, Leibniz Universität Hannover, Appelstraße 2, 30167 Hannover, Germany

We study a one-dimensional atomic lattice gas where interactions are mediated by a weak admixture of a Rydberg state. This Rydberg dressing is combined with dissipative dynamics induced by optical pumping. We derive an effective quantum master equation for the ground state manifold and show that this driven dissipative dynamics can result in highly entangled stationary states. For a defined set of parameters, this non-trivial entangled many-body steady state is the ground state of a Hamiltonian which possesses a manifold of approximate Rokhsar-Kivelson points. This Rokhsar-Kivelson state is a coherent superposition of all possible configurations respecting the dipole blockade induced by the Rydberg dressing [1].

- [1] I. Lesanovsky, Phys. Rev. Lett. 106,025301 (2011).

Q 19.6 Tue 12:15 f342

Dipolar photon- and excitation-transport in Rydberg-EIT media — •DANIEL VISCOR and THOMAS POHL — Max Planck Institut für Physik komplexer Systeme

We investigate the effects of excitation-exchange interactions on the propagation dynamics of quantum light through a strongly interacting Rydberg gas under conditions of electromagnetically induced transparency (EIT). Considering the most simple setting of a single Rydberg-polariton interacting with a stored collective Rydberg excitation, we show that long-range excitation-exchange between the two spin wave components gives rise to a photon propagation that differs fundamentally from the more common case of static van der Waals interactions. Using numerical simulations and analytical arguments, we characterise the resulting dissipative and dispersive optical response of the medium and discuss potential applications of the emerging new features.

Q 19.7 Tue 12:30 f342

Nonlinear Optics in a Rydberg-Excited Semiconductor Cavity — •VALENTIN WALTHER, ROBERT JOHNE, and THOMAS POHL — Max Planck Institute for the Physics of Complex Systems, Dresden

Recent experiments have demonstrated excitons with extraordinarily large binding energies in some two-dimensional semiconductors (TMDCs), whose Rydberg states give rise to giant interactions and,

therefore, hold great promise for optical utility.

We evaluate the optical response under conditions of electromagnetically induced transparency (EIT), accounting for the full excited level structure and numerous decoherence mechanisms in a semiconductor. Strong exciton-exciton interactions result in enormous effective photon-photon potentials. Using experimental parameters, we show that the photonic nonlinearity exceeds that of traditional semiconductors by several orders of magnitude and we assess the material properties required for coherent optical applications.

Further, we investigate interesting optical effects in the transverse mode structure of a driven-dissipative cavity arising from the unusually large nonlinearity.

Q 19.8 Tue 12:45 f342

Multicritical behaviour in dissipative Ising models — •VINCENT OVERBECK¹, MOHAMMAD MAGHREBI², ALEXEY GORSHKOV², and HENDRIK WEIMER¹ — ¹Institut für Theoretische Physik, Leibniz Universität Hannover, Deutschland — ²Joint Quantum Institute, NIST/University of Maryland, College Park, MD, USA

Stationary states of dissipative quantum many-body systems are of great interest, having the possibility to undergo dissipative phase transitions that are fundamentally different from thermal equilibrium. We consider a dissipative extension of the Ising model, where the dissipation preserves the Z_2 symmetry. Using a variational approach [1,2], we find a second order and a first order phase transition line, which meet at a multicritical point that is not found in the equilibrium case. We make an analysis of the full phase diagram, discussing in detail the role of fluctuations in this model. Finally, we present a possible

experimental realization based on Rydberg-dressed spin interactions.

[1] H. Weimer, Variational Principle for Steady States of Dissipative Quantum Many-Body Systems, Phys. Rev. Lett. **114**, 040402 (2015).

[2] H. Weimer, Variational analysis of driven-dissipative Rydberg gases, Phys. Rev. A **91**, 063401 (2015).

Q 19.9 Tue 13:00 f342

Effect of lattice geometry on bosonic quantum phases of Rydberg dressed lattice gases — •ANDREAS GEISSLER¹, MATHIEU BARBIER¹, YONGQIANG LI², and WALTER HOFSTETTER¹ — ¹Institut für Theoretische Physik, Goethe Universität Frankfurt am Main, Germany — ²Department of Physics, NUDT, China

Our recent results [1] have shown the rich diversity of quantum phases which are induced by the strong correlations inherent to Rydberg dressed bosonic atoms trapped in optical lattices. While experimental feasibility of the dressing itself has just recently been demonstrated for the first time [2], a better understanding of the crystallisation is still required. We analyse Rydberg dressed lattice systems for various lattice geometries by further applying our real space dynamical mean-field theory (RB-DMFT) methods. These results serve as a benchmark of Gutzwiller type mean-field simulations where dissipative dynamics can be simulated within the Lindblad master equation approach. Within the latter approach we can observe crystallisation dynamics and the stability of crystalline structures. We additionally focus on quasiparticle excitations which we determine from linearised Gutzwiller equations.

[1] A. Geißler et al., arXiv:1509.06292, [physics.cond-mat]

[2] Y.-Y. Jau et al., Nat. Phys., npphys3487 (2015)

Q 20: Quantum Optics III

Time: Tuesday 11:00–13:00

Location: f442

Q 20.1 Tue 11:00 f442

Towards Rydberg polariton dynamics with cold atoms in quasi 1D geometries — •MOHAMMAD NOAMAN, MARIA LANGBECKER, and PATRICK WINDPASSINGER — QUANTUM, Institut für Physik, Johannes Gutenberg-Universität Mainz, Staudingerweg 7, 55128 Mainz, Germany

Cold atoms inside hollow-core fibers present a promising candidate to study strongly coupled light-matter systems. Combined with the long range Rydberg interaction which is controlled through an EIT process, a corresponding experimental setup should allow for the generation of a strong and tunable polariton interaction. Due to dipole blockade, polaritons are restricted to a quasi one dimensional structure. Using this scheme, novel photonic states, eg. crystallization of photons, can be observed with possible applications in quantum information and simulation. This talk will review the current status of our experimental setup where laser cooled Rubidium atoms are transported into a hollow-core fiber. We present the first measurements of Rydberg EIT of the optical molasses in front of the fiber and discuss the progress towards Rydberg physics in a quasi-one-dimensional geometry.

Q 20.2 Tue 11:15 f442

Storage of fiber-guided light in a nanofiber-trapped ensemble of cold atoms — •BERNHARD ALBRECHT, CHRISTOPH CLAUSEN, CLÉMENT SAYRIN, PHILIPP SCHNEEWEISS, and ARNO RAUSCHENBEUTEL — VCQ, Atominstitut, TU Wien, Stadionallee 2, 1020 Wien, Austria

The storage of a classical optical pulse is an important capability for the realization of all-optical signal processing schemes. Simple optical buffers can be extended to work as optical quantum memories, in which quantum states of light can be stored and retrieved. They are crucial elements of a global quantum optical network. The storage of light has been achieved with several systems. However, the realization of efficient, long-lived fiber-integrated optical memories is still subject to active research.

Here, we report on the progress of a novel implementation of an integrated optical quantum memory. We use an optical-nanofiber-based experimental platform for trapping and optically interfacing laser-cooled cesium atoms. Using the effect of electromagnetically induced transparency we are able to slow down fiber-guided light pulses to only 50 m/s [1]. We also experimentally show the storage and retrieval of fiber-guided light pulses on the single-photon level. We achieve a

good overall efficiency and a largely improved characteristic memory lifetime compared to previously demonstrated fiber-integrated optical memories. Our results are an important step towards fully fiber-based quantum networks.

[1] C. Sayrin *et al.*, Optica **2**, 353-356 (2015).

Q 20.3 Tue 11:30 f442

Anregung atomarer Übergänge mit einem Vortex Laserstrahl[1] — •JONAS SCHULZ, CHRISTIAN TOMÁS SCHMIEGELOW, HENNING KAUFMANN, THOMAS RUSTER, ULRICH POSCHINGER und FERDINAND SCHMIDT-KALER — QUANTUM, Institut für Physik, Universität Mainz, Staudingerweg 7, 55128 Mainz, Germany

Aufgrund ihres internen Spins tragen Photonen Drehimpuls, der abhängig von der Lichtpolarisation die Werte $\pm 1\hbar$ annehmen kann. Vortex-Strahlen besitzen zusätzlichen externen Bahndrehimpuls. Wir demonstrieren den Transfer von optischem Bahndrehimpuls (OAM) aus dem Vortex-Strahl auf interne, elektronische Freiheitsgrade eines Atoms. Wir platzieren dafür ein einzelnes $^{40}\text{Ca}^+$ Ion im Zentrum eines Vortex-Strahls und treiben den $S_{1/2} \leftrightarrow D_{5/2}$ Quadrupolübergang. Abhängig von der Polarisation des Lichtes (σ^{\pm}) und der Vortizität des Strahls (OAM=0, ± 1) erhalten wir modifizierte Auswahlregeln für die Übergänge zwischen Zeeman Niveaus mit $\Delta m=0, \pm 1$ und ± 2 was zeigt, dass Spin- und Bahndrehimpuls der Photonen zu einem effektiven Gesamtdrehimpuls mit den Werten $0\hbar$, $\pm 1\hbar$ und $\pm 2\hbar$ gekoppelt werden.

[1] Christian T. Schmiegelow et al., arXiv:1511.07206 (2015)

Q 20.4 Tue 11:45 f442

Phase shifting a weak coherent beam by a single $^{174}\text{Yb}^+$ ion — •MARTIN FISCHER^{1,2}, LUCAS ALBER^{1,2}, BHARATH SRIVATHSAN^{1,2}, MARKUS WEBER^{1,2}, MARKUS SONDERMANN^{1,2}, and GERD LEUCHS^{1,2,3} — ¹Max Planck Institute for the Science of Light, Erlangen, Germany — ²Friedrich-Alexander University Erlangen-Nürnberg (FAU), Department of Physics, Erlangen, Germany — ³Department of Physics, University of Ottawa, Canada

We report on the phase shift induced on a weak coherent beam of light acting on the π -transition of a single $^{174}\text{Yb}^+$ ion. The π -transition is driven by focusing a radially-polarized donut-mode with a deep parabolic mirror, covering 94% of the relevant solid angle, onto the ion. The phase shift is measured in a heterodyne configuration with a local oscillator detuned by twenty linewidths from the investigated

atomic transition. Measurements with a still imperfectly corrected parabolic mirror show phase shifts of 3° , as expected for the coupling efficiency determined through saturation measurements.

The measured phase shift deviates significantly from the predicted phase shift of a two-level system [1]. We discuss the influence of coupling to a $J = 1/2$ to $J = 1/2$ transition instead of coupling to a two-level system and estimate the residual aberrations limiting the observable phase shift. Prospects of using $^{174}\text{Yb}^{2+}$ as a target for the dispersive interaction are discussed.

[1] M. Sondermann *et al.*, J. Europ. Opt. Soc. Rap. Public. **8**, 13052 (2013)

Q 20.5 Tue 12:00 f442

Towards a quantum simulator using engineered spin arrays in diamond — ●NIKOLAS TOMEK¹, THOMAS UENDEN¹, TIMO WEGGLER¹, FLORIAN FRANK¹, ALEXANDRE LE BOITÉ², JIANMING CAI³, PAZ LONDON⁴, ALEX RETZKER⁵, KOHEI ITOH⁶, MARTIN BODO PLENIO², BORIS NAYDENOV¹, and FEDOR JELEZKO¹ — ¹Institute for Quantum Optics, 89081 Ulm University, Ulm, Germany — ²Institute for Theoretical Physics, Ulm University, 89081 Ulm, Germany — ³School of Physics, Huazhong University of Science and Technology, Wuhan 430074, China — ⁴Department of Physics, Technion, Israel Institute of Technology, Haifa 32000, Israel — ⁵Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem 91904, Israel — ⁶Department of Applied Physics and Physico-Informatics, Keio University, Hiyoshi, Yokohama, Japan

Numerical simulations of strongly correlated quantum many-body systems are becoming intractable for as few as <100 particles. This gave rise to the idea of quantum simulation to gain access to nonequilibrium mechanics of large systems. As solid state system for our quantum simulator experiments we use a dense layer of C13 nuclear spins inside an otherwise C12-enriched bulk diamond. Initialization, control and read-out of this spin array is accomplished with nitrogen-vacancy (NV) centers implanted in the diamond. The system stands out due to exceptional long coherence times even at room temperature. Using nuclear magnetic resonance techniques we can control the dipole-dipole interaction between the nuclear spins in the 2D ensemble. This will allow us to simulate a wide variety of strongly correlated spin models.

Q 20.6 Tue 12:15 f442

The Resonant Fluorescence of Nitrogen-Vacancy Centers — ●THAI HIEN TRAN¹, PETR SIYUSHEV², JÖRG WRACHTRUP¹, and ILJA GERHARDT^{1,3} — ¹3. Physikalisches Institut, Universität Stuttgart — ²Institut für Quantenoptik, Universität Ulm — ³Max-Planck-Institut

für Festkörperforschung, Stuttgart

The interaction between photons and single quantum systems is a key question and necessity for quantum information processing in means of reading, writing, and storing information. In our study we investigate the efficient optical interaction between a laser beam and a negative charged nitrogen-vacancy (NV⁻) center in diamond – a promising solid state spin qubit. We are able to observe the interference and the relative phase shift between the exciting laser and the coherently emitted photons. This allows us to distinguish the coherently and the incoherently scattered photons within the narrow zero phonon line.

Q 20.7 Tue 12:30 f442

Single Molecule NMR using NV centers — ●MATTHIAS KOST^{1,2}, JIANMING CAI^{1,2,3}, and MARTIN B. PLENIO^{1,2} — ¹Institut für Theoretische Physik, Albert-Einstein Allee 11, Universität Ulm, 89069 Ulm, Germany — ²Center for Integrated Quantum Science and Technology, Universität Ulm, 89069 Ulm, Germany — ³School of Physics, Huazhong University of Science and Technology, Wuhan 430074, China

Nuclear magnetic resonance spectroscopy (NMR) allows for the structure determination of molecules and proteins and therefore contributes fundamentally to the advancement of the biological sciences. The recent progress in the control of a single electron spin in Nitrogen-vacancy (NV) centers in diamond offers a new perspective here as it becomes possible to use optically detected magnetic resonance to read out the effect of smallest magnetic fields.

This talk presents, how to utilize the sensitivity of shallow NV centers to perform NMR-like protocols at a single molecule level, which yields information on e.g. coupling strength and spatial structure of the target molecule. Theoretical simulations demonstrate application of the protocol addressing small amino acid.

Q 20.8 Tue 12:45 f442

Robust dynamical decoupling sequences for individual-nuclear-spin addressing — JORGE CASANOVA, ZHENYU WANG, ●JAN HAASE, and MARTIN PLENIO — Institut für Theoretische Physik and IQST, Albert-Einstein-Allee 11, Universität Ulm, D-89069 Ulm, Germany

We propose the use of non-equally-spaced decoupling pulses for high-resolution selective addressing of nuclear spins by a quantum sensor. The analytical model of the basic operating principle is supplemented by detailed numerical studies that demonstrate the high degree of selectivity and the robustness against static and dynamic control-field errors of this scheme. We exemplify our protocol with a nitrogen-vacancy-center-based sensor to demonstrate that it enables the identification of individual nuclear spins that form part of a large spin ensemble.

Q 21: Matter Wave Optics

Time: Tuesday 14:30–16:30

Location: a310

Q 21.1 Tue 14:30 a310

Impact of retro-reflective geometries on atomic Bragg diffraction — ●ALEXANDER FRIEDRICH¹, ENNO GIESE¹, WOLFGANG P. SCHLEICH¹, and ERNST M. RASEL² — ¹Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQST), Universität Ulm, Albert-Einstein-Allee 11, D-89081 Ulm, Germany — ²Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany

Light-pulse based atom interferometry has become a valuable tool for high precision measurements of inertial forces, fundamental constants and tests of the weak equivalence principle. Most light-pulse interferometers rely on either Bragg or Raman diffraction. In both cases wave-front distortions and the effects of mirror vibrations can be reduced by retroreflective setups with two counterpropagating laser pairs from a common optical fibre. This approach comes at the cost of introducing off-resonant transitions into the diffraction process which contribute to the phase of the matter wave and thereby the interferometer phase. In case of Raman diffraction this so called two-photon light shift is well understood.^[1,2] We present an analogue analysis as well as analytic expressions for the two-photon light shift in Bragg diffraction. Furthermore we demonstrate that this behaviour can be significantly improved by appropriately shaping the pulse envelopes.

[1] A. Gauguier *et al.*, Phys. Rev. A **78**, 043616 (2008)

[2] T. Lévêque *et al.*, Phys. Rev. Lett. **103**, 080405 (2009)

Q 21.2 Tue 14:45 a310

Modeling molecular diffraction at ultra-thin gratings — ●CHRISTIAN BRAND¹, JOHANNES FIEDLER², THOMAS JUFFMANN^{1,3}, MICHELE SCLAFANI^{1,4}, CHRISTIAN KNOBLOCH¹, STEFAN SCHEEL², YIGAL LILACH⁵, ORI CHESHNOVSKY⁵, and MARKUS ARNDT¹ — ¹University of Vienna, Faculty of Physics, Boltzmanngasse 5, A-1090 Vienna, Austria — ²University of Rostock, Institute of Physics, Albert-Einstein-Straße 23, 18055 Rostock — ³Stanford University, Physics Department, 382 Via Pueblo Mall, Stanford, USA — ⁴ICFO - Institut de Ciències Fotòniques, 08860 Castelldefels (Barcelona), Spain — ⁵School of Chemistry, Tel-Aviv University, Tel Aviv 69978, Israel

For quantum diffraction experiments with molecular matter-waves material gratings have the advantage that they are independent of the particles' internal properties. However, this universality is limited by the attractive Casimir-Polder interaction which might remove molecules from the beam and thereby prevents them from traversing the gratings. Here we compare three different theoretical models to describe the attractive interaction between a molecular matter-wave and a material grating at different scales of complexity. While even simple approximations lead to reliable results and give significant physical insights, simulations based on quantum electrodynamics point to the influence of an additional attractive contribution in the experiments.

These are identified as originating from charges in the grating material, implanted during the fabrication process. The consequences for matter-wave diffraction of complex particles are discussed.

Q 21.3 Tue 15:00 a310

Matter-wave interferometry and its application to molecular spectroscopy — ●JOHANNES FIEDLER and STEFAN SCHEEL — Institute of Physics, University of Rostock, Rostock, Germany

The wave-particle duality provides a wide range of interesting effects on microscopic objects such as atoms, molecules or clusters. One of them is the possibility to create interferences by diffraction on a periodic structure, e.g. standing-wave laser fields or material gratings. Current experiments investigate the influence of the particle mass on their interference capability. At present, the wave nature of particles has been demonstrated for masses up to 10,000 a.m.u. [1]. Of particular interest is the interference of particles at material diffraction gratings. During the diffraction process, the particles achieve very small distances to the grating bars. Hence, the Casimir-Polder interaction of the particles with the object becomes important [2]. To a good approximation the interaction can be described by a phase shift. Consequently, this phase shift is engraved in the interference pattern. We will present a possible measurement set-up to fully reconstruct a matter wave by using a combination of measuring the amplitude of the interference pattern and the phase of the wave with an adapted Hartmann-Shack sensor. With the knowledge of the wave front, together with the geometry of the interferometer, we will present an algorithm for the estimation of the Casimir-Polder potential and the polarizability of the involved particle.

[1] S. Eibenberger, S. Gerlich et al., *Phys. Chem. Chem. Phys.* **15**, 14696 (2013). [2] C. Brand, J. Fiedler et al., *Ann. Phys. (Berlin)* **527**, 580 (2015).

Q 21.4 Tue 15:15 a310

Quantum reflection and Liouville transformations — ●GABRIEL DUFOUR^{1,2}, ROMAIN GUÉROUT², ASTRID LAMBRECHT², and SERGE REYNAUD² — ¹Institute of Physics, Albert-Ludwigs University, Freiburg, Germany — ²Laboratoire Kastler Brossel, UPMC-Sorbonne Universités, Paris, France

Collisions of ultracold atoms with surfaces are governed by quantum reflection of the atomic matter wave from the attractive Casimir-Polder potential. While no reflection is expected classically, the quantum reflection probability goes to one for slow atoms and weak atom-surface interactions. These counterintuitive results are best understood by performing a Liouville transformation of the Schrödinger equation, which preserves the scattering amplitudes while changing the potential landscape. We discuss the properties of these transformations and introduce a special choice of coordinate which allows one to map the problem of quantum reflection on the Casimir-Polder potential well onto that of reflection on a repulsive wall [1]. Within this new approach, we identify the parameters which determine the reflection probability. These results have implications for the GBAR project at CERN, which aims to measure the acceleration of gravity for a cold antihydrogen atom [2].

[1] G. Dufour, R. Guérout, A. Lambrecht, and S. Reynaud, *EPL* **110**, 30007 (2015), *J. Phys. B: At. Mol. Opt. Phys.* **48**, 155002 (2015).

[2] G. Dufour, D. B. Cassidy, P. Crivelli, P. Debu, A. Lambrecht, V. V. Nesvizhevsky, S. Reynaud, A. Y. Voronin, and T. E. Wall, *Advances in High Energy Physics* **2015**, 379642 (2015).

Q 21.5 Tue 15:30 a310

Atomic quantum superposition at the half-meter scale — TIM KOVACHY, ●PETER ASENBAUM, CHRIS OVERSTREET, CHRISTINE DONNELLY, SUSANNAH DICKERSON, ALEX SUGARBAKER, JASON HOGAN, and MARK KASEVICH — Stanford University, Stanford, US

In matter wave interferometers, large wave packet separation is impeded by the need for long interaction times and large momentum beam splitters, which cause susceptibility to decoherence and dephasing. We use light-pulse atom interferometry to realize quantum interference with wave packets separated by up to 54 cm on the time scale of one second. Large superposition states are vital to exploring gravity with atom interferometers in greater detail, e.g. tests of the equivalence principle.

Q 21.6 Tue 15:45 a310

QUANTUS-2 - towards a dual species matter wave interferometer in free fall — ●CHRISTIAN DEPPNER¹, ERNST MARIA RASEL¹, and THE QUANTUS TEAM^{1,2,3,4,5,6,7} — ¹Institut für Quantenoptik, Leibniz Universität Hannover — ²Institut für Physik, Humboldt Universität zu Berlin — ³ZARM, Universität Bremen — ⁴Institut für Physik, Johannes Gutenberg Universität Mainz — ⁵Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik, Berlin — ⁶Institut für Quantenphysik, Universität Ulm — ⁷Institut für angewandte Physik, TU Darmstadt

QUANTUS-2 is a mobile high-flux Rb BEC source used for experiments in microgravity in the Bremen drop tower. To further decrease the residual expansion rate of the BEC, magnetic lensing - also known as delta-kick cooling - is crucial for observations after long evolution times in the range of seconds. Here we present our results of a lens, which leads to an observability of the BEC of up to 2.7s after free expansion, only limited by the microgravity-duration in the drop tower. Anharmonicities of the magnetic lensing potential can introduce distortions of the BEC's shape. We discuss the necessary steps towards harmonic lensing and report our results. This will - in the future - allow us to demonstrate atom interferometry with unprecedented sensitivity on time scales on the order of seconds.

The QUANTUS project is supported by the German Space Agency DLR with funds provided by the Federal Ministry for Economic Affairs and Energy (BMWi) under grant number DLR 50WM1552.

Q 21.7 Tue 16:00 a310

Circumventing Heisenberg's uncertainty principle in atom interferometry tests of the equivalence principle — ●ALBERT ROURA and THE QUANTUS TEAM — Institut für Quantenphysik, Universität Ulm

Atom interferometry tests of universality of free fall based on the differential measurement of two different atomic species provide a useful complement [1] to those based on macroscopic masses. However, gravity gradients pose a serious challenge. In order to achieve very high sensitivities, the relative initial position and velocity for the two species need to be controlled with extremely high accuracy, which can be rather demanding in practice and whose verification may require rather long integration times. Furthermore, gravity gradients lead to a drastic loss of contrast. These difficulties can be mitigated by employing wave packets with narrower position and momentum widths, but this is ultimately limited by Heisenberg's uncertainty principle. We present a novel scheme that simultaneously overcomes the loss of contrast and the initial co-location problem [2]. In doing so, it circumvents the fundamental limitations due to Heisenberg's uncertainty principle and eases the experimental realization by relaxing the requirements on initial co-location by several orders of magnitude.

The QUANTUS project is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry of Economics and Energy (BMWi) under grant number 50WM1556.

[1] D. Schlippert *et al.*, *Phys. Rev. Lett.* **112**, 203002 (2014)

[2] A. Roura, [arXiv:1509.08098](https://arxiv.org/abs/1509.08098)

Q 21.8 Tue 16:15 a310

Multiparticle correlations in complex scattering: birthday paradox and Hong-Ou-Mandel profiles in mesoscopic systems — ●JUAN-DIEGO URBINA¹, JACK KUIPERS¹, KLAUS RICHTER¹, QUIRIN HUMMEL¹, and SHO MATSUMOTO² — ¹Institut für Theoretische Physik, Universität Regensburg, D-93040 Regensburg, Germany — ²Graduate School of Science and Engineering, Kagoshima University, 1-21-35, Korimoto, Kagoshima, Japan

In this presentation we generalize the Hong-Ou-Mandel effect to the mesoscopic regime of complex scattering and to macroscopically occupied incoming wavepackets. This is achieved by a complete enumeration of all processes in terms of interfering many-body paths that allow us to study universal effects due to the interplay between instability of the single-particle classical motion and quantum indistinguishability.

We show how, in the limit of large particle number, one finds a mesoscopic version of the bosonic birthday paradox responsible for a sharp quantum-classical transition. Furthermore, under a scaling that defines the classical-quantum boundary we predict a macroscopic, experimentally accessible Hong-Ou-Mandel profile. Our methods can be extended to the quantum optics domain, and point towards a mesoscopic implementation of the boson sampling problem.

Q 22: Quantum Gases: Bosons II

Time: Tuesday 14:30–16:30

Location: e001

Q 22.1 Tue 14:30 e001

Inducing Bose condensation with a hot needle — ●ALEXANDER SCHNELL¹, DANIEL VORBERG¹, ROLAND KETZMERICK^{1,2}, and ANDRÉ ECKARDT¹ — ¹Max-Planck-Institut für Physik komplexer Systeme, Nöthnitzer Straße 38, 01187 Dresden, Germany — ²Technische Universität Dresden, Institut für Theoretische Physik, 01187 Dresden, Germany

A quantum system exchanging energy with a thermal bath will assume an equilibrium state that is completely determined by the bath temperature. In contrast, when the system is driven out of equilibrium, e.g. by coupling it to two baths of different temperatures, the system will assume a non-equilibrium steady state that does not only depend on the bath temperatures, but on the very details of the system bath coupling.

This offers great freedom to tailor the properties of a system by bath engineering and can also give rise to counter intuitive effects. We consider an ideal one-dimensional Bose gas immersed in a cold bath. We show that the coherence length of the system can be increased by several orders of magnitude by coupling it additionally to a "hot needle" (a second, spatially localized bath that is much hotter than the first one). As a consequence, Bose condensation can be induced by a hot needle in a system of finite extent.

Q 22.2 Tue 14:45 e001

Interplay between statistics and interactions in 1D few-boson systems — ●QUIRIN HUMMEL, BENJAMIN GEIGER, JUAN DIEGO URBINA, and KLAUS RICHTER — Institut für Theoretische Physik, Universität Regensburg, Germany

The theoretical study of quantum few-body systems poses a fundamental challenge since the absence of a large number of particles makes the usually simplifying description within the grand canonical formalism invalid. We analytically address the fundamental interplay between indistinguishability and interactions in systems where the total number of particles is strictly fixed, quantum statistics is treated exactly and interparticle forces are described non-perturbatively, by introducing a set of techniques based on neglecting the discreteness of spectra at the level of a cluster expansion of the canonical partition function. Our approach is specially suitable for the few-body case as it generates thermodynamic and spectral properties in terms of a *finite* set of permutation and interaction events thus overcoming the inappropriate use of virial expansions. For 1D systems with short range interactions we found analytical expressions applicable to both integrable and realistic non-integrable models with harmonic confinement.

Q 22.3 Tue 15:00 e001

Ramsey Interferometry with squeezed collective spin states under decoherence — ●BJÖRN SCHRINSKI¹, STEFAN NIMMRICHTER², and KLAUS HORNBERGER¹ — ¹Fakultät für Physik, Universität Duisburg-Essen — ²Centre For Quantum Technologies, National University of Singapore

We discuss the non-unitary time evolution of number-squeezed collective spin states in Ramsey interferometry. We focus on decoherence models as proposed by the CSL model [1] or utilized by macroscopicity measures [2]. Exemplary experimental realisations are BEC superpositions with ultracold Rubidium atoms in double [3] and single-well [4] potentials. Our analytical results are based on a continuous-variables approach in the basis of Dicke states and are verified using exact numerical simulations in cases when the particle number is conserved.

[1] Bassi et al., Rev. Mod. Phys. 85, 471-527 (2013)

[2] Nimmrichter et al., Phys. Rev. Lett. 110, 160403 (2013)

[3] Berrada et al., Nat. Commun. 4, 2077 (2013)

[4] S. van Frank et al., Nat. Commun. 5, 4009 (2014)

Q 22.4 Tue 15:15 e001

Short time propagation in interacting bosonic systems — ●BENJAMIN GEIGER, QUIRIN HUMMEL, JUAN-DIEGO URBINA, and KLAUS RICHTER — Institut für Theoretische Physik Universität Regensburg, 93040 Regensburg, Germany

In order to investigate general properties of interacting bosonic gases we present a formalism to calculate thermodynamic properties as well as the smoothed density of states by means of short-time propagation and compare our analytical predictions against quantum integrable

models that allow for an exact analysis by means of Bethe ansatz techniques. As an essential input of our approach, we were able to construct the many-body propagator for a one-dimensional free bosonic gas with delta interactions of variable strength. Using this propagator we can give short-time approximations for the Lieb-Liniger model and non-integrable systems including external harmonic potentials. Furthermore we can think of using the spatial information and the time dependence of the propagator to calculate e.g. two-point correlations or to investigate quantum quenches.

Q 22.5 Tue 15:30 e001

Many-particle quantum dynamics after an interaction quench for ground state quantum bright solitons — ●CHRISTOPH WEISS¹ and LINCOLN CARR² — ¹Joint Quantum Centre (JQC) Durham-Newcastle, Department of Physics, Durham University, United Kingdom — ²Colorado School of Mines, Golden, USA

We investigate strongly attractively interacting bosons in a (quasi-)one-dimensional waveguide initially prepared in the ground state of an additional harmonic potential, a quantum bright soliton. An interaction quench that increases the interaction by a factor of four combined with switching off the potential leads to a higher-order soliton for which the mean-field description via the Gross-Pitaevskii equation predicts oscillations of the variance of the single particle density. We investigate the quantum many-particle dynamics after such an interaction quench numerically via TEBD and back our interpretation of the data by calculations based on the Lieb-Liniger model with attractive interactions.

Q 22.6 Tue 15:45 e001

Long-range correlations and superfluidity of the one-dimensional quasi-condensate — ●HANSJÖRG POLSTER and CARSTEN HENKEL — Institute of Physics and Astronomy, University of Potsdam, Germany

A Bose gas confined to two or one dimensions does not show any phase transition. Still, due to interactions, a smooth cross over is found when the density increases, signalled by a reduction of density fluctuations and an increase in the phase correlation length. We discuss exact results for correlation functions of the Bose field, obtained with the help of a mapping to a random walk in the complex plane [1,2].

When the Bose gas is rotated in a closed ring, discrete peaks emerge in the momentum distribution, defined by the winding numbers of the complex field. We discuss the disappearance of these peaks when the rotation velocity is increased and compare to Landau's scenario of the breakdown of superfluidity. Full distribution functions are obtained for both local and global quantities like current density and total momentum.

[1] L. W. Gruenberg and L. Gunther, *Phys. Lett. A* **38** (1972) 463; D. J. Scalapino, M. Sears, and R. A. Ferrell, *Phys. Rev. B* **6** (1972) 3409[2] I. Carusotto and Y. Castin, *C. R. Physique* **5** (2004) 107

Q 22.7 Tue 16:00 e001

Towards the Bose Polaron in an ultracold gas — ●LARS J. WACKER, NILS B. JØRGENSEN, KRISTOFFER T. SKALMSTANG, RASMUS S. CHRISTENSEN, GEORG BRUUN, and JAN ARLT — Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, 8000 Aarhus C, Denmark

An impurity interacting with its surroundings leads to the formation of a quasi particle, called a polaron. This was first described by Landau as a bosonic phonon gas, formed in a solid by the interaction of an electron with the lattice displacements. Ultracold gases with their high degree of control allowed for first experimental investigations of the Fermi polaron in ultracold Fermi gases.

Likewise, bosonic polarons can be investigated using mixtures of ultracold bosonic gases. I present our study of the Bose polaron, employing a magnetic Feshbach resonance to tune the interaction between two spin states of ³⁹K. We record the energy spectrum of the impurity for different interaction strengths, allowing us to distinguish between the mean field energy regime and the appearance of the polaronic signature in the spectrum.

Q 22.8 Tue 16:15 e001

Dynamics of Bose polarons in a BEC — ●FABIAN GRUSD¹,

YULIA SHCHADILOVA¹, RICHARD SCHMIDT^{1,2}, and EUGENE DEMLER¹ — ¹Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA — ²ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA

When neutral impurity atoms are placed in a Bose-Einstein condensate (BEC), they become dressed by a cloud of phonons and form a polaron. We calculate the spectral function of the impurity, which serves as a fingerprint of polarons in experiments with strongly imbalanced atomic mixtures. We also study the dynamics of polaron formation in the time

domain, after a sudden quench of the interaction strength which can be realized using Feshbach resonances. For finite initial velocities of the impurity atoms we predict strong deceleration for long times and find non-trivial transient polaron trajectories.

We analyze the BEC polaron using an extension of the renormalization group (RG) approach [Grusdt et al., *Sci.Rep.*5:12124, 2015] to far-from equilibrium dynamics. Fröhlich polarons are considered first, but we also apply the RG method to go beyond the Fröhlich approximation. This is necessary to describe experiments in the strong-coupling regime.

Q 23: Quantum Information: Concepts and Methods IV

Time: Tuesday 14:30–16:30

Location: e214

Q 23.1 Tue 14:30 e214

The Computational Complexity of Multiboson Correlation Interference — ●SIMON LAIBACHER and VINCENZO TAMMA — Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQST), Universität Ulm, D-89069 Ulm, Germany

In our talk, we demonstrate that a computational power beyond any classical capabilities can be achieved in bosonic linear interferometers even with nonidentical photons [1]. This approach overcomes the challenge of generating identical bosons, which so far have been essential in quantum information processing, including the well-known problem of boson sampling [2].

In contrast to the original formulation of boson sampling, we investigate MultiBoson Correlation Sampling, where time-resolved sampling measurements at the interferometer output are performed [3,4]. Interestingly, even with photons of completely different colors this problem is at least as computationally hard as the original boson sampling problem with identical photons[1].

These results demonstrate the quantum computational supremacy inherent in the fundamental nature of quantum interference [3].

- [1] Laibacher and Tamma, in press in *Phys. Rev. Lett.* (2015)
- [2] Aaronson and Arkhipov, in *Proceedings of the 43rd annual ACM symposium on Theory of computing* (ACM, 2011) pp. 333–342
- [3] Tamma and Laibacher, *Phys. Rev. Lett.* **114**, 243601 (2015)
- [4] Tamma and Laibacher, *Quantum Inf. Proc.* (2015). DOI:10.1007/s11128-015-1177-8

Q 23.2 Tue 14:45 e214

Imaging two-dimensional source geometries using higher order spatial photon correlations — ●ANTON CLASSEN^{1,2}, FELIX WALDMANN¹, RAIMUND SCHNEIDER^{1,2}, THOMAS MEHRINGER^{1,2}, and JOACHIM VON ZANTHIER^{1,2} — ¹Institut für Optik, Information und Photonik, Universität Erlangen-Nürnberg, 91058 Erlangen — ²Erlangen Graduate School in Advanced Optical Technologies (SAOT), Universität Erlangen Nürnberg, 91052 Erlangen)

Measuring higher order correlation functions is an emerging technique in the field of imaging to overcome the classical resolution limit [1–3]. We propose to use higher order spatial correlations of photons emitted by independent classical sources with thermal statistics to implement an imaging technique capable of reconstructing arbitrary two-dimensional source geometries. The detection scheme generalizes our earlier imaging scheme which resolved one-dimensional source geometries with sub-Abbe resolution [3]. The scheme is able to isolate all spatial frequencies of the system sequentially what allows to retrieve the geometry of the sources. We present experimental data verifying the theory.

- [1] M. E. Pearce et al., Precision estimation of source dimensions from higher-order intensity correlations, *Phys. Rev. A* **92**, 043831 (2015)
- [2] D. G. Monticone et al., Beating the Abbe Diffraction Limit in Confocal Microscopy via Nonclassical Photon Statistics, *Phys. Rev. Lett.* **113**, 143602 (2014)
- [3] S. Oppel et al., Superresolving Multiphoton Interferences with Independent Light Sources, *Phys. Rev. Lett.* **109**, 233603 (2012)

Q 23.3 Tue 15:00 e214

Quantumness of spin-1 states — FABIAN BOHNET-WALDRAFF^{1,2}, ●DANIEL BRAUN¹, and OLIVIER GIRAUD² — ¹Institute of theoretical physics, University Tübingen, 72076 Tübingen — ²LPTMS, CNRS, Univ. Paris-Sud, Université Paris-Saclay, 91405 Orsay, France

We derive an analytic expression for the quantumness of pure spin-

1 states, which measures the degree of non-classicality of a quantum state. Quantumness is defined as the Hilbert-Schmidt distance to the convex hull of SU(2)-coherent states. These spin coherent states play the role of pure classical states, while their convex hull defines the set of mixed classical states. Our formula expresses the quantumness of a state in terms of the smallest eigenvalue of its Bloch matrix. The proof of the formula is based on explicitly constructing the closest classical state. We give numerical evidence that the exact formula for pure states, when evaluated at the smallest eigenvalue of the Bloch matrix of some mixed state, provides an upper bound on the quantumness of that state. Finally, by relating the set of two-qubit symmetric separable states to the set of classical spin-1 states, we make a connection to the theory of entanglement: the quantumness of a pure spin-1 state is linked, through a rather complicated function that we provide explicitly, to the negativity of the state. For mixed states the same function serves as upper bound of the quantumness.

Q 23.4 Tue 15:15 e214

Characterising ground and thermal states of few-body Hamiltonians — ●FELIX HUBER and OTFRIED GÜHNE — Universität Siegen

Hamiltonians of naturally occurring physical systems are expected to have few-body interactions only. Accordingly, these Hamiltonians impose only local constraints onto the quantum states governed by them. Thus motivated, we characterise the set of ground and thermal states of few-body Hamiltonians, leading to new insights into the quantum marginal problem and to a generalisation of entanglement. We provide both witnesses as well as a semi-definite program to detect states outside of the convex hull of thermal and ground states having few-body Hamiltonians only. Finally, we give numerical results on the fraction of pure states determined by their marginals, and explore connections to the detection of topologically ordered states.

Q 23.5 Tue 15:30 e214

Non-equidistant dynamical decoupling and weighted Cesàro means — ●JÓZSEF ZSOLT BERNÁD — Institut für Angewandte Physik, TU Darmstadt, Germany

Dynamical decoupling is a method which decouples quantum systems from their environments and increases the coherence times of the quantum states. One possibility to optimize the suppression of the decoherence is to use non-equidistant pulse sequences, like Uhrig's dynamical decoupling scheme. We investigate this problem from a general point of view and relate to ergodic theorems and weighted Cesàro means. We show that in the limit of continuous control the suppression mechanism becomes independent from the non-equidistant timing of the pulses. In the case of finite number of pulses an inequality is derived and within this approach the non-equidistant application of the pulses is optimized.

Q 23.6 Tue 15:45 e214

One-to-one mapping between steering and joint measurability problems — ●ROOPE UOLA¹, COSTANTINO BUDRONI¹, OTFRIED GÜHNE¹, and JUHA-PEKKA PELLONPÄÄ² — ¹Universität Siegen, Siegen, Germany — ²Turku Centre for Quantum Physics, Turku, Finland

Quantum steering refers to a quantum information task where one party, say Alice, tries to remotely steer another party's, say Bob's, state by performing local measurements on her half of a bipartite system. Two necessary ingredients for steering are entanglement and incompatibility of Alice's measurements. In particular, it has been

recently proven that for the case of pure states of maximal Schmidt rank the problem of steerability is equivalent to the problem of joint measurability for Alice's observables. We show that such an equivalence holds in general, namely, the steerability of any assemblage can always be formulated as a joint measurability problem, and vice versa. We use this connection to introduce steering inequalities from joint measurability criteria and develop quantifiers for the incompatibility of measurements.

Q 23.7 Tue 16:00 e214

Simultaneous gates in frequency-crowded multilevel systems using fast, robust analytic control shapes — ●LUKAS S. THEIS, FELIX MOTZOI, and FRANK K. WILHELM — Saarland University, 66123 Saarbrücken, Germany

We present a few-parameter ansatz for pulses to implement simultaneous single-qubit rotations in frequency-crowded multi-level systems. Specifically, we consider a system of two qutrits whose working and leakage transitions suffer from spectral crowding (detuned by δ). In order to achieve precise controllability, we make use of two driving fields (each having two quadratures) at two different tones to simultaneously apply arbitrary combinations of rotations about axes in the X–Y plane to both qubits. Expanding the waveforms in terms of Hanning windows, we show how analytic pulses containing smooth and

composite-pulse features can easily achieve gate errors $< 10^{-4}$ and considerably outperform known adiabatic techniques. Moreover, we find a generalization of the WahWah method [Phys. Rev. A **88**, 052330 (2013)] that allows precise separate single-qubit rotations for all gate times beyond a quantum speed limit. We find in all cases a quantum speed limit slightly below $2\pi/\delta$ for the gate time and show that our pulses are robust against variations in system parameters and filtering due to transfer functions, making them suitable for experimental implementations.

Q 23.8 Tue 16:15 e214

The Magic of Combining Coherent Control with Switchable Noise — ●THOMAS SCHULTE-HERBRÜGGEN¹, VILLE BERGHOLM^{1,2}, and FRANK WILHELM³ — ¹Technical University of Munich (TUM) — ²University of Helsinki — ³University of Saarbrücken

Combining coherent control with simplest noise control seems magic: it allows to *interconvert arbitrary quantum states* no matter whether they are pure or mixed. We sketch possible experimental implementation in superconducting devices.

We analyse the capabilities of switchable noise in view of the limits between open-loop control and closed-loop feedback control.

All these findings fit nicely in a Lie-geometric picture of dynamic systems control.

Q 24: Ultracold plasmas and Rydberg systems II (with A)

Time: Tuesday 14:30–16:30

Location: f303

Q 24.1 Tue 14:30 f303

Dynamically probing ultracold lattice gases via Rydberg molecules — ●OLIVER THOMAS^{1,2}, TORSTEN MANTHEY¹, THOMAS NIEDERPRÜM¹, TANITA EICHERT¹, PHILIPP GEPPERT¹, and HERWIG OTT¹ — ¹Department of Physics and Research Center OPTIMAS, University of Kaiserslautern, Germany — ²Graduate School Materials Science in Mainz, Gottlieb-Daimler-Strasse 47, 67663 Kaiserslautern, Germany

Rydberg Molecules have been an ongoing field of interest since their first theoretical prediction and experimental realization in ultra cold gases nearly 7 years ago. Since then great progress, theoretically and experimentally, has been made in understanding these exotic states, in which one or more ground state atoms are bound in the electronic wave function of a highly excited Rydberg state by a Fermi contact type interaction.

We show that the excitation of long-range Rydberg molecules can be used to probe position- and time-sensitive the occupation of sites in an ultra-cold many body system, by using the natural decay of the excited molecular state into an ion as a continuous probe. We use this technique to dynamically probe the occupation in a many body quantum system when crossing the superfluid to Mott insulator transition. With the technique of scanning electron microscopy, we also show the position sensitiveness of the used scheme, depleting only atoms located in the inner region of the prepared many body system.

Q 24.2 Tue 14:45 f303

Pumping squeezed states of a micro-mechanical oscillator with Rydberg atoms. — ●ROBIN STEVENSON¹, JIRI MINAR¹, SEBASTIAN HOFFERBERTH², and IGOR LESANOVSKY¹ — ¹School of Physics and Astronomy, The University of Nottingham, Nottingham NG7 2RD, United Kingdom — ²Physikalisches Institut, Universität Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany

We investigate a system comprising of a stream of Rydberg atoms passing close by a micro-mechanical oscillator. We show in the situation where the atomic transition is resonant with a single-phonon transition of the oscillator, this system is equivalent to a micromaser, realised for example by atoms passing one by one through a cavity. This in principle allows the observation of a lasing transition and the creation of coherent states.

Furthermore, we demonstrate that when the atoms are on resonance with a two-phonon transition of the oscillator we can generate non-classical states in the oscillator. In the small interaction limit, the oscillator is driven towards coherent superpositions of coherent states with opposite sign. In the presence of thermal coupling the oscillator is driven towards squeezed states that can have variance lower than the vacuum state. Finally, we discuss experimental parameters and

explore whether the non-classical states discussed here are achievable with current technology.

Q 24.3 Tue 15:00 f303

Optimal preparation of the crystalline states and the GHZ states on Rydberg many-body systems — ●JIAN CUI¹, RICK VAN BIJNEN², THOMAS POHL², SIMONE MONTANGERO¹, and TOMMASO CALARCO¹ — ¹Institute for Complex Quantum Systems, Ulm, Germany — ²Max-Planck-Institute for the Physics of Complex Systems, Dresden, Germany

Rydberg atoms, characterized by their exaggerated strong and long-range interactions, serve as one of the most promising candidate platforms for quantum simulators. The finite lifetimes of Rydberg atoms set the duration limits within which experiments have to be performed. To identify the dynamics satisfying this lifetime condition based on the current experimental technologies in Rydberg many-body systems, however, turns out to be highly nontrivial. Presently, most methods in this regard rely on the adiabatic evolution, which is slow by definition. Here, we apply the methods from optimal control theory to solve this problem. Optimized control pulses for preparing the crystalline states and the GHZ states on the ultra-cold Rydberg atomic gases with much less time cost than the corresponding adiabatic schemes have been numerically identified. Besides the lifetimes, other realistic experimental constraints and imperfections including the lost of atoms, finite detuning and coupling strengths as well as the limited bandwidths of control pulses, among others, have been taken into account in deriving the results, so that they can be readily applied in real experiments.

Q 24.4 Tue 15:15 f303

Resolved quadrupole shifts of a single trapped Rydberg ion — ●GERARD HIGGINS^{1,2}, FABIAN POKORNY^{1,2}, WEIBIN LI³, CHRISTINE MAIER², JOHANNES HAAG², FLORIAN KRESS², QUENTIN BODART¹, YVES COLOMBE², IGOR LESANOVSKY³, and MARKUS HENNRICH^{1,2} — ¹Stockholm University, Sweden — ²Universität Innsbruck, Austria — ³University of Nottingham, United Kingdom

Trapped Rydberg ions are a novel approach to quantum information processing, which joins the advanced quantum control of trapped ions with the strong dipolar interactions between Rydberg atoms [1-2]. The strong electric fields used for trapping Rydberg ions give rise to fundamental phenomena which are not usually observed in neutral Rydberg atom experiments. Here we present recent experimental results in which effects of the trap on a Rydberg ion were observed.

A single strontium ion was trapped in the center of the electric quadrupole field of a linear Paul trap and excited to Rydberg S- and D-states using two ultraviolet photons. The Rydberg ion was subjected to both the DC and the radio-frequency electric quadrupole fields of the trap as well as an applied magnetic field. The Rydberg states were

split by the magnetic field due to the Zeeman effect, which explains the observed resonance structure of the excited Rydberg S-states. Rydberg D-states possess an electric quadrupole moment and couple to the gradients of the trapping fields, which has allowed effects of both the DC and RF trapping fields to be resolved in D-state resonances.

- [1] M. Müller, et al., *New J. Phys.* **10**, 093009 (2008)
 [2] T. Feldker, et al., *Phys. Rev. Lett.* **115**, 173001 (2015)

Q 24.5 Tue 15:30 f303

Rydberg-atom interfaces between photons and superconducting cavities — ●WILDAN ABDUSSALAM, DANIEL VISCOR, and THOMAS POHL — Max Planck Institute for the Physics and Complex Systems, Dresden, Germany

Owing to their large polarisability Rydberg atoms hold promise for realising strong coupling between microwave photons and superconducting cavities. Yet, the very same property makes Rydberg states prone to surface noise which has thus far hampered efficient interfacing.

Here, we study the coupled dynamics of a single cavity photon and a strongly interacting ensemble of Rydberg atoms and show that available Rydberg-Rydberg atom interactions can be utilised to overcome this problem. Using realistic noise sources and accounting for additional decay of Rydberg states, we demonstrate that collective photon coupling to interacting Rydberg ensembles provides a promising to noise-resistant quantum interfaces.

Q 24.6 Tue 15:45 f303

Quantum state tomography of a nano-mechanical oscillator using Rydberg atoms — ●ADRIÁN SANZ MORA, SEBASTIAN WÜSTER, and JAN-MICHAEL ROST — Max Planck Institute for the Physics of Complex Systems, Nöthnitzer Str. 38, 01187 Dresden, Germany

Rydberg atoms have proven to be an excellent tool to observe the quantum dynamical features of a microwave cavity mode[1]. Here we investigate their applicability to characterize instead the motional state of a nano-mechanical oscillator. Attaching a ferroelectric domain to the oscillator supplies it with a permanent electric dipole moment. Coupling between mechanical vibrations of such oscillator and a Rydberg transition dipole is thus enabled via an electric dipole-dipole interaction. Atomic Ramsey interference measurements of phase-shifts acquired by Rydberg atom-oscillator states in an off-resonance scenario provides a non-destructive detection of discrete mechanical quanta. Translations in phase space of the mechanical oscillator, required for its full tomographical reconstruction[2], are performed using the aforementioned coupling while the atoms are simultaneously driven by optical fields in an off-resonant Raman scenario. The Wigner function for a given

initial motional state of the mechanical oscillator is recreated by applying several sequences of Ramsey measurements at many different sampling points in the phase space of the mechanical oscillator.

- [1] S. Deléglise et al., *Nature* **455**, 510 (2008).
 [2] M.R. Vanner et al., *Ann. Phys.* **527**, 15 (2014).

Q 24.7 Tue 16:00 f303

Decoherence dynamics in a single photon switch — ●CALLUM MURRAY¹, ALEXEY GORSHKOV², and THOMAS POHL¹ — ¹Max Planck Institute for the Physics of Complex Systems, Dresden, Germany — ²University of Maryland, Maryland, USA

In this talk, we will discuss the decoherence processes affecting the performance of a dissipative single photon switch. A device of this kind uses a single gate photon to block the transmission of many other target photons via conditional absorption, and has recently been demonstrated in a Rydberg EIT medium. However, the decoherence processes affecting the gate photon in this case are still not very well understood. In this talk, a complete characterisation of this decoherence will be presented along with the impact this has on the maximum achievable switch fidelity.

Q 24.8 Tue 16:15 f303

Experimental demonstration of Rydberg dressing in a many-body system — ●JOHANNES ZEIHNER¹, PETER SCHAUSS¹, SEBASTIAN HILD¹, ANTONIO RUBIO ABADAL¹, JAE-YOON CHOI¹, RICK VAN BIJNEN², THOMAS POHL², IMMANUEL BLOCH^{1,3}, and CHRISTIAN GROSS¹ — ¹Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany — ²Max-Planck-Institut für Physik komplexer Systeme, Nöthnitzer Straße 38, 01187 Dresden, Germany — ³Fakultät für Physik, Ludwig-Maximilians-Universität München, Schellingstraße 4, 80799 München, Germany

Rydberg atoms offer the possibility to study long range interacting systems of ultracold atoms due to their strong van der Waals interactions. Admixture of a Rydberg state to a ground state, known as Rydberg dressing, allows for greatly increased experimental tunability of these interactions. Here we report on our results of the realization of Rydberg dressing in a many-body spin system. Starting from a two-dimensional spin-polarized Mott insulator state of rubidium-87, we optically couple one spin component to a Rydberg p-state on a single photon ultra-violet transition at 297 nm. Using Ramsey interferometry in the ground state manifold, we measure the spin-spin correlations induced by the long range interactions. To show the predicted versatility of Rydberg dressing, we realize an increased interaction range by selecting a different Rydberg state and experimentally study anisotropic interactions by tilting the quantization axis.

Q 25: Nano-Optics I

Time: Tuesday 14:30–16:45

Location: f342

Q 25.1 Tue 14:30 f342

Photon Statistics Excitation Spectroscopy of a Single Two Level System — ●JANIK WOLTERS^{1,2}, MAX STRAUSS², MARLON PLACKE², SÖREN KREINBERG², CHRISTIAN SCHNEIDER³, MARTIN KAMP³, SVEN HÖFLING³, and STEPHAN REITZENSTEIN² — ¹Universität Basel, Departement Physik, CH-4056 Basel — ²Institut für Festkörperphysik, Quantum Devices Group, Technische Universität Berlin, Hardenbergstrasse 36, EW 5-3, 10623 Berlin, Germany — ³Technische Physik, Universität Würzburg, Am Hubland, 97074 Würzburg, Germany

The interaction of coherent light with a single two level system (TLS) is one of the corner stones of quantum optics. In recent years experiments in this exciting field of quantum optics have been extended from atomic systems to semiconductor nanostructures, e.g. to the coherent control of self-assembled quantum dots (QDs). Here, we address the so far unexplored regime of resonance fluorescence in which the QD is excited not with a coherent laser, but with a narrowband chaotic light source. By analysing the resonantly scattered emission of the TLS, we find that the photon statistics of the excitation source greatly influences the TLS's dynamics in quantitative agreement with theoretical predictions.

Q 25.2 Tue 14:45 f342

All-optical coherent control of silicon vacancy color cen-

ters in diamond using picosecond laser pulses — ●JONAS NILS BECKER¹, CARSTEN AREND¹, BENJAMIN PINGAULT², CHRISTIAN HEPP², METE ATATÜRE², and CHRISTOPH BECHER¹ — ¹Universität des Saarlandes, Saarbrücken, Germany — ²Cavendish Laboratory, University of Cambridge, United Kingdom

In the last decade diamond-based impurity spins have been proven to be interesting systems for applications in quantum information processing. Besides the well known nitrogen vacancy center, in particular the negatively charged silicon vacancy center (SiV) has recently attracted attention because of its favourable spectral properties. In previous works we presented a detailed investigation of the electronic structure of the SiV [1] and we demonstrated access to its electronic spin within the excited state [2] as well as the ground state manifold [3]. However, the coherent optical manipulation of the SiV has not been demonstrated so far. Using picosecond laser pulses, we here present fast coherent control of the SiV employing Rabi oscillations. Furthermore, a Ramsey-type pulse sequence allows for a more general control of the created quantum state as well as for a measurement of the excited state coherence time scales. Both techniques are key requirements for applications in quantum information processing and for more complex manipulation schemes in the future.

- [1] Hepp et al., *Phys. Rev. Lett.* **112**, 036405 (2014).
 [2] Müller et al., *Nat. Commun.* **5**, 3328 (2014).
 [3] Pingault, Becker et al., *Phys. Rev. Lett.* **113**, 263601 (2014).

Q 25.3 Tue 15:00 f342

Probing non-Markovian dephasing processes in deterministic quantum-dot microlenses — ●ALEXANDER THOMA¹, PETER SCHNAUBER¹, MANUEL GSCHREY¹, MARC SEIFRIED¹, JANIK WOLTERS¹, JAN-HINDRIK SCHULZE¹, ANDRÉ STRITTMATTER¹, SVEN RODT¹, ALEXANDER CARMELE², ANDREAS KNORR², TOBIAS HEINDEL¹, and STEPHAN REITZENSTEIN¹ — ¹Institut für Festkörperphysik, TU Berlin, Berlin, Germany — ²Institut für Theoretische Physik, TU Berlin, Berlin, Germany

Bright quantum light sources based on single semiconductor quantum dots (QDs) integrated into photonic microstructures are key building blocks for the realization of advanced quantum computation schemes. Further progress toward applications will rely on deterministic fabrication technologies. Despite practical aspects, a profound knowledge of decoherence processes affecting the photon-indistinguishability is crucial for any optimization of future devices. Here, we probe time-dependent dephasing processes in deterministic QD-microlenses [1]. In particular, we explore the photon-indistinguishability as a function of the time δt elapsed between consecutive photon emission events to gain experimental access to the underlying decoherence processes at a ns time-scale. Gradually increasing δt from 2 ns to 12 ns results in a plateau-like behaviour at low δt with visibilities close to unity, while the visibility decreases for larger δt (> 8 ns). Our experimental observations are theoretically described by a non-Markovian noise process in agreement with fluctuating charge carriers in the QD's vicinity.

[1] Thoma et. al, arXiv:1507.05900 (2015)

Q 25.4 Tue 15:15 f342

Sub-shot-noise emission from a single photon source — ●XIAOLI CHU¹, STEPHAN GÖTZINGER^{2,1}, and VAHID SANDOGHDAR^{1,2} — ¹Max-Planck Institute for the Science of Light, D-91058 Erlangen, Germany — ²Department of Physics, Friedrich Alexander University of Erlangen-Nürnberg, D-91058 Erlangen, Germany

Recently, we introduced the concept of a dielectric antenna, which allowed us to demonstrate collection efficiencies from a single emitter in excess of 99% [1][2][3]. Such near-unity collection efficiency paves the way for creating a truly deterministic single photon source, whose inherent statistics is radically different from that of a classical light source. In the present work, we couple a single molecule to a metallo-dielectric antenna and demonstrate sub-poissonian photon statistics. The structure consists of a standard coverglass coated with thin dielectric layers with decreasing refractive indices and a gold mirror. Using standard optics, we are able to measure both high count rates and a noise level below the shot-noise. These experiments bring us one step closer to a perfectly deterministic single photon source that would be highly desirable for information processing and metrology.

[1] K. G. Lee et al., Nat. Phot. 5, 166 (2011)

[2] X.-W. Chen, S. Götzinger, and V. Sandoghdar, Opt. Lett. 36, 3545 (2011)

[3] X.-L. Chu et al., Optica 1, 203 (2014)

Q 25.5 Tue 15:30 f342

Single molecules coupled to nano-photon structures — ●OLIVER NEITZKE¹, GUENTHER KEWES¹, PIETRO LOMBARDI², NICO GRUHLER³, WOLFRAM PERNICE³, COSTANZA TONINELLI², and OLIVER BENSON¹ — ¹Inst.f.Physik, Humboldt Universitaet zu Berlin, Germany — ²LENS, Florence, Italy — ³KIT, Karlsruhe, Germany

Organic dye molecules are well-suited candidates for hybrid single photon sources and optical nonlinearities for future integrated photonics and quantum photonic circuits. Embedded in a crystal host matrix, dye molecules are very bright stable single photon emitters with very narrow zero-phonon-line emission at cryogenic temperatures.

In order to integrate single photon emission into nano-optical structures, coupling of single emitters to waveguides, resonators, and plasmonic structures is investigated thoroughly by many research groups. Our studies focus on single DBT molecules in a protective anthracene host matrix. The crystal matrix stabilizes the photon emission and reduces the intersystem crossing rates significantly, thereby reducing blinking and bleaching of the molecules under laser excitation. The robust thin-film shell enables mechanical nano-manipulation techniques and easy deposition onto our fabricated structures. We designed and fabricated SiN waveguides with optimized grating coupler ports, allowing us to focally excite and detect molecules and also observe the coupled fluorescence into the waveguide structures. We are employing different photonic structures, e.g. tapered fibers, slot waveguides, and nano antennas, to compare and improve the coupling efficiencies of the

single molecule emitters.

Q 25.6 Tue 15:45 f342

Single molecules evanescently coupled to optical nanofibers — ●SARAH MARGARETHA SKOFF, HARDY SCHAUFFERT, DAVID PAPPENCORDT, and ARNO RAUSCHENBEUTEL — Institute of Atomic and Subatomic Physics, Vienna University of Technology, Stadionallee 2, 1020 Vienna, Austria

In recent years, single molecules in solids have gained increased interest as building blocks for quantum networks, quantum metrology and nanosensors. For all these applications strong light-matter interactions are essential.

A versatile tool to achieve such interactions is an optical nanofiber, which is the tapered part of a commercial optical fiber that has a sub-wavelength diameter waist. This allows an appreciable amount of light to propagate outside the fiber in the form of an evanescent waist. Due to the strong transverse confinement of the light field which prevails over the entire length of the nanofiber, the interaction with emitters close to the surface can be significant.

Here we will show how single terrylene molecules in a p-terphenyl matrix can be evanescently coupled to the guided modes of optical nanofibers. This presents a new platform based on solid state emitters that is used for quantum optics and can be naturally integrated into any optical fiber based quantum network.

Q 25.7 Tue 16:00 f342

All-optical preparation of coherent dark states of a single rare earth ion spin in a crystal — ●KANGWEI XIA¹, ROMAN KOLESOV¹, PETR SIYUSHEV², ROLF REUTER¹, THOMAS KORNER¹, ANDREAS D. WIECK³, and JÖRG WRACHTRUP¹ — ¹Universität Stuttgart — ²Universität Ulm — ³Ruhr-Universität Bochum

Rare-earth-doped crystals are excellent hardware for quantum storage of optical information. In quantum memories the quantum state of a photon is stored in an ensemble of spins. This type of memory is an essential ingredient of quantum repeaters and quantum computing protocols based on linear optics. Despite progress made with ensembles of rare-earth ions, the detection and manipulation of individual ions is one of the ways to reach scalability of rare earth-based quantum devices. Here, we present high-fidelity optical initialization, coherent manipulation, and optical readout of a single electron spin of Ce ion in YAG. Under dynamic decoupling, spin coherence lifetime reaches 2ms. The generation of coherent dark state of a single Ce in YAG will be also present. The dark state was formed under the condition of coherent population trapping. In addition, high-resolution spectroscopic studies of single Ce ions have been performed. They revealed narrow and spectrally stable optical transitions between the spin sublevels of the ground and excited optical states, indicating the feasibility of interfacing single photons with a single electron spin of a cerium ion. Combined with high brightness of Ce³⁺ emission and a possibility of creating photonic circuits out of the host material, this makes cerium spins an interesting option for integrated quantum photonics.

Q 25.8 Tue 16:15 f342

Low temperature spectroscopy of defect in diamond showing positive ODMR signature — ●MATHIAS H. METSCH¹, PRIYADHARSHINI BALASUBRAMANIAN¹, LACHLAN J. ROGERS¹, MARCUS W. DOHERTY², and FEDOR JELEZKO¹ — ¹Institute for Quantum Optics and Center for Integrated Quantum Science and Technology, University Ulm, D-89081 Germany — ²Laser Physics Centre, Research School of Physics and Engineering, Australian National University, ACT 0200, Australia

Natural diamonds may contain a wide variety of defects of which only a hand full have been intensively studied. The most well known color center in diamond is the negatively charged nitrogen vacancy center, and it is of particular interest as it provides spin polarization and an optical spin read-out mechanism at ambient temperature (via optically detected magnetic resonance - ODMR). This ability to manipulate individual spins in the solid state has a wide range of exciting applications in quantum sensing, quantum information processing, and quantum communication. Only a few other color centres in diamond have been demonstrated to provide the ability to manipulate individual spins, including the silicon-vacancy (SiV) and an unidentified defect named ST1.

In this talk I will present results of low temperature spectroscopy measurements on a novel defect showing these properties which is found in natural diamond. The ODMR properties of this defect resemble those of the ST1 center. One aim of these measurements is to

identify the defect responsible.

Q 25.9 Tue 16:30 f342

Optical dynamic nuclear spin polarisation in diamond — ●JOCHEN SCHEUER¹, ILAI SCHWARTZ², QIONG CHEN², DAVID SCHULZE-SÜNNINGHAUSEN³, PATRICK CARL⁴, PETER HÖFER⁴, ALEXANDER RETZKER⁵, HITOSHI SUMIYA⁶, JUNICHI ISOYA⁷, BURKHARD LUY³, MARTIN B. PLENIO², BORIS NAYDENOV¹, and FEDOR JELEZKO¹ — ¹Institute of Quantum Optics, Ulm University, Germany — ²Institute of Theoretical Physics, Ulm University, Germany — ³Institute of Organic Chemistry and Institute for Biological Interfaces, Karlsruhe Institute of Technology, Germany — ⁴Bruker BioSpin GmbH, Rheinstetten, Germany — ⁵Racah Institute of Physics, The Hebrew University of Jerusalem, Israel — ⁶Sumitomo Electric Indus-

tries Ltd., Itami, Japan — ⁷Research Centre for Knowledge Communities, University of Tsukuba, Japan

The sensitivity of Magnetic Resonance Imaging (MRI) depends critically on nuclear spin polarisation and therefore dynamical nuclear spin polarisation has recently been applied to enhance MRI protocols. ¹³C nuclear spins in diamond possess uniquely long spin lattice relaxation times. If present in nanodiamonds, especially when strongly polarised, they form a promising contrast agent for MRI. Available schemes for achieving hyperpolarization, however, require cryogenic temperatures. We present an efficient scheme that realises ¹³C nuclear spin hyperpolarisation at room temperature and low magnetic field, which is robust against misalignment. Optical pumping of a Nitrogen-Vacancy (NV) centre creates a continuously renewable electron spin polarisation which can then be transferred to surrounding ¹³C nuclear spins.

Q 26: Quantum Optics IV

Time: Tuesday 14:30–16:00

Location: f442

Q 26.1 Tue 14:30 f442

Quadrature squeezed photons from a two-level system — CARSTEN SCHULTE, JACK HANSOM, ALEX JONES, ●CLEMENS MATTHIENSEN, CLAIRE LE GALL, and METE ATATUR — Cavendish Laboratory, University of Cambridge, United Kingdom

The interaction of a two-level atom with a resonant light field is of fundamental importance in quantum optics. Despite its conceptual simplicity it gives rise to intriguing phenomena, such as the Mollow triplet, antibunching and coherent light scattering.

While quantum optics experiments have traditionally been confined to the realms of atomic optics, the past 15 years have seen a branching out from ‘natural’ to ‘artificial atoms’ such as semiconductor quantum dots.

Enabled by the high scattering rate of a resonantly driven self-assembled InGaAs quantum dot we verify a prediction from the 1980s that the quantum fluctuations in the stream of single photons are below the fundamental level set by the vacuum fluctuations [1]. We employ homodyne intensity correlations to observe quadrature squeezing in single-atom resonance fluorescence for the first time [2].

[1] D.F. Walls and P. Zoller, PRL 47, 709 (1981).

[2] C. H. H. Schulte et al., Nature 525, 222 (2015).

Q 26.2 Tue 14:45 f442

Squeezed Light from Entangled Nonidentical Emitters via Nanostructured Environments — HARALD R. HAAKH and ●DIEGO MARTIN-CANO — Nano-Optics Division, Max Planck Institute for the Science of Light, Erlangen, Germany.

Most sources of squeezed light are based on large systems, such as nonlinear crystals or atomic vapors. Recent experiments [1,2] have proven quadrature squeezing in scattered resonance fluorescence from a single emitter, a long-standing prediction in quantum optics [3]. To assist the weak signals in such challenging measurements and to push the limits of their generation, we have recently researched the ability of nanostructures to create squeezed light from a single two-level emitter [4]. Here we present a step forward by studying nonclassical properties in collective resonance fluorescence aided by nanostructures [5]. The broadband character of the nano-architecture allows for an enhanced two-photon nonlinearity that generates squeezed light from two far-detuned quantum emitters. Our approach permits to overcome the intrinsic limitations from noninteracting single emitters and is more robust against phase decoherence induced by the environment. More generally, we show that the reduced light fluctuations arising from the interaction between the emitters provide a means to detect their entanglement. **References:** [1] C. Schulte et al., Nature 525, 222 (2015). [2] A. Ourjoumtsev et al, Nature 474, 623 (2011) [3] D. Walls and P. Zoller, PRL 47, 709 (1981). [4] D. Martin-Cano et al, PRL 113, 263605 (2014). [5] H. Haakh and D. Martin-Cano, ACS Phot, DOI:10.1021/acsp Photonics.5b00585.

Q 26.3 Tue 15:00 f442

Optical Harmonic Generation from Bright Squeezed Vacuum — ●KIRILL SPASIBKO^{1,2,3}, DENIS KOPYLOV³, TATIANA MURZINA³, MARIA CHEKHOVA^{1,2,3}, and GERD LEUCHS^{1,2} — ¹MPI for the Science of Light, Erlangen, Germany — ²FAU Erlangen-Nürnberg, Erlangen, Germany — ³M.V.Lomonosov MSU, Moscow, Russia

Bright squeezed vacuum (BSV) is a macroscopic but still highly non-classical state of light. Its non-classical features include quadrature and two-mode squeezing. Moreover with this state even the Bell inequalities could be, in principle, violated. Due to the high brightness, BSV is very attractive for any nonlinear light-matter interactions, where it provides much higher efficiency than faint non-classical states of light.

The simplest case is the generation of optical harmonics. Usually it is done with laser beams that have coherent statistics. Depending on the conditions, single-mode BSV has thermal or superbunched statistics. Such statistics leads to the enhancement in the generation of the m -th harmonic by a factor of $m!$ or $(2m-1)!!$ compared to coherent light with the same mean intensity. For example, for the generation of the second (third) harmonics the enhancement factors are 2 (6) and 3 (15). Thus, BSV offers higher sensitivity in nonlinear interactions with the same mean intensity, which is important for fragile samples.

Here we study the generation of the second and third harmonics from the filtered single-mode and multimode BSV radiation. We compare harmonics generation from single-mode superbunched BSV, single-mode BSV with thermal statistics, and multimode BSV mimicking coherent radiation.

Q 26.4 Tue 15:15 f442

An Operational Measure for Squeezing — ●MARTIN IDEL, DANIEL LERCHER, and MICHAEL M. WOLF — Technische Universität München, Zentrum Mathematik, M5, Garching, Deutschland

Squeezing of quantum states in continuous variable systems is valuable albeit difficult since it always requires the use of nonlinear media. From a mathematical perspective, this makes it an interesting resource theory. We introduce two operational measures for squeezing for multimode quantum systems: the first measure quantifies the integrated interaction strength of active Hamiltonians required to prepare the given state. The second measure may be dubbed “squeezing of formation” as it is the squeezing analogue of the well-known entanglement of formation. The two measures are shown to be equivalent and we prove some of their properties such as convexity and continuity. Moreover, we derive simple bounds and provide a convex programming algorithm for computing the measure. Finally, we show an example where the preparation procedures obtained from the measure are superior (in terms of squeezing needed) to naive preparation procedures.

Q 26.5 Tue 15:30 f442

Quantumness Quantification — ●MELANIE MRAZ¹, JAN SPERLING², WERNER VOGEL², and BORIS HAGE¹ — ¹AG Experimentelle Quantenoptik, Institut für Physik, Universität Rostock, Rostock, Deutschland — ²AG Theoretische Quantenoptik, Institut für Physik, Universität Rostock, Rostock, Deutschland

Nonclassical quantum states have an advantage over classical states for various applications. Hence, it is of a fundamental interest to study properties of these states. It is already possible to say if a state is nonclassical or not, but how can we decide how much nonclassicality is in our system? We propose a degree of nonclassicality being a nonclassicality measure. It is determined by the decomposition of a quantum state into superpositions of coherent states. On the one hand, coherent states resembles the behavior of a classical harmonic oscillator most closely. On the other hand, the more quantum superpositions of coher-

ent states are needed, the more quantum interferences arise. A method for such a decomposition of quantum states is presented and the degree of nonclassicality is determined for different states theoretically. Following this approach the next step is to apply this measure to an experiment. But how can we extract the information necessary to estimate the amount of quantumness in our system? Therefore pattern functions are used to reconstruct a density matrix in coherent state basis. This basis is chosen as the quantumness measure itself is based on superpositions of coherent states. Using this method we will try to witness the amount of nonclassicality in our system.

Q 26.6 Tue 15:45 f442

Unified nonclassicality criteria and continuous sampling — ●SEMJON KÖHNKE, SERGEJ RYL, ELIZABETH AGUDELO, JAN SPERLING, MELANIE MRAZ, BORIS HAGE, and WERNER VOGEL — Arbeitsgruppe Experimentelle Quantenoptik, Institut für Physik, Universität Rostock, D-18059 Rostock, Germany

Q 27: Poster: Quantum Optics and Photonics II

Time: Tuesday 16:30–19:00

Location: Empore Lichthof

Q 27.1 Tue 16:30 Empore Lichthof

Nonthermal Fixed Points and Superfluid Turbulence in Ultracold Bose Gases — HALIL ÇAKIR¹, STEFANIE CZISCHEK¹, ●MARKUS KARL^{1,2}, EIKE NICKLAS¹, THOMAS GASENZER^{1,2}, and MARKUS K. OBERTHALER¹ — ¹Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Im Neuenheimer Feld 227, 69120 Heidelberg — ²Institut für Theoretische Physik, Ruprecht-Karls-Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg

Ultracold quantum gases provide various means to probe universal many-body dynamics far from equilibrium. Here, we focus on the non-linear dynamical evolution induced in an ultra cold Bose gas by a sudden initial parameter quench. Considering one- or multi-component (spin) systems, various types of spatial and wavenumber- space patterns emerge, being characterized by universal scaling functions associated with non-thermal fixed points. Such fixed points can be observed in existing experiments and are closely related to quantum turbulence usually discussed in systems of more than one spatial dimension. While these situations are associated with quenches to a symmetry-broken state, quenches within the symmetric phase offer a way to probe the properties of universal dynamics similar to those near a quantum critical point in equilibrium. Scaling properties have been found which indicate the importance of pre-thermalisation temperatures long before dephasing has occurred in the nearly gapless system. We discuss the theoretical results in the light of and illustrated by recent experimental measurements.

Q 27.2 Tue 16:30 Empore Lichthof

Strong-wave-turbulence character of non-thermal fixed points in Bose gases — ●ISARA CHANTESANA^{1,2,3} and THOMAS GASENZER^{2,3} — ¹Institut für Theoretische Physik, Ruprecht-Karls-Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany — ²Kirchhoff Institut für Physik, INF 227, 69120 Heidelberg, Germany — ³ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstraße 1, 64291 Darmstadt, Germany

Far-from equilibrium dynamics of a dilute Bose gas is studied by means of the two-particle irreducible effective action formalism. We investigate the properties of non-thermal fixed points predicted previously, which are related to non-perturbative strong wave turbulence solutions of the many-body dynamic equations. Instead of using a scaling analysis, we study the Boltzmann equation of the scattering integral by means of direct integration equation for sound waves. In this way we obtain a direct prediction of the scaling behaviour of the possible fixed-point solutions in the context of sound-wave turbulence. Implication for the real-time dynamics of the non-equilibrium system are discussed.

Q 27.3 Tue 16:30 Empore Lichthof

Engineering scaling laws: What to learn from driven quantum turbulence — ●FABIAN BROCK^{1,3}, MARKUS KARL^{1,2,3}, and THOMAS GASENZER^{2,3} — ¹Institut für Theoretische Physik, Ruprecht-Karls-Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany — ²ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstraße 1, 64291 Darmstadt, Germany — ³Kirchhoff-Institut für Physik, INF 227, 69120 Heidelberg, Germany

One principle scope of quantum physics is the formulation of measurable conditions, which are fulfilled for classical systems but may be violated for nonclassical ones. Hence a number of nonclassicality criteria have been formulated to certify quantum features of states.

One hierarchy is based on Bochner's theorem and the characteristic function of the Glauber-Sudarshan representation (P function). Another hierarchy is formulated in terms of the matrix of moments. We combine the advantages of the CF and the MOM of the P function, resulting in a generalization of Bochner's theorem. For applications of the generalized nonclassicality probes, we provide direct sampling formulas for balanced homodyne detection. A squeezed vacuum state is experimentally realized and characterized with our method.

Furthermore we present a continuous phase sampling technique. In contrast to discrete phase-locked measurements, the continuous sampling of a regularized P function allows an unconditional verification of nonclassicality, as we demonstrate for the phase-sensitive squeezed vacuum state.

trum für Schwerionenforschung GmbH, Planckstraße 1, 64291 Darmstadt, Germany — ³Kirchhoff-Institut für Physik, INF 227, 69120 Heidelberg, Germany

We investigate the long-standing issue of driven quantum turbulence in a Bose–Einstein condensate from a new perspective. Having the recently developed concept of non-thermal fixed points in mind, we study the response of a Bose gas in two spatial dimensions to a power-law shaped stochastic driving force. Two classes of non-equilibrium steady states are found, depending on the ability of the system to form quantum vortices. We show that, if vortex formation is suppressed, a turbulent steady state with a freely adjustable scaling law in the energy distribution emerges. We present numerical evidence that the driven-dissipative Bose gas is then part of the Kardar-Parisi-Zhang dynamic universality class. On the other hand, if vortex proliferation is allowed, a completely different scenario applies where the system is, irrespective of the driving force, attracted by one universal fixed point.

Q 27.4 Tue 16:30 Empore Lichthof

Far from equilibrium integrable systems — ●SEBASTIAN ERNE^{1,2,4}, THOMAS SCHWEIGLER⁴, BERNHARD RAUER⁴, VALENTIN KASPER¹, TIM LANGEN⁴, JÜRGEN BERGES¹, THOMAS GASENZER^{1,2,3}, and JÖRG SCHMIEDMAYER⁴ — ¹Institut für Theoretische Physik, Ruprecht-Karls-Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany — ²ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstraße 1, 64291 Darmstadt, Germany — ³Kirchhoff-Institut für Physik, INF 227, 69120 Heidelberg, Germany — ⁴Vienna Center for Quantum Science and Technology (VCQ), Atominsttitut, TU Wien, Vienna, Austria

Relaxation of far-from equilibrium integrable systems is to date an open and interesting question. Recent progress in cold atom experiments in low dimensional systems, allow for a detailed study of integrable field theories. Specifically we consider a system of linearly coupled quasi one-dimensional condensates, realizing the quantum sine-Gordon and Lieb-Liniger theories. By studying quenches in the mass of the sine-Gordon model, we are able to explore fundamental questions of quantum physics. In particular we investigate prethermalization and the Generalized Gibbs Ensemble, higher order correlations and their factorization properties in and out of equilibrium, dynamics and decay of topological excitations and false vacua, quantum many body revivals, and tomography of quasiparticle. We compare the experiment to analytical and numerical results, for the latter using the (stochastic) Gross-Pitaevskii equations as well as Monte-Carlo simulations.

Q 27.5 Tue 16:30 Empore Lichthof

Studying spin-dynamics in one dimension with BECs — ●MAXIMILIAN PRÜFER, PHILIPP KUNKEL, DANIEL LINNEMANN, HELMUT STROBEL, WOLFGANG MÜSSEL, CHRISTIAN-MARCEL SCHMIED, THOMAS GASENZER, and MARKUS K. OBERTHALER — Kirchhoff-Institut für Physik, Im Neuenheimer Feld 227, 69120 Heidelberg

We use spin-changing collisions in ⁸⁷Rb as a experimentally precisely controllable method to couple the external and internal degrees of freedom. This non-linear process is investigated in a quasi one-dimensional

trap geometry.

We discuss our experimental setup to investigate spatial correlations arising in the course of spin-mixing. We first characterise the microscopic process, which creates atom pairs with opposite momenta. For this the experimental techniques in controlling this non-linear mechanism are presented. Going into a parameter regime where many momentum modes are accessible, we detail the use of correlation functions to extract the arising spatial structures. Remarkably, we find general features independent of our initial preparation, which are compared to simulations based on the truncated Wigner approximation.

Q 27.6 Tue 16:30 Empore Lichthof

Heating rates of interacting Bosons in shaken optical lattices — JAKOB NÄGER^{1,2}, ●MARTIN REITTER^{1,2}, LUCIA DUCA^{1,2}, TRACY LI^{1,2}, MONIKA SCHLEIER-SMITH⁴, IMMANUEL BLOCH^{1,2}, and ULRICH SCHNEIDER³ — ¹Ludwig-Maximilians-Universität München, Schellingstr. 4, 80687 München — ²Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 85748 Garching — ³University of Cambridge, Cambridge, UK — ⁴Stanford University, Stanford, CA 94305, Vereinigte Staaten

Periodically driven systems have been successfully used to implement topological band structures with non-zero Chern numbers for non-interacting neutral particles. The extent to which the engineered topological properties survive in the presence of interactions, and which many-body phases result, remains however a largely open question. In order to experimentally control the interactions, and to study the resulting many-body physics, we prepare a BEC of 39K which has an accessible Feshbach resonance. By tuning the interactions as well as the driving strengths and frequencies, we can systematically explore the non-equilibrium dynamics in a shaken 1D lattice as well as in a shaken honeycomb lattice. We will present the current status as well as future prospects of the experiment.

Q 27.7 Tue 16:30 Empore Lichthof

Rydberg Excitation and Many-Body Localization in a Two-Dimensional Quantum Gas — SEBASTIAN HILD¹, JOHANNES ZEIHNER¹, ●ANTONIO RUBIO ABADAL¹, SIMON HOLLERITH¹, JAE-YOON CHOI¹, TARIK YEFSAH¹, IMMANUEL BLOCH^{1,2}, and CHRISTIAN GROSS¹ — ¹Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany — ²Fakultät für Physik, Ludwig-Maximilians-Universität München, Schellingstraße 4, 80799 München, Germany

Ultracold atoms in optical lattices provide an ideal testbed for the study of strongly correlated many-body systems. The detection and manipulation of single atoms in two-dimensional optical lattices offer a versatile toolbox to investigate condensed matter models. In our setup we are capable of such control and local detection at the single-atom level by fluorescence-imaging of a two-dimensional bosonic gas of Rubidium-87. In recent work we have investigated Rydberg gases, which feature strong van der Waals interactions and can be used for the study of strongly correlated long-range many-body systems. This has allowed us to observe crystalline states and to microscopically characterize Rydberg superatoms, as well as to detect spin correlations induced by Rydberg-dressed interactions. We have also explored the localization transition occurring in a disordered interacting bosonic system in two dimensions, in which a for large enough disorder strength non-thermal states prevail. To this end we prepare a highly-excited Mott insulator state and study its thermalization in the presence of a random disorder potential.

Q 27.8 Tue 16:30 Empore Lichthof

Excitations of a Bose–Einstein condensate with angular spin-orbit coupling — ●IVANA VASIĆ and ANTUN BALAZ — Scientific Computing Laboratory, Institute of Physics Belgrade, University of Belgrade, Pregrevica 118, 11080 Belgrade, Serbia

A theoretical model of a Bose–Einstein condensate with angular spin-orbit coupling has been recently introduced and it has been established that a half-skyrmion configuration represents the ground state in a certain regime of spin-orbit coupling and interaction. We investigate low-lying excitations of this phase by using the method of Bogoliubov and simulations of the time-dependent Gross–Pitaevskii equation. We find that a sudden shift of the trap bottom results in a complex motion of the center-of-mass of the system in the x - y plane that is markedly different from a response of a competing phase. This behaviour of the half-skyrmion phase comprises a low-frequency interaction-dependent oscillation as well as a high-frequency contribution. Moreover, the breathing mode frequency of the half-skyrmion is set by the spin-orbit

coupling and interaction strength, while it takes a universal value in the competing state.

Q 27.9 Tue 16:30 Empore Lichthof

Observation of a superradiant Mott insulator in the Dicke-Hubbard model — ●CHRISTOPH GEORGES, HANS KESSLER, JENS KLINDER, JOSE VARGAS, and ANDREAS HEMMERICH — Institut für Laserphysik, Universität Hamburg, Luruper Chaussee 149, D-22761 Hamburg, Germany

It is well known that the bosonic Hubbard model possesses a Mott insulator phase. Likewise, it is known that the Dicke model exhibits a self-organized superradiant phase. By implementing an optical lattice inside of a high finesse optical cavity both models are merged such that an extended Hubbard model with cavity-mediated infinite range interactions arises. In addition to a normal superfluid phase, two superradiant phases are found, one of them coherent and hence superfluid and one incoherent Mott insulating [1].

[1] J. Klinder et al., arXiv:1511.00850

Q 27.10 Tue 16:30 Empore Lichthof

Direct Observation of Chiral Superfluid Order — ●CARL HIPPLER, THORGE KOCK, HANNES WINTER, and ANDREAS HEMMERICH — Universität Hamburg

The overall goal of our experiment is to explore ultracold bosonic quantum gases in excited bands of an optical lattice. We investigate Rb-87 atoms in a bipartite interferometric lattice allowing us to change the lattice geometry dynamically. We observe the formation of a chiral superfluid order, arising from the interplay between the contact interaction of the atoms on each lattice site and the degeneracy of the p orbitals in the second Bloch band. A periodic pattern of locally alternating orbital currents and circular currents establishes in the lattice, time-reversal symmetry being spontaneously broken. We report on a technique that lets us directly observe the phase properties of the superfluid order parameter. Here, two independent atomic samples are produced in the second band at well separated spatial regions of the lattice and subsequently brought to interference.

Q 27.11 Tue 16:30 Empore Lichthof

Laser using narrow band intercombination line of Calcium — HANNES WINTER, ●TORBEN LASKE, and ANDREAS HEMMERICH — Institut für Laserphysik, Hamburg

We present our setup for realizing a superradiant laser [1] similar to the proposal to [2] using the narrow Calcium intercombination line $4^1S_0 \leftrightarrow 4^3P_1$ as the laser transition. Such a laser operates in the bad-cavity regime, in which the coherence is not stored in the intra cavity light field but in the gain medium. The ultracold Calcium atoms are trapped in the Lamb-Dicke regime by a one dimensional intra cavity lattice to control the Doppler effect. Unlike conventional lasers, the expected frequency stability of this light source is not limited by mechanical fluctuations of the cavity length, which yields important implications for applications like time metrology.

[1] M. Holland and J. Thompson et al. Nature, 484(7392):78-81, (2012). [2] M. Holland et al., Phys. Rev. Lett. 102(16):163601, (2009).

Q 27.12 Tue 16:30 Empore Lichthof

Towards an experimental realization of a periodic quantum Rabi model with ultracold atoms — SIMONE FELICETTI¹, ENRIQUE RICO^{1,2}, CARLOS SABÍN³, ●TILL OCKENFELS⁴, MARTIN LEDER⁴, CHRISTOPHER GROSSERT⁴, MARTIN WEITZ⁴, and ENRIQUE SOLANO^{1,2} — ¹Department of Physical Chemistry, University of the Basque Country UPV/EHU, Bilbao, Spain — ²IKERBASQUE, Basque Foundation for Science, Bilbao, Spain — ³Instituto de Física Fundamental, CSIC, Madrid, Spain — ⁴Institut für Angewandte Physik, Universität Bonn, Bonn

The quantum Rabi model [1,2,3] describes the interaction between a two-level quantum system and a single bosonic mode. Whereas the regime of ultra-strong coupling (USC) has just been recently investigated, and an experimental realization of the quantum Rabi model in the deep strong coupling (DSC) regime has so far been absent. We propose a setup to perform a full quantum simulation of the quantum Rabi model regarding an effective two-level quantum system, provided by the occupation of Bloch bands by ultra-cold atoms in tailored optical lattices [4], interacting with a quantum harmonic oscillator implemented with an optical dipole trap. This setup will enable us to study the crossover between USC and DSC regimes, where a pattern

of collapse and revival is predicted.

- [1] I.I. Rabi, Phys. Rev. 49, 324 (1936).
- [2] D. Braak, Phys. Rev. Lett. 107, 100401 (2011).
- [3] J. Casanova et al., Phys. Rev. Lett. 105, 263603 (2010).
- [4] T. Salger et al., Phys. Rev. Lett. 107, 240401 (2011).

Q 27.13 Tue 16:30 Empore Lichthof

First order coherence of an ideal Bose gas of light — ●TOBIAS DAMM¹, JULIAN SCHMITT¹, DAVID DUNG¹, CHRISTIAN WAHL¹, FRANK VEWINGER¹, JAN KLAERS^{1,2}, and MARTIN WEITZ¹ — ¹Institute of Applied Physics, University of Bonn — ²Present address: Institute for Quantum Electronics, ETH Zürich

Bose-Einstein condensation in the gaseous regime has been observed with cold atoms, exciton-polaritons and more recently with photons in a dye-filled optical microcavity. The latter system is thermally equilibrated both below and above criticality due to repeated absorption and re-emission processes of the dye molecules.

In this work we report on the measurements of the first order coherence of the photon gas confined in a dye-filled optical microcavity below as well as above the phase transition to a photon condensate. Tunable Michelson and Mach-Zehnder interferometers are used to split up and recombine the cavity emission to obtain temporal and spatial coherence information respectively. The observed coherence times range from sub-picoseconds for noncritical system sizes up to microseconds for condensed systems. While below criticality the coherence length is in the micrometer regime, above criticality phase coherence is established macroscopically over the whole mode volume.

Q 27.14 Tue 16:30 Empore Lichthof

Microstructuring of Trapping Potentials for Coupled Photon Condensates — ●CHRISTIAN KURTSCHNEID¹, ERIK BUSLEY¹, DAVID DUNG¹, TOBIAS DAMM¹, JULIAN SCHMITT¹, FRANK VEWINGER¹, JAN KLÄRS², and MARTIN WEITZ¹ — ¹Institut für Angewandte Physik, Universität Bonn — ²Institut für Quantenelektronik, ETH Zürich

We present recent work on multiple coupled photon condensates in a single optical microcavity. Unlike Bose-Einstein condensates of dilute atomic gases, the realization of a photon condensate is not feasible using a blackbody radiator by cooling, because the photons then simply vanish in the system walls. In recent work we have realized Bose-Einstein condensation of photons in a dye-filled optical microcavity at room temperature. The dye-solution acts both as a heat bath and particle reservoir for the trapped photon gas. Thermal contact to the dye-solution is achieved by subsequent absorption and reemission processes. The microresonator introduces a low frequency cutoff to the dispersion relation, resulting in a non-trivial ground state. The harmonically trapped photon gas is formally equivalent to a 2D gas of massive bosons. We present measurements on photon tunneling between lattice sites and their creation with the polymer. New approaches of cavity pumping are presented. Further, in a more recent approach we have developed a permanent microstructuring technique to create variable trapping potentials for the photon gas in the microcavity.

Q 27.15 Tue 16:30 Empore Lichthof

Microscopic Model of Photon Condensation — ●MILAN RADONJIC^{1,2}, WASSILIJ KOPYLOV³, TOBIAS BRANDES³, ANTUN BALAZ², and AXEL PELSTER⁴ — ¹Faculty of Physics, University of Vienna, Austria — ²Institute of Physics Belgrade, University of Belgrade, Serbia — ³Institute for Theoretical Physics, Technische Universität Berlin, Germany — ⁴Physics Department and Research Center OPTIMAS, Technische Universität Kaiserslautern, Germany

Effectively a two-dimensional photon gas in an optical microcavity filled with dye solution features Bose-Einstein condensation. This has first been experimentally demonstrated in Bonn [1] as well as recently in London [2], and can be theoretically understood within the framework of a non-equilibrium description [3,4]. We critically analyze and extend the latter description by including coherent coupling between microcavity photons and dye molecules, influenced by the solvent, in addition to a dissipative coupling that leads to thermalization. Our preliminary results indicate that strong interaction of the dye and the solvent favors the thermalization and makes possible Bose-Einstein condensation of photons, while weak solvent influence promotes the coherent dynamics and enables formation of a laser-like state.

- [1] J. Klaers, J. Schmitt, F. Vewinger, and M. Weitz, Nature (London) **468**, 545 (2010)
- [2] J. Marelic and R. A. Nyman, Phys. Rev. A **91**, 033813 (2015)
- [3] P. Kirton and J. Keeling, Phys. Rev. Lett. **111**, 100404 (2013)

- [4] P. Kirton and J. Keeling, Phys. Rev. A **91**, 033826 (2015)

Q 27.16 Tue 16:30 Empore Lichthof

Hard-Core Bosons in Lattices with Intermediate Geometries Between Quadratic and Triangular — ●MATHIAS MAY¹ and AXEL PELSTER² — ¹Physics Department, Freie Universität Berlin, Germany — ²Physics Department and Research Center OPTIMAS, Technische Universität Kaiserslautern, Germany

The extended Bose-Hubbard model has recently been realized on a quadratic lattice utilizing magnetic dipolar ¹⁶⁸Er atoms [1]. This motivated us to perform a Gutzwiller mean-field analysis of hard-core bosons in two-dimensional lattices, which continuously interpolate between the non-frustrated quadratic and the frustrated triangular case [2,3]. In particular at negative hopping we find interesting new supersolid phases, which do not exist in either of these limiting cases and combine the checkerboard symmetry known from the quadratic lattice with the honeycomb pattern known from the triangular lattice. For instance, there is a supersolid phase, in which the phases of the condensate order parameters form a checkerboard pattern and at the same time the densities fulfill a honeycomb symmetry.

- [1] S. Baier, M. J. Mark, D. Petter, K. Aikawa, L. Chomaz, Z. Cai, M. Baranov, P. Zoller, and F. Ferlaino, arXiv:1507.03500.
- [2] D. Yamamoto, G. Marmorini, and I. Danshita, Phys. Rev. Lett. **112**, 127203 (2014).
- [3] D. Sellmann, X.-F. Zhang, and S. Eggert, Phys. Rev. B **91**, 081104(R) (2015).

Q 27.17 Tue 16:30 Empore Lichthof

Improved Ginzburg-Landau Theory for Bosons in Optical Lattices via Degenerate Perturbation Theory — ●MARTIN KÜBLER¹, EDNILSON SANTOS², and AXEL PELSTER¹ — ¹Physics Department and Research Center OPTIMAS, Technische Universität Kaiserslautern, Germany — ²Departamento de Física, Universidade Federal de São Carlos, Brazil

Bosons in an optical lattice yield a paradigmatic quantum phase transition between a Mott insulator and a superfluid. Recently, a Ginzburg-Landau theory for the underlying Bose-Hubbard model has been developed, which allows to determine the location of this quantum phase transition quite accurately [1-3]. Here we extend the validity range of this Ginzburg-Landau theory with the help of a degenerate perturbation theory. This allows to study also harmonically confined optical lattices, where a wedding cake structure of insulating Mott shells with superfluid regions between the Mott shells emerge [4].

- [1] F.E.A. dos Santos, and A. Pelster, Phys. Rev. A **79**, 013614 (2009).
- [2] B. Bradlyn, F.E.A. dos Santos, and A. Pelster, Phys. Rev. A **79**, 013615 (2009).
- [3] D. Hinrichs, A. Pelster, and M. Holthaus, Appl. Phys. B **113**, 57 (2013).
- [4] K. Mitra, C.J. Williams, and C.A.R. Sa de Melo, Phys. Rev. A **77**, 033607 (2008).

Q 27.18 Tue 16:30 Empore Lichthof

Experimental realization of a Bose-Hubbard model with cavity-mediated long-range interactions — ●NISHANT DOGRA, RENATE LANDIG, LORENZ HRUBY, MANUELE LANDINI, RAFAEL MOTTL, TOBIAS DONNER, and TILMAN ESSLINGER — HPF D4, Quantum Optics Group, Institute for Quantum Electronics, ETH Zurich, Otto-Stern-Weg-1, Zurich, Switzerland-8093

We experimentally investigate an extended Bose-Hubbard model with cavity-mediated long-range interactions using an ultracold atomic gas. The long-range interactions are generated by coupling a BEC to the single mode of a high-finesse cavity and pumping it with a transverse laser-field. The competition among three energy scales- tunnelling, short-range interactions and long-range interactions gives rise to a rich phase diagram consisting of four different phases - a superfluid, a supersolid, a Mott insulator and a charge density wave. Moreover, we study the transition between the two insulating phases - charge density wave and Mott insulator - and observe a hysteretic behaviour. We also investigate theoretically the various features of such an extended Bose-Hubbard model using different mean-field approaches.

Q 27.19 Tue 16:30 Empore Lichthof

Coherent interaction of a Bose-Einstein condensate with two crossed cavity modes — ●PHILIP ZUPANČIČ, JULIAN LEONARD, ANDREA MORALES, TILMAN ESSLINGER, and TOBIAS DONNER — ETH Zürich, Zürich, Schweiz

Coupling a quantum gas to the field of a single high-finesse optical cavity gives rise to interactions of infinite range between the atoms, which can create a self-organized state when exceeding a critical strength. It is desirable to tune range and directionality of these interactions, which enables explorations of more complex self-organized states or quantum soft matter physics, such as superfluid glasses and associative memory. However, this requires extending the atom-photon interactions to multiple cavity modes.

We report on the realization of such an extended system, involving a Bose-Einstein condensate coupled to two crossed cavities modes. This already allows to spatially shape the interactions, leading to multiple new crystalline phases, e.g. with hexagonal, triangular or stripe order.

Q 27.20 Tue 16:30 Empore Lichthof

Towards light induced 2D spin-orbit coupling for ultracold neutral atoms — ●SEBASTIAN BODE, FELIX KÖSEL, NACEUR GAALOU, HOLGER AHLERS, and ERNST M. RASEL — Institut für Quantenoptik Uni Hannover

Presentation of the experimental efforts we pursue towards engineering a 2D spin-orbit-coupling [1] of a neutral Rubidium Bose-Einstein condensate (BEC). Using multiple Raman transitions to couple cyclically three hyperfine Zeeman states of the atoms, an effective gauge field is predicted to be created which resembles the one occurring in spintronic systems [2]. Such an artificial interaction could be used to build advanced solid state simulators with non-Abelian character in a versatile cold-atom system. The first experimental steps realized to build a BEC machine featuring a hybrid source concept [3] are presented.

[1] Y.-J. Lin et al., Nature (London) 471, 83-86 (2011).

[2] H. C. Koo et al., Science 325, 1515 (2009).

[3] Y.-J. Lin, et al., Phys. Rev. A 79, 063631 (2009)

Q 27.21 Tue 16:30 Empore Lichthof

Mode switching in bimodal lasers by varying the pump power — ●DANIEL VORBERG¹, HEINRICH A.M. LEYMANN², THOMAS LETTAU², CASPAR HOPFMANN³, ANNA MUSIAL³, CHRISTIAN SCHNEIDER⁵, MARTIN KAMP⁵, SVEN HÖFLING⁵, ROLAND KETZMERICK^{1,4}, JAN WIERSIG², STEPHAN REITZENSTEIN³, and ANDRÉ ECKARDT¹ — ¹Max-Planck-Institut für Physik komplexer Systeme, Dresden — ²Otto-von-Guericke-Universität Magdeburg, Institut für Theoretische Physik — ³Technische Universität Berlin, Institut für Festkörperphysik — ⁴Technische Universität Dresden, Institut für Theoretische Physik — ⁵Universität Würzburg, Technische Physik

We investigate the switching of the lasing mode occurring in bimodal lasers when varying the pump power. Starting from a birth-death model we derive an analytic theory describing how many and which modes are lasing and how strong the lasing modes are occupied. This can be understood in the framework similar to that of the Bose selection [PRL 111, 240405 (2013)] and gives a new perspectives on multimode lasing. Fitting the model to experimental data for quantum-dot-based microlasers allows us to extract system parameters such as the mode-coupling rates or the ratio of the two emission rates into the cavity modes. Moreover, on the basis of the full photon statistics obtained numerically within the birth-death model, we show that the non-lasing modes exhibit strong (super-thermal) intensity fluctuations $g_{ii}^2(0) > 2$ and anti-correlations $g_{12}^2(0) < 1$ emerge whenever a mode starts or stops lasing.

Q 27.22 Tue 16:30 Empore Lichthof

Non-equilibrium dynamics of interacting Bosons in an optical lattice — ●JIAN JIANG, CHRISTIAN BAALS, BODHADITYA SANTRA, RALF LABOUVIE, and HERWIG OTT — Research Center OPTIMAS and Fachbereich Physik, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany

We study the non-equilibrium dynamics of ultracold Bose gases in optical lattices. Using a scanning electron microscope, we prepare different experimental scenarios, which allow us to study unitary and non-unitary time evolution. In a first experiment we characterize the emerging steady-states of a driven-dissipative Josephson junction array, realized with a BEC in a one-dimensional optical lattice. Furthermore, we investigate the dynamics of the center of mass in a three dimensional optical lattice. Therefore we instantaneously shift the position of the confining dipole trap after loading the atoms into the periodic potential. Finally the atomic cloud is imaged with high resolution using electron microscopy. In a third experiment we measure the coherence of the matter-wave field in an optical lattice using near-field interferometry.

Q 27.23 Tue 16:30 Empore Lichthof

Time-periodic driving of a spin-dependent honeycomb lattice — ●TOBIAS KLAFKA, CHRISTOPH ÖLSCHLÄGER, MALTE WEINBERG, JULIETTE SIMONET, and KLAUS SENGSTOCK — Institut für Laserphysik, Universität Hamburg

The presence of Dirac points in honeycomb lattice structures such as graphene gives rise to many intriguing phenomena. For bosonic quantum gases in spin-dependent optical lattices these Dirac cones can be opened in a controlled manner by lifting the degeneracy of the diatomic basis. However, the experimentally realized band structure reacts very sensitively to stray magnetic fields.

Here we present an active compensation setup for dc- and ac-magnetic fields attenuated below 1mG for frequencies up to 1kHz. Such an improved control over the magnetic field permits new driving schemes and thus the targeted engineering of exotic properties.

Q 27.24 Tue 16:30 Empore Lichthof

Numerical Simulation of BEC-impurity interaction — ●TOBIAS LAUSCH¹, FABIAN GRUSD^{1,2,3}, MICHAEL FLEISCHHAUER^{1,2}, and ARTUR WIDERA¹ — ¹TU Kaiserslautern and Forschungszentrum OPTIMAS, Erwin-Schroedinger-Strasse 46, 67663 Kaiserslautern, Germany — ²Graduate School Materials Science in Mainz, Gottlieb-Daimler Strasse 47, 67663 Kaiserslautern, Germany — ³Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

Cooling atoms to temperatures, where quantum effects become dominant, has become a standard in cold atom experiments. Especially interactions of quantum baths such as fermi gases and the implementation of impurities, which form fermi polarons, have been studied theoretically and experimentally in detail. However, detailed experiments on the bose polaron and the interaction between impurities and a bose gas are still elusive.

We consider a model, where we immerse a single impurity into a BEC, which is described by Bogoliubov approximation. From the master equation, we derived the impurity's momentum resolved scattering and cooling dynamics for numerical simulations. Such cooling processes should enable momentum resolved radio-frequency spectroscopy of the BEC polaron.

Q 27.25 Tue 16:30 Empore Lichthof

Effects of noncondensed particles in BEC experiments — ●CHRISTIAN UFRECHT, ALBERT ROURA, and WOLFGANG SCHLEICH — Institut für Quantenphysik, Universität Ulm, Albert-Einstein-Allee 11, 89081 Ulm

In recent years, matter-wave interferometry with Bose-Einstein condensates as a source of atomic clouds with very narrow momentum distributions has become an important experimental technique. Unfortunately, theoretical models based on the Gross-Pitaevskii equation, which is strictly valid only at $T=0$ and in the proper thermodynamic limit, do not account for thermal and quantum depletion of the condensate mode. The existence of a cloud of noncondensed particles, however, might for instance affect the contrast in interferometry experiments in a non-negligible way, particularly in dynamical situations. With the help of generalized equations which describe the coupling of condensate and noncondensed cloud, we estimate this effect in situations far from equilibrium, such as the expansion from a suddenly switched-off trap or delta-kick collimation.

Q 27.26 Tue 16:30 Empore Lichthof

Generation and Detection of Atomic Spin Entanglement in Optical Lattices — HAN-NING DAI^{1,2,3}, ●BING YANG^{1,2,3}, ANDREAS REINGRUBER^{1,4}, YU-AO CHEN^{2,3}, ZHEN-SHENG YUAN^{2,3,1}, and JIAN-WEI PAN^{2,3,1} — ¹Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany — ²Hefei National Laboratory for Physical Sciences at Microscale and Department of Modern Physics, University of Science and Technology of China, Hefei, Anhui 230026, China — ³CAS Centre for Excellence and Synergetic Innovation Centre in Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei, Anhui 230026, China — ⁴Department of Physics and Research Center OPTIMAS, University of Kaiserslautern, Erwin-Schroedinger-Strasse, Building 46, 67663 Kaiserslautern, Germany

We report on the generation, manipulation and detection of atomic spin entanglement in an optical superlattice. Spin entanglement of the two atoms in the double wells of the superlattice is generated via dynamical evolution governed by spin superexchange. By observing collisional atom loss with in-situ absorption imaging we measure

spin correlations of atoms inside the double wells and obtain the lower boundary of entanglement fidelity as 0.79 ± 0.06 , and the violation of a Bell's inequality with $S = 2.21 \pm 0.08$. The above results represent an essential step towards scalable quantum computation with ultracold atoms in optical lattices.

Q 27.27 Tue 16:30 Empore Lichthof

Many-body correlations in the spectrum of two-dimensional Bose-Hubbard models — •DARIUS HOFFMANN¹, DAVID FISCHER¹, and SANDRO WIMBERGER^{1,2,3} — ¹Institut für Theoretische Physik, Universität Heidelberg, 69120 Heidelberg, Germany — ²Dipartimento di Fisica e Scienze della Terra, Università di Parma, Via G. P. Usberti 7/a, 43124 Parma, Italy — ³INFN, Sezione di Milano Bicocca, Gruppo Collegato di Parma, Italy

We present detailed results on two-dimensional Bose Hubbard models of finite sizes. Such systems are relevant for high-fidelity experiments with ultracold quantum gases loaded into periodic lattice structures. Our analysis is based on the spectral characterization of two-dimensional lattices with a variety of bonds and different boundary conditions, representing different lattice geometries. In the limit of maximally linked lattice clusters regular motion prevails, which is understood by the applicability of mean-field methods in these cases. On the other hand, in standard lattices with less bonds, such as realized in typical experiments, quantum chaotic behavior is found for a wide range of parameters. Our analysis includes measures of spectral complexity from Random-Matrix Theory (RMT), i.e. nearest neighbor (gap) statistics and long-range spectral correlations, but also a new measure recently introduced in the context of many-body localization in isolated quantum systems. Implications for the temporal evolution of two-dimensional interacting lattices gases are discussed as well.

Q 27.28 Tue 16:30 Empore Lichthof

Beam separation schemes in an ion interferometer for the measurement of the electric Aharonov-Bohm effect — •GEORG SCHÜTZ, ALEXANDER REMBOLD, ANDREAS POOCH, HENRIKE PROCHEL, and ALEXANDER STIBOR — Institute of Physics and Center for Collective Quantum Phenomena in LISA⁺, University of Tübingen, Auf der Morgenstelle 15, 72076 Tübingen

We present the design and the current status in the construction of a biprism interferometer for hydrogen and helium ions and propose an experiment for the first proof of the type I electric Aharonov-Bohm effect. The performances of three different beam separation schemes are simulated and compared to experimental results for electrons. In our proposed scheme, the coherent ion beam is generated by a single atom tip (SAT) source and separated by either two biprisms with a quadrupole lens, two biprisms with an einzel-lens or three biprisms. The beam path separation is necessary to integrate two metal tubes that can be pulsed with different electric potentials. The high time resolution of a delay line detector allows working with a continuous ion beam and circumventing the pulsed beam operation that was originally suggested by Aharonov and Bohm. We demonstrate that the higher mass and therefore lower velocity of ions compared to electrons combined with the high expected SAT ion emission puts the direct proof of this quantum effect for the first time into reach of current technical possibilities.

Q 27.29 Tue 16:30 Empore Lichthof

Correction of multifrequency dephasing in matter-wave interferometry — •ALEXANDER REMBOLD, GEORG SCHÜTZ, ANDREAS GÜNTHER, and ALEXANDER STIBOR — Institute of Physics and Center for Collective Quantum Phenomena in LISA⁺, University of Tübingen, Auf der Morgenstelle 15, 72076 Tübingen

In various fundamental quantum mechanical experiments as well as in technical applications it is essential to achieve high contrast matter-wave interferograms. However, vibrations, electromagnetic oscillations and temperature drifts often dephase the matter wave and reduce the contrast. It complicates sensitive phase measurements such as in Aharonov-Bohm physics and decoherence studies. In opposition to decoherence, dephasing can in principle be reversed. Here we demonstrate a method for the analysis and reduction of the influence of dephasing noise and perturbations consisting of several external frequencies. Thereby, artificially perturbing oscillations are introduced in a biprism electron interferometer. The technique uses the high spatial and temporal resolution of a delay line detector to reveal and remove dephasing perturbations by second order correlation analysis. We provide a full theoretical description of the particle correlations where the significant parameters, such as the interference pattern periodicity and

the contrast can be extracted from the disturbed interferogram. The method allows matter-wave experiments under perturbing laboratory conditions in electron, atom, ion, neutron and molecule interferometers. It decreases the efforts for shielding and vibrational or temperature stabilization and has applications in sensor technology.

Q 27.30 Tue 16:30 Empore Lichthof

Quantum reflection off periodically structured surfaces — •TOBIAS NITSCHKE, BENJAMIN A. STICKLER, and KLAUS HORNBERGER — Fakultät für Physik, Universität Duisburg-Essen, Deutschland

We present a theoretical study of quantum reflection, i.e. the classically forbidden reflection of matter waves from an attractive potential [1], of polarizable point particles off periodically shaped surfaces. The Casimir-Polder interaction between the particle and the surface allows us to express the transmitted waves in terms of rotated WKB waves close to the surface. Using them as boundary conditions, we formulate the theory of quantum reflection and interference of matter waves from arbitrarily shaped, periodic surface structures. The resulting diffraction pattern is obtained by numerically solving the Schrödinger equation.

[1] H. Friedrich, J. Trost: Working with WKB waves far from the semi-classical limit, Phys. Rep. 397, 6 (2004)

Q 27.31 Tue 16:30 Empore Lichthof

Diffraction of biomolecules at nanomechanical gratings — •CHRISTIAN BRAND¹, CHRISTIAN KNOBLOCH¹, BENJAMIN STICKLER², LISA WÖRNER¹, MICHELE SCLAFANI^{1,3}, THOMAS JUFFMANN^{1,4}, YIGAL LILACH⁵, ORI CHESHNOVSKY⁴, KLAUS HORNBERGER², and MARKUS ARNDT¹ — ¹University of Vienna, Faculty of Physics, Vienna, Austria — ²University of Duisburg-Essen, Faculty of Physics, Duisburg, Germany — ³ICFO - Institut de Ciències Fotòniques, Castelldefels (Barcelona), Spain — ⁴The Center for Nanosciences and Nanotechnology & School of Chemistry, Tel-Aviv University, Tel Aviv, Israel — ⁵Stanford University, Physics Department, Stanford, USA

The high complexity of molecular matter-waves makes them very sensitive to external perturbations originating, for instance, from electric fields or single photons. These can be exploited to study internal properties of the molecules and differentiate between constitutional isomers [1,2]. When material gratings are employed as diffracting elements in these kinds of experiment, it is crucial to characterize the interaction between the matter-wave and the beamsplitter very precisely. Here, we study the diffraction of the biomolecule hypericin at nanomechanical gratings. The observed partial decoherence of the matter-wave is explained by the phase-averaging due to the interaction between the permanent dipole moment and charges in the grating. This sets constraints to matter-wave experiments with biomolecules.

[1] Eibenberger et al. Phys. Rev. Lett. 112, 250402 (2014)

[2] Tüxen et al. Chem. Comm. 46, 4145 (2010)

Q 27.32 Tue 16:30 Empore Lichthof

Time-domain interferometry with nanoparticles — •NADINE DÖRRE, JONAS RODEWALD, PHILIPP GEYER, PHILIPP HASLINGER, and MARKUS ARNDT — Universität Wien, VCQ, Wien, Austria

We present an optical matter-wave interferometer for clusters and complex molecules that uses absorptive light gratings in combination with Talbot-Lau interferometry in the time domain. In this setup, neutral particles pass alongside a mirror that reflects three equally timed UV lasers pulses. The resulting standing light waves act as absorptive structures by removing particles from the antinodes upon absorption of a single photon. In contrast to material absorptive masks, such gratings allow to be operated in a pulsed mode, which makes the longitudinal motion of the particles negligible and thus brings gain in visibility and measurement precision.

We discuss two depletion mechanisms in the laser gratings. Ionization occurs for particles with ionization energies lower than the photon energy and fragmentation dominates when two photons would be necessary for ionization of van der Waals clusters. We show interference with clusters of various organic molecules with masses up to 3000 u that also serve as a motivation to explore cluster properties with time domain metrology. The experiment is widely applicable in the sense that it allows working with a large class of nanoparticles. It may act on atoms, molecules but also giant clusters. We may, thus, set new experimental bounds on collapse models that suggest a fundamental breakdown of quantum theory once a certain complexity scale is reached.

Q 27.33 Tue 16:30 Empore Lichthof

Aberrations of atomic beam splitters — ●ANTJE SCHREIBER and REINHOLD WALSER — Institut für Angewandte Physik TU-Darmstadt, Darmstadt, Germany

Atom interferometry provides the opportunity of high-precision measurements of rotation and acceleration. Therefore atoms are the ultimate sensors for inertial navigation, geological exploration and fundamental physics. In the QUANTUS free-fall experiments atom interferometry is the central method as well [1].

Like in optical systems all matter wave devices like traps, beam splitters and mirrors exhibit imperfections. For that reason it is necessary to quantify the amount of aberrations that are caused by real devices.

In this contribution we focus on atomic beam splitters in three dimensions, using a quantum Monte Carlo simulation [2, 3]. We characterize non-ideal behaviour due to the spatial variations of the laser beam profiles, wave front curvatures and spontaneous emission. In particular we will study the response of a beam splitter due to velocity dispersion.

The theoretical concepts as well as first simulation results are shown on our poster.

References:

- [1] H. Müntinga et al., Phys. Rev. Lett. **110**, 093602 (2013)
- [2] R. Dum et al., Phys. Rev. A **45**, 4879 (1992)
- [3] K. Mølmer et al., J. Opt. Soc. Am. B **10**, 524 (1993)

Q 27.34 Tue 16:30 Empore Lichthof

Matter wave optics with Bose-Einstein condensates — ●JAN TESKE and REINHOLD WALSER — Institut für Angewandte Physik, Technische Universität Darmstadt, Hochschulstraße 4A, Darmstadt D-64289, Germany

Freely expanding Bose-Einstein condensates in weightlessness is the central research topic of the QUANTUS experiments. These experiments are performed at the drop tower in Bremen (ZARM). Ultra cold atoms can be used as precise quantum sensors for acceleration and rotations. Expansion times of many seconds can be reached and lead to macroscopic systems sizes [1,2]. In the present contribution we perform realistic simulation in time and three spatial dimensions of the Gross-Pitaevskii equation. In particular we study long time expansion as well as delta kick cooling with realistic magnetic chip trap potentials. We will study the effect of self interaction as well as aberration caused by anharmonic chip trap potentials.

- [1] van Zoest et al. Bose-Einstein condensation in Microgravity. *Science*, **328**, 1540 (2010).
- [2] G. Nandi, R. Walser, E. Kajari, and W. P. Schleich. Dropping cold quantum gases on earth over long times and large distances. *Phys. Rev. A*, **76**, 063617 (2007).

Q 27.35 Tue 16:30 Empore Lichthof

QUANTUS-2 - towards a dual species matter wave interferometer in free fall — ●CHRISTOPH GRZESCHIK¹, MARKUS KRUTZIK¹, ACHIM PETERS^{1,2}, and THE QUANTUS TEAM^{1,2,3,4,5,6,7} — ¹Institut für Physik, Humboldt-Universität zu Berlin — ²Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik, Berlin — ³Institut für Quantenoptik, Leibniz Universität Hannover — ⁴ZARM, Universität Bremen — ⁵Institut für Physik, Johannes Gutenberg Universität Mainz — ⁶Institut für Quantenphysik, Universität Ulm — ⁷Institut für angewandte Physik, TU Darmstadt

QUANTUS-2 is a mobile high-flux Rb-87 BEC source used for experiments in microgravity in the Bremen drop tower. To further decrease the residual expansion rate of the BEC, magnetic lensing - also known as delta-kick cooling - is crucial for observations after long evolution times in the range of seconds. Here we present our results of a lens, which leads to an observability of the BEC of up to 2.7 s after free expansion, only limited by the microgravity-duration in the drop tower. Anharmonicities of the magnetic lensing potential can introduce distortions of the BEC's shape. We discuss the necessary steps towards harmonic lensing and report our results. This will - in the future - allow us to demonstrate atom interferometry with unprecedented sensitivity on time scales on the order of seconds.

The QUANTUS project is supported by the German Space Agency DLR with funds provided by the Federal Ministry for Economic Affairs and Energy (BMWi) under grant number DLR 50WM1553.

Q 27.36 Tue 16:30 Empore Lichthof

Functional Truncated Wigner Method and Beyond: Theory

for Many-Body Scattering of Interacting Bosons Through Mesoscopic Cavities — ●JOSEF MICHL, FABIAN STÖGER, JUAN-DIEGO URBINA, and KLAUS RICHTER — Institut für Theoretische Physik, Universität Regensburg, 93040 Regensburg, Germany

We report our progress in constructing a theory for mesoscopic scattering of identical particles through open chaotic cavities suitable for studying the interplay between three physical effects: universality of single-particle transport, many-body correlations due to quantum indistinguishability, and the presence of interparticle interactions.

Already at the level of non-interacting particles, indistinguishability alone produces non-trivial combinations of single-particle scattering matrices in the transport of many particles through mesoscopic chaotic cavities[1], which result in a mesoscopic version of the Hong-Ou-Mandel effect known from quantum optics[2]. Going beyond non-interacting systems, the study of interaction effects requires a proper choice of the underlying single-particle basis for the Fock space. We show, that in the basis of single-particle scattering states, the many-body Hamiltonian takes a universal form for open chaotic cavities, which is ready to be used in the non-perturbative framework of a functional truncated Wigner approximation. We present analytical and numerical results for this method, as well as how to go beyond the truncated Wigner approximation.

- [1] J. D. Urbina et al., arXiv:1409.1558v1
- [2] Hong, C. K., Ou, Z. Y., Mandel, L., PRL **18**, 2044 (1987)

Q 27.37 Tue 16:30 Empore Lichthof

The role of initial conditions in measurements with open atom interferometers — ●WOLFGANG ZELLER¹, ALBERT ROURA¹, WOLFGANG P. SCHLEICH¹, and THE QUANTUS TEAM^{1,2,3,4,5,6,7,8} — ¹Institut für Quantenphysik, Universität Ulm — ²Institut für Quantenoptik, LU Hannover — ³ZARM, Universität Bremen — ⁴Institut für Physik, HU Berlin — ⁵Institut für Physik, JGU Mainz — ⁶Institut für angewandte Physik, TU Darmstadt — ⁷MUARC, University of Birmingham, UK — ⁸Lab. Kastler Brossel, E. N. S., France

In the last 25 years light-pulse atom interferometers have opened a new route to high-precision measurements of fundamental constants, inertial sensing and gravimetry. In particular, differential measurements with two species can test the universality of free fall (UFF) with quantum objects and offer a valuable complement to classical tests. In the presence of gravity gradients or rotations the interference signal depends on the central position and momentum of the initial atomic wave packet. In UFF tests, this can mimic a violation and is known as the co-location problem. In our contribution, we exploit the formalism developed in [1,2] to cast light on such a dependence on the initial conditions from the point of view of open interferometers. This insight helps to find suitable strategies to significantly relax the co-location problem.

The QUANTUS project is supported by the German Space Agency DLR with funds provided by the Federal Ministry of Economics and Energy (BMWi) under grant number 50WM1556.

- [1] Roura, Zeller and Schleich, New J. Phys. **16**, 123012 (2014).
- [2] Zeller, Roura and Schleich, in preparation.

Q 27.38 Tue 16:30 Empore Lichthof

Sub-Shot-Noise Regime in Light-Pulse Atom Interferometry — ●STEPHAN KLEINERT, WOLFGANG P. SCHLEICH, and THE QUANTUS TEAM — Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQST), Universität Ulm

Entanglement as a key feature of quantum mechanics is an useful resource in quantum information as well as in quantum metrology. In particular, entanglement in high-precision measurements is used to enhance the phase sensitivity of interferometer devices. The implementation of quantum correlated atoms for instance opens the possibility of beating the (classical) standard quantum limit.

The representation-free description of light-pulse atom interferometry [1] provides a general theoretical framework for arbitrary interferometer geometries in the presence of external potentials and non-inertial forces. Here, we generalize this representation-free approach in order to describe efficiently many-particle entanglement in light-pulse atom interferometers and thus operate beyond the shot-noise limit.

The QUANTUS project is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry of Economics and Energy (BMWi) under grant number 50WM1556.

- [1] S. Kleinert, et al., Representation-free description of light-pulse

atom interferometry including non-inertial effects, Physics Reports (2015).

Q 27.39 Tue 16:30 Empore Lichthof

Atom interferometry with ultracold thermal clouds and realistic laser pulses — ●JENS JENEWEIN, ALBERT ROURA, WOLFGANG P. SCHLEICH, and THE QUANTUS TEAM — Institut für Quantenphysik, Universität Ulm

Our work concerns a real-time simulation of atom interferometry with symmetric and asymmetric pulse separations using a Mach-Zehnder scheme. Short times are useful for modelling experiments performed on ground and long times for extrapolating those results to experiments in microgravity. We use realistic, non-idealized pulses that induce Bragg diffraction leading to discrete momentum jumps. Velocity selectivity effects and excitations of off-resonant diffraction orders are also taken into account. This approach is employed to investigate the expected sensitivity in interferometry measurements, which is proportional to the contrast C and the square root of the atom number N . Techniques such as evaporative cooling lead to an increase of C but lower N . One can try to enhance the sensitivity by stopping the evaporative cooling before reaching quantum degeneracy to have a higher atom number. Delta-Kick-Collimation techniques are then necessary to mitigate the increase in momentum width and the associated loss of contrast due to velocity selectivity effects. Our goal is to determine the highest sensitivity achievable taking into account these competing effects.

The QUANTUS project is supported by the German Space Agency DLR with funds provided by the Federal Ministry of Economics and Energy (BMWi) under grant number 50WM1556.

Q 27.40 Tue 16:30 Empore Lichthof

Shaping of Electron Beams with Laser Fields — ●MORITZ CARMESIN¹, MAXIM A. EFREMOV¹, and WOLFGANG P. SCHLEICH^{1,2} — ¹Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQST), Universität Ulm, Albert-Einstein-Allee 11, 89081 Ulm, Germany — ²Texas A & M University Institute for Advanced Study (TIAS), Institute for Quantum Science and Engineering (IQSE), and Department of Physics and Astronomy, Texas A & M University, College Station, Texas 77843-4242, USA

Applications such as electron microscopy or the free-electron laser require electron beams with a narrow distribution of the kinetic energy. In order to control the width of this distribution, we suggest to scatter electrons off two counterpropagating light waves, that is we utilize induced Compton scattering. Within a description based on classical mechanics we have found the optimal parameters such as the profile and amplitude of the laser field envelope, that minimize the variance of the energy distribution.

This work is supported by the German-Israeli Cooperation (DIP). W.P.S. is grateful to Texas A&M University for a Texas A&M University Institute for Advanced Study (TIAS) Faculty Fellowship.

Q 27.41 Tue 16:30 Empore Lichthof

Coherence measurements of electrons from a field-emission tip triggered by few femtosecond laser pulses — ●STEFAN MEIER, PHILIPP WEBER, TAKUYA HIGUCHI, and PETER HOMMELHOFF — Department Physik, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Staudtstrasse 1, 91058 Erlangen

Field-emission tips represent excellent electron sources with regard to spatial coherence properties, which limits the spatial resolution of microscopic and diffraction experiments. Triggering the electron emission from such tips by laser pulses provides additional temporal resolution to these techniques. Recently, with the help of electron interference fringes obtained with a carbon nanotube as an electrostatic biprism, electrons emitted via single-photon absorption of continuous-wave and rather long laser pulses (duration ~ 21 ps) were shown to exhibit a similarly small effective source radius (0.80 ± 0.05 nm) as that of dc-field emitted electrons (0.55 ± 0.02 nm) [1]. The degree of global coherence of 36% is among the highest ever observed [2]. In this presentation, we will discuss if such supreme spatial coherence is maintained in non-linear photoemission, triggered by few-cycle near-infrared laser pulses, which is a key to further confine the electron wave packet in time [2]. The current status of the experiment will be reported.

[1] D. Ehberger et al., Phys. Rev. Lett. **114**, 227601 (2015).

[2] M. Krüger et al., Nature **475**, 78 (2011).

Q 27.42 Tue 16:30 Empore Lichthof

Atom-chip gravimetry with Bose-Einstein condensates — ●MARTINA GEBBE¹, SVEN ABEND², MATTHIAS GERSEMANN², HAUKE MÜNTINGA¹, HOLGER AHLERS², ERNST M. RASEL², CLAUD LÄMMERZAHL¹, and THE QUANTUS TEAM^{1,2,3,4,5,6,7} — ¹ZARM, Uni Bremen — ²Institut für Quantenoptik, LU Hannover — ³Institut für Physik, HU Berlin — ⁴Institut für Laser-Physik, Uni Hamburg — ⁵Institut für Quantenoptik, Uni Ulm — ⁶Institut für angewandte Physik, TU Darmstadt — ⁷Institut für Physik, JGU Mainz

Due to their small spatial and momentum width ultracold Bose-Einstein condensates (BEC) or even delta-kick cooled (DKC) atomic ensembles are very well suited for high precision atom interferometry. We generate such an ensemble in a miniaturized atom-chip setup and apply Bragg beam splitting to perform different types of inertial sensitive measurements. Using the chip as a retroreflector we have realized a compact gravimeter and determined local g with an accuracy of $5 \cdot 10^{-5}g$ limited by vibrational noise. We demonstrate that the sensitivity can be enhanced with the help of an optical lattice to re-launch the atoms and large momentum transfer beam splitters. Additionally, we introduce a symmetric Double-Bragg diffraction technique that offers interesting features. We exploit this to access the horizontal axis and demonstrate geometries that are also sensitive to rotations and gravity gradients. This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry for Economic Affairs and Energy (BMWi) due to an enactment of the German Bundestag under grant numbers DLR 50WM1552-1557 (QUANTUS-IV-Fallturm).

Q 27.43 Tue 16:30 Empore Lichthof

Mobile quantum gravity sensor with unprecedented stability — ●BASTIAN LEYKAUF, CHRISTIAN FREIER, VLADIMIR SCHKOLNIK, MATTHIAS HAUTH, MARKUS KRUTZIK, and ACHIM PETERS — Institut für Physik, Humboldt-Universität zu Berlin, Germany

The gravimetric atom interferometer GAIN is based on interfering ensembles of laser-cooled ⁸⁷Rb atoms in a fountain setup, using stimulated Raman transitions. Its transportable design allows to measure local gravity at sites of geodetic and geophysical interest.

We compared the performance of our instrument with falling corner-cube and superconducting gravimeters in two measurement campaigns in Germany and Sweden and demonstrated continuous absolute gravity measurements over several days with a stability of 0.5 nm/s^2 , the best reported value for absolute gravimeters to date [1]. Due to effective control over systematic effects, including wavefront distortions of the Raman beams [2], the measured gravity value's accuracy can be specified at 38 nm/s^2 .

We will discuss the experimental apparatus, the latest measurements and future improvements, including our progress towards a gradiometer based on a juggling atom fountain.

[1] Freier et al. *Mobile quantum gravity sensor with unprecedented stability*, submitted.

[2] Schkolnik et al. *The effect of wavefront aberrations in atom interferometry*, Applied Physics B (2015).

Q 27.44 Tue 16:30 Empore Lichthof

Laser system for dual-species atom interferometry with K and Rb in space — ●KLAUS DOERINGSHOFF¹, VLADIMIR SCHKOLNIK¹, MARKUS KRUTZIK¹, ACHIM PETERS¹, and THE MAIUS TEAM^{1,2,3,4,5} — ¹Institut für Physik, Humboldt-Universität zu Berlin — ²Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik, Berlin — ³ZARM, Zentrum für Angewandte Raumfahrttechnologie und Mikrogravitation, Bremen — ⁴Institut für Physik, JGU Mainz — ⁵IQO, Leibniz Universität Hannover

Future application of precision atom interferometry in space missions dedicated to Earth observation or fundamental physics, such as testing Einstein's equivalence principle (EEP), requires robust and compact laser systems.

We present the overall architecture of a laser system at 780 nm and 767 nm for dual species atom interferometry with BECs of Rb and K on a sounding rocket. The system is designed for laser cooling of both species and simultaneous Raman- or Bragg double-diffraction interferometry. It further features a dipole trap laser at 1064 nm for mixing of the species and optical delta-kick-cooling of the matter-wave packets.

We report on technological details such micro-integrated diode lasers and advanced Zerodur optical bench technology, as well as environmental testing and system parameters relevant for dual species atom interferometry.

This work is supported by the German Space Agency DLR with

funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant number DLR 50 WP 1432.

Q 27.45 Tue 16:30 Empore Lichthof

Microwave system for Atom Manipulation on a Sounding Rocket — ●HOSSEIN ABEDI, HOSSEIN FAZELI KHALILI, THIJS WENDRICH, WOLFGANG ERTMER, and ERNST RASEL — Institut für Quantenoptik, Leibniz Universität Hannover

A space-bound quantum test of the universality of free fall based on interferometry with mixtures of ultra-cold quantum Rb/K gases is proposed within ESA's Cosmic Vision program. The sounding-rocket experiment MAIUS of the DLR gives us the opportunity to demonstrate methods necessary for performing interferometry in extended free fall. The experiments will use Double-Raman-scattering between the hyperfine ground states for forming the interferometer. State preparation in the states with lowest magnetic susceptibility, $|F=1,2 m_F=0\rangle$, is achieved by a microwave adiabatic rapid passage starting from the trapped BEC and hence requires for ^{87}Rb a magnetic microwave field at 6.8 GHz. It is however a challenge to combine all the requirements of vacuum, optical access, DC, RF and microwave magnetic fields in a compact atom-chip design.

This poster presents a microwave system that satisfies the requirements of the experiment. It shows how an electromagnetic field with the required frequency can be generated and explains the transmission system.

The QUANTUS/MAIUS project is supported by the German Space Agency DLR with funds provided by the Federal Ministry for Economic Affairs and Energy (BMWi) under grant number 50WM1431.

Q 27.46 Tue 16:30 Empore Lichthof

MAIUS-II/III: Towards dual species atom interferometry with Bose-Einstein condensates in space — ●BAPTIST PIEST¹, MAIKE LACHMANN¹, DENNIS BECKER¹, MERLE CORNELIUS¹, MICHAEL ELSEN², and ERNST RASEL¹ — ¹Institut für Quantenoptik, Leibniz Universität Hannover — ²ZARM, Universität Bremen

One of the underlying principles of general relativity is the Einstein equivalence principle. It can directly be probed by measuring the free fall acceleration of any two test objects with different internal composition and masses. Precise quantum measurements can be achieved by simultaneous atom interferometry of a mixed species Bose-Einstein condensate (BEC). To increase the precision of such an experiment the enclosed space-time path of the interferometry sequence has to be maximized which demands a weightless environment. Within the QUANTUS-experiments, we already demonstrated the creation of BECs in microgravity[1] and the realisation of a BEC based atom interferometer in microgravity[2]. Primary goals of the sounding rocket mission MAIUS-II are the first sequential creation of BECs consisting of Rb-87 and K-41 in space and the realisation of a double-diffraction type atom interferometer. In MAIUS-III this shall be extended to the simultaneous creation of the dual species BEC. One of the next steps towards the mission will be the commissioning of the experimental chamber on ground with a dedicated laser system to demonstrate its capability to create and observe BECs of Rb-87 and K-41.

[1] T. van Zoest et al., *Science* **328**, 1540 (2010).

[2] H. Müntinga et al., *Phys. Rev. Lett.* **110**, 093602 (2013).

Q 27.47 Tue 16:30 Empore Lichthof

Quantum Test of the Universality of Free Fall — ●DIPANKAR NATH, HENNING ALBERS, CHRISTIAN MEINERS, LOGAN L. RICHARDSON, DENNIS SCHLIPIPERT, CHRISTIAN SCHUBERT, ETIENNE WODEY, WOLFGANG ERTMER, and ERNST M. RASEL — Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover

The Universality of Free Fall (UFF) is one of the constituents of the Einstein's Equivalence Principle. Most modifications to quantum field theory to include gravity predict a violation of UFF. Tests of UFF have been carried out using macroscopic objects to verify the theory of general relativity with no violations observed so far [1]. A quantum test of the UFF is possible using atom interferometers. Test of the UFF at a 100 ppb uncertainty using two different atomic species, ^{39}K and ^{87}Rb has already been carried out [2]. We propose a test at ppb level uncertainty by correlating an atom interferometer with a seismometer along with the implementation of a common optical dipole trap to reduce systematic uncertainty. Test of the UFF up to a level of 1 part in 10^{13} is also under development. Attaining such small uncertainty will require the implementation of atom interferometry with long free fall times of the order of seconds. This entails the usage of very long base-

lines [3] along with the usage of alkaline-earth like species Ytterbium and novel experimental techniques.

[1] S. Schlamminger et al., *Phys. Rev. Lett.* **100**, 041101 (2008)

[2] D. Schlippert et al., *Phys. Rev. Lett.* **112**, 203002 (2014)

[3] J. Hartwig et al., *New J. Phys.* **17**, 035011 (2015)

Q 27.48 Tue 16:30 Empore Lichthof

Setting up a transportable absolute quantum gravimeter — ●NINA GROVE, MARAL SAHELGOZIN, JONAS MATTHIAS, MATTHIAS GERSEMANN, SVEN ABEND, WALDEMAR HERR, WOLFGANG ERTMER, and ERNST M. RASEL — Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover

We report on the recent development of the Quantum Gravimeter QG-1; presenting the setup of the double MOT system consisting of a 2D^+ -MOT and a 3D mirror MOT. State of the art gravimeters based on laser cooled atoms are limited in accuracy due to the expansion of the thermal ensemble during the interrogation time of the interferometer. In order to minimize such uncertainties, the Quantum Gravimeter QG-1 is designed to use ultra-cold ^{87}Rb -atom samples generated by an atom-chip source. Aiming for high precision the following parameters should be achieved: (i) 1 Hz repetition rate (ii) drift-free longterm measurements with a bandwidth at mHz-level (iii) accurate measurement of local gravity below the μGal -level (10^{-8} ms^{-2}).

This work is a collaboration with the Institut für Erdmessung (IfE) and supported by the Deutsche Forschungsgemeinschaft (DFG) in the scope of the SFB 1128 geo-Q.

Q 27.49 Tue 16:30 Empore Lichthof

Preparations for the LISA three-backlink experiment — ●LEA BISCHOF¹, KATHARINA-SOPHIE ISLEIF¹, OLIVER GERBERDING¹, SONJA VEITH¹, MICHAEL TRÖBS^{1,2}, KARSTEN DANZMANN^{1,2}, and GERHARD HEINZEL^{1,2} — ¹Institut für Gravitationsphysik, Leibniz Universität Hannover, 30167 Hannover — ²Max-Planck Institut für Gravitationsphysik (Albert Einstein Institut), 30167 Hannover

The Laser Interferometer Space Antenna (LISA) is a planned space-based, low-frequency gravitational wave detector with arm-lengths of several million kilometres and a displacement sensitivity in the order of $10 \text{ pm}/\sqrt{\text{Hz}}$. To suppress laser frequency noise in this detector two or more arms have to be compared to synthesize a quasi Michelson interferometer. This is non-trivial due to an orbit induced breathing of the angle between the arms, which requires an adaptable link (so-called backlink) between two optical benches in one satellite. Previous experiments at the AEI in Hannover have shown that a reciprocal fiber-based backlink is not an optimal solution, due to Rayleigh scattering induced noise. A new experiment is currently being set-up at the AEI in Hannover to compare this method with a free beam and a frequency-offset fiber-based implementation.

We will give an overview of this experiment and describe the required laser preparation set-up. Especially, we will show the current performance of our laser locking scheme that uses digitally controlled offset-frequency locks to stabilize four lasers to well defined relative frequencies and low laser frequency noise. This scheme is the basis for the heterodyne readout that we will use in the three backlink experiment.

Q 27.50 Tue 16:30 Empore Lichthof

Ion Coulomb crystals in scalable ion traps for precision spectroscopy — ●JAN KIETHE, DIMITRI KALINCEV, JONAS KELLER, TOBIAS BURGERMEISTER, and TANJA E. MEHLSTÄUBLER — Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

We report on progress towards a multi-ion clock based on In^+/Yb^+ ion Coulomb crystals, stored in a segmented linear Paul trap. In our currently operational prototype trap we characterized systematic shifts due to micromotion^[1] and excess heating rates at the level of fractional frequency shifts of 10^{-19} and below. A heating rate of 1.4 phonons per second at 500 kHz was observed.

A next generation ion trap based on aluminum nitride ceramics, was tested at the CMI in Prague. The warming of the trap was measured to be 2 K at operational conditions, in agreement with simulations^[2].

The well-controlled Coulomb crystals in our setup are also used to study many-body physics of strongly interacting systems. In particular, we investigate the dynamics of solitons in two-dimensional ion Coulomb crystals.

[1] Keller et al., *J. Appl. Phys.* **118**, 104501 (2015)

[2] Dolezal et al., *Metrologia* **52**, 842 (2015)

Q 27.51 Tue 16:30 Empore Lichthof

Progress Towards an Al^+ Quantum Logic Optical Clock —

•JOHANNES KRAMER¹, NILS SCHARNHORST¹, STEPHAN HANNIG¹, IAN D. LEROUX¹, and PIET O. SCHMIDT^{1,2} — ¹Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany — ²Leibniz Universität Hannover, 30167 Hannover, Germany

We present the status of our aluminum ion optical clock, based on a single ²⁷Al⁺ clock ion confined in a linear Paul Trap together with a ⁴⁰Ca⁺ logic ion. The latter is used for sympathetic cooling and internal state detection of the clock ion via the Coulomb interaction. ²⁷Al⁺ provides a narrow (8 mHz) clock transition at 267 nm which exhibits negligible electric quadrupole shift and an exceptionally low sensitivity to black-body radiation. A measurement of the trap temperature combined with numerical simulations allows us to bound the black-body radiation shift to $< 10^{-19}$ [1]. We use EIT cooling for fast ground-state cooling and we stabilize all relevant lasers via a so-called transfer-lock scheme [2] which transfers the short-term stability of a stable master laser to slave lasers of different wavelengths via a compact, reliable fiber frequency comb. We will present a characterization of time dilation shifts from residual secular and micromotion of the Al⁺ ion.

[1] M. Doležal *et al.*, arXiv: 1510.05556 (2015).

[2] N. Scharnhorst *et al.*, Opt. Express **23**, 19771–19776 (2015).

Q 27.52 Tue 16:30 Empore Lichthof

A monolithic doubling cavity for the clock laser of a transportable Al⁺ clock — •STEPHAN HANNIG¹, NILS SCHARNHORST¹, JOHANNES KRAMER¹, IAN D. LEROUX¹ und PIET O. SCHMIDT^{1,2} — ¹Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany — ²Leibniz Universität Hannover, 30167 Hannover, Germany

We present the status of our second generation aluminum ion optical clock using quantum logic techniques for cooling and reading out the ²⁷Al⁺ clock ion via a ⁴⁰Ca⁺ logic ion.

We have set up a vacuum chamber including a segmented multi-layer linear Paul trap. The system is intended to not only act as a reference for the first Al⁺/Ca⁺ system developed in our laboratory, but also paves the way towards experimental investigation of novel interrogation schemes of more than one clock ion.

To drive the clock transition at 267.4 nm, light from a fiber laser is frequency doubled twice. While the first doubling takes place in a commercially available waveguide, we built a mechanically monolithic bow tie cavity for the second step. Here, we present the design focussed on low sensitivity on mechanical and acoustic disturbances. Since the clock is planned to be portable, high stability and reproducibility of the alignment were additional design goals.

Q 27.53 Tue 16:30 Empore Lichthof

A transportable optical lattice clock — •JACOPO GROTTI, SILVIO KOLLER, STEFAN VOGT, SEBASTIAN HÄFNER, SOFIA HERBERS, UWE STERR, and CHRISTIAN LISDAT — Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

The excellent performance of optical clocks offers new prospects for applications as well as fundamental research. Applications include the operation of optical clocks for time keeping and relativistic geodesy.

We are now working on a new apparatus for an optical lattice clock with strontium atoms, which is designed to be transportable. This kind of clocks, that can be operated outside the laboratory, can be used for direct frequency comparison between distant experiments and local measurements of the geo-potential (relativistic geodesy). The portable apparatus allows to resolve the clock transition with few Hertz linewidth. The evaluation of the uncertainty budget is ongoing. In February 2016 a first geodesy experiment is planned.

This work is supported by QUEST, DFG (RTG 1729, CRC 1128), EU-FP7 (SOC2, FACT) and EMRP (ITOC, QESOCAS). The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

Q 27.54 Tue 16:30 Empore Lichthof

Design of a Transportable Cavity Using Mirrors with Single-Crystalline Coatings. — •SOFIA HERBERS, SEBASTIAN HÄFNER, UWE STERR, and CHRISTIAN LISDAT — Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig

Ultra-stable high-finesse cavities are key components of laser systems used in optical clocks, which are applicable in relativistic geodesy or space-time research. However, many applications require a transportable system that cannot rely on a well-controlled laboratory environment. Present transportable cavities exhibit mainly two limiting factors: One is Brownian noise especially in the mirror substrates and

coatings, the other is vibration sensitivity due to the mounting. The transportability of the cavity confines the length since longer spacers cause higher vibration sensitivity. Hence, the influence of the thermal noise due to the mirrors cannot be reduced by very long resonators.

Here, we present a design of a reference cavity for a transportable strontium lattice clock using single-crystalline coated mirrors to reduce Brownian noise and a special mounting system to minimize the vibration sensitivity of the cavity. Finite element simulations predict a frequency noise floor of 1×10^{-16} . Furthermore, measurements using a provisionally spacer with the single-crystalline coated mirrors result in a finesse of about 130000.

This work is supported by QUEST, DFG (RTG 1729, CRC 1128), and the European Metrology Research Programme (EMRP) in ITOC, and QESOCAS. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

Q 27.55 Tue 16:30 Empore Lichthof

A cryogenic lattice clock at PTB — •ALI AL-MASOUDI, SÖREN DÖRSCHER, SEBASTIAN HÄFNER, UWE STERR, and CHRISTIAN LISDAT — Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

Optical clocks have been pushing the frontier of frequency metrology and hold strong promise for a broad range of applications, e.g., in fundamental physics and geosciences. Lattice clocks are particularly well suited for delivering on this promise, since they intrinsically exhibit the highest stabilities and thus support high-precision investigations of time-dependent effects that require short averaging times. The total systematic uncertainties of the best strontium lattice clocks have been limited by uncertainty of the black-body radiation (BBR) field and the resulting Stark shift for some time. However, different approaches for overcoming this limitation have recently been demonstrated in several groups, achieving fractional uncertainties in the low 10^{-18} regime and moving lattice clocks to the forefront in accuracy. Here, we report on the realisation of a cryogenic lattice clock at PTB. By interrogating the atoms in a uniform environment at cryogenic temperatures we achieve BBR-induced shift uncertainties of about 1×10^{-18} . This enables a total systematic uncertainty below 1×10^{-17} , which we are going to exploit in future clock comparisons.

This work is supported by QUEST, the DFG within CRC 1128 (geo-Q) and RTG 1729, and the EMRP within ITOC and QESOCAS. The EMRP is jointly funded by the EMRP-participating countries within EURAMET and the European Union.

Q 27.56 Tue 16:30 Empore Lichthof

Optical resonators with ultra-high frequency stability using AlGaAs coatings — •SANA AMAIRI PYKA, MORITZ NAGEL, KLAUS DÖRINGSHOFF, SYLVIA SCHIKORA, EVGENY V. KOVALCHUK, and ACHIM PETERS — Humboldt-Universität zu Berlin, Institut für Physik, AG Optische Metrologie, Newtonstraße 15, 12489 Berlin

We present the study of the thermal noise limited performance of two orthogonal cavities implemented in a single block of fused silica. The fused silica mirror substrates of both cavities are coated with high-reflectivity monocrystalline AlGaAs coating. The common mode suppression of systematic effects in this system allows us the study of the thermal noise limit in both cavities via the comparison of two stabilized laser frequencies. The presentation will include details on the AlGaAs coating finesse, optical performance and frequency stability results. The AlGaAs mirror coating present an alternative for lower thermal noise limit in cavity stabilized sub-Hertz linewidth lasers as well as in the field of gravitational wave detection.

Q 27.57 Tue 16:30 Empore Lichthof

Optical spectroscopy of Bloch bands in optical lattice — •NANDAN JHA, STEFFEN RÜHMANN, DOMINIKA FIM, KLAUS ZIPFEL, STEFFEN SAUER, WALDEMAR FRIESEN, FELIX KEGLER, ANDRÉ KULOSA, WOLFGANG ERTMER, and ERNST RASEL — Institut für Quantenoptik, Leibniz Universität Hannover, Deutschland

We report on our spectroscopy measurement of the spin forbidden ¹S₀ → ³P₀ clock transition in laser cooled ²⁴Mg in a shallow optical lattice. The narrow clock transition allows a measurement of the effect of Bloch band curvature in optical spectroscopy. This provides a magnified view of the possible frequency shift and broadening due to Bloch band curvature that may affect state of the art optical clocks. It has been previously shown that in the regime where the Rabi frequency is smaller than the energy width of the lowest Bloch band in the optical lattice, a modified lineshape with two shifted maxima is observed in the clock transition [1]. We perform sideband resolved

measurements in the similar regime for 1000 ^{24}Mg atoms, trapped at 4 μK temperature in a shallow optical lattice of trap depths as low as 6 recoil energies. The optical lattice wavelength is varied in the vicinity of the $^1S_0 \rightarrow ^3P_0$ transition magic wavelength. We observe a dependence of the carrier lineshape on the lattice wavelength, and we demonstrate its application in measuring the magic wavelength.

[1] P. Lemonde and P. Wolf, Phys. Rev. A 72, 033409 (2005).

Q 27.58 Tue 16:30 Empore Lichthof

Towards an optical lattice clock with bosonic ^{24}Mg — ●STEFFEN SAUER, STEFFEN RÜHMANN, DOMINKA FIM, KLAUS ZIPFEL, NANDAN JHA, WALDEMAR FRIESEN, FELIX KEGLER, ANDRÉ KULOSA, WOLFGANG ERTMER, and ERNST RASEL — Institut für Quantenoptik, Leibniz Universität Hannover, Deutschland

We report on the progress towards a frequency measurement of ^{24}Mg $^1S_0 \rightarrow ^3P_0$ clock transition in a deeper optical lattice, with a linewidth in the range of tens of Hz, which depends on the trap depth of the optical lattice potential. We have also implemented a new normalization scheme, leading to a better signal to noise ratio. Therefore we are able to measure the magic wavelength of the optical lattice, the clock transition frequency and the 2nd order Zeeman shift with a higher accuracy.

Since a Sub-Doppler cooling scheme is not available for Mg, we prepare the atoms in an elongated optical dipole trap using a continuous loading scheme [1]. Atoms are subsequently transferred to the 1D optical lattice, leading to a dilute cloud of 1000 atoms distributed over 130,000 lattice sites [2], reducing the atomic collisions which is an advantage for bosonic lattice clocks. Line broadening due to atomic tunneling between lattice sites is currently limiting the precision of our frequency measurement. Therefore, going forward, the new spectroscopy setup with deeper optical lattice should allow us to study the systematic effects e.g. tunneling effect, collisional shifts, blackbody radiation shift, Zeeman shift and ac Stark shift.

[1] M. Riedmann et al., Physical Review A, 043416 (2012).

[2] A. Kulosa et al., accepted for PRL, arXiv:1508.01118 (2015).

Q 27.59 Tue 16:30 Empore Lichthof

Compact laser system for manipulating $^9\text{Be}^+$ ions at a high magnetic field — ●ALEXANDER IDEL¹, SEBASTIAN GRONDKOWSKI¹, MALTE NIEMANN¹, TERESA MEINERS¹, STEFAN ULMER³, and CHRISTIAN OSPELKAUS^{1,2} — ¹Leibniz Universität Hannover, Institut für Quantenoptik, Hannover — ²Physikalisch-Technische Bundesanstalt, Braunschweig — ³Ulmer Initiative Research Unit, RIKEN

In this project, we are developing quantum logic spectroscopy techniques for single (anti-)protons with the ultimate goal of supporting a g-factor based test of CPT invariance [1]. We discuss laser systems for cooling, repumping and controlling of $^9\text{Be}^+$ hyperfine qubit ions at a high magnetic field of 5 T. The light for Doppler cooling, repumping and Raman sideband transitions will be provided by three tunable infrared fiber-lasers generating two beams via sum-frequency generation (SFG) and subsequent second harmonic generation, similar to [2]. We build a compact system split into three single, stackable breadboards (600 mm × 600 mm), connected via fibers. One breadboard is used for two independent SFG stages. The SFG wavelength is stabilized to an iodine vapor cell. The light is then frequency-doubled on the other breadboards to generate the required wavelength of about 313 nm for ion and qubit manipulation.

[1] D. J. Heinzen and D. J. Wineland, Phys. Rev. A 42, 2977 (1990).

[2] A.C. Wilson et al., Appl. Phys. B, 105: 741-748 (2011).

Q 27.60 Tue 16:30 Empore Lichthof

Implementation of the Quantum Fourier Transform in a Solid State Spin Register — ●NIKOLAS ABT, SEBASTIAN ZAISER, PHILIPP NEUMANN, and JÖRG WRACHTRUP — 3. Physikalisches Institut, University of Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany

We report on the implementation of the quantum Fourier transform (QFT) [1] in diamond where we use the NV center and the associated ^{14}N spin as well as ^{13}C spins in the environment which couple to the NV through hyperfine interaction. To perform a QFT, not only local but non-local gates are necessary. To this end, we make use of the electron spin of NV⁻ as an ancilla and state selective rotations [2]. We further evaluate the performance of the QFT under experimental constraints like finite coherence times or finite number of available spins. Since the electron is already incorporated into the system, it might be profitable to combine the sensitive sensing capabilities of the electron spin, the robust memory properties of a nuclear spin and the QFT

to a hybrid quantum-sensor-quantum-memory tool which will also be discussed.

[1] Nielsen, Michael A., and Isaac L. Chuang. Quantum Computation and Quantum Information. Cambridge University Press, 2010.

[2] Waldherr, G., et al. Quantum Error Correction in a Solid-State Hybrid Spin Register. Nature 506, 204 (2014)

Q 27.61 Tue 16:30 Empore Lichthof

A nano-mechanical oscillator inside a hollow core photonic crystal fiber — ●DAVID GRASS, JULIAN FESEL, NIKOLAI KIESEL, and MARKUS ASPELMEYER — University of Vienna

Optical levitation of nano-particles has attracted significant attention as ultra-high Q mechanical oscillators for force sensing applications and in the context of quantum optomechanics. We report an optical conveyor belt for transport of levitated nano-particles over several centimeters in air or vacuum inside a hollow core photonic crystal fiber. Detection of the transmitted light field allows 3-dimensional read-out of the particles' center of mass motion. An additional laser enables 1-dimensional radiation pressure based feedback cooling over the whole fiber length. This enables a precise measurement of the damping due to the local environment of the levitated particle i.e. the pressure. It allows a measurement of the pressure distribution inside a hollow core fiber (10cm long, 10 μm diameter) that connects two reservoirs separated by several orders of magnitude in pressure. Next steps include force sensing applications when the particle is functionalized, e.g., with a single or few charges to sense local electric fields.

Q 27.62 Tue 16:30 Empore Lichthof

Towards chemical shift resolution in nanoscale NMR using the Nitrogen Vacancy centre — ●SIMON SCHMITT¹, GERHARD WOLFF¹, CHRISTOPH MÜLLER¹, BORIS NAYDENOV¹, LIAM MCGUINNESS¹, JUNICHI ISOYA², and FEDOR JELEZKO¹ — ¹Institute for Quantum Optics, University Ulm, Germany — ²Research Center for Knowledge Communities, University of Tsukuba, Ibakiri, Japan

The nitrogen vacancy (NV) centre in diamond has proven to be an outstanding magnetic field sensor by enabling nanoscale NMR to be performed at ambient conditions. Recently, a few experiments have demonstrated that the sensitivity of the NV center is sufficient to perform NMR spectroscopy at the single molecule level. However, the spectral resolution of the NV center is lacking, and to date has not allowed structural information on external molecules to be obtained. Here we discuss work on improving the resolution of the NV center, to a level enabling detection of chemical shifts. This would allow for non-destructive structural analysis of single molecules and bring NV-based NMR spectroscopy closer to atomic level imaging.

Q 27.63 Tue 16:30 Empore Lichthof

Steps towards NMR sensing of single molecules — ●GERHARD WOLFF¹, SIMON SCHMITT¹, CHRISTOPH MÜLLER¹, BORIS NAYDENOV¹, LIAM MCGUINNESS¹, JUNICHI ISOYA², and FEDOR JELEZKO¹ — ¹Institute for Quantum Optics, University Ulm, Germany — ²Research Center for Knowledge Communities, University of Tsukuba, Ibakiri, Japan

The nitrogen vacancy (NV) centre in diamond offers the intriguing opportunity to provide an atomic sized sensor with very high sensitivity. Recently it has been shown that it is even possible to sense the magnetic field of a single spin at ambient conditions. We aim to extend previous measurements to high magnetic fields, where the NV's sensitivity may enable detection of chemical shifts at a single molecule level. Since the chemical shift depends on the external magnetic field we conceptualize a cooperated setup consisting of a confocal microscope and a superconducting magnet operating at several Tesla. This also includes the designing of structures to control the position of the target molecules as well as microwave resonators to coherently control the spin NV system at high magnetic fields.

Q 27.64 Tue 16:30 Empore Lichthof

Astigmatism compensation in a non-planar four mirror-Cavity — ●ANDREAS NOACK — Max Planck Institute for Gravitational Physics (Albert Einstein Institute Hannover) Callinstr. 38 / 30167 Hannover

One of the limiting noises in the second generation of interferometric gravitational wave detectors (GWD) is the thermal noise of the test masses. For the next generation GWD some methods have been proposed to reduce the thermal noise. One method suggests to use higher order modes instead of the fundamental Gaussian mode. Laguerre-

Gaussian modes (LG) are compatible with spherical mirrors and can therefore be used in the current setup of the advanced GWDs. The best tradeoff between clipping loss in the current setup and thermal noise reduction is the LG33 mode. Our simulations and experimental

results show that astigmatism prevents the LG33 mode from resonating inside a planar Bow-Tie-Cavity. We present the feasibility of using a non-planar four mirror Bow-Tie-Cavity as a mode cleaner for the LG33 mode.

Q 28: Laser Development I

Time: Wednesday 11:00–13:00

Location: a310

Q 28.1 Wed 11:00 a310

Nd:Sapphire Ridge Waveguide Laser — ●SVEN H. WAESSELMANN¹, SEBASTIAN HEINRICH¹, CHRISTIAN E. RÜTER², DETLEF KIP², CHRISTIAN KRÄNKEL^{1,3}, and GÜNTER HUBER^{1,3} — ¹Institut für Laser-Physik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany — ²Faculty of Electrical Engineering, Helmut Schmidt Universität, 22043 Hamburg, Germany — ³The Hamburg Centre for Ultrafast Imaging, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany

Sapphire is well known for its outstanding thermo-mechanical properties among the common laser host crystals. It is thus a highly desirable host material for rare-earth (RE) doping. Unfortunately, RE:sapphire cannot be grown in the thermal equilibrium. We performed off-equilibrium growth of Nd:Sapphire films via pulsed laser deposition (PLD). With doping concentrations of 1 at.% Nd, PLD films of 2.6 μm thickness proved to function as planar waveguide lasers. In order to obtain two-dimensional confinement, we applied diamond dicing to the thin films to prepare ridge waveguides. At 2.5 W of incident pump power at a wavelength of 833 nm we obtained a maximum of 116 mW of cw output at 1093 nm with a slope efficiency of 5% in a 47 μm wide ridge waveguide with a length of 8 mm.

Q 28.2 Wed 11:15 a310

Kontinuierliches UV-Lasersystem bei 254 nm durch Frequenzvervierfachung eines Flüssigstickstoff-gekühlten Faserverstärkers bei 1015 nm — ●RUTH STEINBORN, PATRICK BACHOR, THOMAS DIEHL, SASCHA RAU, MATTHIAS STAPPEL und JOCHEN WALZ — Johannes Gutenberg-Universität und Helmholtz-Institut Mainz, D-55099 Mainz

Durch Kühlung von Ytterbium-dotierten Glasfasern auf kryogene Temperaturen lässt sich die Absorption in der Faser im Wellenlängenbereich von 1000 nm bis 1050 nm deutlich reduzieren. Dieser Effekt wird ausgenutzt, um einen Faserverstärker bei 1015 nm zu betreiben. Dazu wird von einem Diodenlasersystem erzeugtes Licht in einer auf 77 K gekühlten Ytterbium-Faser verstärkt. Dieses System erreicht zuverlässig und polarisationsstabil Ausgangsleistungen von über 10 W. Die experimentellen Ergebnisse sowie Vergleiche mit Simulationen des Verstärkers bei unterschiedlichen Temperaturen werden vorgestellt.

Das verstärkte Licht wird in zwei Stufen auf die Wellenlänge 254 nm frequenzvervierfacht, welche dem $6^1S_0 \rightarrow 6^3P_1$ -Übergang in Quecksilber entspricht. Die erste Frequenzverdopplung mit einem periodisch gepolten Lithiumniobat-Kristall (PPLN) erreicht im Einfachdurchgang eine Ausgangsleistung von 2 W. Das so erzeugte grüne Licht wurde in einem Überhöhungsresonator mit verschiedenen Cäsium-Lithiumborat-Kristallen (CLBO) frequenzverdoppelt, wobei ein starker Einfluss der Kristallqualität auf die erzeugte UV-Leistung beobachtet wurde. Mit einem der Kristalle kann eine stabile Ausgangsleistung von bis zu 500 mW bei 254 nm erzeugt werden.

Q 28.3 Wed 11:30 a310

Oscillator-pumped femtosecond laser source with nearly gap free tuning range from 1.4 to 12 μm — ●FLORIAN MÖRZ, TOBIAS STEINLE, ANDY STEINMANN, and HARALD GIESSEN — 4th Physics Institute and Research Center SCOPE, University of Stuttgart, 70550 Stuttgart, Germany

We present a femtosecond laser source that provides infrared radiation between 1.4 and 12 μm . The setup consists of a multi-Watt mid-infrared optical parametric master oscillator power amplifier (MOPA) that is tunable from 1370 nm to 4120 nm, and a difference frequency generation (DFG) stage, in which the MOPA signal and idler are mixed. The MOPA generates up to 4.3 W average output power at 1370 nm, corresponding to a photon conversion efficiency of 78 %. Nearly Fourier-limited pulses and excellent power stability are observed. The DFG setup provides radiation of up to 50 mW average output power at 6 μm and several mW up to 12 μm at a passive long

term stability of < 1 % RMS. This MOPA DFG setup is pumped by a single Yb:KGW femtosecond oscillator with 8 W average pump power.

Q 28.4 Wed 11:45 a310

High-repetition rate, high-power femtosecond difference frequency generation behind an OPO for the mid-infrared fingerprint region — ●JOACHIM KRAUTH, TOBIAS STEINLE, ANDY STEINMANN, and HARALD GIESSEN — 4th Physics Institute and Research Center SCoPE

We demonstrate a high power, femtosecond optical parametric oscillator (OPO) based on periodically poled lithium niobate crystal used for pumping a subsequent difference frequency generation (DFG) setup based on an AgGaSe₂ crystal. The linear cavity OPO generates up to 1.33 W (signal) and 1.63 W (idler) output power while it is synchronously pumped by a Yb:KGW oscillator that provides up to 7 W output power with 440 fs pulses at 41 MHz repetition rate at 1033 nm. The generated signal and idler are mixed in the DFG setup to generate as much as 150 mW in the mid-infrared (mid-IR) fingerprint region, with a tuning range between 4.9 and 7.3 μm . This stable, high power setup is useful for various applications including mid-IR spectroscopy. A complete characterization of the OPO and DFG stage along with power scaling, stability and mid-IR DFG spectral measurements will be presented.

Q 28.5 Wed 12:00 a310

Thin-film filter wavelength-stabilized, grating combined high-brightness direct diode laser — ●MATTHIAS HAAS, SIMON NAGEL, SIMON RAUCH, MARKUS GINTER, ROLF BEISSWANGER, ALEXANDER KILLI, and HAGEN ZIMER — TRUMPF Laser GmbH, Schramberg, Germany

Direct diode lasers are of great interest in many fields of today's industrial laser material processing. During the past decade low-brightness multi-kW direct diode lasers have successfully replaced flash lamp pumped rod lasers in laser metal processing applications such as surface treatment, brazing and welding. The striking advantage of such lasers compared to optically pumped solid state lasers consists of higher compactness and enhanced electrical-to-optical conversion efficiency of up to 50%. Quite recently high-brightness external cavity dense wavelength beam combined diode lasers have come of age which are able to serve all kinds of high-brilliance laser applications as for instance flat-sheet metal cutting or remote welding. In our talk we report on dense wavelength beam combining (DWBC) of ten horizontally stacked broad-area laser diode bars by using a novel multi-laser cavity approach based on a thin-film filter (TFF) as a dispersive optical element. The wavelength-stabilized output of the TFF cavity is beam combined upon a transmission grating in Littrow configuration. Hereby a cylindrical telescope is used for dispersion matching between the TFF and the combiner grating. We demonstrate a direct diode laser with an output power of 500 W from a 100- μm , 0.1-NA fiber and discuss limitations of beam quality preservation using this DWBC architecture.

Q 28.6 Wed 12:15 a310

Passiv harmonisch-modengekoppelter Yb:CALGO-Laser — ●HAUKE BENSCH¹ und UWE MORGNER^{1,2} — ¹Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, D-30167 — ²Laser Zentrum Hannover, Hollerithallee 8, D-30419 Hannover

Um hohe Pulsenergien zu erreichen werden normalerweise Laseroszillatoren verlängert, wodurch bei gleicher mittlerer Leistung die Pulsenergie ansteigt. Durch diese Verlängerung der Resonatoren sinkt jedoch die Repetitionsrate des Systems. Um die höheren Pulsenergien bei langen Resonatoren mit höheren Repetitionsraten nutzen zu können, bietet die harmonische Modenkopplung eine mögliche Lösung. Dieser Lösungsansatz wird an einem SESAM-modengekoppelten Yb:CALGO-Oszillator präsentiert, dessen solitärer Multipulsbetrieb passiv so gesteuert werden kann, dass der Laserbetrieb sich auf das genaue Vielfache der fundamentalen Repetitionsrate stabilisiert. Um diese Phasen-

stabilität zu verdeutlichen, wird der harmonisch gelockte Multipulsbetriebs anhand des Radiofrequenzspektrum mit einer schnellen Photodiode untersucht, wozu um einen die resonatorinterne Leistung und zum anderen die Gesamtdispersion des Systems variiert wird. Anhand dieser Messungen ist ersichtlich, dass beim harmonisch-modengekoppelten Multipulsbetrieb die fundamentale Repetitionsrate komplett unterdrückt werden kann, während dies bei einem einfachen Multipulsbetrieb nicht zu beobachten ist. Somit vereint der präsentierte SESAM-modengekoppelte Yb:CALGO Oszillator die Vorteile höherer Pulsenergie bei gleichzeitig höheren Repetitionsraten.

Q 28.7 Wed 12:30 a310

Development of a cavity dumped 4-crystal oscillator based on Yb:CALGO — ●JANA KAMPMANN¹, BERNHARD KREIPE¹, and UWE MORGNER^{1,2} — ¹Institute für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover — ²Centre for Quantum Engineering and Space-Time Research

The possibility to scale the output parameters of oscillators by using multiple gain media is explored and different approaches on a modular setup were tested. In this scheme, the total pump power that is needed to scale the pulse energy can be enhanced without accumulating too much heat in a single crystal. Operating the system with cavity-dumping enables high outcoupling ratios, whereas the reduced

repetition rate will lead to even higher pulse energies. Due to beneficial properties like a high thermal conductivity and a large bandwidth, Yb:CALGO is chosen as gain material.

Q 28.8 Wed 12:45 a310

Polarization effects in bulk and waveguide lasers in cubic Pr³⁺:KY₃F₁₀ — ●DOMINIK BRÜSKE¹, THOMAS CALMANO^{1,2}, PHILIP WERNER METZ¹, CHRISTIAN KRÄNKEL^{1,2}, DANIEL-TIMO MARZAHL¹, and GÜNTER HUBER^{1,2} — ¹Institut für Laser-Physik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany — ²The Hamburg Centre for Ultrafast Imaging, Luruper Chaussee 149, 22761 Hamburg, Germany

Due to the cubic structure of rare earth doped KY₃F₁₀ no polarization dependence in the spectroscopic characteristics is expected. However, since each doping ion is surrounded by eight fluorine ions in C_{4v} symmetry a predominant local symmetry axis is provided, resulting in polarization dependent spectroscopic characteristics despite the cubic structure. With a suitable doping ion, this effect allows for switching of the laser wavelength by simply changing the pump light polarization. Utilizing Pr³⁺:KYF, we achieved wavelength switching between 610 nm in the orange and 645 nm in the red in bulk and fs-laser written waveguide lasers.

Q 29: Quantum Gases: Bosons III

Time: Wednesday 11:00–13:00

Location: e001

Group Report

Q 29.1 Wed 11:00 e001

BEC Heidelberg: Exploring non-linear dynamics - from discrete to continuous — ●PHILIPP KUNDEL, MAXIMILIAN PRÜFER, DANIEL LINNEMANN, HELMUT STROBEL, WOLFGANG MÜSSEL, CHRISTIAN-MARCEL SCHMIED, THOMAS GASENZER, and MARKUS K. OBERHALER — Kirchhoff-Institut für Physik, Im Neuenheimer Feld 227, 69120 Heidelberg

Spinor Bose-Einstein condensates are ideally suited to study complex many-particle dynamics, as they offer a unique level of experimental control. Our experiments focus on spin-mixing as the non-linear mechanism coupling internal and external degrees of freedom. We study this interplay using spin-changing collisions in Rb-87 in quasi one-dimensional confinement in two different regimes. By tuning the longitudinal trap frequency we first generate a situation of only few accessible modes. In this situation the spin-changing collisions act on top of an effective potential. We use spin-mixing as a tool to probe this potential and experimentally observe the population of different spatial modes. The possibility of creating nonlocal entanglement in this controlled few spatial modes situation is investigated. Going into the continuous regime, Bogoliubov theory predicts unstable momentum modes, which are occupied due to the local creation of atom pairs with opposite momenta. Experimentally we find strong spatial correlations for short evolution times. For later times, irrespective of different initial conditions the dynamics are governed by many modes but nevertheless general features can be found. We identify emerging, long living structures correlating the collective spin and the total density.

Q 29.2 Wed 11:30 e001

Observation of the phononic Lamb shift in the Fröhlich model of a quantum impurity — ●FABIÁN OLIVARES, TOBIAS RENTROP, ARNO TRAUTMANN, FRED JENDRZEJEWSKI, and MARKUS K. OBERHALER — Kirchhoff-Institut für Physik, Im Neuenheimer Feld 227, 69120 Heidelberg

The interaction of particles with fields can profoundly change their properties. Typical examples are Landau quasiparticles in metals or the QED electron mass renormalisation in vacuum. Ideally these complex phenomena can be studied best when the interaction strengths and particle confinement potentials are freely tuned. We engineer such a system, in which fermionic and bosonic impurities are immersed in a Bose-Einstein condensate (BEC). Its phonon field interacts with the impurities thus changing their effective parameters according to the Fröhlich polaron scenario. Using a dedicated spectroscopy method of Ramsey type we measure the energy shifts of confined impurities induced by the phonon-impurity interactions. These shifts cannot be explained by an effective mass concept alone, but only combined with a phonon-induced Lamb shift. The experimental observations are in

excellent agreement with the theoretical expectation.

Q 29.3 Wed 11:45 e001

Dirty Bosons in a Quasi-One-Dimensional Harmonic Trap — ●TAMA KHELLIL¹, ANTUN BALAZ², and AXEL PELSTER³ — ¹Physics Department, Freie Universität Berlin, Germany — ²Scientific Computing Laboratory, Institute of Physics Belgrade, University of Belgrade, Serbia — ³Physics Department and Research Center OPTIMAS, Technische Universität Kaiserslautern, Germany

The emergence of a Bose-glass phase in a quasi one-dimensional Bose-Einstein-condensed gas in a harmonic trapping potential with an additional delta-correlated disorder potential at zero temperature is studied using two approaches [1]. At first, the corresponding time-independent Gross-Pitaevskii equation is numerically solved for the condensate wave function, and disorder ensemble averages are evaluated. With this we analyze quantitatively the emergence of mini-condensates in the local minima of the random potential, which occurs for weak disorder preferentially at the border of the condensate, while for intermediate disorder strength this happens in the trap center. Second, in view of a more detailed physical understanding of this phenomenon, we extend a quite recent non-perturbative approach towards the weakly interacting dirty boson problem, which relies on the Hartree-Fock theory and is worked out on the basis of the replica method, from the homogeneous case to a harmonic confinement [2].

[1] T. Khellil, A. Balaz, and A. Pelster, arXiv:1510.04985.

[2] T. Khellil and A. Pelster, arXiv:1511.08882.

Q 29.4 Wed 12:00 e001

Enhanced Quantum Simulation of Quantum Phase Transitions using Non-Destructive Measurements — ●ROBERT HECK¹, MARK BASON², OTTÓ ELÍASSON¹, ROMAIN MÜLLER¹, MARIO NAPOLITANO¹, ASKE R. THORSEN¹, JAN ARLT¹, and JACOB F. SHERSON¹ — ¹Institute of Physics and Astronomy, Aarhus University, Denmark — ²School of Physics and Astronomy, University of Nottingham, United Kingdom

In the age of quantum simulation, experiments must give as tight bounds as possible to guide the construction of theoretical models describing complex many-body quantum systems.

We report on three separate investigations using Faraday imaging, a method relying on the dispersive light-matter interaction: Firstly, we report that the shot-to-shot fluctuating initial conditions in the cold atomic cloud deterministically shift the transition point to a BEC. Then we demonstrate that precise knowledge of these initial conditions lead to enhanced precision in the determination of the transition point. Secondly, we probe the dynamics of the condensation process by repeated in-situ Faraday imaging of the same cloud. We quantify experimental sources of noise and demonstrate that the transition

point depends on the number of probe photons in a deterministic manner. This is an important step towards the direct observation of the stochastic nature of the condensation process, due to bosonic stimulation. Finally, as a step towards single shot mapping of entire phase diagrams, we quasi-conservatively drive the transition to a BEC up to 30 times using repeated application of a tightly focused laser beam.

Q 29.5 Wed 12:15 e001

Formation of Jones-Roberts solitons in a flat Bose-Einstein condensate — •NADINE MEYER, HARRY PROUD, JIXUN LIU, CHARLOTTE O'NEALE, MARISA PEREA-ORTIZ, GIOVANNI BARONTINI, and KAI BONGS — School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B152TT, United Kingdom

Nonlinear systems out of equilibrium give rise to vortex and soliton solutions that play an important role in high speed optical communication, energy transport mechanisms in molecular biology and astrophysics. Collective excitations are of special interest in this respect. However, plane solitons in 2D are intrinsically dynamical unstable, leaving the open question of reliable transport mechanism on surfaces in nature. The so-called Roberts solitons predicted in 1982 are part of the rich family of formstable soliton solutions with enhanced dynamical stability aspects regarding transport. In order to gain a deeper insight into these phenomena well controlled and flexible many body quantum systems at finite temperatures can be used for the simulation of these fundamental collective excitations of the nonlinear Gross-Pitaevski equation (GPE) and their dynamics. Here we employ phase imprinting methods for the first generation of these Jones Roberts solitons in ultracold gases of ^{87}Rb . By tailoring the optical imprint of a spatial light modulator (SLM), the quantum phase of the Bose-Einstein condensate can be arbitrarily engineered. The evolution and dynamics of Jones Roberts solitons prove them as long lived stable excitations travelling on extended surfaces.

Q 29.6 Wed 12:30 e001

Coupled Photon Condensates in Variable Trapping Potentials — •DAVID DUNG¹, CHRISTIAN KURTSCHIED¹, TOBIAS DAMM¹, JULIAN SCHMITT¹, FRANK VEWINGER¹, JAN KLÄRS², and MARTIN WEITZ¹ — ¹Institut für Angewandte Physik, Universität Bonn — ²Institut für Quantenelektronik, ETH Zürich

We report on recent work to create multiple coupled photon condensates in a single microcavity setup at room-temperature. Bose-Einstein condensation has been observed for cold atomic gases, solid state quasi-

particles as exciton-polaritons, and more recently with photons. The latter can be realized in a dye-filled optical microcavity. Number-conserving thermalization of photons in the dye-microcavity is achieved by multiple absorption and fluorescence processes on dye-molecules. The short mirror spacing in the microcavity creates a suitable ground state for condensation, equivalent to a non-vanishing effective photon mass. By locally thermo-optically changing the refractive index inside the microcavity an effective trapping potential for photons can be induced. For this, a focused external control laser beam locally heats an absorbing silicon layer implemented below one of the cavity mirror coatings, leading to a local refractive index change of a thermo-responsive polymer mixed with the dye solution. The range of depths and trapping frequencies one can adjust with this technique have been determined. We also present measurements on photon tunneling between the microsites in the system. Moreover, a temporally retarded effective photon self-interaction is observed.

Q 29.7 Wed 12:45 e001

Phase and number correlations of Bose-Einstein-condensed light in a dye microcavity — •JULIAN SCHMITT¹, TOBIAS DAMM¹, DAVID DUNG¹, CHRISTIAN WAHL¹, FRANK VEWINGER¹, JAN KLÄRS², and MARTIN WEITZ¹ — ¹Institut für Angewandte Physik, Universität Bonn, Wegelerstraße 8, 53115 Bonn — ²Institute for Quantum Electronics, ETH Zürich, Auguste-Piccard-Hof 1, 8093 Zürich

Large statistical number fluctuations are a fundamental property known from the thermal behaviour of bosons, as has been revealed for both photons and material particles. In contrast to incoherent thermal ensembles, Bose-Einstein condensates can show both long-range phase coherence as well as damped intensity fluctuations. By examining the temporal interference of a Bose-Einstein condensate of photons in a dye microcavity, we observe the phase evolution and the emergence of temporal coherence of the photon condensate. In a Hanbury Brown-Twiss experiment, we identify a regime with large statistical intensity fluctuations, which are a consequence of grand-canonical statistical conditions realized by the photo-excitabile dye molecules constituting both a particle and a heat reservoir. For small condensate sizes, we observe phase jumps of the condensate attributed to spontaneous symmetry breaking following condensate fluctuations to small photon numbers. For large systems, our experimental data shows phase coherence even in the presence of statistical number fluctuations. More recently, we have focussed on the study of the spatio-temporal correlations of the photon gas both in the thermal and the condensed phase.

Q 30: Quantum Information: Concepts and Methods V

Time: Wednesday 11:00–13:00

Location: e214

Q 30.1 Wed 11:00 e214

Approaching equilibrium: Fermionic Gaussification — MAREK GLUZA¹, •CHRISTIAN KRUMNOW¹, MATHIS FRIEDSDORF¹, CHRISTIAN GOGOLIN^{2,3}, and JENS EISERT¹ — ¹Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, Berlin, Germany — ²ICFO-The Institute of Photonic Sciences, Mediterranean Technology Park, Barcelona, Spain — ³Max-Planck-Institut für Quantenoptik, Garching, Germany

When and by which mechanism do closed quantum many-body systems equilibrate? This fundamental question has been in the focus of attention for many years. It lies at the very basis of the connection between thermodynamics, quantum mechanics of many constituents and condensed matter theory. In the setting of free fermionic evolutions, we rigorously capture the time evolution in abstract terms and by basing our proof on intuitive mathematical concepts like Lieb-Robinson bounds, notions of particle transport and an algebraic expansion of operators, we uncover the underlying mechanism how local memory of the initial conditions is forgotten. Specifically, starting from an initially short range correlated fermionic states which can be very far from Gaussian, we show that if the Hamiltonian provides sufficient transport, the system approaches a state that cannot be distinguished from a corresponding Gaussian state by local measurements. For experimentally relevant instances of ultra-cold fermions in optical lattices, our result implies equilibration on realistic physical time scales. Moreover, we characterise the equilibrium state, finding an instance of a rigorous convergence to a fermionic Generalized Gibbs ensemble.

Q 30.2 Wed 11:15 e214

A road to Non-Markovian Quantum Thermodynamics — •REBECCA SCHMIDT^{1,2}, SABRINA MANISCALCO², and TAPPO ALANISSILÄ¹ — ¹CQE and COMP, Department of Applied Physics, Aalto University School of Science, P.O.Box 11100, 00076 Aalto, Finland — ²TCQP, Department of Physics and Astronomy, University of Turku, FI-20014, Turun Yliopisto, Finland

Common assumptions in the theoretical description of open quantum system dynamics, such as non-Markovianity or perturbative treatments, do not hold for state-of-the-art realisations of mesoscopic quantum devices. There is a need for a consistent description of non-Markovian open quantum dynamics to form the theoretical framework for ongoing and upcoming experiments in quantum thermodynamics. Also, there is evidence that non-Markovianity can be exploited as a resource to enhance the performance of quantum thermodynamic devices [1]. To bridge the gap between an information theoretic and a thermodynamic description, we applied the information theoretic measures of non-Markovianity [2] to the quantum thermodynamic setting of a generic driven Spin-Boson model [3].

[1] B. Bylicka, D. Chruscinski and S. Maniscalco, *Sci. Rep.* 4, 5720 (2014); S.F. Huelga, A. Rivas, and M.B. Plenio, *PRL* 108, 160402 (2012) [2] S. Wissmann, A. Karlsson, E.-M. Laine, J. Piilo, and H.-P. Breuer, *PRA* 86, 062108 (2012); C. Benedetti, M. G. A. Paris, S. Maniscalco, *PRA* 89, 012114 (2014). [3] R. S., M.F. Carusela, J.P. Pekola, S. Suomela and J. Ankerhold, *PRB* 91, 224303 (2015).

Q 30.3 Wed 11:30 e214

The energy cost of quantum measurements — •KAIS ABDELKHALEK¹, DAVID REEB¹, and YOSHIFUMI NAKATA² — ¹Institut

für Theoretische Physik, Leibniz Universität Hannover, Germany — ²Universitat Autònoma de Barcelona, Spain

We investigate the energy cost for performing a quantum measurement. In a general, microscopic model employing all systems involved in the measurement process, we establish a new fundamental lower bound on the energy cost for general measurements. We show that, in contrast to naïve intuition and previous results by [Sagawa/Ueda] valid only for a small class of measurements, our result implies that useful energy can, in principle, be extracted by general measurements. In the important special case of projective measurements we prove that the corresponding energy cost is proportional to the Shannon entropy of the outcome probability distribution. We elucidate immediate consequences of these results for examples in quantum control theory and measurement-based feedback processes (such as quantum error correction) and highlight a link to quantum thermodynamics.

Q 30.4 Wed 11:45 e214

Memory Cost for Simulating all Contextuality Correlations in the Peres-Mermin Square — ●GABRIEL FAGUNDES CAMARGO^{1,2} and MATTHIAS KLEINMANN² — ¹Federal University of Minas Gerais, Belo Horizonte, Brazil — ²University of the Basque Country, Leioa, Spain

Contextuality is a feature of quantum theory which classical models can not reproduce. However, for contextuality scenarios realized in sequential measurements, the capabilities of the classical models may embrace an additional feature: internal memory. For the Peres-Mermin square, three internal states are required to be not in contradiction with quantum theory [1]. We extend this analysis and compute the memory needed for fully agreeing with quantum correlations, i.e., to agree with the predictions of any quantum state of any compatible sequence of measurements. Despite this comprehensive approach we find that three internal states are sufficient and then in particular allow to violate any corresponding non-contextuality inequality.

[1] M. Kleinmann, O. Gühne, J. R. Portillo, J.-A. Larsson, and A. Cabello, *New J. Phys.* **13**, 113011 (2011)

Q 30.5 Wed 12:00 e214

Collisional model approach to quantum memory effects — SILVAN KRETSCHMER, ●KIMMO LUOMA, and WALTER STRUNZ — Institut für Theoretische Physik, Technische Universität Dresden, Dresden, Germany

Collisional models offer an alternative route to open quantum system dynamics. A collision model consists of a system that interacts with localized environment particles in sequential manner. As such, in collisional models the dynamics is given discretely in time in terms of maps instead of usual continuous in time master equations. The description of the dynamics using sequential collisions is appealing because it guarantees the complete positivity of the open system dynamics by its construction.

A scenario where the system interacts at each collision with a new uncorrelated environment particle leads to dynamical map with semigroup structure, i.e. to Markovian evolution.

In this work we construct a collisional model with an interaction between the environment particles. The interaction allows to propagate system environment correlations forward in time. With our construction we can simulate multimode Jaynes-Cummings model discretely in time and in the continuous time limit we can produce the well known analytical results.

Q 30.6 Wed 12:15 e214

Mixing properties of local diffusion processes on the unitary group — ●EMILIO ONORATI, WINTON BROWN, OLIVER BUERSCHAPER, MARTIN KLIESCH, ALBERT WERNER, and JENS EISERT — Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, 14195 Berlin, Germany

In recent years, random quantum processes have been the object of numerous investigations. Random quantum circuits are discrete processes of this type: unitary local gates are randomly chosen accord-

ing to some distribution and repeatedly applied to quantum states. Continuous-time evolutions belong to this class too, e.g. the ones induced by fluctuating local Hamiltonians.

In this work, we prove that a diffusion process on the unitary group generated by a fluctuating local Hamiltonian has mixing properties analogous to those shown for random quantum circuits, hence providing a unifying picture for the two frameworks. More precisely, we show that local Wiener processes are approximate unitary k -designs after a polynomial run time. This result follows from previous techniques developed for random quantum circuits as well as new insights from representation theory.

In addition, we show that decoupling, a relevant concept for a large variety of applications in both physics and quantum information, can be obtained with almost linear scaling in the system size in the setting of fluctuating local Hamiltonians. To prove this, we construct an abstract continuous-time random walk over Pauli strings and show that it satisfies a certain mixing criterion which then implies decoupling.

Q 30.7 Wed 12:30 e214

Quantum information processing in phase space: A modular variables approach — ●ANDREAS KETTERER¹, ARNE KELLER², STEPHEN P. WALBORN³, THOMAS COUDREAU¹, and PÉROLA MILMAN¹ — ¹Laboratoire Matériaux et Phénomènes Quantique, Université Paris Diderot, Paris, France — ²Institut de Sciences Moléculaires d'Orsay, Université Paris-Sud, Orsay, France — ³Instituto de Física, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil

Binary quantum information can be fault tolerantly encoded in states defined in infinite dimensional Hilbert spaces [1]. Such states define a logical basis, and permit a perfect equivalence between continuous and discrete universal operations. The drawback of this encoding is that the corresponding logical states are unphysical, meaning infinitely localized in phase space. In this talk, we apply the modular variables formalism to show theoretically that, in a number of protocols relevant for quantum information and for the realization of fundamental tests of quantum mechanics, it is possible to loosen the requirements on the encoded subspace without jeopardizing neither their usefulness nor their successful implementation. Such protocols involve measurements of appropriately chosen modular observables that permit the readout of encoded discrete quantum information from the corresponding logical states [2,3].

[1] D. Gottesman et al., *Phys. Rev. A* **64**, 012310 (2001)

[2] A. Ketterer et al., *in preparation* (2015)

[3] A. Ketterer et al., *Phys. Rev. A* **91**, 012106 (2015)

Q 30.8 Wed 12:45 e214

Certified efficient simulation of local unitary dynamics by ground state preparations — ●DOMINIK HANGLEITER, MARTIN KLIESCH, MARTIN SCHWARZ, and JENS EISERT — Freie Universität Berlin

Typically, one cannot expect to find efficient classical simulation schemes for quantum systems. Hence, the usual scientific method to “predict-and-test” in order to falsify a theory is not guaranteed to work in the context of quantum many-body systems. So, is there at all a way to certify such systems? Recent experimental advances allowing for precise engineering of, and high-resolution measurements on large-scale quantum systems have brought this question from the theorist’s desk into the lab. In this work, we explore alternative strategies to certify that a system engineered in the lab – a quantum simulator – is indeed well described by some target model. We find that there are conceivable physical systems that can be certified and which are, indeed, expected to be classically intractable. For example, this is the case for frustration-free and gapped Hamiltonians: their ground states can be certified by local energy measurements and encode the full complexity of quantum computers. This example shows: we do not need to merely trust quantum simulators but can also certify their outcome. To show our results, we bring together methods from quantum tomography and Hamiltonian complexity, in particular, constructions based on the Feynman-Kitaev Hamiltonian used to prove the QMA-hardness of the Local Hamiltonian Problem.

Q 31: Ultra-cold atoms, ions and BEC I (with A)

Time: Wednesday 11:00–13:00

Location: f107

Q 31.1 Wed 11:00 f107

Polaronic effects in one- and two-band quantum systems — •TAO YIN¹, DANIEL COCKS², and WALTER HOFSTETTER¹ — ¹Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität, 60438 Frankfurt/Main, Germany — ²College of Science, Technology & Engineering, James Cook University, Townsville 4810, Australia

In this work we study the formation and dynamics of polarons in a system with a few impurities in a lattice immersed in a Bose-Einstein condensate (BEC). This system has been experimentally realized using ultracold atoms and optical lattices. Here we consider a two-band model for the impurity atoms, along with a Bogoliubov approximation for the BEC, with phonons coupled to impurities via both intra- and inter-band transitions. We decouple this Fröhlich-like term by an extended two-band Lang-Firsov polaron transformation using a variational method. The new effective Hamiltonian with two (polaron) bands differs from the original Hamiltonian by modified coherent transport, polaron energy shifts and induced long-range interaction. A Lindblad master equation approach is used to take into account residual incoherent coupling between polaron and bath. This polaronic treatment yields a renormalized inter-band relaxation rate compared to Fermi's Golden Rule. For a strongly coupled two-band Fröhlich Hamiltonian, the polaron is tightly dressed in each band and can not tunnel between them, leading to an *inter-band self-trapping* effect.

[1] T. Yin, D. Cocks and W. Hofstetter, arXiv:1509.08283 (2015).

Q 31.2 Wed 11:15 f107

Probing superfluidity of Bose-Einstein condensates via laser stirring — •VIJAY PAL SINGH^{1,2}, WOLF WEIMER², KAI MORGENER², JONAS SIEGL², KLAUS HUECK², NICLAS LUICK², HENNING MORITZ², and LUDWIG MATHEY^{1,2} — ¹Zentrum für Optische Quantentechnologien, Universität Hamburg, 22761 Hamburg, Germany — ²Institut für Laserphysik, Universität Hamburg, 22761 Hamburg, Germany

We investigate the superfluid behavior of a Bose-Einstein condensate of ⁶Li molecules. In the experiment by Weimer *et al.*, Phys. Rev. Lett. **114**, 095301 (2015) a condensate is stirred by a weak, red-detuned laser beam along a circular path around the trap center. The rate of induced heating increases steeply above a velocity v_c , which we define as the critical velocity. Below this velocity, the moving beam creates almost no heating. In this paper [1], we demonstrate a quantitative understanding of the critical velocity. Using both numerical and analytical methods, we identify the non-zero temperature, the circular motion of the stirrer, and the density profile of the cloud as key factors influencing the magnitude of v_c . A direct comparison to the experimental data shows excellent agreement.

[1] V. P. Singh, W. Weimer, K. Morgener, J. Siegl, K. Hueck, N. Luick, H. Moritz, and L. Mathey, arXiv: 1509.02168.

Q 31.3 Wed 11:30 f107

Robustness of many-body localization in the presence of dissipation — •EMANUELE LEVI¹, MARKUS HEYL², IGOR LESANOVSKY¹, and JUAN P. GARRAHAN¹ — ¹School of Physics and Astronomy, University of Nottingham, University Park, NG7 2RD, United Kingdom — ²Physik Department, Technische Universität München, 85747 Garching, German

Many-body localization (MBL) has emerged as a novel paradigm for robust ergodicity breaking in closed quantum many-body systems. However, it is not yet clear to which extent MBL survives in the presence of dissipative processes induced by the coupling to an environment. In this talk I will discuss the findings of [1] about heating and ergodicity for a paradigmatic MBL system –an interacting fermionic chain subject to quenched disorder in the presence of dephasing. Even though the system is eventually driven into an infinite-temperature state, heating as monitored by the von Neumann entropy can progress logarithmically slowly, implying exponentially large time scales for relaxation. This slow loss of memory of initial conditions make signatures of non-ergodicity visible over a long, but transient, time regime. Time allowing I will discuss a potential controlled realization of the considered setup with cold atomic gases held in optical lattices.

[1] E. Levi, M. Heyl, I. Lesanovsky, J.P. Garrahan, What survives of many-body localization in the presence of dissipation,

arXiv:1510.04634

Q 31.4 Wed 11:45 f107

Observation of mixing between singlet and triplet scattering channels in Rb₂ Rydberg molecules — •KARL MAGNUS WESTPHAL, FABIAN BÖTTCHER, ANITA GAJ, MICHAEL SCHLAGMÜLLER, KATHRIN SOPHIE KLEINBACH, ROBERT LÖW, TARA CUBEL LIEBISCH, TILMAN PFAU, and SEBASTIAN HOFFERBERTH — 5. Physikalisches Institut and Center for Integrated Quantum Science and Technology, Universität Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany

We present high-resolution spectroscopy of Rb₂ ultralong-range Rydberg molecules bound by mixed singlet-triplet electron-neutral atom scattering [1]. The mixing of the scattering channels is a consequence of the hyperfine interaction in the ground-state atom, as predicted recently by Anderson *et al.* [2]. Using our experimental data we determine the effective zero-energy singlet s-wave scattering length. Furthermore, we calculate molecular potentials using a full diagonalization approach including the p-wave contribution and all orders in the relative momentum k , and compare the obtained molecular binding energies to the experimental data. We show that an applied external magnetic field changes the contributions of the singlet and the triplet scattering and therefore the binding energies of the observed molecules. Ultimately, we extract the molecular magnetic moments, which differ from the magnetic moments of the asymptotic atomic states.

1 F. Böttcher *et al.*, arXiv:1510.01097, (2015)

2 D. A. Anderson *et al.*, Phys. Rev. A **90**, 062518 (2014)

Q 31.5 Wed 12:00 f107

Towards the production of RbCs ground-state molecules from degenerate gases in an optical lattice — •ANDREAS SCHINDEWOLF¹, LUKAS REICHSÖLLNER², SILVA MEZINSKA¹, BEATRIX MAYR¹, RUDOLF GRIMM^{1,2}, and HANNS-CHRISTOPH NÄGERL¹ — ¹Institut für Experimentalphysik, Universität Innsbruck — ²Institut für Quantenoptik und Quanteninformation IQOQI, Innsbruck

Ultracold dipolar systems are of high interest for quantum chemistry, precision spectroscopy, quantum many-body physics, and quantum simulation. Our goal is the production of a low entropy sample of dipolar RbCs molecules in the rovibronic and hyperfine ground-state. To be able to mix degenerate samples of Rb and Cs, the inter-species scattering length a_{RbCs} has to be tuned close to zero by means of a magnetic Feshbach resonance. Since Cs three-body losses would cause a breakdown of a Cs BEC in the magnetic-field region, in which RbCs Feshbach resonances are available, we initially prepare a Cs Mott insulator with unity filling spatially separated from the Rb sample. The optical lattice wavelength and depth are chosen in a way that Rb is still superfluid and can be overlapped with Cs after switching the magnetic field to achieve $a_{\text{RbCs}} = 0$. Precise control over the relative position of the two degenerate samples and high magnetic field stability will enable the formation of RbCs Feshbach molecules with a high filling factor of the optical lattice followed by the application of the STIRAP transfer to the absolute molecular ground-state, as demonstrated in Ref. [1].

[1] T. Takekoshi *et al.*, Phys. Rev. Lett. **113**, 205301 (2014)

Q 31.6 Wed 12:15 f107

Out-of-equilibrium dynamics of two interacting bosons — •TIM KELLER and THOMAS FOGARTY — Theoretische Physik, Universität des Saarlandes, D-66123 Saarbrücken, Germany

We study the out-of-equilibrium dynamics of two interacting bosons in a one-dimensional harmonic trap after a quench by a centrally located delta-function potential. We are interested in the role of interactions and correlations on this dynamics and have observed many complex phenomena. We make use of an approximate variational calculation called the Lagrange-mesh method to solve the Schrödinger equation numerically. We examine the dynamics by calculating the single particle density and through the time-dependent fidelity (Loschmidt echo) we investigate the irreversibility of the quenched system and its non-linear dependence on the particles interactions. We discern distinct scattering states created by the quench through a thorough examination of its dynamical properties described by the spectral function. We link the probability distribution of the Loschmidt echo after a

long-time evolution to the structure of the spectral function and identify four characteristic distributions which are dependent on quench strength and particle interactions. We lay special focus on the case of a distorted bell-shaped distribution which is caused by a distinct beating in the Loschmidt echo due to the interference of different spectral components. This resonance also has consequences for the particles correlations which mirrors that of the Loschmidt echo.

Q 31.7 Wed 12:30 f107

Molecular ion formation in atom-ion three body recombination — ●AMIR MOHAMMADI, ARTJOM KRÜKOW, JOSCHKA WOLF, AMIR MAHDIAN, and JOHANNES HECKER DENSCHLAG — Universität Ulm, Institut für Quantenmaterie, Albert-Einstein-Allee 45, D-89069 Ulm, Deutschland

Producing transitionally and internally cold molecular ions is one of the challenges and long standing goals in cold atom-ion experiments. One good strategy for this purpose is creating initially cold molecular ions by associating cold ions and cold atoms. In our hybrid atom-ion experiment, we investigate the interaction of a laser-cooled trapped ^{138}Ba ion with an ultracold cloud of ^{87}Rb atoms. At very low kinetic energies (i.e. sub-mK) and densities of 10^{12} cm^{-3} , three-body atom-atom-ion recombination is the dominant reaction process in our experiment[1]. It has been predicted [2] that a weakly bound BaRb^+ ion should be the dominant molecular product. In this talk, we indeed report on the first experimental observation of these molecules after three-body recombination. Furthermore, we discuss the effects of secondary and ternary collisions of BaRb^+ with cold Rb atoms.

[1] A. Krükow et al., arXiv:1510.04938 (2015)

[2] J.Pérez-Rios and C.H. Greene, The journal of Chemical Physics **143**, 041105 (2015)

Q 31.8 Wed 12:45 f107

Nontrivial topological phases in quantum mechanical many-body systems with gain and loss effects — ●MARCEL KLETT, HOLGER CARTARIUS, and GÜNTER WUNNER — 1. Institut für Theoretische Physik, Universität Stuttgart, 70550 Stuttgart

Non-Hermitian \mathcal{PT} -symmetric potentials are capable of effectively describing quantum systems with balanced in- and outfluxes. They allow for the existence of a \mathcal{PT} -symmetric phase with purely real energy spectra of the non-Hermitian Hamiltonian. Good candidates for the realization of a genuine \mathcal{PT} -symmetric quantum system are Bose-Einstein condensates. Recently a possible relation between the appearance of the \mathcal{PT} -symmetric phase and topologically nontrivial states were found in two studies of simple model systems. However, they came to opposite conclusions. In the Su-Schrieffer-Heeger (SSH) model [1] the topological phase has a major influence. As soon as topologically nontrivial states appear \mathcal{PT} symmetry gets broken. This is in contrast to the non-Hermitian Kitaev model [2], in which \mathcal{PT} symmetry breaking does not depend on the topological phase. Our work is based on including different non-Hermitian potentials in the SSH model as well as the Kitaev model. We perform exact calculations of the eigenvalues and the eigenstates, clarify the relation between \mathcal{PT} symmetry and topological phases, and explain why opposite results were found in the above mentioned systems. Consequences for \mathcal{PT} -symmetric Bose-Einstein condensates are discussed.

[1] Baogang Zhu et al., Phys. Rev. A **89**, 062102 (2014)*

[2] Xiaohui Wang et al., Phys. Rev. A **92**, 012116 (2015)

Q 32: Biophotonics

Time: Wednesday 11:00–13:00

Location: f342

Q 32.1 Wed 11:00 f342

Label-free imaging of single proteins and viruses ejected from a living cell — ●MATTHEW McDONALD, KATHARINA KÖNIG, MAREK PILIARIK, RUI QI ZHAO, and VAHID SANDOGHDAR — Max Planck Institute for the Science of Light, Erlangen, Germany

A number of important physiological processes—such as cellular signaling and viral invasions—are marked by their secretomic behavior. Real-time, in-vivo sensing of these cellular secretion events commonly relies on labeled proteins and is thus inherently accompanied by the perturbation of the system. Here, we present a novel, label-free method that enables the detection of single protein secretions from living cells via an interferometric scattering technique (iSCAT). Secretomic events from an individual cell are imaged by way of iSCAT wherein single proteins and bioparticles from the kDa to MDa range are synchronously detected in real-time. The developed method has the potential to solve a wide range of problems in cellular physiology, such as intercellular signaling, immunology, and cancer malignancy.

Q 32.2 Wed 11:15 f342

Extending the applicability of Scanning Laser Optical Tomography using antibody staining and nonlinear contrast mechanisms — ●LENA NOLTE¹, NADINE TINNE¹, GEORGIOS ANTONOPOULOS¹, MARKO HEIDRICH¹, JENNIFER SCHULZE², KRISTIN SCHWANKE², ROBERT ZWEIGERDT², ATHANASIA WARNECKE², ALEXANDER HEISTERKAMP³, TAMMO RIPKEN¹, and HEIKO MEYER¹ — ¹Laser Zentrum Hannover, Germany — ²Medizinische Hochschule Hannover, Germany — ³Leibniz Universität Hannover, Germany

Scanning laser optical tomography (SLOT) enables three dimensional visualization of large samples up to a magnitude of several centimeters using absorption and autofluorescence as intrinsic contrast mechanisms. However, this intrinsic contrast is sometimes not strong enough to image significant details inside the sample. One challenge is the visualization of hair cells and neurofilaments inside the human cochlea. For this reason, we developed a protocol for decalcification, antibody staining and optical clearing to image the cochlea in toto using SLOT.

Optical clearing is an efficient way to look into thick and turbid samples, but also prohibits the application of in vitro studies. Using near-infrared light, the scattering coefficient of the sample is lower and imaging of non-cleared samples can be improved. Therefore, we integrated a fs-pulsed laser source into the SLOT to enable the gen-

eration of two-photon fluorescence inside the sample. This way, living cell aggregates, with a diameter up to hundreds of micrometers, can be studied with respect to their three-dimensional structure without optical clearing.

Q 32.3 Wed 11:30 f342

Aberration correction in STED nanoscopy for super-resolution imaging deep inside living tissue — ●JASMIN K. PAPE, NICOLAI T. URBAN, JENNIFER-M. MASCH, and STEFAN W. HELL — Max Planck Institute for Biophysical Chemistry, Department of NanoBiophotonics, Göttingen, Germany

Stimulated emission depletion (STED) nanoscopy is a far-field fluorescence imaging technique capable of resolving structures on the nanometer scale. It is remarkably well suited for dynamic imaging of live cells and tissues, especially due to its short acquisition times. When imaging deep inside living tissue, however, two main factors limit the imaging performance: one is the loss of intensity due to absorption and scattering, the other is the distortion of the wavefront shape caused by the inhomogeneous refractive index inside the sample medium.

We address the latter problem by pre-shaping the wavefront of the STED beam using a spatial light modulator, with the aim of recovering a high-quality donut-shaped intensity distribution, which is essential for achieving high spatial resolutions. We determine the optimal correction parameters for compensating the sample-induced aberrations by employing an algorithm which records a series of images and then evaluates different properties of each image. The correction process is improved in a way that reduces the number of acquisitions necessary to find the best correction. The correction capabilities of this method will be compared both in artificial samples and in live cells.

Q 32.4 Wed 11:45 f342

Synchronization-free all-solid-state laser system for stimulated Raman scattering microscopy — ●MORITZ FLOESS¹, TOBIAS STEINLE¹, VIKAS KUMAR², ANDY STEINMANN¹, MARCO MARANGONI², GIULIO CERULLO², and HARALD GIESSEN¹ — ¹14th Physics Institute and Research Center Scope, University of Stuttgart, D-70569 Stuttgart, Germany — ²IFN-CNR, Dipartimento di Fisica, Politecnico di Milano, Piazza Leonardo da Vinci 32, I-20133 Milan, Italy

We demonstrate a simple all-solid-state laser source for stimulated Raman scattering (SRS) microscopy. An 8 W, 450 fs Yb:KGW oscillator

with 41 MHz repetition rate pumps an OPA that is seeded by a cw tunable external-cavity diode laser (ECDL). The second-harmonic of the OPA output radiation, generated in a PPLN crystal, acts as the Raman pump beam, tunable between 760 and 820 nm. In contrast to using an OPO as tunable laser source the cw-seeding of the OPA avoids synchronization issues. We demonstrate SRS images with pixel dwell times down to 30 μ s with signal-to-noise ratios of up to 50 when investigating polymer beads. Thanks to the favorable noise properties of the solid-state oscillator SNRs of 5 are still possible with 500 ns pixel dwell time.

Q 32.5 Wed 12:00 f342

Microcavity based detection of single ions interacting with plasmonic nanorods — ●MARTIN D. BAASKE and FRANK VOLLMER — Max-Planck-Institut für die Physik des Lichts, Erlangen, Germany

Whispering gallery mode based microresonators provide powerful tools for the all optical detection of nanoscopic objects such as nanoparticles and viruses[1,2]. Their sensitivity can further be boosted by modification of the microcavities with resonant plasmonic nanoparticles allowing for the detection of single molecules and their interactions[3].

Here we present experimental data on the microcavity based observation of single ions interacting with immobilized plasmonic nanorods in aqueous environment. We show that different types of interactions can be identified by their transient behavior. Furthermore we discuss the influence of the solution's ionic strength on the type of interaction observed for bivalent ions of two different elements.

[1] L. He et al., *Nature Nanotech.*, **6**, 428 (2011)

[2] F. Vollmer et al., *PNAS*, **105**, 20701 (2008)

[3] M.D. Baaske et al., *Nature Nanotech.*, **9**, 933 (2014)

Q 32.6 Wed 12:15 f342

Optimizing thiol DNA-gold reaction using whispering gallery microcavities — ●EUGENE KIM, MARTIN D. BAASKE, and FRANK VOLLMER — Max-Planck-Institute for the science of light

In this work, the transient kinetics of thiol DNA-gold interactions in aqueous environment are studied at the single-molecule level utilizing high Q plasmonic-photon whispering gallery mode microcavities. Three different regimes of thiol-gold interactions were found depending on the environmental conditions. Statistical analysis of the detection frequency, dwell-/binding-time, and size distribution of transient interactions with respect to their dependence on pH and electrolyte concentration allow us for the optimization of thiol-gold bonding.

Q 32.7 Wed 12:30 f342

Detection and simulation of optoacoustic signals generated in layered tissues — ●O. MELCHERT, E. BLUMENROETHER, M. WOLLWEBER, M. RAHLVES, and B. ROTH — Hannover Centre for Optical Technologies, Leibniz Universität Hannover, Hannover, Germany

The absorption of electromagnetic waves by media induces a spatial pressure distribution, proportional to the density of the deposited energy, followed by thermoelastic expansion and emission of acoustic waves. While the deposition of energy is assumed to be instantaneous, the propagation of acoustic waves is determined by the sound velocity of the material. From a theoretical point of view, the resulting mathematical problem is governed by an inhomogeneous wave equation featuring an optoacoustic source term.

Here, we consider optically inhomogeneous, i.e. layered media, where scattering is effectively negligible and the absorbed energy density follows Beer-Lambert's law, i.e. is characterized by an exponential decay within the layers and discontinuities at interfaces. We complement test experiments on samples where the material properties are known *a priori*, with numerical simulations based on solving the optoacoustic wave equation, tailored to suit our experimental setup. Experimentally we characterize the acoustic signal observed by a piezoelectric detector in the acoustic far-field in backward mode and we discuss the implication of acoustic diffraction on our measurements as well as possibilities to retrieve the absorption coefficient from measurements in the forward mode.

Q 32.8 Wed 12:45 f342

Simulation of the OCT-depth signal of homogeneous turbid media via an extended Monte-Carlo model — ●ARTHUR VARKENTIN, MAYA OTTE, MERVE WOLLWEBER, MAIK RAHLVES, and BERNHARD ROTH — Hannoversches Zentrum für Optische Technologien - HOT, Leibniz Universität Hannover, Germany

Optical coherence tomography (OCT) is widely used for imaging of biological tissue. In most cases the result is a 2D or 3D tomogram showing scattering structures of the studied sample. This qualitative information indicates the morphology of the tissue. The extraction of quantitative information such as the scattering coefficient μ_s is straight forward only for weakly scattering media where ballistic photon scattering can be assumed. For highly scattering media, however, additional phenomena have to be taken into account. For example, multiple scattering has to be considered, where photons that are scattered more than once, but are still within the coherence length of the OCT also contribute to the signal. A cluster of equal scatterers can appear as one single scatterer with different optical properties. These effects lead to concentration dependent scattering which shows non-linear behavior. We present a simple model to simulate OCT-depth signals in weakly and strongly scattering media. Multiple scattering is implemented and, in addition, a weighting function rescales the photon signal according to the number of undergone scattering events. Based on a parameter study of this weighting function we are able to implicitly predict the influence of dependent scattering without modeling the process explicitly. In future, our quantitative approach could improve biological imaging.

Q 33: Quantum Effects: Entanglement and Decoherence I

Time: Wednesday 11:00–13:00

Location: f442

Q 33.1 Wed 11:00 f442

Ancilla-assisted preparation of steady-state entanglement — ●JOACHIM FISCHBACH and MATTHIAS FREYBERGER — Institut für Quantenphysik, Universität Ulm, D-89069 Ulm, Germany

The dissipative creation of entanglement is a promising field of research, that has seen many theoretical advances as well as experimental verifications in the last years. Dissipatively preparing an entangled state is not only an every day task for protocols in quantum information theory, but also bears interesting fundamental questions about how decoherence can counter-intuitively lead to entanglement. In our work [1], we show how the bipartite entanglement in a system of two two-level systems can be enhanced by coupling it with a dissipative ancilla. The steady-state is furthermore analyzed in terms of the eigenstates of the Hamiltonian, describing system and ancilla without environment. In this picture we are able to give an explanation for the enhancement effect. This could not only be used for practical purposes, like preparing entangled states, but also for further research of how engineered environments can be used for dissipative state preparation.

[1] J. Fischbach, M. Freyberger, *Phys. Rev. A* **92**, 052327 (2015)

Q 33.2 Wed 11:15 f442

Entanglement through complex photonic environments — ●SVEN MORITZ HEIN^{1,2}, CAMILLE ARON^{2,3,4}, HAKAN E. TÜRECI², ANDREAS KNORR¹, and ALEXANDER CARMELE¹ — ¹Institut für theoretische Physik, Technische Universität Berlin, Hardenbergstraße 36, 10623 Berlin, Deutschland — ²Department of Electrical Engineering, Princeton University, Princeton, NJ 08544, USA — ³Laboratoire de Physique Théorique, École Normale Supérieure, CNRS, 24 rue Lhomond, 75005 Paris, France — ⁴Instituut voor Theoretische Fysica, KU Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium

Creating, controlling and stabilizing nonclassical entangled states is one of the main challenges in current quantum optics. A promising approach is to couple the quantum-optical system to a non-Markovian reservoir to induce frequency-dependent dissipative dynamics. We present two approaches that utilize non-Markovian reservoirs to create and stabilize qubit entanglement. One is based upon time-delayed quantum-coherent feedback [1], which acts upon single qubits in a quantum network [2]. The second one uses resonant Raman scattering to counteract dephasing in qubits coupled to cavity modes, based upon a recent proposal of Aron *et al.* [3].

- [1] Pyragas, K., Phys. Lett. A **6**, 421–428 (1992)
 [2] Hein, S., *et al.*, Phys. Rev. A **91**, 052321 (2015)
 [3] Aron, C. *et al.*, Phys. Rev. A **90**, 062305 (2014)

Q 33.3 Wed 11:30 f442

Effects of Local Measurements on Quantum Statistical Ensembles — ●WALTER HAHN¹ and BORIS FINE^{1,2} — ¹Institute for Theoretical Physics, University Heidelberg, Germany — ²Skolkovo Institute of Science and Technology, Moscow, Russia

We investigate the effect of local measurements on quantum statistical ensembles for macroscopic systems. The system chosen is a lattice of spins 1/2 subject to projective measurements of individual spins. We find that the effect of measurements depends on system's Hamiltonian and on the initial statistical ensemble. The above findings justify prescriptions for protecting unconventional statistical ensembles.

Q 33.4 Wed 11:45 f442

Controlled generation of multipartite quantum correlations in a large spin ensemble — ●JOHANNES GREINER, DURGA DASARI, and JÖRG WRACHTRUP — 3. Phys. Institut, Universität Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart

The complex behavior of many body dynamics offers new insights into the emergence of correlated clusters, spread of entanglement and in general to non-equilibrium phenomena of quantum systems. We show how color centers in diamond can be used as a testbed to study these phenomena in a well-controlled fashion. Within the central spin model comprised of the spin states of a Nitrogen-Vacancy center in diamond coupled to a spin-ensemble, we show how correlated states can be generated and analyse them using entanglement witnesses. For finite ensemble sizes these states can also be used for quantum error correction and state transport.

Q 33.5 Wed 12:00 f442

Detection of Bell correlations in a spin-squeezed Bose-Einstein condensate — ●MATTEO FADEL¹, ROMAN SCHMIED¹, JEAN-DANIEL BANCAL¹, BAPTISTE ALLARD¹, VALERIO SCARANI², PHILIPP TREUTLEIN¹, and NICOLAS SANGOUARD¹ — ¹University of Basel, Switzerland — ²National University of Singapore, Singapore

The results of measurements by different observers can show correlations that are stronger than any classical theory allows. These Bell correlations can be confirmed by violating a Bell inequality, for which quantum entanglement is not sufficient.

A family of Bell inequalities has recently been proposed that requires only single- and two-particle measurements even for many-body systems [1]. Based on this work, we present the first experimental observation of Bell correlations in squeezed states of a two-mode Bose-Einstein condensate (BEC).

The system consists of a two-component 87Rb BEC of a few hundred atoms created on an atom-chip [2]. A state-selective potential gives rise to nonlinear one-axis twisting dynamics, which we use to prepare spin-squeezed states of the condensate, with up to 7dB of squeezing according to the Wineland criterion.

We measure the first and second moments of the collective spin operator along several axes. These measurement results demonstrate the presence of Bell correlations in our system by more than three standard deviations [3].

[1]J. Tura, *et. al.* Science 344, 1256 (2014) [2]M.F. Riedel, *et. al.* Nature 464, 1170 (2010) [3]R. Schmied, *et. al.* submitted (2015)

Q 33.6 Wed 12:15 f442

Simulating spin-boson models with trapped ions — ●ANDREAS LEMMER¹, CECILIA CORMICK², SUSANA HUELGA¹, TOBIAS SCHAEZT³, and MARTIN BODO PLENIO¹ — ¹Institut für Theoretische Physik, Universität Ulm, Germany — ²FaMAF, National University of Cordoba, Argentina — ³Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Germany

The spin-boson model is a paradigmatic model for the emergence of

dissipation and decoherence in quantum mechanics and has motivated a lot of research in the past and present [1]. Still, no closed analytic solution of the model's Hamiltonian is known. On the other hand, it is known that the dynamics of the model is fully determined by the so-called spectral density of the environment [1]. Here, we propose a method to simulate environments with continuous spectral densities in the setup of trapped ions using mixed species crystals and a small set of damped modes. In comparison with previous proposals [2] this has the advantage of reducing the experimental complexity and therefore moves the study of the statistical mechanics of the spin-boson model firmly into the realm of current ion trap technology.

[1] U. Weiss, Quantum Dissipative Systems (World Scientific, Singapore, 2008) Third Edition

[2] D. Porras *et al.*, Phys. Rev. A **78**, 010101(R) (2008)

Q 33.7 Wed 12:30 f442

Multi-qubit Zeno subspaces through repetitive projections — ●NORBERT KALB¹, JULIA CRAMER¹, DANIEL TWITCHEN², MATTHEW MARKHAM², RONALD HANSON¹, and TIM TAMINIAU¹ — ¹QuTech and Kavli Institute of Nanoscience, Delft, The Netherlands — ²Element Six Innovation, Oxford, United Kingdom

Quantum superposition states are susceptible to decoherence due to interactions with the environment. Generally, these interactions are uncontrolled and undesired: they cause a rapid loss of the phase of the quantum state and the associated information. Here we experimentally demonstrate that adding a strong channel of decoherence in the form of repeated projections of multi-qubit operators can actually protect complex quantum states from environmental decoherence.

We create quantum states of up to three ¹³C nuclear spins in diamond [1] using a nitrogen vacancy center and repetitively project a joint observable of the nuclear spins. This projection freezes the unwanted evolution due to the environment through the Quantum Zeno effect, while leaving the remaining degrees of freedom available to encode multiple protected logical quantum bits, including entangled states. We quantify the suppression of dephasing through the derivation and experimental verification of a number-independent scaling law. This result enables the exploration of quantum computations with multiple logical quantum bits and studying complex spin dynamics under engineered decoherence.

[1] T.H. Taminiu *et al.*, Nature Nanotech. **9**, 171, 2014

Q 33.8 Wed 12:45 f442

Testing No-signalling principle in an optical parity-time symmetric system — ●LIDA ZHANG and JÖRG EVERS — Max Planck Institute for Nuclear Physics, 69117 Heidelberg

As compared to traditional Hermitian dynamics, recently, a new class of Hamiltonians respecting parity-time (PT) reflection symmetry have revealed a great variety of fascinating phenomenon in optical system, i.e., nonreciprocal propagation, negative refractive index, etc.. We propose a novel scheme to test no-signalling principle in an atomic system where an optical PT-symmetric Hamiltonian is formed. We first create a vector laser beam pair having inseparable structures with respect to the different degrees of freedom, i.e., space distribution and polarization, which serves as a classical analogy of quantum-entangled state. The beam pair then passes through two different paths, where the laser beam experiences PT-symmetric evolution at one path and Hermitian evolution at the other. Finally, the beam pair is detected at two stations called "PT" and "Hermitian", which are remote from each other. It is found that the single probability detected at the "Hermitian" station is not equal to the summation of joint probabilities over the "PT" station, thus violating the no-signalling principle. Since the detection is independent from the evolution process, we thus find that the no-signalling violation originates from the non-Hermiticity of the optical PT-symmetric Hamiltonian. Furthermore, based on the analytical findings, we show that there is linear correlation between the parameter characterizing no-signalling violation and the order parameter defining the PT-symmetry transition.

Q 34: Annual General Meeting: Quantum Optics and Photonics

Time: Wednesday 13:15–14:15

Location: a310

Annual General Meeting

Q 35: Laser Development II

Time: Wednesday 14:30–16:00

Location: a310

Q 35.1 Wed 14:30 a310

Kontinuierliches Summen-Differenzfrequenzmischen zu 185 nm in Quecksilberdampf — ●SASCHA RAU, PATRICK BACHOR, THOMAS DIEHL, MATTHIAS STAPPEL, RUTH STEINBORN und JOCHEN WALZ — Johannes Gutenberg-Universität Mainz und Helmholtz-Institut Mainz, D-55099 Mainz

Laserlichtfelder bei Wellenlängen von 254 nm und 408 nm können in Quecksilberdampf sowohl über eine doppelte Einphotonenresonanz als auch über eine Zweiphotonenresonanz eine Population im 7^1S -Niveau erzeugen. Zwischen diesem und dem 6^1P -Niveau kann eine Besetzungsinversion entstehen, die zu verstärkter spontaner Emission (ASE) bei einer Wellenlänge von 1014 nm führt. Durch Summen-Differenzfrequenzmischung (SDFG) dieser drei Lichtfelder kann kontinuierliche Strahlung bei einer Wellenlänge von 185 nm erzeugt werden.

In Rubidium konnte SDFG, bei der eines der Lichtfelder durch ASE im Medium erzeugt wird, bereits demonstriert werden. Aufgrund der im Vergleich zum Rubidiumschemata um mehrere Größenordnungen höheren Übergangslinienstärke des 6^1P -Niveaus in den Grundzustand, bildet die Reabsorption des erzeugten Lichtfelds in Quecksilberdampf einen Konkurrenzprozess zur SDFG. Durch Einstrahlung und Nutzung eines externen, blauverstimmtten, infraroten Laserlichtfelds soll diese Problematik umgangen werden. Damit ließe sich eine durchstimmbare, kontinuierliche Laserlichtquelle bei einer Wellenlänge von 185 nm erzeugen und die erzeugte, nutzbare Leistung steigern.

Es wird der aktuelle Stand des Experiments präsentiert.

Q 35.2 Wed 14:45 a310

Adaptive optics with a thermally activated mirror for the correction of phase front disturbances in high-power laser systems — ●RICHARD LANGE, DANIEL SAUDER, and DANIEL KOLBE — DLR, Institut für Technische Physik, Pfaffenwaldring 38-40, 70569 Stuttgart

In a solid state laser system high pump powers can result in strong temperature gradients affecting the phase front of the beam due to deformation and locally varying refractive indices in the active medium. A dynamic correction process is desirable in order to compensate distortions at different pumping powers. Here we present an adaptive optics (AO) system applicable to high power beams. Main component of the system is a mirror that consists of a colored glass absorbing below 900 nm and a coating which is highly reflective above 950 nm. It can be heated and deformed by the intensity distribution of an 808 nm beam that has been modulated via a DMD. The resolving capacities of the AO have been analyzed and measures taken to improve them. In the next step, the performance of the AO correcting an incoming wave modified with defined distortions will be investigated. In future, the system will be implemented into a thin-disk amplifier to compensate phase aberrations of the active medium. The current status of the project is presented.

Q 35.3 Wed 15:00 a310

A FPGA-based single laser atom-cooling system — ●WOLFGANG BARTOSCH, HOLGER AHLERS, THIJS WENDRICH, WOLFGANG ERTMER, and ERNST RASEL — Leibniz Universität Hannover

Atom optic experiments usually require frequency stabilized light with several wavelengths. For example, the cooling and trapping of ^{87}Rb atoms in a magneto-optical trap requires typically three lasers. One for the actual atom cooling, one to re-excite atoms that decayed in a dark state far from the cooling cycle (repumping) and one to reference the absolute frequency of the other lasers to a spectroscopy. Here a system that unifies these tasks in a single laser, by making fast frequency jumps with 100 μs cycle time is demonstrated. The system is realized with a digital, FPGA-based feed-forward filter to control the DFB laser and is able to suppress short-term thermal drifts after a jump. A system like this can ease the development of apparatuses for atom interferometry as well as for commercial laser applications.

This work is part of the LASUS project which is supported by the

German Space Agency DLR with funds provided by the Federal Ministry of Economic Affairs and Energy (BMWi) under grant number 50WM1239.

Q 35.4 Wed 15:15 a310

Power stabilization for the AEI 10m Prototype using a photodiode array — ●JONAS JUNKER — Max-Planck-Institute for Gravitational Physics (AEI)

Low noise lasers are essential for sensitive interferometric experiments. A highly sensitive 10m long laser interferometer is set up at the Albert Einstein Institute (AEI) in Hannover designed to reach the standard-quantum limit of interferometry. Therefore a laser source with a relative power noise as low as $2 \cdot 10^{-9} \text{ Hz}^{-1/2}$ is required. A 35W laser system with a wavelength of 1064nm is used and will be stabilized with an active control loop. To reduce the shot noise level at the control loop's sensor four in-loop and four out-of-loop photodiodes have to be used. We will present the experimental realization and the preliminary results.

Q 35.5 Wed 15:30 a310

Compact mode-locked diode laser system for precision frequency comparison in microgravity — ●HEIKE CHRISTOPHER^{1,2}, EVGENY KOVALCHUK^{1,2}, ANDREAS WICHT^{1,2}, GÜNTHER TRÄNKLE², and ACHIM PETERS^{1,2} — ¹Humboldt-Universität zu Berlin — ²Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik, Berlin

We have developed a compact mode-locked diode laser to generate an optical frequency comb in the wavelength range of 780 nm. It is designed for use in precision experiments in microgravity testing the universality of free fall (UFF) using light pulse atom interferometry for Potassium and Rubidium ultra-cold quantum gases.

The extended-cavity diode laser contains an AlGaAs ridge-waveguide diode chip, aspheric micro-optics for collimation and an external dielectric mirror. Passive mode-locking is realized by reverse biasing a short section of the structured laser diode. A broadband spectral output of more than 15 nm at -20 dB level was achieved. Nearly zero group velocity dispersion (GVD) of the external mirror allows for a highly stable pulse performance at a repetition rate of about 3.4 GHz and pulse widths of approx. 5 ps. We present the current status of our work and discuss options for further improvements, e.g. extending the spectral bandwidth even further as well as active stabilization of the mode-locking process.

This project is supported by the German Space Agency DLR, with funds provided by the Federal Ministry for Economic Affairs and Energy (BMWi) under grant numbers 50WM1237-1240.

Q 35.6 Wed 15:45 a310

Einfrequente 2 μm Laser mit hoher Pulsenergie für Lidar — ●CHRISTOPH BOLLIG — Abacus Laser, Hannah-Vogt-Str. 1, 37085 Göttingen, Deutschland — CSIR National Laser Centre, Pretoria, Südafrika

Einfrequente gütegeschaltete Pulse im augensicheren Wellenlängenbereich um 2 μm sind von hohem Interesse für Lidaranwendungen, insbesondere für die Fernmessung von Wind. So bereitet zum Beispiel die NASA eine Mission vor, bei der mit einem 2 μm Laser die globalen Windfelder vom Weltraum aus vermessen werden sollen.

Die „Laser Sources“ Forschungsgruppe am CSIR National Laser Center in Südafrika hat ausgiebig in diesem Bereich geforscht und eine Reihe von einfrequenz gepulsten 2 μm Lasern entwickelt. TEM₀₀ Pulse mit bis zu 330 mJ bei 50 Hz wurden mit einem Ho:YLF Slab-Verstärker erzielt, welches die höchste je erreichte einfrequente Pulsenergie bei 2 μm ist.

Der Vortrag gibt eine Einführung in einfrequenz gütegeschalteten Laserbetrieb und Strategien zur Energieskalierung von 2 μm Lasern. Ein Überblick über die während des fünfjährigen Forschungsprojektes erzielten Ergebnisse wird präsentiert.

Q 36: Quantum Gases: Bosons IV

Time: Wednesday 14:30–16:15

Location: e001

Q 36.1 Wed 14:30 e001

Generation and Detection of Atomic Spin Entanglement in Optical Lattices — ●HAN-NING DAI^{1,2,3}, BING YANG^{1,2,3}, ANDREAS REINGRUBER^{1,4}, YU-AO CHEN^{2,3}, ZHEN-SHENG YUAN^{2,3,1}, and JIAN-WEI PAN^{2,3,1} — ¹Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany — ²Hefei National Laboratory for Physical Sciences at Microscale and Department of Modern Physics, University of Science and Technology of China, Hefei, Anhui 230026, China — ³CAS Centre for Excellence and Synergetic Innovation Centre in Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei, Anhui 230026, China — ⁴Department of Physics and Research Center OPTIMAS, University of Kaiserslautern, Erwin-Schrodinger-Strasse, Building 46, 67663 Kaiserslautern, Germany

We report on the generation, manipulation and detection of atomic spin entanglement in an optical superlattice. Spin entanglement of the two atoms in the double wells of the superlattice is generated via dynamical evolution governed by spin superexchange. By observing collisional atom loss with in-situ absorption imaging we measure spin correlations of atoms inside the double wells and obtain the lower boundary of entanglement fidelity as 0.79 ± 0.06 , and the violation of a Bell's inequality with $S = 2.21 \pm 0.08$. The above results represent an essential step towards scalable quantum computation with ultracold atoms in optical lattices.

Q 36.2 Wed 14:45 e001

Many body localization of bosons in a two dimensional square lattice — ●JAE-YOON CHOI¹, SEBASTIAN HILD¹, JOHANNES ZEIHNER¹, ANTONIO RUBIO ABADAL¹, IMMANUEL BLOCH^{1,2}, and CHRISTIAN GROSS¹ — ¹Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany — ²Fakultät für Physik, Ludwig-Maximilians-Universität München, Schellingstraße 4, 80799 München, Germany

Under which conditions well isolated quantum systems do thermalize is a fundamental question. Many-body localization (MBL) marks a general class of systems which do not thermalize. Microscopic detection of diverging observables near the phase transition remains experimentally challenging, and demonstration of the MBL in higher dimensions is still demanding. We report on recent experiments on many body localization of Bosons in a two dimensional square lattice geometry. We prepare a structured highly excited Mott insulating state which relaxes to a thermal state for vanishing disorder. A projected on-site random disorder potential changes the time evolution significantly and leads to localization. Local observables down to the single atom and single lattice site are used to quantify the temporal changes of the bosonic many body state for different disorder strength.

Q 36.3 Wed 15:00 e001

A Thouless quantum pump with ultracold bosonic atoms in an optical superlattice — ●MICHAEL LOHSE^{1,2}, CHRISTIAN SCHWEIZER^{1,2}, ODED ZILBERBERG³, MONIKA AIDELSBURGER^{1,2}, and IMMANUEL BLOCH^{1,2} — ¹Fakultät für Physik, LMU München, Germany — ²Max-Planck-Institut für Quantenoptik, Garching, Germany — ³Institut für Theoretische Physik, ETH Zürich, Switzerland

Topological charge pumping enables the transport of charge through an adiabatic cyclic evolution of the underlying Hamiltonian. In contrast to classical transport, the transported charge is quantized and purely determined by the topology of the pump cycle, making it robust to perturbations. Here, we report on the realization of such a pump with ultracold bosonic atoms forming a Mott insulator in a dynamically controlled optical superlattice. By taking in situ images of the cloud, we observe a quantized deflection per pump cycle. We reveal the pump's genuine quantum nature by showing that, in contrast to groundstate particles, a counterintuitive reversed deflection occurs for particles in the first excited band. Furthermore, we directly demonstrate that the system undergoes a controlled topological transition in higher bands when tuning the superlattice parameters. These results open a route to the implementation of more complex pumping schemes, including spin degrees of freedom and higher dimensions.

Q 36.4 Wed 15:15 e001

Reservoir induced topological order and quantized charge

pumps in open lattice models with interactions — ●DOMINIK LINZNER¹, MALTE KOSTER¹, FABIAN GRUSDITZ², and MICHAEL FLEISCHHAUER¹ — ¹Fachbereich Physik und Forschungszentrum OPTIMAS, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Deutschland — ²Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

Since the discovery of the quantum Hall effect, topological states of matter have attracted the attention of scientists in many fields of physics. By now there is a rather good understanding of topological order in closed, non-interacting systems. In contrast the extension to open systems in particular with interactions is entirely in its infancy. Recently there have been advances in characterizing topology in reservoir driven systems without interactions [1], but the topological invariants introduced lack a clear physical interpretation and are restricted to non-interacting systems. We consider a one-dimensional interacting topological system whose dynamics is entirely driven by reservoir couplings. By slowly tuning these couplings periodically in time we realize an open-system analogue of the Thouless charge pump [2] that proves to be robust against unitary and non-unitary perturbations. Making use of this Thouless pump we introduce a topological invariant, which has a clear physical meaning and is applicable to interacting systems.

[1]C.E. Bardyn, et al., New J. Phys. 15, 085001 (2013)

[2]D. J. Thouless, Phys. Rev. B 27, 6083 (1983)

Q 36.5 Wed 15:30 e001

Coherent interaction of a Bose-Einstein condensate with two crossed cavity modes — ●JULIAN LEONARD, ANDREA MORALES, PHILIP ZUPANCIC, TILMAN ESSLINGER, and TOBIAS DONNER — Institute for Quantum Electronics, ETH Zürich, Switzerland

Coupling a quantum gas to the field of a single high-finesse optical cavity gives rise to interactions of infinite range between the atoms, which can create a self-organized state when exceeding a critical strength. It is desirable to tune range and directionality of these interactions, which enables explorations of more complex self-organized states or quantum soft matter physics, such as superfluid glasses and associative memory. However, this requires extending the atom-photon interactions to multiple cavity modes.

We report on the realization of such an extended system, involving a Bose-Einstein condensate coupled to two crossed cavities modes. This already allows to spatially shape the interactions, leading to multiple new crystalline phases, e.g. with hexagonal, triangular or stripe order.

Q 36.6 Wed 15:45 e001

Heating rates of interacting Bosons in shaken optical lattices — ●JAKOB NÄGER^{1,2}, MARTIN REITTER^{1,2}, LUCIA DUCA^{1,2}, TRACY LI^{1,2}, MONIKA SCHLEIER-SMITH⁴, IMMANUEL BLOCH^{1,2}, and ULRICH SCHNEIDER³ — ¹Ludwig-Maximilians-Universität München, Schellingstr. 4, 80687 München — ²Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 85748 Garching — ³University of Cambridge, Cambridge, UK — ⁴Stanford University, Stanford, CA 94305, Vereinigte Staaten

Periodically driven systems have been successfully used to implement topological band structures with non-zero Chern numbers for non-interacting neutral particles. The extent to which the engineered topological properties survive in the presence of interactions, and which many-body phases result, remains however a largely open question. In order to experimentally control the interactions, and to study the resulting many-body physics, we prepare a BEC of 39K which has an accessible Feshbach resonance. By tuning the interactions as well as the driving strengths and frequencies, we can systematically explore the non-equilibrium dynamics in a shaken 1D lattice as well as in a shaken honeycomb lattice.

Q 36.7 Wed 16:00 e001

Quantum phases emerging from competing short- and long-range interactions in an optical lattice — ●LORENZ HRUBY, RENATE LANDIG, NISHANT DOGRA, MANUELE LANDINI, RAFAEL MOTTL, TOBIAS DONNER, and TILMAN ESSLINGER — Quantumoptics group, Institute for Quantum Electronics, ETH Zurich, Switzerland

We experimentally realize a bosonic lattice model with competing short- and infinite-range interactions, and observe the appearance of

four distinct phases - a superfluid, a supersolid, a Mott insulator and a charge density wave. Our system is based on a Bose-Einstein condensate trapped in an optical lattice inside a high Finesse optical cavity. The strength of the short-ranged on-site interactions is controlled by means of the optical lattice depth. The infinite-range interaction

potential is mediated by a vacuum mode of the cavity and is independently controlled by tuning the cavity resonance. When probing the phase transition between the Mott insulator and the charge density wave in real-time, we discovered a behavior characteristic of a first order phase transition.

Q 37: Quantum Information: Concepts and Methods VI

Time: Wednesday 14:30–16:30

Location: e214

Q 37.1 Wed 14:30 e214

Topological entanglement entropy and the Jones-Kosaki-Longo index — ●LEANDER FIEDLER¹ and PIETER NAAIJKENS^{2,3} — ¹Institut für Theoretische Physik, Leibniz Universität Hannover, Germany — ²Department of Mathematics, University of California, Davis, USA — ³Institute for Quantum Computing, RWTH Aachen, Germany

In the thermodynamic limit of quantum spin systems with anyonic charge content a characteristic quantity is the Jones-Kosaki-Longo index. This index was derived from the algebraic properties of the theory and is equal to the quantum dimension of the anyonic model. We show how it relates to the topological entanglement entropy derived for finitely many particles and thereby provide an operational interpretation in terms of a data hiding task.

Q 37.2 Wed 14:45 e214

Evaluation of convex roof entanglement measures — ●GÉZA TÓTH^{1,2,3}, TOBIAS MORODER⁴, and OTFRIED GÜHNE⁴ — ¹Theoretical Physics, University of the Basque Country UPV/EHU, E-48080 Bilbao, Spain — ²IKERBASQUE, Basque Foundation for Science, E-48011 Bilbao, Spain — ³Wigner Research Centre for Physics, H-1525 Budapest, Hungary — ⁴Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Straße 3, 57068 Siegen, Germany, Germany

We show a powerful method to compute entanglement measures based on convex roof constructions. In particular, our method is applicable to measures that, for pure states, can be written as low order polynomials of operator expectation values. We show how to compute the linear entropy of entanglement and the convex roof of the three-tangle for three-qubit states, and several other useful quantities. Our method is based on showing that the quantities above can be defined as a result of an optimisation over the set of symmetric separable states. This implies that calculating certain entanglement measures based on convex roofs is essentially as difficult as identifying separable states in symmetric systems.

Q 37.3 Wed 15:00 e214

Upper bound for SL-invariant entanglement measures for mixed states of arbitrary rank — ●ANDREAS OSTERLOH — Universität Duisburg-Essen, Lotharstr. 1, 47048 Duisburg, Germany.

I present an alternative algorithm to ref. [1], exploiting the knowledge obtained for the rank-two case. Whereas the known algorithm has an advantage of taking into consideration the whole range of the density matrix ρ , it on the other hand has the disadvantage of searching in a high-dimensional Hilbert space: imagine the states $|\psi_i\rangle$, where $E[|\psi_i\rangle]$ vanishes; the algorithm then calculates the distance to the barycenter of them as an upper bound of E , which comes with a disadvantage, of course.

Here, I only consider rank two states but calculate the upper bound obtained by the method presented in [2,3]. I discuss examples where the advantage of the new algorithm is obvious, but also highlight on the obvious disadvantage of only considering rank two parts of ρ .

[1] S. Rodrigues, N. Datta, and P. Love, Phys. Rev. A **90**, 012340 (2014).

[2] R. Lohmayer, A. Osterloh, J. Siewert, and A. Uhlmann, Phys. Rev. Lett. **97**, 260502 (2006).

[3] A. Osterloh, J. Siewert, and A. Uhlmann, Phys. Rev. A **77**, 032310 (2008).

Q 37.4 Wed 15:15 e214

The nine ways of four qubit entanglement and their three-tangle — ●ANDREAS OSTERLOH — Universität Duisburg-Essen, Lotharstr. 1, 47048 Duisburg, Germany.

The mixed threetangle for the nine four qubit representant states found in Phys. Rev. A **65**, 052112 (2002) is calculated. The convex roof is

found exactly in seven out of nine classes. In two classes an upper bound for the threetangle is found, where I have strong evidence that it is at least not far away from the convex roof. We compare our results with the findings of Phys. Rev. Lett. **113**, 110501 (2014).

Q 37.5 Wed 15:30 e214

Optimal detection of useful quantum entanglement with few expectation values — ●IAGOBA APELLANIZ¹, MATTHIAS KLEINMANN¹, OTFRIED GÜHNE², and GÉZA TÓTH^{1,3,4} — ¹Department of Theoretical Physics, University of the Basque Country, Bilbao, Spain — ²Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Siegen, Germany — ³IKERBASQUE, Basque Foundation for Science, Bilbao, Spain — ⁴Wigner Research Center for Physics, Hungarian Academy of Sciences, Budapest, Hungary.

In this work we show an optimal lower bound for the quantum Fisher information (qFI), $\mathcal{F}_Q[\rho, J_z]$, for a given set of expectation values of the initial state, $\{w_i = \text{tr}(\rho \tilde{W}_i)\}_{i=1}^M$.

It is well known that a complete state tomography of an increasing number of particles becomes unfeasible. Therefore, different simplifying techniques have been developed recently in order to evaluate the qFI based on few expectation values of the initial state [1,2].

We apply our method to the results of various multi-particle quantum states prepared in experiments with photons and trapped ions. We also verify with our method the saturability of the archetypical lower bound for spin squeezed states [3].

[1] Z. Zang and L. M. Duan, New J. Phys. **16** 103037, (2014).

[2] F. Fröwis *et al.*, arxiv: 1509.0333, (2015).

[3] L. Pezzé and A. Smerzi, Phys. Rev. Lett. **102** 100401, (2009).

Q 37.6 Wed 15:45 e214

Quantifying entanglement of two-qutrit states with positive partial transpose — CHRISTOPHER ELTSCHKA¹, ●GAÉL SENTIS², and JENS SIEWERT^{2,3} — ¹University of Regensburg, Regensburg, Germany — ²University of the Basque Country UPV/EHU, Bilbao, Spain — ³Ikerbasque, Basque Foundation for Science

A bipartite system with local dimensions $d \geq 3$ may be in an entangled state albeit its partially transposed density matrix has only non-negative eigenvalues. Such PPT-entangled states constitute a subject of continued interest in quantum information since, e.g., no singlet entanglement can be distilled from them. As PPT-entangled states in general are highly mixed the quantification of their entanglement in terms of established entanglement measures has remained an open question. In this contribution we present a family of highly symmetric two-qutrit states which contains regions with PPT entanglement. We discuss the possibility of exact quantification of the entanglement by using concurrence-based entanglement monotones.

Q 37.7 Wed 16:00 e214

Anticoherence and entanglement of spin states — ●JOHN MARTIN¹, DORIAN BAGUETTE¹, FRANÇOIS DAMANET¹, THIERRY BASTIN¹, and OLIVIER GIRAUD² — ¹Institut de Physique Nucléaire, Atomique et de Spectroscopie, Université de Liège, 4000 Liège, Belgium — ²LPTMS, CNRS, Univ. Paris-Sud, Université Paris-Saclay, 91405 Orsay, France

We investigate multiqubit permutation-symmetric states with maximally mixed reduced density matrices in the symmetric subspace [1]. Such states can be viewed as particular spin states, namely anticoherent spin states [2]. Using the Majorana representation of spin states in terms of points on the unit sphere [3], we analyze the consequences of degeneracies of the Majorana points and of a point-group symmetry in their arrangement on the existence of anticoherent spin states. We provide different characterizations of anticoherence and establish a link between point symmetries, anticoherence, and SLOCC classes [4].

We consider in detail the case of small numbers of qubits and solve the 4-qubit case completely by identifying and characterizing all 4-qubit anticonherent states.

[1] D. Baguette, T. Bastin, and J. Martin, *Phys. Rev. A* **90**, 032314 (2014); O. Giraud *et al.*, *Phys. Rev. Lett.* **114**, 080401 (2015); D. Baguette *et al.*, *Phys. Rev. A* **92**, 052333 (2015).

[2] J. Zimba, *Electron. J. Theor. Phys.* **3**, 143 (2006).

[3] E. Majorana, *Nuovo Cimento* **9**, 43 (1932).

[4] SLOCC classes : Classes of states equivalent through stochastic local operations with classical communication.

Q 37.8 Wed 16:15 e214

Proving multipartite entanglement from separable marginals

— ●MARIUS PARASCHIV, NIKOLAI MIKLIN, TOBIAS MORODER, and OTFRIED GÜHNE — Universität Siegen Department Physik Emmy-

Noether-Campus Walter-Flex-Straße 3 57068 Siegen Germany

We address here the question of whether or not global entanglement of a quantum state can be inferred from local properties. Specifically, we are interested in genuinely entangled multipartite states whose two-body marginals are separable. Due to the fact that any biseparable state is also a PPT mixture, we can focus only on the class of fully decomposable entanglement witnesses. This type of witness is positive for all PPT mixtures. The problem thus formulated naturally falls within the field of semidefinite programming (SDP). By running an iteration over two different SDPs, one for the global quantum state with PPT two-body marginals, the other for the witness, fully decomposable and restricted to two-body interactions, we have found states that obey the above requirements for up to 6 qubits. We present an analytical construction of such states for an arbitrary number of particles.

Q 38: Ultra-cold atoms, ions and BEC II (with A)

Time: Wednesday 14:30–16:30

Location: f303

Q 38.1 Wed 14:30 f303

Time-resolved Scattering of a Single Photon by a Single Atom

— ●VICTOR LEONG^{1,2}, MATHIAS ALEXANDER SEIDLER¹, MATTHIAS STEINER^{1,2}, ALESSANDRO CERÉ¹, and CHRISTIAN KURTSIEFER^{1,2} — ¹Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, Singapore 117543 — ²Department of Physics, National University of Singapore, 2 Science Drive 3, Singapore 117542

The efficiency of light-matter interfaces between single photons and single atoms depends on the bandwidth and temporal shape of the single photon, and is crucial for realistic implementations of many quantum information protocols. In particular, an exponentially rising single photon is predicted to excite a single atom with a higher efficiency compared to any other temporal shape [1].

A four-wave mixing photon pair source, in conjunction with an asymmetric cavity, generates heralded single photons of tunable bandwidth with exponentially decaying or rising shapes [2,3]. We combine the photon pair source with a trapped single atom and investigate the free space scattering for different bandwidths and temporal shapes.

We study the scattering dynamics by measuring the atomic emission and the reduction in the number of transmitted photons. We observe that the atomic absorption dynamics are imprinted in the single-photon excitation mode.

[1] Y. Wang *et al.*, *PRA* **83**, 063842 (2011)

[2] B. Srivathsan *et al.*, *PRL* **111**, 123602 (2013)

[3] B. Srivathsan *et al.*, *PRL* **113**, 163601 (2014)

Q 38.2 Wed 14:45 f303

Fermi-Bose mixture of ⁶Li and ⁴¹K

— RIANNE S. LOUS^{1,2}, ●ISABELLA FRITSCHÉ^{1,2}, BO HUANG¹, MICHAEL JAG^{1,2}, MARKO CETINA^{1,2}, JOOK T.M. WALRAVEN^{1,3}, and RUDOLF GRIMM^{1,2} — ¹Inst. for Quantum Optics and Quantum Information (IQOQI), Austrian Academy of Science, Austria — ²Inst. for Experimental Physics, University of Innsbruck, Austria — ³Van der Waals-Zeeman Institute, Institute of Physics, University of Amsterdam, Amsterdam, Netherlands

We report on the production of a double-degenerate, strongly mass-imbalanced Fermi-Bose mixture of ⁶Li and ⁴¹K. In our experimental sequence the potassium atoms are sympathetically cooled by the lithium atoms, which are evaporatively cooled in an optical dipole trap at a magnetic field of 1190 G. We obtain 10⁴ ⁴¹K atoms with a 33% BEC fraction and a $T/T_F \approx 0.1$ with 10⁵ Li atoms in each spin state. We are currently implementing a species-selective optical dimple potential to increase the BEC fraction. This paves the way to observing the collective behavior of two coupled superfluids with strong mass imbalance. We also scan the magnetic field in a region from 0 G to 1200 G and we observe multiple interspecies Feshbach resonances, which can be exploited for interaction control in strongly interacting Fermi-Bose mixtures.

Q 38.3 Wed 15:00 f303

Interaction-free measurements with ultracold atoms

— JAN PEISE¹, ●BERND LÜCKE¹, LUCA PEZZÉ², FRANK DEURETZBACHER¹, WOLFGANG ERTMER¹, JAN ARLT³, AUGUSTO SMERZI², LUIS SANTOS¹, and CARSTEN KLEMP¹ — ¹Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany — ²Istituto Nazionale di

Ottica (INO), Consiglio Nazionale delle Ricerche (CNR), and European Laboratory for Non-Linear Spectroscopy (LENS), 50125 Firenze, Italy — ³QUANTOP, Institut for Fysik og Astronomi, Aarhus Universitet, 8000 Aarhus C, Denmark

Interaction-free measurements (IFMs) permit the detection of an object without the need of any interaction with it. Existing proposals for IFMs demand a single-particle source. Here, we realize a new many-particle IFM concept based on an indirect quantum Zeno effect in an unstable spinor Bose-Einstein condensate. For IFMs, it is necessary to discriminate between zero and a finite number of particles. We overcome this considerable experimental challenge by implementing an unbalanced homodyne detection for ultracold atoms. This new technique achieves single-particle sensitivity and serves as an important tool for future experiments in the field of quantum atom optics.

Q 38.4 Wed 15:15 f303

Resonant quantum dynamics of few ultracold bosons in periodically driven finite lattices

— ●SIMEON MISTAKIDIS¹, THOMAS WULF¹, ANTONIO NEGRETTI^{1,2}, and PETER SCHMELCHER^{1,2} — ¹Zentrum fuer Optische Quantentechnologien, Universitaet Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany — ²The Hamburg Centre for Ultrafast Imaging, Universitaet Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany

The out-of-equilibrium dynamics of few ultracold bosons in periodically driven one-dimensional optical lattices is investigated. Our study reveals that the driving enforces the bosons in different wells to oscillate in-phase and to exhibit a dipole-like mode. A wide range from weak-to-strong driving frequencies is covered and a resonance-like behaviour of the intra-well dynamics is discussed [1]. In the proximity of the resonance a rich intraband excitation spectrum is observed. The single particle excitation mechanisms are studied in the framework of Floquet theory elucidating the role of the driving frequency. The impact of the interatomic repulsive interactions is examined in detail yielding a strong influence on the tunneling period and the excitation probabilities. Finally, the dependence of the resonance upon a variation of the tunable parameters of the optical lattice is examined. Our analysis is based on the ab-initio Multi-Configuration Time-Dependent Hartree Method for bosons.

[1] S. I. Mistakidis, T. Wulf, A. Negretti, and P. Schmelcher, *J. Phys. B: Atomic, Molecular and Optical Physics*, **48**(24), 244004 (2015).

Q 38.5 Wed 15:30 f303

Transport through Bose-Einstein condensates with vortices

— ●LUKAS SCHWARZ, HOLGER CARTARIUS, and GÜNTER WUNNER — 1. Institut für Theoretische Physik, Universität Stuttgart, 70550 Stuttgart

Vortex solutions of the nonlinear Schrödinger equation, which describes Bose-Einstein condensates in a mean-field approximation as well as several other physical systems such as optical lattices, have attracted wide interest in the last years. In these systems complex potentials can be used to effectively describe gain and loss effects. If this gain and loss is spatially separated but balanced, the underlying Hamiltonian is \mathcal{PT} symmetric. We investigate Bose-Einstein condensates in such a non-Hermitian \mathcal{PT} symmetric external potential with the goal to find vortices describing a net transport through the condensate. Due to the

\mathcal{PT} symmetry truly stationary solutions with real eigenvalues exist in spite of a coherent and balanced in- and outcoupling of atoms. We present vortex solutions of a two-dimensional Bose-Einstein condensate trapped in different potentials with varying in- and outcoupling.

Q 38.6 Wed 15:45 f303

temperature measurement of a BEC with tunable interaction by in-situ imaging using semi-classical and hartree-fock model — ●PIERRE JOUVE — University of Nottingham UK

Various model of differing complexity can be used to model the density of Bose-Einstein condensate (BEC) in an harmonic trap to extract quantities such as temperature and chemical potential. We present two different method, the semi-classical thermal cloud and Hartree Fock model. We demonstrate that the Hartree-Fock method leads to more accurate result for temperature of the system close to T_c , the Bose-Einstein condensation temperature transition.

Q 38.7 Wed 16:00 f303

Towards Ultracold Interaction and Chemistry - Ba⁺ and Rb in an optical dipole trap — ●ALEXANDER LAMBRECHT, JULIAN SCHMIDT, PASCAL WECKESSER, LEON KARPA, and TOBIAS SCHAETZ — Universitaet Freiburg

Examining collisions of atoms and ions at extremely low temperature will permit gaining information about the corresponding sympathetic cooling rates and subsequent quantum effects, such as cluster formation of an ion binding atoms within the common $1/r^4$ potential[1]. In the last years several experimental groups investigated cold collisions between atoms and ions, leading to a better understanding of the atom-ion interaction [2-5]. Our approach to reach the regime of ultracold interaction is to precool a Ba⁺ ion, trapped in a conventional Radio-Frequency (RF) trap by Doppler cooling. By transferring the ion into an optical dipole trap[6], followed by sympathetic cooling via an ambient Rb MOT we plan to overcome the current limitations set by heating due to RF micromotion. We describe our apparatus

and present first experimental results on optical trapping of ions and atoms.

- [1] R. Côté et al., Phys. Rev. Lett. 89, 093001 (2002)
- [2] A. Härter et al., Contemp. Phys. 55, 33 (2014)
- [3] A.T. Grier et al., Phys. Rev. Lett. 102, 223201 (2009)
- [4] L. Ratschbacher et al., Nature Phys. 8, 649 (2012)
- [5] F. H. J. Hall et al., Mol. Phys. 111, 1683-1690 (2013)
- [6] T. Huber et al., Nat. Comm. 5, 5587 (2014)

Q 38.8 Wed 16:15 f303

Satisfying the Einstein-Podolsky-Rosen criterion with massive particles — JAN PEISE¹, ILKA KRUSE¹, ●KARSTEN LANGE¹, BERND LÜCKE¹, LUCA PEZZÈ², JAN ARLT³, WOLFGANG ERTMER¹, KLEMENS HAMMERER⁴, LUIS SANTOS⁴, AUGUSTO SMERZI², and CARSTEN KLEMP¹ — ¹Institut für Quantenoptik, Leibniz Universität Hannover, Germany — ²QSTAR, INO-CNR and LENS, Firenze, Italy — ³Institut for Fysik og Astronomi, Aarhus Universitet, Denmark — ⁴Institut für Theoretische Physik, Leibniz Universität Hannover, Germany

Entanglement was first discussed in the thought experiment of Einstein, Podolsky, and Rosen (EPR). They considered a quantum-mechanical state consisting of two maximally correlated particles. A measurement of one subsystem seemingly allows for a prediction of the second subsystem with a precision beyond the Heisenberg uncertainty relation. We utilize spin-changing collisions in a ⁸⁷Rb BEC to generate a two-mode entangled state. By employing an atomic homodyne detection, we verify the EPR correlation according to Reid's criterion. We find an EPR entanglement parameter of 0.18 which is 2.4 standard deviations below the threshold of 1/4. This demonstration of continuous-variable EPR correlations is the first realization with massive particles [1]. Furthermore, the state is fully characterized by a tomographic reconstruction of the underlying many-particle quantum state. This reconstruction is obtained via a Maximum Likelihood algorithm.

- [1] J. Peise et al., Nat Commun 6, 8984 (2015)

Q 39: Nano-Optics II

Time: Wednesday 14:30–16:30

Location: f342

Q 39.1 Wed 14:30 f342

Cavity-enhanced Raman Microscopy of Individual Carbon Nanotubes — ●THOMAS HÜMMER^{1,2}, MATTHIAS S. HOFMANN¹, JONATHAN NOE¹, ALEXANDER HÖGELE¹, THEODOR W. HÄNSCH^{1,2}, and DAVID HUNGER^{1,2} — ¹Ludwig-Maximilians-Universität München, Deutschland — ²Max-Planck Institut für Quantenoptik, Garching, Deutschland

We use a tunable high-finesse optical microcavity[1] to demonstrate Purcell enhancement of Raman scattering in combination with high-resolution scanning-cavity imaging[2]. We detect cavity-enhanced Raman spectra[3] of individual single-walled carbon nanotubes and colocalize measurements with cavity-enhanced absorption microscopy. Direct comparison with confocal Raman microscopy yields a 1000-times enhanced collectable Raman scattering spectral density and a 20-fold enhancement of the integrated count rate for the same excitation intensity. We expand the technique to hyperspectral imaging, where we can deduce information such as the diameter and the metallic or semiconducting character of the nanotubes. The quantitative character, the inherent spectral filtering, and the absence of intrinsic background in cavity-vacuum stimulated Raman scattering renders our technique a promising tool for molecular imaging.

- [1] Hunger et al., NJP 12, 065038 (2010) [2] Mader et al., Nat Commun 6, 7249 (2015) [3] Hümmer et al., arXiv:1508.06810 (2015)

Q 39.2 Wed 14:45 f342

Suppression of spontaneous Raman scattering for resolution improvement in label-free microscopy — ●STEFFEN RIEGER¹, KLAUS-JOCHEN BOLLER², and CARSTEN FALLNICH^{1,2} — ¹Institute of Applied Physics, Westfälische Wilhelms-Universität Münster, Germany — ²MESA+ Institute for Nanotechnology, University of Twente, Enschede, The Netherlands

The electronic excitation of a complex molecule with UV light can lead to a significant change of its vibrational behavior and therefore to a heavily altered Raman spectrum. This effect can be used for the sup-

pression of Raman scattering, which is a prerequisite for a STED-like resolution improvement in label-free microscopy [1].

We present first experimental results from our Resonance Raman Spectroscopy, which show already a suppression of specific Raman lines by up to 50% relative to the background – an effect that is strong enough to provide a resolution improvement by more than a factor of two.

To achieve this, we currently use a spontaneous Raman scattering spectrometer with an excitation wavelength of 355 nm and pulse powers of up to 10 μJ to perform Resonance Raman Spectroscopy on the metal complex Tris(bipyridine)ruthenium(II) in Acetonitrile, which is known for its excited state Raman resonances.

- [1] C. Cleff et al., Phys. Rev. A 86, 023825 (2012).

Q 39.3 Wed 15:00 f342

Fast and Precise Studying of Dynamical Processes on Live Cell Membranes Using Interferometric Scattering Microscopy (iSCAT) — ●MIHAIL PETEV^{1,2}, RICHARD W. TAYLOR¹, HAWZHIN HOZHABRPOUR^{1,2}, CHRISTIAN RIESS², and VAHID SANDOGHDAR^{1,2} — ¹Max Planck Institute for the Science of Light, D-91058 Erlangen, Germany — ²Fredrich-Alexander-Universität Erlangen-Nürnberg (FAU), D-91058 Erlangen, Germany

By monitoring the diffusion of single transmembrane proteins within the live cell membrane, one gains much important understanding of their subtle and nuanced function and interactions. To monitor all of the rich dynamics of such proteins requires very high spatial and temporal resolution that should be sustained over long duration. These requirements are simply inaccessible by conventional fluorescence microscopes. Using interferometric scattering imaging (iSCAT) and by labeling single transmembrane proteins in the live HeLa cell with a gold nanoparticle, we are able to overcome these limitations.

iSCAT microscopy exploits coherent interference between sample-scattered light and a homodyne reference to measure weakly scattered signals with improved signal-to-noise ratio. The interferometric nature of the imaging is thus sensitive to the fine three-dimensional motion of

the gold nano-probe on the cell membrane, which we are able to track with nanometric precision at the fast microsecond time scale. An additional advantage of this approach is that one can also extend it to label-free cell membrane imaging, thus eliminating any marker related effects.

Q 39.4 Wed 15:15 f342

Tabletop extreme ultraviolet coherence tomography — ●JOHANN JAKOB ABEL¹, SILVIO FUCHS^{1,2}, MARTIN WÜNSCHE¹, JULIUS BIEDERMANN¹, STEFAN AULL¹, JAN BERNERT¹, CHRISTIAN RÖDEL^{1,2}, MAX MÖLLER¹, and GERHARD G. PAULUS^{1,2} — ¹Institute of Optics and Quantum Electronics, Friedrich-Schiller University of Jena, Max-Wien-Platz 1, Jena — ²Helmholtz Institute Jena, Helmholtzweg 4, Jena

We present a tabletop setup of a 3D nanometer imaging technique called XUV coherence tomography (XCT). Our XCT setup uses broadband extreme ultraviolet radiation from high harmonic generation (HHG).

Optical coherence tomography (OCT) reaches axial resolution on the order of the coherence length $l_c \propto \lambda_0^2 / \Delta\lambda_{FWHM}$ which only depends on spectral properties of the light source [1,2]. By using short wavelengths XCT extends OCT by improving the axial resolution from micrometers to nanometers. In contrast to optical coherence tomography the depth resolution of XCT is mainly limited by transmission windows of the investigated sample [3]. XCT was successfully demonstrated at synchrotron sources in the silicon (30-99 eV) and the water transmission window (280-530 eV), before.

Here we show results using a tabletop XCT setup. We investigated different silicon based samples and achieved depth resolution of 27 nm.

[1] D. Huang et al., *Science* **254**, 1178-1181 (1991). [2] W. Drexler and J. G. Fujimoto, *Optical Coherence Tomography* (Springer Verlag, Berlin, 2008). [3] S. Fuchs et al., *Appl. Phys. B* **106**, 789-795 (2012).

Q 39.5 Wed 15:30 f342

Entanglement-free sub-shot noise microscopy — ●THOMAS JUFFMANN, BRANNON KLOPFER, and MARK KASEVICH — Stanford University, California 94305, USA

We present a new technique for sub-shot noise and low damage microscopy based on repeated probe sample interactions. We show first results in absorption and polarization microscopy as well as design studies for a low damage electron microscope based on the same principle.

Q 39.6 Wed 15:45 f342

A segmented printed-circuit-board trap for macroscopic particles — ●JOACHIM ZOLL, HEATHER PARTNER, ALEXANDER KUH-LICKE, and OLIVER BENSON — AG Nanooptik, Institut für Physik, Humboldt-Universität zu Berlin, Newtonstraße 15, 12489 Berlin, Germany

In this presentation, a linear Paul trap for the investigation of levitating macroscopic particles such as diamonds with nitrogen-vacancy-defects [1] is introduced. The trap consists of two printed-circuit-boards (PCB), which are easy and fast to fabricate. For a rapid characterization of many different particles, the trap is separated in 12 segments, to establish loading, storing and subsequent analysis. Good optical access is ensured through a window in the side of the PCB. This is important for the detection of low optical signals. I will present a finite-element-simulation of the pseudo-potential for different

particles, which have been stabilized in the PCB-trap. The stability of the trap was tested with microspheres (SiO₂) and various diamonds under atmospheric pressure.

[1] A. Kuhllicke, A. Schell, J. Zoll, and O. Benson, *Applied Physics Letters* **105**, 073101 (2014)

Q 39.7 Wed 16:00 f342

Fibre optic surface plasmon resonance sensor for smart-phones — ●KORT BREMER¹, JOHANNA WALTER², and BERNHARD ROTH¹ — ¹Hannover Centre for Optical Technologies (HOT), Leibniz University Hannover, Nienburger Straße 17, 30167 Hannover, Germany — ²Institute of Technical Chemistry (TCI), Leibniz University Hannover, Callinstrasse 5, 30167 Hannover, Germany

We have demonstrated a low-cost fibre optic surface plasmon resonance sensor designed for smartphones [1] which might be applied for the monitoring of biologically relevant molecules, personalized health care or environmental sensing in the future. For the sensor, the LED and the camera at the back side of a smartphone are used as light source and detector, respectively, and no external electrical components are required for the operation. In a first application example the sensor was realized by using a plastic cladded silica glass fibre and an easy-to-implement silver coating technique. Light from the smartphone is coupled in and out of the optical fiber by using 45° fibre end-faces. A diffraction grating is applied in front of the camera to disperse the light into a line spectrum. In a proof of principle experiment the performance of the sensor was successfully evaluated by using different volume concentrations of glycerol solutions and a sensitivity of $5.96 \cdot 10^{-4}$ refractive index units (RIU)/pixel for a RI values between 1.33 and 1.36 was obtained. In the talk we present our latest work towards higher sensitivity and functionalization of the sensor system.

[1] K. Bremer and B. Roth, *Opt. Express* **2015**, 23 (13), 17179-17184

Q 39.8 Wed 16:15 f342

Einzel-Ionen Mikroskopie — ●KARIN GROOT-BERNING^{1,2}, GEORG JACOB¹, SEBASTIAN WOLF¹, FERDINAND SCHMIDT-KALER¹ und KILIAN SINGER² — ¹QUANTUM, Institut für Physik, Universität Mainz, Staudingerweg 7, 55128 Mainz, Germany — ²Experimental Physik, Universität Kassel, Heinrich-Plett-Straße 40, 34132 Kassel, Germany

Wir berichten über ein neuartiges Transmissionsmikroskop auf der Grundlage einer linearen Paul-Falle. Dabei werden einzelne ⁴⁰Ca⁺ Ionen lasergekühlt und anschließend deterministisch extrahiert [1]. Dieses Verfahren kann zur Bildgebung verwendet werden und zeichnet sich zusätzlich durch eine äußerst geringe Aufladung oder Beschädigung der Probe aus. Dabei wird eine räumliche Auflösung von besser als 10nm erreicht [2]. Gegenüber herkömmlichen Quellen mit Poisson-scher Teilchenzahlstatistik erlaubt unser deterministischer Ansatz ein verbessertes Signal-zu-Rausch Verhältnis. Als eine praktische Anwendung stellen wir mikroskopische Abbildungen von photonischen Strukturen in einem Diamantfilm vor.

Um den Informationsgewinn bei jeder Extraktion zu maximieren, nutzen wir die "Bayes experimental design" Methode. Damit bestimmen wir nm-genau die Position von Markierungen auf Diamant Proben, was für viele Anwendungen von Nutzen sein kann, wie z.B. für die Implantation einzelner Ionen bezüglich photonischer Strukturen oder Kontrollelektroden auf einer Probe.

[1] W. Schnitzler et al., *Phys. Rev. Lett.* **102**, 070501 (2009).

[2] G. Jacob et al., [arxiv.org:1405.6480](https://arxiv.org/abs/1405.6480) (2014).

Q 40: Precision spectroscopy of atoms and ions I (with A)

Time: Wednesday 14:30–16:30

Location: f428

Invited Talk

Q 40.1 Wed 14:30 f428

Atomic level scheme of neutral actinium — ●SEBASTIAN RAEDER¹, RANDOLF BEERWERTH², RAFAEL FERRER³, CAMILO GRANADOS³, AMIN HAKIMI⁴, MUSTAPHA LAATAOUI¹, VOLKER SONNENSCHNEIN⁵, NORBERT TRAUTMANN⁶, and KLAUS WENDT⁴ — ¹Helmholtz Institut Mainz — ²Helmholtz Institut Jena — ³KU Leuven — ⁴Institut für Physik, Universität Mainz — ⁵University of Jyväskylä — ⁶Institut für Kernchemie, Universität Mainz

The atomic structure of actinium was investigated as preparation for laser spectroscopy on short lived radio isotopes. Albeit it is the name-giving element of the actinide series the available information on the

atomic level scheme of neutral actinium is insufficient for laser spectroscopic applications. Using wide range tunable Ti:sa lasers allowed for the identification of new atomic energy levels, resulting in a precise determination of the first ionization potential and provided the information on auto-ionizing states for further resonance ionization spectroscopy. Additionally, the hyperfine structure of several levels was investigated using an injection-locked narrow bandwidth pulsed Ti:sa laser. Besides the identification of a suitable optical transition with high sensitivity to nuclear properties some errors in the available literature on the atomic levels were identified. The measured level properties are compared to theoretical multi configuration Dirac-Fock (MCDF) calculations resulting in a revised level scheme for low lying

atomic levels in actinium.

Q 40.2 Wed 15:00 f428

MCDF Isotope-Shift Calculations for Medium and Heavy Elements — ●RANDOLF BEERWERTH^{1,2} and STEPHAN FRITZSCHE^{1,2} — ¹Helmholtz-Institut Jena, 07743 Jena, Germany — ²Theoretisch-Physikalisches Institut, Universität Jena, 07743 Jena, Germany

The isotope shift is described in terms of the mass and field-shift parameters. The former arises due to the nuclear recoil, while the latter links the electronic response to changes in the nuclear radius. This allows to use optical spectroscopy to obtain information about the nucleus, when the isotope-shift parameters are known. When it is infeasible to determine the isotope-shift parameters purely experimentally, atomic calculations can instead be utilized to provide estimates.

We apply the Multi-Configuration Dirac-Fock (MCDF) method to calculate the isotope-shift parameters for medium to heavy elements. After computation of the wave function, we utilize the configuration-interaction method to calculate the isotope-shift parameters for a chain of isotopes.

Since the isotope shift of heavy elements is dominated by the field shift, we put special emphasis on its computation. Very often it is estimated from the electronic charge density inside the nucleus, however this estimate is only precise for light elements. For light to medium elements, our method agrees very well with this estimate. However, for heavy elements we obtain significantly lower values.

We present results for Actinium and Nobelium, where several experiments were recently performed. The extracted nuclear parameters compare well with results for other elements.

Q 40.3 Wed 15:15 f428

Design and commissioning of the ALPHATRAP ion transfer beamline — ●ALEXANDER EGL^{1,2}, IOANNA ARAPOGLOU^{1,2}, J.R. CRESPO LOPEZ-URRUTIA¹, HENRIK HIRZLER^{1,2}, SANDRO KRAEMER^{1,2}, PETER MICKE^{1,3}, TIM SAILER^{1,2}, ANDREAS WEIGEL^{1,2}, ROBERT WOLF¹, SVEN STURM¹, and KLAUS BLAUM¹ — ¹Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg — ²Fakultät für Physik, Universität Heidelberg — ³Physikalisch-Technische Bundesanstalt, QUEST, 38116 Braunschweig

The Penning-trap experiment ALPHATRAP at the Max-Planck-Institut für Kernphysik aims to test bound-state quantum electrodynamics by determining the g -factor of the bound electron in the electric field of highly charged ions (HCI) with ultra-high precision. HCI up to hydrogen-like $^{208}\text{Pb}^{81+}$ will be provided by the Heidelberg Electron Beam Ion Trap (Heidelberg-EBIT). Therefore, an ultra-high vacuum room temperature ion transfer beamline will be used to guide HCI to the ALPHATRAP setup, consisting of a custom-made cryostat and a superconducting magnet containing the precision Penning-trap system. Superior vacuum conditions are essential to reduce recombination reactions of the HCI to negligible levels. In addition to the Heidelberg-EBIT, a compact room temperature EBIT is available, which allows flexible creation of HCI from injected gas, e.g. $^{40}\text{Ar}^{15+}$ or $^{129}\text{Xe}^{25+}$. These ions in turn will be used during the commissioning phase of ALPHATRAP. The design and commissioning of the ion transfer beamline as well as results from the compact room temperature EBIT will be presented.

Q 40.4 Wed 15:30 f428

Investigation of Ir^{17+} as a sensitive detector of variation of the fine-structure constant — ●HENDRIK BEKKER¹, ALEXANDER WINDBERGER^{1,2}, OSCAR O. VERSOLATO², ANASTASIA BORCHEVSKY³, NATALIA S. ORESHKINA¹, JULIAN C. BERENGUT⁴, ZOLTÁN HARMAN¹, CHRISTOPH H. KEITEL¹, and JOSÉ R. CRESPO LÓPEZ-URRUTIA¹ — ¹Max-Planck-Institut für Kernphysik, Heidelberg — ²Advanced Research Center for Nanolithography, Amsterdam — ³Van Swinderen Institute for Particle Physics and Gravity, Groningen — ⁴University of New South Wales, Sydney

Many highly charged ions have been proposed for use in next generation optical clocks for metrology purposes. We aim at implementing one of the original proposals, to use Ir^{17+} to investigate variation of the fine-structure constant [1]. But as with all the proposed systems, theory is not capable of predicting the energy level structure to the precision required for laser spectroscopy. Therefore we investigated Ir^{17+} which we produced, trapped, and collisionally excited in the Heidelberg electron beam ion trap. The wavelengths of subsequent optical fluorescence light were determined at the ppm-level using a grating spectrometer. Direct identification of the 30 observed lines was not possible due to their dense spacing and uncertainties on the

predictions. But by employing several other techniques we identified transitions important for future high-precision laser spectroscopy experiments. The identification techniques and additional new results will be presented.

[1] J. C. Berengut *et al.*, Phys. Rev. Lett. **106**, 210803 (2011)

[2] A. Windberger *et al.*, Phys. Rev. Lett. **114**, 150801 (2015)

Q 40.5 Wed 15:45 f428

Influence of ion movement in a particle trap on the bound-electron g -factor — ●NIKLAS MICHEL, JACEK ZATORSKI, and CHRISTOPH H. KEITEL — Max-Planck-Institut für Kernphysik, Heidelberg, Deutschland

The bound-electron g -factor is defined via the energy difference of a spin-up and spin-down state of the electron in an external magnetic field and its measurement provides one of the most stringent tests of QED in strong external fields. When measured in a Penning trap, the electron spin also couples to the external electric trapping potential and the total momentum of the ion. Therefore, the motional state of an ion in a particle trap influences measurements of internal observables such as energy levels or the g -factor [1]. We calculated the resulting relativistic shift of the Larmor frequency and the corresponding g -factor correction for a bound electron in a hydrogenlike ion in the 1S state due to the ion moving in a Penning trap.

[1] N. Michel, J. Zatorski, C. H. Keitel, Phys. Rev. A **92**, 052509 (2015).

Q 40.6 Wed 16:00 f428

A highly sensitive single particle detector at 75 MHz — ●MATTHIAS BORCHERT¹, KLAUS BLAUM², TAKASHI HIGUCHI^{3,4}, YASUYUKI MATSUDA⁴, TERESA MEINERS¹, ANDREAS MOOSER³, HIROKI NAGAHAMA^{3,4}, MALTE NIEMANN¹, CHRISTIAN OSPELKAUS¹, WOLFGANG QUINT⁶, GEORG SCHNEIDER⁷, STEFAN SELLNER³, CHRISTIAN SMORRA^{3,8}, JOCHEN WALZ^{5,7}, YASUNORI YAMAZAKI⁹, and STEFAN ULMER³ — ¹Institut für Quantenoptik, Leibniz Universität Hannover, Hannover, Germany — ²Max-Planck-Institut für Kernphysik, Heidelberg, Germany — ³Ulmer Initiative Research Unit, RIKEN, Wako, Japan — ⁴Graduate School of Arts and Sciences, University of Tokyo, Tokyo, Japan — ⁵Helmholtz-Institut Mainz, Mainz, Germany — ⁶GSI-Helmholzzentrum für Schwerionenforschung, Darmstadt, Germany — ⁷Institut für Physik, Johannes Gutenberg-Universität Mainz, Mainz, Germany — ⁸CERN, Geneva, Switzerland — ⁹Atomic Physics Laboratory, RIKEN, Wako, Japan

The BASE collaboration aims at a stringent test of the CPT symmetry by comparing the magnetic moments of the proton and the antiproton with high precision. The magnetic moment in units of the nuclear magneton is determined by measuring the ratio of the spin-precession frequency to the cyclotron frequency, respectively, in an advanced cryogenic Penning trap system.

One limitation in current state of the art experiments is given by noise induced quantum transitions in the modified cyclotron mode of the trapped particles. Higher magnetic field strengths reduce the heating rate of the cyclotron mode, which inspires the development of a non-destructive image-current detector for the modified cyclotron frequency at 75 MHz. For a proton this corresponds to a magnetic field strength of about 5 Tesla.

In this talk I will present the development of such a detector based on a superconducting resonator.

Q 40.7 Wed 16:15 f428

Comparison of the $L_{\gamma}(2,3)$ line shape for Ba^{2+} compounds and metal — ●MALKHAZ JABUA, DETLEV GOTTA, and THOMAS STRAUCH — Institut für Kernphysik, Forschungszentrum Jülich, D-52425 Jülich, Deutschland

The $L_{\gamma}(2,3)$ line from Ba^{2+} compounds shows a complex structure. Nevertheless, both peak energy and shape of the complex are apparently unaffected by the nature of the anion. Therefore, a comparison measurement was performed using metallic barium. For the measurement was used the Johann spectrometer at the institute of nuclear physics (IKP) at Forschungszentrum Jülich (FZJ). The set-up allows to record simultaneously an energy interval covering the complete structure $\text{Ba } L_{\gamma}(2,3)$ structure. As Bragg crystal a spherically bent quartz crystal was used. The diffracted X-rays were recorded with a 24 mm x 24 mm charge-coupled device having a pixel size of 40 micrometer x 40 micrometer. The spectra of metallic Ba complete a series of measurements including the spectra from the salts BaCl_2 , BaCO_3 , Ba(OH)_2 , and BaSO_4 . The X-ray energies were determined to an accuracy of about 40 meV. The talk aims to describe the experimental setup, mea-

surement techniques, and to present the data analysis methodology | and some recent results.

Q 41: Quantum Effects: Entanglement and Decoherence II

Time: Wednesday 14:30–16:30

Location: f442

Group Report

Q 41.1 Wed 14:30 f442

A quantum random walk of a Bose-Einstein condensate in momentum space — ●SANDRO WIMBERGER^{1,2,3} and GIL SUMMY⁴ — ¹DiFeST, Università degli Studi di Parma, Via G. P. Usberti 7/a, 43124 Parma, Italy — ²INFN, Sezione di Milano Bicocca, Gruppo Collegato di Parma, 43124 Parma, Italy — ³ITP, Heidelberg University, Philosophenweg 12, 69120 Heidelberg, Germany — ⁴Department of Physics, Oklahoma State University, Stillwater, Oklahoma 74078-3072, USA

Each step in a quantum random walk is typically understood to have two basic components; a "coin-toss" which produces a random superposition of two states, and a displacement which moves each component of the superposition by different amounts. Here we suggest the realization of a walk in momentum space with a spinor Bose-Einstein condensate subject to a quantum ratchet realized with a pulsed, off-resonant optical lattice. By an appropriate choice of the lattice detuning, we show how the atomic momentum can be entangled with the internal spin states of the atoms. For the coin-toss, we propose to use a microwave pulse to mix these internal states. We present the first experimental results showing a new type of ratchet, and through a series of simulations, demonstrate how our proposal can allow for extraordinary control of the quantum walk. This should allow for the investigation of possible biases, and classical-to-quantum dynamics in the presence of natural and engineered noise.

Q 41.2 Wed 15:00 f442

Random Unitary Evolution Model of Dissipation, Dephasing and Quantum Darwinism — ●NENAD BALANESKOVIC¹, GERNOT ALBER¹, and JAROSLAV NOVOTNY² — ¹Institut für Angewandte Physik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany — ²Department of Physics, FNSPE, Czech Technical University in Prague, 11519 Praha 1 - Stare Mesto, Czech Republic

We discuss characteristic properties of Quantum Darwinism (QD) when pure decoherence is disturbed by dissipation and dephasing. Based on digraph interaction models of open qubit systems interacting with their respective environment by iterated and randomly applied (Controlled-NOT-type) unitary operations, we introduce a unitary two-qubit dissipative-dephased operator. We investigate the QD-appearance of Classicality from the analytically determined asymptotic dynamics of the resulting quantum Markov chain. In addition, we concentrate on interaction digraphs which comprise environmental qubits that do not interact among themselves by unitary quantum operations and are thus suitable to describe physically objective quantum measurements performed on an open system by autonomous observers (environmental qubits). In particular, we investigate whether it is possible to achieve the most efficient storage of classical information about a system into its environment by altering the strength parameters of the dissipative-dephased operator. Furthermore, we discuss the structure of the corresponding dissipative-dephased attractor spaces of our extended qubit-model of QD.

Q 41.3 Wed 15:15 f442

A master equation for high-precision spectroscopy — ●ANDREAS ALEXANDER BUCHHEIT and GIOVANNA MORIGI — Universität des Saarlandes, 66123 Saarbrücken, Germany

The progress in high-precision spectroscopy requires one to check the accuracy of theoretical models such as the master equation describing spontaneous emission of atoms. For this purpose, we systematically derive a master equation of an atom interacting with the modes of the electromagnetic field which naturally includes interference in the decay channels and fulfills the requirements of the Lindblad theorem without the need of phenomenological assumptions. We apply our model to the 2S-4P transition in atomic Hydrogen and show that interference effects in the dissipative dynamics can alter the lineshape of the spectroscopic line, leading to frequency shifts ranging from few to tens of kHz, depending on the collection angle of the photodetection setup. These results can contribute in understanding spectroscopic measurements in atomic Hydrogen performed in recent experiments for testing

the validity of quantum electrodynamics.

Q 41.4 Wed 15:30 f442

Controllable Markovian to Non-Markovian Transition in Open Quantum Systems Implemented with Cold Rydberg Atoms — MICHAEL GENKIN, DAVID SCHÖNLEBER, ●ALEXANDER EISENFELD, and SEBASTIAN WÜSTER — MPI für Physik komplexer Systeme, Dresden

We propose a setup of an open quantum system in which the system-environment-interaction can be switched from Markovian to non-Markovian in a controlled fashion. The scheme is implemented with cold Rydberg atoms, utilizing their strong long-range interactions. It helps to assess the applicability of Rydberg aggregates as quantum simulators of molecular systems, and presents a possible new test bench for fundamental studies of the classification of system-environment-interactions in open systems.

Q 41.5 Wed 15:45 f442

Master equation for collective spontaneous emission including quantization of the atomic motion — ●FRANÇOIS DAMANET¹, DANIEL BRAUN², and JOHN MARTIN¹ — ¹Institut de Physique Nucléaire, Atomique et de Spectroscopie, Université de Liège, Bât B15, 4000 Liège, Belgium. — ²Institut für theoretische Physik, Universität Tübingen, 72076 Tübingen, Germany.

We derive a markovian master equation for the internal dynamics of an ensemble of two-level atoms including the quantization of their motion. Our equation provides a unifying picture of the effects of recoil and indistinguishability of atoms beyond the Lamb-Dicke regime on both their dissipative and conservative dynamics. We give general expressions for the decay rates and the dipole-dipole shifts for any motional states, generalizing those in Ref. [1]. We find closed-form formulas for a number of relevant states (gaussian states, Fock states and thermal states). In particular, we show that dipole-dipole interactions and cooperative photon emission [2] can be modulated through the external state of motion. As an application of our general formalism, we study the spatial Pauli blocking of two fermionic atoms beyond the Lamb-Dicke regime [3].

[1] G. S. Agarwal, Springer Tracts In Modern Physics **70**, 1 (1974).

[2] R. H. Dicke, Phys. Rev. **93**, 99 (1954).

[3] R. M. Sandner, M. Müller, A. J. Daley & P. Zoller, Phys. Rev. A **84**, 043825 (2011).

Q 41.6 Wed 16:00 f442

Time-resolved observation of thermalization in an isolated quantum system — ●GOVINDA CLOS¹, DIEGO PORRAS², ULRICH WARRING¹, and TOBIAS SCHAETZ¹ — ¹Physikalisches Institut, Albert-Ludwigs-Universität, Hermann-Herder-Straße 3, 79104 Freiburg, Germany — ²Department of Physics and Astronomy, University of Sussex, Brighton BN1 9QH, United Kingdom

How can thermalization occur in an isolated quantum system? Unitary time evolution does not permit the total system to reach a thermal state. However, for a strongly interacting system with many degrees of freedom, expectation values of local observables can come to agreement with microcanonical predictions. This behaviour is described within a conjecture called Eigenstate Thermalization Hypothesis [1].

Using a near-perfectly isolated trapped-ion system, we experimentally study the evolution of a single spin in a Hilbert space of dimension up to 2^{22} by controlling its coupling to a discrete bosonic environment [2]. Varying the effective size of the system, we measure the dynamics of spin observables and determine its time average and fluctuations to study the onset of thermalization [3].

[1] Eisert *et al.*, *Nature Physics* **11**, 124 (2015).

[2] Porras *et al.*, *Physical Review A* **78**, 010101 (2008).

[3] Clos *et al.*, *arXiv:1509.07712* (2015).

Q 41.7 Wed 16:15 f442

Intrinsic limit to electron spin coherence in InGaAs quantum dots — ROBERT STOCKILL, CLAIRE LE GALL, CLEMENS MATTHIESEN, ●LUKAS HUTHMACHER, and METE ATATÜRE — Cavendish Laboratory,

University of Cambridge, JJ Thomson Avenue, Cambridge CB3 0HE, UK

Single electron spins in self-assembled InGaAs quantum dots show outstanding photonic properties, allowing for ultrafast all-optical control [1] and therefore are a promising candidate for spin qubits. However, the fluctuations of the nuclear spin bath in the surrounding semiconductor limit the electron-spin dephasing to a few nanoseconds [2]. The exact mechanism leading to this limitation is masked by the measurement-induced dynamic polarisation of the nuclear bath, often revealed in the dragging of resonance frequencies, and hence remains

unclear [3]. Here, we introduce an all-optical method allowing us to access the electron-spin without influencing the nuclear bath. By combining this method with a spin-echo decoupling scheme we are able to reach the intrinsic limit to electron-spin coherence, which, for our samples, amounts to a few microseconds, depending on the external magnetic fields. Taking into account the quadrupolar and Zeeman Hamiltonians we show that this bound is set by the quadrupolar interaction of the nuclear bath with inhomogeneous electric field gradients; a result of the naturally occurring strain in these systems. [1] Press, D. et al., *Nature* 456, 218-221 (2008) [2] Greilich, A. et al., *Science* 313, 341-345 (2006) [3] Latta, C. et al., *Nature Phys.* 5, 758-763 (2009)

Q 42: Poster: Quantum Optics and Photonics III

Time: Wednesday 16:30–19:00

Location: Empore Lichthof

Q 42.1 Wed 16:30 Empore Lichthof

Synchronization of Two Ensembles of Atoms via Quantum and Classical Channels — ●ALEXANDER ROTH and KLEMENS HAMMERER — Institute for Theoretical Physics, Leibniz University Hannover

We show synchronization in a system of two cascaded superradiant frequency detuned lasers and point out the differences to two superradiant ensembles of atoms in one cavity [1]. Furthermore we show that this synchronization does not rely on the quantum coupling between both lasers, but can be simulated using a classical channel. Additionally we show that the synchronization of two superradiant ensembles of atoms coupling to the same cavity mode can also be simulated using a classical coupling channel.

[1] PRL 113.15 (Oct. 6, 2014) M. Xu, D. Tieri, E. Fine, J. K. Thompson, and M. Holland. "Synchronization of Two Ensembles of Atoms".

Q 42.2 Wed 16:30 Empore Lichthof

Quantum-phase synchronization — ●LUKAS FIDERER¹, MAREK KUS², and DANIEL BRAUN¹ — ¹Eberhard-Karls-Universität Tübingen, 72076 Tübingen, Germany — ²Center for Theoretical Physics of the Polish Academy of Sciences, 02-068 Warsaw, Poland

We study mechanisms that allow one to synchronize the quantum phase of two qubits relative to a fixed basis. Starting from one qubit in a fixed reference state and the other in an unknown state, we find that contrary to the impossibility of perfect quantum cloning, the quantum-phase can be synchronized perfectly through a joined unitary operation. When both qubits are initially in a pure unknown state, perfect quantum-phase synchronization through unitary operations becomes impossible. In this situation we determine the optimal average quantum-phase synchronization fidelity, the distribution of relative phases and fidelities, and identify quantum circuits that enable this optimal fidelity. A subset of these optimal quantum circuits achieves perfect quantum-phase synchronization for a class of unknown initial states restricted to the equatorial plane of the Bloch sphere.

Q 42.3 Wed 16:30 Empore Lichthof

Retrieving two-dimensional source geometries via spatial frequency filtering using higher order spatial photon correlations — ●FELIX WALDMANN¹, ANTON CLASSEN^{1,2}, RAIMUND SCHNEIDER^{1,2}, THOMAS MEHRINGER^{1,2}, and JOACHIM VON ZANTHIER^{1,2} — ¹Institut für Optik, Information und Photonik, Universität Erlangen-Nürnberg, 91058 Erlangen — ²Erlangen Graduate School in Advanced Optical Technologies (SAOT), Universität Erlangen-Nürnberg, 91052 Erlangen

Measurements of higher order photon correlations are becoming increasingly attractive due to numerous applications in the field of imaging [1,2]. Recently we demonstrated a detection scheme, which resolves regular 1D source geometries of N independent classical emitters with thermal statistics at sub-Abbe resolution by making use of spatial photon correlations of order $m = N$ [2]. Here we present a generalization of this scheme relying on a sequential measurement of spatial photon correlations of different orders to reconstruct 2D source geometries. By choosing specific detector positions the scheme isolates - depending on the correlation order m - sequentially all spatial frequencies of the setup, which we call spatial frequency filtering. Using the gathered information allows to retrieve the 2D source geometry. In the experiment the independent thermal sources are realized by pinholes drilled

in an opaque mask and illuminated with laser light scattered from a rotating ground glass disk.

[1] J. H. Shapiro, R. W. Boyd, *Quantum. Inf. Process.* 4, 949 (2012)
[2] S. Oppel et al., *Phys. Rev. Lett.* 109, 233603 (2012)

Q 42.4 Wed 16:30 Empore Lichthof

Anticoherence of spin states with point-group symmetries — ●DORIAN BAGUETTE¹, FRANÇOIS DAMANET¹, OLIVIER GIRAUD², and JOHN MARTIN¹ — ¹Institut de Physique Nucléaire, Atomique et de Spectroscopie, Université de Liège, 4000 Liège, Belgium — ²LPTMS, CNRS, Univ. Paris-Sud, Université Paris-Saclay, 91405 Orsay, France

We investigate multiqubit permutation-symmetric states with maximal entropy of entanglement. Such states can be viewed as particular spin states, namely antioherent spin states. Using the Majorana representation of spin states in terms of points on the unit sphere, we analyze the consequences of a point-group symmetry in their arrangement on the quantum properties of the corresponding state [1]. We focus on the identification of antioherent states (for which all reduced density matrices in the symmetric subspace are maximally mixed) associated with point-group-symmetric sets of points. We provide three different characterizations of antioherence and establish a link between point symmetries, antioherence, and classes of states equivalent through stochastic local operations with classical communication. We then investigate in detail the case of small numbers of qubits and construct infinite families of antioherent states with point-group symmetry of their Majorana points, showing that antioherent states do exist to arbitrary order.

[1] D. Baguette *et al.*, *Phys. Rev. A* 92, 052333 (2015).

Q 42.5 Wed 16:30 Empore Lichthof

Loading Scheme for Surface Traps With Beryllium Ions — ●JOHANNES MIELKE¹, HENNING HAHN¹, TIMKO DUBIELZIG¹, MARTINA WAHNSCHAFFE^{1,2}, and CHRISTIAN OSPELKAUS^{1,2} — ¹Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany — ²PTB, Bundesallee 100, 38116 Braunschweig, Germany

Surface electron ion traps are promising systems for scalable quantum information processing. In one of the present projects in our group, we are developing advanced trap designs with integrated microwave conductors providing the near field configuration to drive $^9\text{Be}^+$ hyperfine qubit transitions [1]. A scheme for efficient loading of surface traps with beryllium ions is presented. We use a nanosecond pulsed laser for ablation of neutral atoms from a beryllium wire and a laser system for subsequent two-photon ionization. The ionization laser is based on an infrared diode laser, which is frequency quadrupled by two cavity-enhanced frequency doubling stages, similar to [2]. Furthermore we discuss a spectroscopy scheme using a Beryllium-vapor lamp for locking the ionisation laser to the neutral beryllium $2p^1S_0 \rightarrow 2s^1P_1$ transition.

[1] M. Carsjens et al., *Appl. Phys. B*, 114: 243-250 (2014)
[2] H.-Y. Lo et al., *Appl. Phys. B*, 114: 17-25 (2014).

Q 42.6 Wed 16:30 Empore Lichthof

Superconducting Atom Chips — CHRISTOPH HUFNAGEL², DESHUI YU², CHEE HOWE EW², CHIN CHEAN LIM², ALESSANDRO LANDRA², and ●RAINER DUMKE^{1,2} — ¹Division of Physics & Applied Physics, School of Physical & Mathematical Sciences, Nanyang Technological University, Singapore — ²Centre for Quantum Technologies, National University of Singapore, Singapore

Superconducting and Cryogenic Atom Chips

Recently superconducting atom chips have generated a lot of interest due to their attractive properties, such as the Meissner effect for type-I superconductors and vortices for type-II superconductors. Thermal and technical noise in proximity to superconducting surfaces have been shown both theoretically and experimentally to be significantly reduced compared to conventional atom chips. Superconducting atom chips have the potential to coherently interface atomic and molecular quantum systems with quantum solid state devices. I will present recent developments in our superconducting atom chip experiment.

Q 42.7 Wed 16:30 Empore Lichthof

Measurement of ion heating rate in a planar ion trap at variable distance to the trap surface — ●IVAN BOLDIN and CHRISTOF WUNDERLICH — University of Siegen, Germany

Electric field noise in the vicinity of metal surfaces is an important issue in various fields of experimental physics. In experiments with cold trapped ions such noise results in heating of the ions' motional degrees of freedom. In realizations of quantum information processing based on trapped ions this heating can become a major source of decoherence. Since this effect scales as $1/d^4$ (with the ion-electrode separation d), it is particularly prominent for planar electrode ion traps where this separation can be as small as tens of micrometers.

This electric field noise-induced heating has been studied in many experimental and theoretical works over the last years [1 - 3]. However, to our knowledge there has been no direct experimental measurement of the heating rate of ions above a single planar electrode ion trap as a function of the ion-surface separation. Here, we present the result of such measurements. Our trap is made of gold electroplated on sapphire [4]. The ion-surface distance can be varied in the range of 45 - 155 μm . We measure the heating rate by the recoiling method that is, measuring the photon scattering rate as a function of time after allowing the ion to heat up for a certain time.

- 1) L. Deslauriers et al., PRL 97, 103007 (2006);
- 2) M. Brownnutt et al., arXiv:1409.6572 (2014);
- 3) I. Talukdar et al., arXiv:1511.0062 (2015);
- 4) P.J. Kunert et al., Appl. Phys. B 114, 27-36 (2014).

Q 42.8 Wed 16:30 Empore Lichthof

Cryogenic surface-electrode ion trap apparatus — ●TIMKO DUBIELZIG¹, SEBASTIAN GRONDKOWSKI¹, MARTINA WAHNSCHAFFE^{1,2}, and CHRISTIAN OSPALKAUS^{1,2} — ¹Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany — ²PTB, Bundesallee 100, 38116 Braunschweig, Germany

We describe the infrastructure necessary to operate a surface-electrode ion trap with integrated microwave conductors for near-field quantum control of $^9\text{Be}^+$ in a cryogenic environment. These traps are promising systems for analog quantum simulators and for quantum logic applications. Our group developed a trap with an integrated meander-like microwave guide for driving motional sidebands on a $^9\text{Be}^+$ ion [1]. To suppress electrical field noise, acting on the ion and originating from thermal effects [2], the trap will be operated in a cryogenic vacuum chamber. We will discuss the vibration isolated closed cycle cryostat and the design of the vacuum chamber with all electrical supplies necessary to apply two different microwave currents, DC- and RF-voltages. We will also discuss magnetic-field coils producing an ultra-stable magnetic field at 22.3 mT and the resulting field-independent hyperfine qubit. Furthermore we will present the cryogenic, high aperture and fully acromatic imaging system. We report on recent progress in operation of the apparatus.

- [1] Applied Physics B - 10.1007/s00340-013-5689-6 (2013)
- [2] J. Chiaverini and J. M. Sage, PRA 89, 012318 (2014)

Q 42.9 Wed 16:30 Empore Lichthof

Towards multi-qubit near-field microwave quantum logic in a multi-layer surface-electrode trap — ●HENNING HAHN^{1,2}, GIORGIO ZARANTONELLO^{1,2}, MARTINA WAHNSCHAFFE^{1,2}, MATTHIAS KOHNEN^{1,2}, AMADO BAUTISTA-SALVADOR^{1,2}, and CHRISTIAN OSPALKAUS^{1,2} — ¹Leibniz Universität Hannover, Germany. — ²Physikalisch-Technische Bundesanstalt, Braunschweig Germany.

In quantum information processing with trapped ions, tightly focused laser beams are typically used for coupling internal states and motional states of individual ions as required for multi-qubit entangling gates. However, scaling laser-based techniques for multi-qubit gates remains challenging. In an alternative approach, the desired state coupling is achieved by oscillating microwave near-field gradients created by cur-

rents in conductors embedded in a planar ion trap. In an adaption of the first demonstration setup [1], the number of microwave electrodes was reduced to a single meander-like conductor to suppress previously limiting relative phase and current fluctuations by design [2].

Here we discuss the integration of a meander-like conductor into a multi-layer ion trap and address the fabrication process involved. Since residual magnetic fields are reduced, less excitation on off-resonant carrier transitions is expected and thus, gate fidelities can be improved. Moreover, we show a vacuum setup with built-in Ar^+ bombardment for reducing motional heating rates by *in-situ* electrode cleaning [3].

- [1] C. Ospelkaus et al., Nature, **476**, 181 (2011)
- [2] M. Carsjens et al., Appl. Phys. B **114**, 243 (2014)
- [3] D. A. Hite et al., Phys. Rev. Lett. **109**, 103001 (2012)

Q 42.10 Wed 16:30 Empore Lichthof

Randomized Benchmarking on Ground State Qubits — ●MICHAEL METH¹, PHILIPP SCHINDLER¹, MARTIN VAN MOURIK¹, MATTHIAS BRANDL¹, ANTON NOLF¹, THOMAS MONZ¹, and RAINER BLATT^{1,2} — ¹Institut für Experimentalphysik, Universität Innsbruck, Technikerstrasse 25, 6020 Innsbruck, Austria — ²Institut für Quantenoptik und Quanteninformation, Akademie der Wissenschaften, Technikerstrasse 21a, 6020 Innsbruck, Austria

Quantum information processing using optical transitions in ions has been successful for many experiments. Alternatively, quantum information can also be encoded in ground states and processed by lasers driving Raman transitions. This leads to longer coherence times as laser frequency fluctuations have no effect. Here, we report on single qubit operations on ground state qubits in $^{40}\text{Ca}^+$. We characterize the performance of single qubit operations using randomized benchmarking. In order to produce the required number of gates, a new FPGA based control system had to be implemented to allow for longer sequences.

Q 42.11 Wed 16:30 Empore Lichthof

Generating N00N-like (macroscopic) quantum states — ●FALK TÖPPEL^{1,2}, MARIA V. CHEKHOVA^{1,2}, and GERD LEUCHS^{1,2} — ¹Max Planck Institute for the Science of Light, Günther-Scharowsky-Straße 1/Bldg. 24, 91058 Erlangen, Germany — ²Institute for Optics, Information and Photonics, Universität Erlangen-Nürnberg, Staudtstraße 7/B2, 91058 Erlangen, Germany

We demonstrate the potential of a recently proposed protocol for conditional state preparation to generate new and interesting two-mode (macroscopic) quantum states. Our protocol allows one to manipulate the photon number distribution of a two-mode (macroscopic) quantum states of light such that contributions with similar photon numbers in both modes are suppressed. The key feature of the protocol is that quantum entanglement shared between the two modes is preserved.

Let us consider the superposition of a coherent state and a squeezed vacuum state at a 50/50 beam splitter. This quantum state is known to resemble a N00N state with fidelity $> 90\%$ when post-selecting on a certain total photon number, although its photon number distribution is very different from the one of a N00N state. We can enhance the N00N-like contributions of the considered state with the above mentioned protocol. The filtered state exhibits super-resolution when post-selecting on a fixed total number of photons, just as it is known for the considered input state. This indicates that superposition terms are not destroyed by the protocol. We examine entanglement properties of the new quantum state and study its potential to violate Bell's inequality.

Q 42.12 Wed 16:30 Empore Lichthof

Using Schrödinger cat states of Rydberg atoms to measure electric fields — ●EVA-KATHARINA DIETSCHKE, ADRIEN FACON, DORIAN GROSSO, SERGE HAROCHE, JEAN-MICHEL RAIMOND, MICHEL BRUNE, and SEBASTIEN GLEYZES — Laboratoire Kastler Brossel, College de France, ENS-PSL, UPMC-Sorbonne Universite, CNRS, 11 Place Marcelin Berthelot 75005 Paris, France

We present a quantum-enabled measurement of the electric field using Rydberg atoms. We prepare the atom in a quantum superposition of two circular states with principle quantum number $n=50$ and $n=51$. Using a radiofrequency field resonant with the Stark transition in the $n=50$ manifold we transfer the $n=50$ part of the wave function from its horizontal circular orbit to a tilted elliptical trajectory. This creates a Schrödinger cat superposition of two states with very different polarizabilities whose relative phase is highly sensitive to variations in the amplitude of the electric field. Detecting this phase change using Ramsey interferometry allows us to measure the electric field with a

precision below the standard quantum limit (SQL). This single-atom-electrometer allows us to measure weak field variations in the order of 1mV/cm in a few tens of nanoseconds, paving the way to non-invasive space- and time-resolved field measurements.

Q 42.13 Wed 16:30 Empore Lichthof

Entanglement of Indistinguishable Particles and its Quantification — ●FLORIAN SOKOLI and BURKHARD KÜMMERER — Fachbereich Mathematik, TU Darmstadt

In this contribution we propose measures of entanglement for indistinguishable particles which are based on generalized norms. These measures are capable of quantifying entanglement of indistinguishable particles in the most general scenario of arbitrary multipartite (mixed) quantum states in any dimension. In particular, we obtain a necessary and sufficient separability criterion for this case. We demonstrate that these measures are related to corresponding measures of entanglement for distinguishable particles by a state-independent factor of $k!$ where k is the number of particles.

Ref.: F. Sokoli, B. Kümmeler: arXiv:1507.04615v1

Q 42.14 Wed 16:30 Empore Lichthof

Maximally entangled vs. separable: An approach to the characterization of random unitary channels — ●DANIEL BRUNS, JAN SPERLING, and STEFAN SCHEEL — Institut für Physik, Rostock

Modern applications in quantum computation and quantum communication necessitate the characterization of quantum states and quantum channels. In practice, this means that one has to determine the quantum performance of a physical system in terms of measurable quantities. Witnesses, if properly constructed, succeed in doing this task. We derive a method that is capable to construct witnesses for the characterization of channels, whose dynamics can be formulated solely in terms of a statistical mixture of unitary evolutions. Those *random unitary channels* were studied in [1] as giving evidence for classical error mechanisms occurring in the preparation and processing of quantum states.

It has been shown that random unitary channels are equivalent to bipartite quantum states decomposable into a convex combination of maximally entangled states. Conversely, a separable state is defined as a mixture of product states. Based on our treatment we are able to witness these opposing attributes at once and, furthermore, get an insight into the different geometric structures.

[1] K.M.R. Audenaert and S. Scheel. New J. Phys. 10, 023011 (2008)

Q 42.15 Wed 16:30 Empore Lichthof

Gaussian Quantum Steering of Two Bosonic Modes in a Thermal Environment — ●TATIANA MIHAESCU^{1,2} and AURELIAN ISAR² — ¹Institute of Theoretical Physics, Heinrich Heine University of Düsseldorf, Germany — ²Department of Theoretical Physics, National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania

Einstein-Podolsky-Rosen steerability of quantum states is a property that is different from entanglement and Bell nonlocality. We describe the time evolution of a recently introduced measure that quantifies steerability for arbitrary bipartite Gaussian states [1] in a system consisting of two bosonic modes embedded in a common thermal environment.

We work in the framework of the theory of open systems. If the initial state of the subsystem is taken of Gaussian form, then the evolution under completely positive quantum dynamical semigroups assures the preservation in time of the Gaussian form of the state [2].

We study Gaussian quantum steering in terms of the covariance matrix under the influence of noise and dissipation and find that the thermal noise introduced by the environment destroys the steerability between the two parts [3].

We make a comparison with other quantum correlations for the same system, and show that, unlike Gaussian quantum discord, which is decreasing asymptotically in time, the Gaussian quantum steerability suffers a sudden death behaviour, like quantum entanglement.

Q 42.16 Wed 16:30 Empore Lichthof

Joint measurability and Channel Steering — ●FABIANO LEVER — University of Siegen, Siegen, Germany

The task of quantum steering refers to the idea of one party, (Alice) remotely affecting another party (Bob) state by performing local measurements on her half of a bipartite state. While entanglement between the two parties is a fundamental ingredient for the task, alone it is not

sufficient. Steering requires stronger correlations than just entanglement. Moreover, it has recently been shown that in order to prove steering, Alice has to use incompatible measurements on her subsystem. This fact points us to the idea that incompatibility is necessary to perform measurement based quantum tasks.

Our work focuses on the application of this idea to the steering of broadcast quantum channels (i.e. channels with more than one output), modeling scenarios in which some of the information leaks to the environment. In particular, we show that there is a one to one mapping between the steerability of quantum channels and the joint measurability problem for a set of POVMs.

Q 42.17 Wed 16:30 Empore Lichthof

Compatibility and Noncontextuality for Imperfect Measurements — ●JANNIK HOFFMANN, COSTANTINO BUDRONI, and OTFRIED GÜHNE — Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Str. 3, 57068 Siegen, Germany

The notion of contextuality refers to impossibility of a classical description for each observable, which is independent of the measurement context, i.e., the set of compatible measurements done with it. Initially defined for commuting projective measurements [1,2], there have been different attempts to extend the notion of contextuality to deal with imperfect measurements and experimental errors. Here, we will focus on the error parameters introduced by Gühne et al. [3] and Kujala et al. [4] and investigate the questions of which errors can be detected and what is the relation with the original notion of noncontextuality. In particular, we discuss the case of sequential projective measurements, with and without noise, and more general measurements described by positive operator valued measures (POVMs) and instruments.

References

- [1] S. Kochen and E. P. Specker, J. Math. Mech. 17, 59 (1967).
- [2] A. A. Klyachko, M. A. Can, S. Binicioglu, and A. S. Shumovsky, Phys. Rev. Lett. 101, 020403 (2008).
- [3] O. Gühne, M. Kleinmann, A. Cabello, J.-Å. Larsson, G. Kirchmair, F. Zähringer, R. Gerritsma, C.F. Roos, Phys. Rev. A 81, 022121 (2010).
- [4] J. V. Kujala, E. N. Dzhafarov, J.-Å. Larsson Phys. Rev. Lett. 115, 150401 (2015).

Q 42.18 Wed 16:30 Empore Lichthof

Witnessing genuine multilevel entanglement — ●TRISTAN KRAFT, CHRISTINA RITZ, and OTFRIED GÜHNE — Department Physik, Universität Siegen, Germany

Entanglement is arguably one of the most intriguing phenomena in physics and is believed to be a fundamental resource for quantum communication and quantum information. In recent years due to the hard work of many experimentalists the preparation of entangled systems with dimensions larger than two became feasible. Therefore it is necessary to have strong entanglement criteria to detect genuine multilevel entanglement in higher dimensional systems.

Here we present entanglement criteria based on qudit graph states which are generalizations of the well known qubit graph states. We also discuss the fact that in some cases the certification of genuine multilevel entanglement does not imply the ability to coherently manipulate a qudit system in its entirety.

Q 42.19 Wed 16:30 Empore Lichthof

Logic operations with polarization-encoded x-rays processed by nuclear transitions — ●JONAS GUNST, CHRISTOPH H. KEITEL, and ADRIANA PÁLFFY — Max-Planck-Institut für Kernphysik, Heidelberg

Since the computational demands are expected to become increasingly complex over time, a basic goal of information science is to build storage and processing devices in their most compact form. In the case of photonic circuits, the size is fundamentally limited by the diffraction limit of the used photons ($\sim 1\mu\text{m}$ for optical photons) which could be drastically reduced by going to shorter wavelengths like for instance x-rays. However, using polarization-encoded x-rays as information carriers requires control schemes performed on the single-photon level.

Here, we investigate theoretically how to manipulate the x-ray polarization by employing the resonant interaction with low-lying nuclear transitions ($\sim \text{keV}$). In the course of nuclear forward scattering on ensembles of Mössbauer ^{57}Fe nuclei, the collective response becomes sensitive to the incoming polarization state under the impact of an external magnetic field [1]. We show that it is possible to perform logical operations on polarization-encoded x-rays by applying a rotation of the magnetic field temporally synchronized with the nuclear exci-

tation [2]. This x-ray processing scheme can be tested and quantified experimentally at present synchrotron radiation facilities.

[1] Yu. V. Shvyd'ko *et al.*, Phys. Rev. Lett. **77**, 3232 (1999).

[2] J. Gunst *et al.*, arXiv:1506.00517 (2015).

Q 42.20 Wed 16:30 Empore Lichthof

Räumlich getrennte Bellzustände in einer segmentierten Paulfalle — •THOMAS RUSTER, HENNING KAUFMANN, CHRISTIAN SCHMIEGELOW, JONAS SCHULZ, FERDINAND SCHMIDT-KALER und ULRICH POSCHINGER — QUANTUM, Institut für Physik, Universität Mainz, Staudingerweg 7, 55128 Mainz, Germany

Bellzustände sind die Grundlage für vielfältige Anwendungen, z.B. für Quantenrepeater [1], Hochpräzisionsmessungen [2], oder zur Erzeugung dekohärenzfreier Quantenbits [3]. In segmentierten Paulfallen lassen sich Bellzustände nicht nur erzeugen, sondern auch über makroskopische Distanzen voneinander trennen. Das ermöglicht die Skalierung von Experimenten auf eine höhere Anzahl an Ionen und die präzise Vermessung von inhomogenen Magnetfeldern.

Zur Realisierung skalierbarer Experimente kombinieren wir Laser-Ion-Wechselwirkungen mit dem Transport von Ionen innerhalb der Falle und dem Trennen bzw. Zusammenfügen von Ionenkristallen [4,5].

Wir zeigen, dass die Kohärenzzeit von Bellzuständen unverändert bleibt, selbst wenn deren konstituierenden Ionen auf makroskopische Distanzen bis zu 5.5mm voneinander getrennt werden.

[1] H. J. Kimble, Nature **453**, 1023-1030 (2008)

[2] V. Giovannetti *et al.*, Phys. Rev. Lett. **96**, 010401 (2006)

[3] H. Häffner *et al.*, Appl. Phys. B **81**, 151 (2005)

[4] R. Bowler *et al.*, Phys. Rev. Lett. **109**, 080502 (2012)

[5] T. Ruster *et al.*, Phys. Rev. A **90**, 033410 (2014)

Q 42.21 Wed 16:30 Empore Lichthof

Increasing the information content of single photons — •TRISTAN TENTRUP, THOMMAS HUMMEL, ALLARD MOSK, and PEPIJN PINKSE — MESA+ Institute for Nanotechnology, Universiteit Twente

A common way to encode information in single photons is the use of polarization, which allows a maximum of 1 bit per photon. Encoding in a higher dimensional Hilbert space allows to transfer more information per photon. Examples of encoding methods are time binning and the use of orbital angular momentum states. We use a spatial light modulator (SLM) to control the spatial position of single photons generated by a spontaneous parametric down-conversion source. Exploiting modern two-dimensional photon counting imaging systems, we detect their (x,y) positions and discuss the limit on information density. A possible application of this work is Quantum Key Distribution (QKD), where an increase in information per photon not only increases the possible key generation rate but also the security of the protocol.

Q 42.22 Wed 16:30 Empore Lichthof

Proposal for a telecom quantum repeater with single atoms in optical cavities — •MANUEL BREKENFELD, MANUEL UPHOFF, DOMINIK NIEMIETZ, STEPHAN RITTER, and GERHARD REMPE — Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching, Germany

Quantum repeaters hold the promise to enable long-distance quantum communication via entanglement generation over arbitrary distances. Single atoms in optical cavities have been shown to be ideally suited for the experimental realization of many tasks in quantum communication [1]. To utilize these systems for a quantum repeater, it would be desirable to operate them at telecom wavelengths. We propose to use a cascaded scheme employing transitions at telecom wavelengths between excited states of alkali atoms for entanglement generation between a single photon at telecom wavelength and a single atom at the crossing point of two cavity modes [2]. A cavity-assisted quantum gate can be used for entanglement swapping. We estimate the performance of these systems using numerical simulations based on experimental parameters obtained for CO₂ laser-machined fiber cavities in our laboratory. Finally, we show that a quantum repeater employing the aforementioned scheme and current technology could outperform corresponding schemes based on direct transmission.

[1] Ritter *et al.*, Nature **484**, 195 (2012)

[2] Uphoff *et al.*, arXiv:1507.07849 (2015)

Q 42.23 Wed 16:30 Empore Lichthof

A cavity mediated photon-photon gate — •STEPHAN WELTE, BASTIAN HACKER, STEPHAN RITTER, and GERHARD REMPE — Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching

Photons are promising candidates for applications in quantum information processing and quantum communication. However, the direct interaction between two photons is negligible in free space, which is a drawback when it comes to the implementation of quantum logic gates between them. A solution to this problem was proposed by Duan and Kimble [1]. A strongly coupled atom in an optical cavity can mediate an effective interaction between two photons. Recently, we experimentally realized a quantum gate between an intracavity atom and a photon which is reflected off the cavity [2]. This atom-photon gate can be a building block of the aforementioned gate protocol for two photons. We will discuss the prospects and challenges for implementing the Duan-Kimble proposal in our setup and report on the current status of the experiment.

[1] L.-M. Duan, H. J. Kimble, Phys. Rev. Lett. **92**, 127902 (2004)

[2] A. Reiserer, N. Kalb, G. Rempe and S. Ritter, Nature **508**, 237 (2014)

Q 42.24 Wed 16:30 Empore Lichthof

Entanglement Dynamics in Superconducting Phase Qudits under Pythagorean Control — •DANIEL BASILEWITSCH¹, NADAV KATZ², and CHRISTIANE KOCH¹ — ¹Institute of Physics, University of Kassel, Kassel, Germany — ²Rachah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem, Kassel

Pythagorean control of a superconducting phase qudit has recently been demonstrated in first experiments. The concept of Pythagorean control generalizes population inversion in a two level system, which is solved by Rabi oscillations, to four levels. We analyze the observed state dynamics of the qudit and determine the available quantum gates when interpreting the four-level qudit as two coupled qubits. In the strong field regime, the state dynamics differs from that expected with Pythagorean control due to the presence of additional levels and the finite anharmonicity of the qudit ladder. Moreover, Pythagorean control is compromised by the coupling of the qudit to its environment, causing decoherence. We use optimal control theory (OCT) to adapt the analytical controls to the presence of additional levels and decoherence, to counter the effects of finite anharmonicity and to improve gate fidelities and times.

Q 42.25 Wed 16:30 Empore Lichthof

Optimal absorption of a photon by a quantum node — SUSANNE BLUM^{1,2}, •TOM SCHMIT¹, DANIEL REICH^{3,4}, TOMMASO CALARCO⁵, CHRISTIANE KOCH³, and GIOVANNA MORIGI¹ — ¹Universität des Saarlandes, Saarbrücken, Germany — ²Theodor-Heuss-Gymnasium, Esslingen, Germany — ³Universität Kassel, Kassel, Germany — ⁴Universität Aarhus, Aarhus, Denmark — ⁵Universität Ulm, Ulm, Germany

We discuss protocols for achieving perfect absorption of a photon by a single trapped atom, or solid-state emitter, in a high-finesse cavity. Specifically, we compare the efficiency of protocols based on adiabatic transfer with the one of protocols based on optimal control theory. We focus on the setup of [Reiser *et al.*, Nature **508**, 237 (2014)]. Our ultimate goal is to identify the conditions on external fields driving the atom, which are required for absorbing a photon of *arbitrary* spectral form. We discuss the efficiency of the protocols for a certain class of photonic wave forms. This analysis contributes to the development of a toolbox for quantum networks using hybrid platforms.

Q 42.26 Wed 16:30 Empore Lichthof

Analyse einiger Quantenrepeaterprotokolle am konkreten Aufbau einer existierenden Ionenfalle — •ANDREAS PFISTER, MARCEL SALZ, MAX HETRICH, ULRICH POSCHINGER und FERDINAND SCHMIDT-KALER — QUANTUM, Institut für Physik, Johannes-Gutenberg-Universität Mainz

Anhand eines existierenden Aufbaus werden mehrere Protokolle zur Verteilung von Verschränkung in Quantenrepeatern verglichen [1]. Der Aufbau basiert auf einer mikrostrukturierten, segmentierten linearen Paulfalle für ⁴⁰Ca⁺, in der ein faserbasierter Mikroresonator als Licht-Ionen-Schnittstelle fungiert, dessen kleines Modenvolumen eine hohe Kopplungsrate von $g_c = 2\pi \times 20$ MHz ermöglicht, trotz relativ hoher Verluste von $\kappa = 2\pi \times 36.6$ MHz. Ionen können in der Falle in den Resonator hinein- und heraus bewegt werden, so dass mehrere Qubits über einen I/O Port kommunizieren können.

Es wurden ein Protokoll basierend auf Verteilung verschränkter Photonen untersucht [2], eine Variation des DLCZ-Algorithmus [3] und ein hybrides Protokoll [4]. Die Abschätzung für die Verschränkungsverteilung ergibt Raten von ca. 30 s^{-1} für nichtlokale Bellzustände mit Fidelities größer 0.9. Es werden die Parameter identifiziert, die die Rate

am stärksten begrenzen. Raten von einigen hundert Verschränkungen pro Sekunde scheinen mit aktueller Technologie erreichbar.

- [1] A. Pfister et al., arXiv:1508.05272 (2015)
- [2] N. Sangouard et al., *New J. Phys.*, 15(8):085004, 2013.
- [3] L.-M. Duan et al, *Nature*, 414:413–418 (2001).
- [4] P. van Loock et al., *Phys. Rev. Lett.*, 96:240501 (2006).

Q 42.27 Wed 16:30 Empore Lichthof

A Fast Multichannel Signal Generator for Segmented Ion Traps — ●VIDYUT KAUSHAL, HEINZ LENK, KILIAN SINGER, FERDINAND SCHMIDT-KALER, and ULRICH POSCHINGER — QUANTUM, Institut für Physik, Universität Mainz, Staudingerweg 7, 55128 Mainz, Germany

Modern segmented ion traps require hardware for individual real-time control of the segment voltages, with stringent requirements on signal integrity and sampling rate. We present the functional design of a fast multichannel, arbitrary waveform generator, which supports up to 80 independent analog output channels. The device reaches a maximum analog update rate of 3.9 million samples/s for all channels simultaneously. Additionally, the delay between consecutive samples can be controlled in steps of 20 ns, resolving typical trap oscillation periods - a crucial feature for the control of fast shuttling operations [1,2]. The output voltage range of ± 40 V allows for tight confinement of trapped ions and compensation of signal distortion.

We describe the architecture of the device in detail and present a thorough characterization of the relevant signal characteristics, such as slow rate, long-time stability, nonlinearities, glitch impulse areas and output noise. We also discuss future extensions towards a complete real-time control system including feedback capabilities.

- [1] A. Walther et al., PRL 109, 080501 (2012)
- [2] T. Ruster et al., PRA 90, 033410 (2014)

Q 42.28 Wed 16:30 Empore Lichthof

High temperature superconducting surface ion traps — ●DOMINIC SCHÄRTL¹, KIRILL LAKHMANSKIY¹, PHILIP HOLZ¹, MUIR KUMPH², YVES COLOMBE¹, and RAINER BLATT^{1,2} — ¹Institute for Experimental Physics, University of Innsbruck, Austria — ²Institute for Quantum Optics and Quantum Information, Innsbruck, Austria

Ion traps are a promising tool for quantum simulators and quantum computers [1]. Microfabricated surface traps offer the possibility to miniaturize ion traps, which is a possible route towards a scalable quantum computer. However, the proximity of the ions to the surface of the trap leads to motional heating, the origin of which is not well understood [2].

To investigate different sources of motional heating, we operate a surface ion trap made of YBCO, a high-temperature superconducting material. The trap is designed in such a way that Johnson noise should be the dominant source of motional heating above the critical temperature $T_c \approx 85$ K, whereas below T_c it should be negligible compared to other noise sources. Using a local heating element, we adjust the temperature of the trap chip and observe the superconducting transition by measuring the Q factor of the RF resonant circuit or the resistance of on-chip structures. Probing the motional heating of a trapped ion, we expect to observe pronounced changes in the characteristics of the electric field noise in a small temperature range around T_c .

- [1] R. Blatt, C.F. Roos, *Nature Phys.* 8, 277 (2012)
- [2] M. Brownnutt, M. Kumph, P. Rabl, and R. Blatt, arXiv:1409.6572 (2014)

Q 42.29 Wed 16:30 Empore Lichthof

Scaling down cryogenic surface ion traps for quantum information processing — ●KIRILL LAKHMANSKIY¹, PHILIP HOLZ¹, STEFAN PARTEL², STEPHAN KASEMANN², VOLHA MATYLITSKAYA², JOHANNES EDLINGER², YVES COLOMBE¹, and RAINER BLATT^{1,3} — ¹Institute for Experimental Physics, University of Innsbruck, Austria — ²Fachhochschule Vorarlberg, Dornbirn, Austria — ³Institute for Quantum Optics and Quantum Information, Innsbruck, Austria

Ion traps are a promising platform for quantum information processing. We report on our recent experimental results with microfabricated surface ion traps in cryogenic environment using two different trapping architectures. In the first project we use linear surface ion traps based on intrinsic silicon. These traps were fabricated using a deep reactive-ion etching process followed by silicon oxidation and metal deposition. We were able to show very low motional heating rates at an ion-electrode separation of $230 \mu\text{m}$ [1]. Our current goal is to scale down the traps while keeping the heating rate sufficiently low to perform high-fidelity quantum operations. The aim of the second project

is to realize a 2D array of individual point traps for quantum simulation. We use a microfabricated 4×4 ion trap array with an ion-ion separation of $100 \mu\text{m}$. This distance may be reduced while operating the trap using switchable RF electronics [2], to a point where coherent operations mediated by the Coulomb interaction become possible.

- [1] M. Niedermayr et al., *New J. Phys.* 16, 113068 (2014)
- [2] M. Kumph, P. Holz, K. Langer, M. Niedermayr, M. Brownnutt, and R. Blatt, arXiv:1402.0791

Q 42.30 Wed 16:30 Empore Lichthof

Optimizing a quantum computer with randomized benchmarking — ●ROMAN STRICKER, ALEXANDER ERHARD, DANIEL NIGG, ESTEBAN MARTINEZ, PHILIPP SCHINDLER, THOMAS MONZ, and RAINER BLATT — Institute for Experimental Physics, University of Innsbruck, Austria

The realization of a quantum computer has become a major research field over the last decade. For a successful implementation, error-sources need to be kept as small as possible. One promising way of characterizing these errors is by means of randomized benchmarking. We report on an experiment characterizing Clifford operations. The experiment is performed on a $^{40}\text{Ca}^+$ ion-trap quantum computer. The goal was to implement randomly chosen sets of single-qubit gates with arbitrary lengths, where each specific set is chosen to be a self-inverting sequence. Measuring the difference between the experimental outcome and the ideal transformation leads to an estimation of the fidelity of a certain set. To obtain the fidelity of a single gate, we analyze the result of different random sequences. We use this as a tool to improve our experimental setup, such as stabilizing the lasers intensity or reducing fiber noise. We found a single-qubit fidelity of above 99%.

Q 42.31 Wed 16:30 Empore Lichthof

Entangling two single trapped atoms over a distance of 400 m — ●ROBERT GARTHOFF¹, DANIEL BURCHARDT¹, NORBERT ORTEGEL¹, KAI REDEKER¹, WENJAMIN ROSENFELD¹, and HARALD WEINFURTER^{1,2} — ¹Ludwig-Maximilians-Universität, München — ²Max-Planck-Institut für Quantenoptik, Garching

Long distance between entangled quantum systems is essential for quantum repeaters as well as for conclusive tests of Bell's inequality, which itself is a central part in novel applications as device-independent quantum key distribution and certified generation of quantum random numbers.

We present an experimental realization employing heralded entanglement between two single Rb-87 atoms over a distance of 400 meter. To achieve a high degree of entanglement precise control of external parameters is required. In addition to the long distance requiring long coherence times, we implemented an fast and efficient atomic state readout with an overall duration of the state measurement below $1 \mu\text{s}$. In order to obtain a high number of events a longtime stability of the experimental setup presents an additional challenge. Together these ingredients form the basis for robust generation of entanglement and space-like separated measurements on the widely separated atoms as necessary for a conclusive test of Bell's inequality. Moreover this system represents a basic quantum repeater link and may become a testing platform for device-independent quantum key distribution.

Q 42.32 Wed 16:30 Empore Lichthof

Quantum Key Distribution from a mobile phone — GWENAELE MÉLEN¹, TOBIAS VOGL¹, MARKUS RAU¹, ●SILVAN STREIT^{1,2}, PETER FREIWANG¹, GIACOMO CORRIELLI^{3,4}, ANDREA CRESPI^{3,4}, ROBERTO OSELLAME^{3,4}, and HARALD WEINFURTER^{1,5} — ¹Faculty of Physics, Ludwig-Maximilians-Universität, 80799 München, Germany — ²Department of Electrical and Computer Engineering, Technische Universität München, 80333 München, Germany — ³Istituto di Fotonica e Nanotecnologie, Consiglio Nazionale delle Ricerche (IFN-CNR), 20133 Milano, Italy — ⁴Dipartimento di Fisica, Politecnico di Milano, 20133 Milano, Italy — ⁵Max-Planck-Institut für Quantenoptik, 85748 Garching bei München, Germany

We present an integrated optics module enabling Quantum Key Distribution from a small and mobile sender device. The new optics platform ($35 \times 20 \times 8$ mm) uses a VCSEL array, micro-optical elements and laser written waveguides to generate NIR faint polarised laser pulses with 100 MHz repetition rate. Fully automated beam tracking and live basis-alignment on Bob's side ensure user-friendly operation with a secret key rate over 100 kHz. Using BB84-like protocols, Alice's low-cost mobile device can exchange secure key and information everywhere within a trusted node network.

Q 42.33 Wed 16:30 Empore Lichthof

A Fabry-Perot Microcavity for diamond based (NV) quantum information and communication processing — ●ROLAND NAGY¹, SEN YANG¹, HELMUT FEDDER¹, DURGA DASARI^{1,2}, and JÖRG WRACHTRUP^{1,2} — ¹3rd Institute of Physics and Research Center SCOPE, University of Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany — ²Max Planck Institute for Solid State Research, Stuttgart

A high fidelity coupling of solid-state spins to microcavities opens up new perspectives for the field of quantum communications and quantum information processing. With applications towards photon memories, and entangled photon generation they could become key elements in quantum networks transporting quantum states and entanglement over long distances.

In this poster I will present a scheme to couple the electronic states of a Nitrogen Vacancy (NV) center in a thin diamond membrane to a Fabry-Perot cavity [1]. In the presence of a long-lived nuclear spin I will show how this system could become a robust hybrid device to store and entangle photons [2].

[1]. Erika Janitz et al. Phys. Rev. A 92, 043844

[2]. D. D. Bhaktavatsala Rao et al. Phys. Rev. B 92, 081301(2015)(R)

Q 42.34 Wed 16:30 Empore Lichthof

Pulse-controlled quantum gate sequences on a strongly coupled qubit chain — ●HOLGER FRYDRYCH¹, MICHAEL MARTHALER², and GERNOT ALBER¹ — ¹Technische Universität Darmstadt, Germany — ²Karlsruher Institut für Technologie, Germany

We propose a selective dynamical decoupling scheme on a chain of permanently coupled qubits with XX type interactions, which is capable of dynamically suppressing any coupling in the chain by applying sequences of local pulses to the individual qubits. We demonstrate that high-fidelity single- and two-qubit gates can be achieved by this procedure and that sequences of gates can be implemented by this pulse control alone. We discuss the applicability and physical limitations of our model specifically for strongly coupled superconducting flux qubits. Since dynamically modifying the couplings between flux qubits is challenging, they are a natural candidate for our approach.

Q 42.35 Wed 16:30 Empore Lichthof

Estimating necessary detector efficiencies for a Bell test using semidefinite programming — ●ALEXANDER SAUER, NILS TRAUTMANN, and GERNOT ALBER — Institut für Angewandte Physik, Technische Universität Darmstadt

Loophole free violation of Bell inequalities is crucial for fundamental tests of quantum nonlocality. It is also important for future applications, such as device-independent quantum cryptography. Based on a detector model which includes detector inefficiencies and dark counts, we estimate the minimal requirements on detectors for performing a loophole free Bell test. Thereby, we also search for Bell inequalities which are robust against imperfect detectors in a bipartite setup. Our numerical investigation is based on semidefinite programming for characterizing possible quantum correlations[1]. We also examine critical detector efficiencies for a specific energy-time entanglement-based Bell experiment[2] designed to overcome limitations of Franson-type interferometers[3].

[1] M. Navascues, S. Pironio, and A. Acín, 2008, New J. Phys. 10, 073013. [2] A. Cabello, A. Rossi, G. Vallone, F. De Martini, and P. Mataloni, 2009, Phys. Rev. Lett. 102, 040401. [3] J.D. Franson, 1989, Phys. Rev. Lett. 62, 2205.

Q 42.36 Wed 16:30 Empore Lichthof

Entanglement purification of distant atomic qubits with ancillary multiphoton states — ●LUDWIG KUNZ, JÓZSEF ZSOLT BERNÁD, MAURICIO TORRES, and GERNOT ALBER — Institut für Angewandte Physik, Technische Universität Darmstadt, 64289 Darmstadt, Germany

We propose a scheme for conducting entanglement purification on distant two-level atoms. The atomic qubits are sent through a cavity one after the other and interact with a single mode of the radiation field inside the cavity. The atoms are post-selected by measuring the cavity field with the help of a balanced homodyne detection. It is demonstrated that the resulting quantum operation is a convenient basic building block for an entanglement purification protocol.

Q 42.37 Wed 16:30 Empore Lichthof

Two-photon interference with a non-degenerate photon-pair

source — GERHARD SCHUNK, ●GOLNOUSH SHAFIEE, ULRICH VOGL, DMITRY STREKALOV, ALEXANDER OTTERPOHL, NAVID SOLTANI, FLORIAN SEDLMEIR, HARALD G. L. SCHWEFEL, GERD LEUCHS, and CHRISTOPH MARQUARDT — Max Planck Institute for the Science of Light, Institute for Optics, Information and Photonics, University Erlangen-Nuremberg, Erlangen, Germany

Single photons and photon pairs are an important resource for quantum information processing. Our compact source of photon pairs [1] and squeezed light [2] is based on spontaneous parametric down conversion (SPDC) in a triply resonant whispering-gallery resonator (WGR) made of lithium niobate. Single-mode operation of this source has been shown. We recently demonstrated the tuning of our SPDC source to different narrowband atomic transitions in the near-infrared, which makes our source compatible with a wide range of atomic quantum memories [3].

We currently investigate SPDC in counter-propagating modes in one WGR, which can be viewed as two identical photon-pair sources. Here we study entanglement creation via the interference of two heralded signal photons. This system opens up novel possibilities to realize proposed quantum repeater schemes.

[1] M. Förtsch et al., Nat. Commun. 4, 1818 (2013). [2] J. U. Fürst et al., Phys. Rev. Lett. 106, 113901(2011). [3] G. Schunk et al., Optica 2, 773-778 (2015).

Q 42.38 Wed 16:30 Empore Lichthof

Entangling the whole by beam splitting one part — ●CHRISTIAN PEUNTINGER^{1,2}, CALLUM CROAL³, VANESSA CHILLE^{1,2}, CHRISTOPH MARQUARDT^{1,2}, GERD LEUCHS^{1,2}, NATALIA KOROLKOVA³, and LADISLAV MIŠTA JR.⁴ — ¹Max Planck Institute for the Science of Light, Guenther-Scharowsky-Str. 1/Bldg. 24, D-91058 Erlangen, Germany — ²Institute of Optics, Information and Photonics, University of Erlangen-Nuremberg, Staudtstr. 7/B2, D-91058 Erlangen, Germany — ³School of Physics and Astronomy, University of St. Andrews, North Haugh, St. Andrews, Fife, KY16 9SS, Scotland — ⁴Department of Optics, Palacký University, 17.listopadu 12, 771 46 Olomouc, Czech Republic

A beamsplitter is a widely used optical element to create continuous variable entanglement. In the case of Gaussian states, the input modes need to exhibit squeezing for this purpose. We experimentally demonstrate the creation of entanglement by mixing two modes, which do not possess the required squeezing themselves [1]. This is possible if the modes are correlated to a third mode, which can be separable. The three mode states we are utilizing are the prerequisite of the distribution of entanglement [2,3] and the sharing of entanglement [4] by means of a separable mode. The creation of entanglement using a seemingly unsuitable two mode state highlights the role of global correlations.

[1] Callum Croal et al., Phys. Rev. Lett. 115, 190501 (2015).

[2] L. Mišta, Jr. and N. Korolkova, Phys. Rev. A 77, 050302(R) (2008).

[3] L. Mišta, Jr. and N. Korolkova, Phys. Rev. A 80, 032310 (2009).

[4] L. Mišta, Jr., Phys. Rev. A 87, 062326 (2013).

Q 42.39 Wed 16:30 Empore Lichthof

Towards squeezing distillation for free-space links — ●ANDREAS THURN, KEVIN GÜNTNER, CHRISTIAN PEUNTINGER, DOMINIQUE ELSER, CHRISTOPH MARQUARDT, and GERD LEUCHS — Max Planck Institute for the Science of Light (MPL), Erlangen, Germany and Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU)

Squeezed states of light are an important resource for continuous variable quantum information protocols. Such states are fragile and degraded during transmission due to unavoidable coupling to the environment leading to excess noise and loss. Squeezing distillation is a way to overcome this degradation of squeezed states and has already been successfully implemented in a laboratory environment [1]. We want to go beyond laboratory experiments and investigate the potential of squeezing distillation in the case of natural noise stemming from a free-space link. This link is a realistic intra city free-space channel of 1.6km length being subject to atmospheric turbulences [2].

[1] J. Heersink et al., Phys. Rev. Lett. 96, 253601 (2006).

[2] C. Peuntinger et al., Phys. Rev. Lett. 113, 060502 (2014).

Q 42.40 Wed 16:30 Empore Lichthof

Quantum Receivers for Coherent Communication — ●SOURAV CHATTERJEE^{1,2}, CHRISTIAN R. MÜLLER^{1,2}, GERD LEUCHS^{1,2}, and CHRISTOPH MARQUARDT^{1,2} — ¹Max Planck Institute for the Science of Light, Erlangen, Germany — ²Department of Physics, University of Erlangen-Nuremberg (FAU), Germany

The impossibility of perfectly discriminating non-orthogonal states is vital for quantum key-distribution. In classical communication, however, it imposes strict constraints on channel capacity. Conventional receiver architectures for coherent state alphabets are approaching their sensitivity limit –the standard quantum limit (SQL). Quantum mechanics allows for a much lower error bound compared to SQL, the Helstrom bound. This imposes a need for innovations on receiver technologies. Optimal and near-optimal strategies have been proposed and experimentally demonstrated for binary phase-shift keying (BPSK) [1]. For quadrature phase-shift keying (QPSK), a hybrid receiver, based on a combination of homodyne and single photon detection, was demonstrated to outperform the SQL for any signal power [2]. Moreover, a near-optimal, feedback supplemented strategy with photon number resolution technology was proposed in our group [3], and research is in progress to realize this receiver experimentally. We review the recent progress on quantum receivers and compare different strategies on performance and robustness against technical imperfections.

[1] C. Wittmann et al., Phys. Rev. Lett. 101, 210501 (2008) [2] C. R. Müller et al., New J. Phys. 14, 083009 (2012) [3] C. R. Müller et al., New J. Phys. 17, 032003 (2015)

Q 42.41 Wed 16:30 Empore Lichthof

Free-space quantum key distribution at a wavelength of 10.6 μm using continuous variables — ●KEVIN JAKSCH^{1,2}, IMRAN KHAN^{1,2}, TOBIAS FRANK^{1,2}, JONAS GEYER-RAMSTECK^{1,2}, CHRISTIAN PEUNTINGER^{1,2}, BIRGIT STILLER^{1,2,3}, ULRICH VOGL^{1,2}, DOMINIQUE ELSER^{1,2}, CHRISTOPH MARQUARDT^{1,2}, and GERD LEUCHS^{1,2,4} — ¹Max Planck Institute for the Science of Light Erlangen, Germany — ²Institute of Optics, Information and Photonics, University of Erlangen-Nuremberg, Germany — ³Centre for Ultrahigh bandwidth Devices for Optical Systems (CUDOS), School of Physics, University of Sydney, NSW 2006, Australia — ⁴Department of Physics, University of Ottawa, 25 Templeton, Ottawa, ON, Canada

A beam of light, transmitted through the atmosphere, is scattered by atmospheric particles. If the wavelength is much larger than the particle size, these losses are significantly reduced. We propose a novel free-space quantum key distribution (QKD) system operating at a wavelength of 10.6 μm (which is much larger than the size of a water droplet under hazy conditions) in the continuous-variable domain. We plan to use the polarization degree of freedom to encode quantum states and continuous-variable Stokes detection as a measurement scheme. This measurement benefits from a higher detection efficiency than direct detection and acts as a narrowband filter against background noise sources. We study the feasibility of this wavelength for atmospheric quantum communication, considering beam propagation effects and the performance of the available technology. Note, that there are no single-photon detectors available at this wavelength.

Q 42.42 Wed 16:30 Empore Lichthof

Suppression of Rabi oscillations in hybrid optomechanical systems — ●TIMO HOLZ^{1,2}, RALF BETZHOLZ², and MARC BIENERT² — ¹Heinrich-Heine-Universität, Düsseldorf, Germany — ²Universität des Saarlandes, Saarbrücken, Germany

In a hybrid optomechanical setup consisting of a two-level atom in a cavity with a pendular end mirror, the interplay between the light field's radiation pressure on the mirror and the dipole interaction with the atom can lead to an effect, which manifests itself in the suppression of Rabi oscillations of the atomic population. This effect is present when the system is in the so-called single-photon strong-coupling regime. We consider this nonlinear effect in different parameter regimes, both numerically and analytically and study the quantum dynamics in the Wigner phase space. We conclude by discussing the dissipative dynamics of the hybrid optomechanical system.

Phys.Rev.A 92, 043822 (2015)

Q 42.43 Wed 16:30 Empore Lichthof

Coupling cold atoms to a cryogenically cooled optomechanical device — ●TOBIAS WAGNER¹, CHRISTINA STAARMANN¹, PHILIPP CHRISTOPH¹, ORTWIN HELLMIG¹, ANDREAS BICK¹, KLAUS SENGSTOCK¹, HAI ZHONG², ALEXANDER SCHWARZ², and ROLAND WIESENDAUER² — ¹Center for Optical Quantum Technologies, Hamburg, Germany — ²Institute for Applied Physics, Hamburg, Germany

We present work towards a new hybrid quantum system consisting of a sample of cold atoms coupled to a cryogenically precooled mechanical oscillator. Our ultimate goal is the investigation of two very different macroscopically large quantum systems coherently coupled to each other. For this purpose we have set up a Rubidium-BEC apparatus

coupled to a SiN membrane placed inside a fiber Fabry Perot cavity via an optical lattice. This membrane in the middle system is cooled to below 500mK in a dilution refrigerator. We present details on the coupling laser system including a Pound Drever Hall lock of the fiber Fabry Perot cavity, a highly sensitive homodyne detection setup for the membrane motion and a coupling lattice. In order to tune the parameters of the coupling lattice the frequency of the coupling laser is locked to atomic resonance with an adjustable offset via a transfer lock. The homodyne detection is able to detect thermal membrane motion at cryogenic temperatures and we present first results regarding further feedback cooling of the membrane.

This work is supported by the DFG grants no. BE 4793/2-1 and SE 717/9-1.

Q 42.44 Wed 16:30 Empore Lichthof

Hybrid optomechanics with cold atoms and a nanomechanical membrane — THOMAS KARG, ●ANDREAS JÖCKEL, ALINE FABER, TOBIAS KAMPSCHULTE, LUCAS BÉGUIN, and PHILIPP TREUTLEIN — Departement Physik, Universität Basel, Schweiz

Hybrid systems in which a mechanical degree of freedom is coupled to a microscopic quantum system promise control and detection of mechanical motion at the quantum level. This will open up possibilities for precision sensing, quantum signal transduction and fundamental tests of quantum mechanics. In our experiment we study the interaction of a cold atomic ensemble with a silicon nitride membrane inside an optical cavity. Long-distance coupling between the two is established by an optical standing wave that is reflected from the cavity. Recently this mechanism has been exploited to sympathetically cool the membrane's fundamental vibrational mode from room temperature to below 1 Kelvin [1].

Here we will report on the status of a new experimental setup. We are implementing a new cryogenic optomechanical system with larger optomechanical cooperativity and an atomic ensemble with large optical depth in a far-detuned dipole trap. With these improvements we plan to couple the membrane oscillator to collective spin excitations of the atomic ensemble [2], allowing us to achieve strong coupling between the two systems.

[1] Jöckel et al., Nature Nanotechnology 10, 55-59 (2015).

[2] Vogell et al., New Journal of Physics 17, 043044 (2015).

Q 42.45 Wed 16:30 Empore Lichthof

Optomechanical damping of nanomembranes in ring cavities — SIMON SCHUSTER, ●SEBASTIAN SLAMA, ARZU YILMAZ und CLAUD ZIMMERMANN — Eberhard-Karls Universität Tübingen, Phys. Institut, Auf der Morgenstelle 14, 72076 Tübingen

We report on the observation of the optomechanical damping of an oscillating silicon nitride nanomembrane inside an optical ring cavity. The underlying damping mechanism is different from the typical situation achieved in linear cavities, where the cavity resonance frequency depends on the membrane position. This is not the case in a ring cavity, where the damping is solely caused by the fact that the electric fields in the cavity follow the membrane motion not instantaneously, but with the timescale of the cavity decay time. We quantify the different contributions of radiation pressure force, dipole force and bolometric forces, including the action of a second reflector in the cavity. In our setup this second reflector describes back-reflection from imperfections at the mirror surfaces. However, it may also represent a second membrane in the cavity, which makes this system a future playground for studying synchronization effects.

Q 42.46 Wed 16:30 Empore Lichthof

Towards and beyond squeezed vacuum states in a nonlinear crystalline whispering gallery mode resonator — ●ALEXANDER OTTERPOHL^{1,2}, GERHARD SCHUNK^{1,2}, ULRICH VOGL^{1,2}, FLORIAN SEDLMEIR^{1,2}, GOLNOSH SHAFIEE^{1,2}, DMITRY STREKALOV^{1,2}, TOBIAS GEHRING³, HARALD G. L. SCHWEFEL⁴, ULRIK L. ANDERSEN³, GERD LEUCHS^{1,2}, and CHRISTOPH MARQUARDT^{1,2} — ¹Max Planck Institute for the Science of Light, Guenther-Scharowsky-Str. 1 Bldg. 24, 91058 Erlangen, Germany — ²Institute of Optics, Information and Photonics, University of Erlangen-Nuremberg, Staudtstr. 7 B2, 91058 Erlangen, Germany — ³Department of Physics, Technical University of Denmark, Fysikvej, 2800 Kgs. Lyngby, Denmark — ⁴Department of Physics, University of Otago, 730 Cumberland Street, 9016 Dunedin, New Zealand

Macroscopic crystalline whispering gallery mode resonators (WGMR) made out of LiNbO₃ are a versatile source of non-classical light generated via optical parametric down-conversion [1]. In particular, we

have demonstrated squeezing of a single parametric beam as well as twin-beam squeezing at above threshold operation. Here, we present the prospects for generating squeezed vacuum states in WGMRs, which requires degenerate operation below threshold. Furthermore, the pathway to degeneracy allows us to produce frequency combs and facilitates more elaborate proposals such as enhanced optomechanical position detection via intra-cavity squeezing [2].

[1] J. U. Fürst et al., *Phys. Rev. Lett.* **106**, 113901(2011).

[2] V. Peano et al., arXiv:1502.06423v1 (2015), accept. on PRL

Q 42.47 Wed 16:30 Empore Lichthof

Optical ablation of gold bowtie nanoantenna — ●LIPING SHI — Welfengarten1

We experimentally demonstrate the optical ablation of gold bowtie nanoantenna under the irradiation of laser pulses output from Ti: Sapphire femtosecond oscillator. The temporal behavior of third harmonic enhancement factor from bowtie antennas is introduced to determine durability of nanostructure. We observed two different channels of optical ablation from gold bowtie nanoantenna: thermal effects induced melting and near-field enhancement induced ion ejection. It is shown that by employing thicker nanoantenna can significantly increase the thermal damage fluence threshold, but the optical ablation originated from field emission is inevitable in vacuum. However, our experiments show that if the nanoantenna are exposed in air, this field emission can be dramatically suppressed, which might be attributed to the adsorption of gas molecules at sharp features of field-enhancing structures. We also numerically employed the two-temperature model to estimate the free electrons as well as gold lattice temperature, and solved the one-dimensional heat diffusion equation to simulate the spatial and temporal distribution of temperature in substrate sapphire.

Q 42.48 Wed 16:30 Empore Lichthof

3D Pointillism Microscopy setup with two objectives — ●NORA SCHMIDT¹, JANA HÜVE^{1,2}, and JÜRGEN KLINGAUF^{1,2} — ¹Institute of Medical Physics and Biophysics, Robert-Koch-Straße 31, and CeN-Tech, Heisenbergstraße 11, 48149 Münster — ²Authors contributed equally to this work

We have custom-built a setup for localisation microscopy techniques like PALM or STORM with two objectives. This enables us to collect two times more photons from each fluorescent molecule and therefore to increase the resolution accuracy by a factor of $\sqrt{2}$ [1]. Optional three-dimensional imaging is possible by inserting additional cylindrical lenses into the beam path.

We have characterised the localisation accuracy of this setup and found that using a second objective clearly improves our results. For 6600 photons we have obtained a localisation accuracy of 4 nm in the lateral plane and of 9 nm along the axial direction.

To further test the performance of our setup, we have imaged well-known biological structures of sub-resolution size, and have obtained results which match well with previously reported observations.

To further improve the localisation accuracy along the optical axis, we plan to use interferometric detection of the fluorescence light [2] as a second detection option. With this technique, we expect to improve the axial localisation accuracy to values similar to or even better than the localisation accuracy in the lateral plane.

[1]: K. Xu et al. *Nat. Methods*, **9**, 185 (2012)

[2]: G. Shtengel et al. *Proc. Natl. Acad. Sci. U.S.A.*, **106**, 3125 (2009)

Q 42.49 Wed 16:30 Empore Lichthof

Cold atom-semiconductor hybrid quantum system — ●JANIK WOLTERS¹, LUCAS BÉGUIN¹, FEI DING², ALINE FABER¹, JAN-PHILIPP JAHN¹, ANDREAS JÖCKEL¹, ANDREAS KUHLMANN¹, MATHIEU MUNSCH¹, ARMANDO RASTELLI³, NICOLAS SANGOUARD¹, OLIVER G. SCHMIDT², PHILIPP TREUTLEIN¹, and RICHARD J. WARBURTON¹ — ¹Universität Basel, Departement Physik, CH-4056 Basel — ²IFW Dresden, Germany — ³Johannes-Kepler University Linz, Austria

Semiconductor quantum dots are excellent single-photon sources, providing triggered single-photon emission at a high rate and with high spectral purity. Independently, atomic ensembles have emerged as one of the best quantum memories for single photons, providing high efficiency storage and long memory lifetimes. In this project, we combine these two disparate physical systems to exploit the best features from both worlds. On the one hand, we have characterized a new type of self-assembled GaAs/AlGaAs quantum dots that emit narrow-band single-photons ($\Delta\nu \sim 1$ GHz) at Rb wavelengths. Fine tuning of the photon frequency is achieved via strain. This allows performing spec-

trospecty of the Rb D2-line at the single-photon level, proving the addressability the different hyperfine transitions [1]. On the other hand, detailed theory of an EIT-based memory scheme in a dense ultracold ensemble of ⁸⁷Rb atoms (OD ~ 1000) was developed [2]. In the long term, such a memory will form the basis for experiments on hybrid entanglement and quantum networks.

[1] J.-P. Jahn et al., arXiv:1508.06461 (2015).

[2] M. T. Rakher et al., *Phys. Rev. A* **88** 053834 (2013).

Q 42.50 Wed 16:30 Empore Lichthof

Interfacing single molecules with optical nanofibers — ●HARDY SCHAUFFERT, SARAH SKOFF, DAVID PAPENCORDT, and ARNO RAUSCHENBEUTEL — Technische Universität Wien, Atominstut, Stationallee 2, 1020 Wien

In recent years, tapered optical fibers with nanowaist have gained a lot of attention as versatile platforms for strong light-matter interaction due to their small effective mode volume. The sub-wavelength diameter of the waist results in a crucial amount of light propagating outside of the fiber as a high intensity evanescent wave. An emitter brought close to the surface of the nanofiber can then have a big effect on the guided light field. Possible emitters are single organic molecule embedded in a crystal matrix such as terylene in p-terphenyl. These molecules exhibit a naturally strong Zero-phonon-line, which can be as narrow as tens of MHz at cryogenic temperature and are very photostable. This together with optical nanofiber makes them promising candidates as building blocks for fiber integrated quantum networks. We will show first results on single molecule spectroscopy using optical nanofibers and give an outlook of the rich variety of experiments that can be done with such a platform.

Q 42.51 Wed 16:30 Empore Lichthof

Towards efficient solid-state based light-matter interfaces based on dielectric slot waveguides — ●MARTIN ZEITLMAIR¹, LARS LIEBERMEISTER¹, PETER FISCHER¹, LUKAS WORTHMANN¹, MARKUS WEBER³, and HARALD WEINFURTER^{1,2} — ¹Ludwig-Maximilians-Universität, München — ²Max-Planck-Institut für Quantenoptik, Garching — ³Max-Planck-Institut für die Physik des Lichts, Erlangen

Efficient light-matter interfaces are a crucial prerequisite for future applications in applied quantum information science and ultra-sensitive phase, absorption, and fluorescence spectroscopy. Such light-matter interfaces require two key components: a non-classical light source and a waveguiding structure to control the propagation of photons. Here, we present progress towards a novel on-chip interface operating over a broad spectral range in the visible spectrum, which is based on diamond defect centers and tailored dielectric slot waveguides.

The proposed scheme uses defect centers hosted in a nanodiamond as a stable nonclassical light source. With the help of an AFM-based pick-and-place technique, the nanodiamond will be positioned inside the slotted region of a fabricated Ta₂O₅ waveguide. By optimizing the slot waveguide geometry with the additional requirement of allowing access for the AFM-tip, coupling efficiencies over 60% for the whole spectrum of the NV-center are expected with slot widths of 40nm.

Q 42.52 Wed 16:30 Empore Lichthof

Investigating Single Quantum Emitters in Nanodiamonds for Quantum Optics — ●DOMINIK ZEPP, ALEXANDER LANDOWSKI, MICHAEL RENNER, GEORG VON FREYMAN, and ARTUR WIDERA — TU Kaiserslautern

We study color centers in nanodiamonds for applications as single photon emitter in quantum optics. We use a custom-built microscope setup which is capable of simultaneously imaging the spatial distribution of particles on the sample and measuring the spectrum of one diffraction limited spot. This allows us to investigate blinking behavior, photostability and spectral dynamics of an ensemble of fluorescing nanodiamonds when illuminated with various wavelengths ranging from white LED, 780nm, and 532nm. We will report on the current status to control such emitters and their emitted photons for micro-sized quantum optical experiments.

Q 42.53 Wed 16:30 Empore Lichthof

SiV Centres in Microcavities - an Efficient Single Photon Source at Room Temperature — ●JULIA BENEDIKTER^{1,2}, ELKE NEU³, ROLAND ALBRECHT³, CHRISTOPH BECHER³, THEODOR W. HÄNSCH^{1,2}, and DAVID HUNGER^{1,2} — ¹Ludwig-Maximilians-Universität München, Germany — ²Max-Planck-Institut für Quantenoptik, Garching, Germany — ³Universität des Saarlandes, Saar-

brücken, Germany

Single photon sources are an integral part of various quantum information applications. Solid state emitters offer on-demand single photon emission without the need for very involved set-ups. The emission properties, especially the very narrow single phonon line, and stability of the silicon vacancy centre in diamond make it a promising candidate for a single photon source at room temperature. We use fibre-based microcavities [1, 2] to Purcell-enhance and efficiently collect the emission of single SiV centres in nanodiamonds. We operate in the bad emitter regime, where a cavity with a mode volume of a few cubic wavelengths can achieve high effective Purcell factors up to about 20. We report on measurements on narrow-line bright single SiV centres in free space and in an ultra-small mode volume cavity and compare rates and time constants. Furthermore, we will discuss an empirical model for shelving and deshelling processes.

[1] Hunger et al., NJP 12, 065038 (2010)

[2] Hunger et al., AIP Advances 2, 012119 (2012)

Q 42.54 Wed 16:30 Empore Lichthof

Spectral diffusion of Silicon-Vacancy centers in Nanodiamonds — ●O. WANG¹, L. ROGERS¹, A. KURTZ¹, D. RUDNICKI², U. JANTZEN¹, V.A. DAVYDOV³, V.N. AGAFONOV⁴, A. KUBANEK¹, and F. JELEZKO¹ — ¹Institute of Quantum Optics, Ulm, Germany — ²Institute of Physics, Jagiellonian University, Krakow, Poland — ³Institute for High Pressure Physics, Russian Academy of Science, Moscow, Russia — ⁴Gremam, Universit F. Rabelais, Tours, France

With appealing properties, weak side band and mostly polarized fluorescence, silicon vacancy centers (SiVs) in diamonds have become an attractive and promising system for the realization of bright, narrow bandwidth, single-photon sources. In bulk diamond at cryogenic temperatures the SiV ZPL has been observed with a linewidth limited only by fluorescence lifetime, and the transitions were spectrally stable over hours. Unfortunately the spin coherence time was found to be severely limited by phonon processes in the ground state, which may be quenched in small nanodiamonds (NDs).

However, SiV centres in NDs are found to exhibit an intermittency in their luminescence, which is known as “blinking”, and also significant spectral diffusion. We have investigated the fluorescence of SiV in small NDs produced using a novel High Pressure and High Temperature synthesis. These have exhibited ZPL linewidths five times narrower than any other reported SiV in NDs. We have measured spectral diffusion as a function of excitation laser intensity, and found it to be suppressed with lower laser power. This suggests the mechanism may arise from photo-chemistry on the ND surface.

Q 42.55 Wed 16:30 Empore Lichthof

Towards efficient readout of electron spin state in Silicon Vacancy centers in diamond — ●AROOSA IJAZ, PETR SIYUSHEV, LACHLAN ROGERS, and FEDOR JELEZKO — Institute for Quantum Optics, Universitat Ulm, Germany

Efficient qubit systems are being actively researched globally. A qubit needs to have an efficient photon interface, long coherence times, stability and easy control. Some active systems of research include trapped ions, quantum dots and color centers in solids. Currently, the most prominent color center for quantum information is Nitrogen Vacancy (NV) center in diamond. The stiff lattice of diamond protects the coherent properties of the center’s spin.

The spin-photon interface for NV centers is, however, poor. Silicon Vacancy (SiV) center has recently emerged as a competitor to the NV center due to its uniquely attractive optical properties. Compared to NV centers, it provides a feasible interface between stationary and flying qubits. This center has also been shown to emit indistinguishable photons which will pave the way towards scalable quantum networks.

We use the extinction of light by single defects in bulk diamond to obtain high contrast resonant detection as compared to the usual off-resonant measurements over the phonon side band. This technique improves electron spin state readout when the defect is addressed resonantly and allows for single-shot optical readout of electron spin.

Q 42.56 Wed 16:30 Empore Lichthof

Narrowband, room-temperature single photon emitters based on silicon-vacancy centers in diamond nanocrystals produced by a wet-milling process — ●SARAH LINDNER¹, ALEXANDER BOMMER¹, ANDREAS MUZHA², ANKE KRUEGER², LAIA GINES³, OLIVER WILLIAMS³, and CHRISTOPH BECHER¹ — ¹Fachrichtung 7.2 (Experimentalphysik), Universität des Saarlandes, Campus E2.6, 66123 Saarbrücken — ²Institut für Organische Chemie,

Universität Würzburg, Am Hubland, 97074 Würzburg — ³School of Engineering, Cardiff University, Newport Road, Cardiff CF24 3AA

Single-photon sources with well-defined spectral properties are of special interest to quantum technologies. Silicon vacancy (SiV) color centers in diamond nanocrystals are especially promising single photon sources due to their narrow emission bandwidth and high emission rate at room temperature [1]. To even further enhance these properties, SiV centers can be coupled to optical systems, which require nanodiamonds of sizes < 100 nm and low strain, to preserve the advantageous optical properties of the SiV center. Here we report on SiV centers in nanodiamonds which are produced by milling down a polycrystalline diamond film [2] containing SiV centers exploiting a wet-milling process [3]. Different center wavelengths of the zero-phonon-lines and varying linewidths among SiV centers in distinct nanodiamonds are observed. As some of the nanodiamonds contain single SiV centers they are favorable candidates for the integration into photonic systems.

[1] E. Neu et al., NJP 13, 25012 (2011), [2] O. A. Williams et. al., PSS A 203, 3375 (2006), [3] S. Heyer et. al., ACS Nano 8, 5757 (2014)

Q 42.57 Wed 16:30 Empore Lichthof

Coupling of color centers in nanodiamonds to open access micro-cavities — ●MARCEL SCHMIDT¹, A. BOMMER¹, S. LINDNER¹, L. GINES², O. WILLIAMS², A. MUZHA³, A. KRUEGER³, and C. BECHER¹ — ¹Fachrichtung 7.2 (Experimentalphysik), Universität des Saarlandes, Campus E2.6, 66123 Saarbrücken — ²School of Engineering, Cardiff University, Newport Road, Cardiff CF24 3AA, Wales — ³Institut für Organische Chemie, Universität Würzburg, Am Hubland, 97074 Würzburg

Since its first demonstration as qubit in quantum information applications, the nitrogen vacancy (NV) centre gained much attention as promising candidate for remote entanglement schemes [1] and quantum sensing [2]. A way to improve its suitability is the coupling of single NV centres to open access micro-cavities which increases the photon rate per frequency interval [3]. A theoretical model predicts a transition into a Purcell-enhanced regime at cryogenic temperatures, when the narrow zero phonon line (ZPL) of the NV centre is coupled to a fundamental mode of the cavity. We here report our progress towards cryogenic cavity coupling of NV centres. In recent years, another color centre, the silicon vacancy (SiV) centre has been established as bright single photon source [4]. Due to its narrow ZPL linewidth at room temperature and its short lifetime of the excited state, coupling this color centre to a micro-cavity can provide a high speed, high efficiency single photon source at room temperature. [1] B. Hensen, Nature 526, 682-686 (2015) [2] L. Rondin, Rep. Prog. Phys. 77 (2014) [3] R. Albrecht, PRL 110, 243602 (2013) [4] E. Neu, NJP 13, 025012 (2011)

Q 42.58 Wed 16:30 Empore Lichthof

Color centers in diamond as nanoscale quantum sensors — ●RICHARD NELZ, AMANDEEP KAUR, ETTORE BERNARDI, SELDA SONUSEN, and ELKE NEU — Universität des Saarlandes, FR 7.2 Experimentalphysik, Campus E2.6, 66123 Saarbrücken

Single nitrogen vacancy (NV) color centers in diamond are highly suitable as nanoscale quantum sensors for e.g. optical near fields and magnetic fields; the later due to their coherent, optically addressable electronic spin-states [1]. As a result of the high refractive index of diamond it is intrinsically challenging to efficiently extract the fluorescence of the NV center. Optical read-out of the NV sensor requires efficiently collecting the center’s fluorescence which we achieve using dedicated diamond nanostructures: We integrate NV centers into nanopillars that function as tips for scanning probe microscopy and waveguides for light. We present optimized approaches towards the fabrication of all diamond scanning probe devices and their applications.

[1] Rondin et al., Rep. Prog. Phys. 77 056503 (2014)

Q 42.59 Wed 16:30 Empore Lichthof

A microfluidic high-finesse open access cavity — ●MATTHIAS MADER^{1,2}, THEODOR W. HÄNSCH^{1,2}, and DAVID HUNGER^{2,1} — ¹Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching — ²Ludwig-Maximilians-Universität München, Schellingstraße 4, 80799 München

Optical characterisation of individual nanosystems provides a wealth of information. However, it is very challenging to observe quantitative spectroscopy signals beyond fluorescence from a single nanoparticle.

Here we present first steps towards a novel method for extinction and dispersion spectroscopy on single nanosystems in an aqueous environment to investigate single biological and chemical nano systems.

Combining an open access high-finesse Fabry-Perot resonator [1] with a microfluidic cell allows ultra-sensitive spectroscopy of individual nano systems under well-controlled conditions. In addition to dispersive detection of the nano object by detecting a shift in the resonance frequency, absorption measurements are possible by observing the transmitted light [2]. Using the cavity mode which is fully accessible for the particle as an optical trap, our approach opens the possibility to store a particle without binding to a surface and to investigate e.g. reaction dynamics on a single particle level.

[1] D. Hunger, T. Steinmetz, Y. Colombe, C. Deutsch, T. W. Hänsch, J. Reichel, *New J. Phys.* 12, 065038 (2010).

[2] M. Mader, J. Reichel, T. W. Hänsch, D. Hunger, *Nature Commns.* 6 7249 (2015)

Q 42.60 Wed 16:30 Empore Lichthof

Rotational diffusion of nanorods studied by interferometric scattering detection (iSCAT) — JENS EHRIG, MAHDI MAZAHERI, and VAHID SANDOGHDAR — Max Planck Institute for the Science of Light, Erlangen, Germany

We use interferometric scattering detection microscopy (iSCAT) to study the rotational diffusion of gold nanorods (GNR) linked to an artificial bilayer lipid membrane on a glass substrate. The technique relies on the interference between light scattered from the GNR and the reference beam reflected from the glass-water interface. Streptavidin-conjugated gold nanorods of length 63 nm and diameter of 25 nm were attached to headgroup-biotinylated DOPE lipids in DOPC supported lipid bilayers. By illuminating the sample with polarized laser light and polarization separation in the detection path, the fast tracking of rotational diffusion of the GNR becomes possible. Specifically, we can calculate the angle of the rod in each video frame, i.e., within a few microseconds. Using this approach one can simultaneously study the rotational and lateral diffusion of very small membrane inclusions and from that infer information on the physical properties and local dynamic behavior of the membrane such as local viscosity, short range diffusion, and compositional heterogeneity.

Q 42.61 Wed 16:30 Empore Lichthof

Nonlocal continuity and invariant currents in locally symmetric photonic crystals — CHRISTIAN MORFONIOS¹, PANAYOTIS KALOZOU MIS², FOTIOS DIAKONOS², and PETER SCHMELCHER^{1,3} — ¹Centre for Optical Quantum Technologies, Hamburg University, Germany — ²Physics Department, Athens University, Greece — ³Centre for Ultrafast Imaging, Hamburg, Germany

Within a nonlocal discrete continuity formalism, we demonstrate the spatial invariance of stationary state currents in one-dimensional domains with inversion-(time-) or translation-(time-) symmetric sub-Hamiltonians. Cases of complete, overlapping, and gapped domainwise symmetry in model setups of effective Schrödinger photonic waveguide crystals are shown, including systems with balanced gain and loss. The invariants enable a mapping between the wave amplitudes of symmetry-related sites, generalizing the Bloch and parity theorems to local translation and inversion symmetry. In scattering systems, simultaneously vanishing inversion-symmetry invariants signify completely transmitting states with correspondingly symmetric density. In periodically driven setups, the invariants are retained for period-averaged quasi-energy eigenstates. Encoding local potential and coupling symmetries into arbitrary stationary states, the theory of symmetry-induced continuity and local invariants may contribute to the understanding of wave structure and response in systems with localized spatial regularities.

Q 43: Ultracold plasmas and Rydberg systems (with A)

Time: Wednesday 16:30–19:00

Location: Empore Lichthof

Q 43.1 Wed 16:30 Empore Lichthof

Building up a two-species Rydberg experiment with a spatially resolving ion detector — THOMAS SCHMID, CHRISTIAN VEIT, NICOLAS ZUBER, ROBERT LÖW, and TILMAN PFAU — 5th Physical Institute, University of Stuttgart, Stuttgart, Germany

We are building up an experiment for the production of an ultracold mixture of lithium and rubidium gases with the possibility of Rb Rydberg excitation. The machine, to that end, comprises a two-species Zeeman slower [1]. In the science chamber, a high numerical aperture

Q 42.62 Wed 16:30 Empore Lichthof

Optical helicity and duality symmetry in matter — KOEN VAN KRUNING and JÖRG GÖTTE — Max Planck Institut für Physik komplexer Systeme, Nöthnitzer Straße 38; 01187 Dresden

In vacuum, electric and magnetic fields can be interchanged without changing the form of Maxwell's equations. This is the electric-magnetic duality symmetry and its associated conserved quantity is optical helicity. When light traverses a medium, this symmetry is typically broken. We investigate under what conditions electric-magnetic duality is conserved even for light traversing the most general linear medium and derive a generalised expression for the optical helicity. With the aid of some simple examples we illustrate the consequences of helicity conservation in a medium.

Q 42.63 Wed 16:30 Empore Lichthof

Modelling and fabrication of Rb:KTP waveguides — MATTEO SANTANDREA, CHRISTOF EIGNER, LAURA PADBERG, HELGE RÜTZ, and CHRISTINE SILBERHORN — Universität Paderborn, Integrierte Quantenoptik, Warburger Str. 100, D-33098 Paderborn

In the future, quantum networks will almost certainly require interfaces between different physical systems, such as atoms and low loss fibers. These interfaces will require low loss, high efficiency and low noise frequency conversion. Optical waveguides in nonlinear materials are ideal candidates for this task due to their inherent phase stability, high nonlinearity, flexibility, small footprint and modularity.

We are developing a quantum interface to convert photons at 397 nm, correspondent to the ⁴⁰Ca⁺ transition, to photons in the telecom C-band, around 1550 nm. In order to bridge this huge energy gap, we exploit the process of sum frequency generation (SFG) in periodically-poled, rubidium-exchanged potassium titanyl phosphate (Rb:KTP) waveguides. Rb:KTP waveguides are ideal candidates for SFG due to their unique combination of high nonlinear coefficients, a wide transmission window extending from infrared to ultraviolet, high photorefractive damage resistance and the possibility to achieve poling periods in the μm range.

Here, we show our technique for the production of those waveguides, discuss a model for the refractive index distribution in our waveguides and present some methods for assessing discrepancies between the model and our waveguides.

Q 42.64 Wed 16:30 Empore Lichthof

Duty cycle optimized periodically poled Rb:KTP waveguides — LAURA PADBERG, CHRISTOF EIGNER, MATTEO SANTANDREA, HELGE RÜTZ, and CHRISTINE SILBERHORN — Universität Paderborn, Integrierte Quantenoptik, Warburger Str. 100, D-33098 Paderborn

Periodically poled potassium titanyl phosphate (KTP) waveguides are very attractive for non-linear processes in integrated quantum optics. Especially the high optical damage threshold makes it interesting for operating in the visible.

Rubidium-potassium-ion exchange is a practical approach for waveguide fabrication in KTP. However, the doping dependent ionic conductivity of Rb:KTP makes periodic poling a challenging task.

We show our approach for the technologically-challenging periodic poling process, where we utilize an optical monitoring technique. This allows us to monitor the domain-growth inside the waveguide and obtain a reliable 50/50 duty cycle. Successful periodic poling is verified by selective surface etching as well as non-linear optical characterization measurement. With these characterization methods we compare two different poling periods which are attractive for quantum optical applications.

optical lens is incorporated for focused Rydberg excitation. Besides, eight field plates arranged in a clover leaf configuration allow for ultra-stable electric field control and field-ionization of the Rydberg atoms. Single ions can be detected temporally and spatially resolved with a delay-line detector [2]. The time resolution is approximately 100 ps, the spatial resolution at the detector is around 100 μm . The detector can handle single particle rates up to several MHz. In order to get a spatial resolution in the micrometer regime at the position of the ultracold cloud in the centre of the science chamber an ion microscope with

a magnification above 100 is planned. It consists of three electrostatic triple-cylinder-lenses and has a total length of about 1.5 m.

[1] G. E. Marti, D. M. Stamper-Kurn et al.; *Phys. Rev. A* **81**, 043424 (2010).

[2] O. Jagutzki, H. Schmidt-Böcking et al.; *Nucl. Instrum. Meth. A* **477**, 244 (2002).

Q 43.2 Wed 16:30 Empore Lichthof

Correlations and many-body dynamics of Rydberg excitations in the anti-blockade regime — ●FABIAN LETSCHER^{1,2}, OLIVER THOMAS^{1,2}, THOMAS NIEDERPRÜM¹, TANITA EICHERT¹, MICHAEL FLEISCHHAUER¹, and HERWIG OTT¹ — ¹Department of Physics and Research Center OPTIMAS, University of Kaiserslautern, Germany — ²Graduate School Materials Science in Mainz, Gottlieb-Daimler-Strasse 47, 67663 Kaiserslautern, Germany

We present experimental and theoretical studies of the many-body dynamics of Rydberg excitations in an optically driven lattice gas in the dissipative anti-blockade regime. Making use of continuous ionization of atoms in a Rydberg state we monitor the time evolution and temporal correlations of Rydberg excitations. We observe large relaxation times (compared to the lifetime of a Rydberg excitation) and strong bunching. To describe the approximate dynamics of the system, we use an efficient many-body rate equation method and compare them with experimental results. Moreover, we construct a simple cluster model which allows a qualitative understanding of the experimental data.

Q 43.3 Wed 16:30 Empore Lichthof

Storage of coherences and single-photon sources via Rydberg state in thermal vapors — ●YI-HSIN CHEN, FABIAN RIPKA, ROBERT LÖW, and TILMAN PFAU — 5. Physikalisches Institut, Universität Stuttgart

Photons are good information carriers, which can be stored and retrieved among different quantum devices. We perform the storage of coherences via a highly excited Rydberg state in thermal vapors. These photonic quantum devices are intrinsically reproducible and scalable, towards the potential application of the photonic-based quantum security communication and information processing. The scheme is based on the combination of four-wave-mixing (FWM) and Rydberg blockade effects in a 220 micrometer thick vapor cell. In the pulsed FWM scheme, we observe coherent dynamics [1] and measure the lifetime of the stored coherence, which is around 1 ns, limited by motional dephasing of the thermal vapors. Moreover, we are going to reduce the excitation volume towards below the Rydberg interaction range by use of high-NA optics and spatial confinement for generating a deterministic single-photon source [2].

[1] Huber et al., PRA 90, 053806 (2014) [2] M. M. Müller et al., PRA 87, 053412 (2013)

Q 43.4 Wed 16:30 Empore Lichthof

Towards coherence measurements of Rydberg atoms with all-optical detection — ●LARA TORRALBO-CAMPO, JENS GRIMMEL, FLORIAN KARLEWSKI, CAROLA ROGULJ, and JÓZSEF FORTÁGH — Physikalisches Institut der Universität Tübingen, Germany

We have developed a non-destructive and time-resolved method to optically detect the population of atoms in a selected Rydberg state as alternative to selective field ionization. This scheme is based on electromagnetically induced transparency (EIT). By monitoring the optical density of the probe laser over time, we can imply the initial population of the Rydberg state. We have tested the new method as proof-of-principle in a cold gas of 87-Rb atoms where lifetimes of Rydberg states under various environment conditions were measured. This method promises also to provide information regarding the initial coherence of the system. We present the ongoing work towards measurements of the coherence in a Rydberg gas.

Q 43.5 Wed 16:30 Empore Lichthof

Rydberg P-state-molecules — ●TANITA EICHERT¹, PHILIPP GEPPERT¹, THOMAS NIEDERPRÜM¹, OLIVER THOMAS^{1,2}, TORSTEN MANTHEY¹, and HERWIG OTT¹ — ¹Department of Physics and Research Center OPTIMAS, University of Kaiserslautern, Germany — ²Graduate School Materials Science in Mainz, Gottlieb-Daimler-Strasse 47, 67663 Kaiserslautern, Germany

We report on the experimental realization of P-state Rydberg-molecules. These molecules are created by photoassociation in a dense sample of ultracold rubidium. High resolution spectroscopy is carried out over a range of more than 10 GHz allowing us to precisely deter-

mine the binding energies of molecular states around the 25P state. By characterizing the observed molecular states by their permanent dipole moments and their lifetimes we can distinguish between pure long range Rydberg molecules and bound states in the vicinity of the crossing butterfly state. Rydberg molecules show significantly shortened lifetimes compared to resonant Rydberg excitations caused by the bound ground state atom. Furthermore we demonstrate how the obtained knowledge on the bound states can be used to probe the site occupancy in optical lattices.

Additionally we report on a laser system that will be used to excite Rydberg S- and D-states in ultracold rubidium gases. For this purpose, two external cavity diode lasers for both 420 nm and 1030 nm have been assembled. Due to small linewidths and without the necessity of second harmonic generation, we achieve a high spectroscopic resolution and efficient excitation with increased stability.

Q 43.6 Wed 16:30 Empore Lichthof

Stable optical lattices for creating and imaging ultracold quantum fluids of potassium — ●EMIL PAVLOV, STEPHAN HELM-RICH, ALDA ARIAS, TOBIAS WINTERMANTEL, and SHANNON WHITLOCK — Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg

Ultracold Rydberg atoms with their long-range interactions offer a controllable environment for realizing synthetic model systems to be studied, e.g. unconventional superfluids and extended Hubbard models. The strength and range of their interactions can be controlled via coherent coupling of the Rydberg states to the ground states (Rydberg dressing). In our experiment we plan to reveal the resulting quantum phases using a quantum gas microscope with single-site resolution. For this purpose we have designed a novel two-dimensional optical lattice induced by three-beam interference, which, when combined with a pancake-shaped trap, provides the necessary two-dimensional geometry. In order to minimize adverse heating effects on the atoms, the whole setup must exhibit high intensity, phase and pointing stability. We will present our evaluation of the lattice stability as well as initial experimental results.

Q 43.7 Wed 16:30 Empore Lichthof

Measurements and numerical calculations of ⁸⁷Rb Rydberg Stark and Zeeman maps — ●JENS GRIMMEL, MANUEL KAISER, LARA TORRALBO-CAMPO, MARKUS MACK, FLORIAN KARLEWSKI, and JÓZSEF FORTÁGH — Physikalisches Institut der Universität Tübingen

Rydberg atoms are extremely sensitive to external electric and magnetic fields and consequently have a rich Stark and Zeeman spectrum. We present measurements and numerical calculations of Stark and Zeeman shifts for Rydberg states of ⁸⁷Rb. We have extended our previous calculations [1] to take into account the differential Zeeman shifts as well as the transition strength between all states in the EIT ladder scheme. We have also performed high precision measurements of Zeeman maps in a heated vapour cell with magnetic fields up to 10mT. Recently, we have implemented a new heatable microcell setup for measurements of Stark and Zeeman maps at different temperatures and atomic densities.

[1] J. Grimmel, M. Mack, F. Karlewski, F. Jessen, M. Reinschmidt, N. Sándor and J. Fortágh, N. J. Phys. 17, 053005 (2015).

Q 43.8 Wed 16:30 Empore Lichthof

Probing electric fields spatially resolved inside hollow core fibers with Rydberg atoms — ●DANIEL WELLER¹, GEORG EPPLE^{1,2}, JOSEPHINE GUTEKUNST¹, CHRISTIAN VEIT¹, TILMAN PFAU¹, PHILIP RUSSEL², and ROBERT LÖW¹ — ¹5. Physikalisches Institut, Universität Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany — ²Max Planck Institute for the Science of Light and Department of Physics, University of Erlangen, Günther-Scharowsky-Str. 1, 91058 Erlangen, Germany

The exceptional large polarizability of highly excited Rydberg atoms makes them of great interest for sensitive AC and DC electric field sensors. In addition, long-range interactions between the Rydberg atoms give rise to phenomena such as the Rydberg blockade, enabling the creation of optical nonlinearities at the single photon level. A promising route to technically feasible, miniaturized, room-temperature devices is based on the excitation of Rydberg atoms inside hollow-core photonic crystal fiber (HC-PCF). The confinement of both atoms and light enforces a large inline interaction region, resulting in perfect atom-light coupling. Recently, we demonstrated coherent three-photon excitation to Rydberg states in a cesium vapor confined in both Kagome-style

HC-PCF and capillaries. Spectroscopic signals exhibiting sub-Doppler features for principal quantum numbers up to $n = 46$ revealed line shifts. To investigate these shifts in detail, two kinds of spatially resolved spectroscopy were implemented: one uses an array of field plates along the fiber, the other relies on higher order modes of the excitation beams, to locally select atoms within the fiber.

Q 43.9 Wed 16:30 Empore Lichthof

The bound and scattering properties in waveguide around Feshbach resonance — ●GAOREN WANG¹, PANAGIOTIS GIANNAKEAS², and PETER SCHMELCHER^{1,3} — ¹Zentrum für Optische Quantentechnologien, Universität Hamburg, Hamburg, Germany — ²Department of Physics and Astronomy, Purdue University, Indiana, USA — ³The Hamburg Centre for Ultrafast Imaging, Universität Hamburg, Hamburg, Germany

The two-body bound and scattering properties in an one-dimensional harmonic waveguide around the free-space magnetic Feshbach resonance are investigated based on the K matrix method. The multichannel characteristics of the interatomic interaction is taken into account, and the free-space phase shift is calculated in the frame work of quantum defect theory. We emphasize the following point: the bound state in the waveguide crosses the ground level of the transversal confinement at the magnetic field where the effective one-dimensional scattering length diverges.

Q 44: Precision spectroscopy of atoms and ions (with A)

Time: Wednesday 16:30–19:00

Location: Empore Lichthof

Q 44.1 Wed 16:30 Empore Lichthof

Quantum Algorithmic Readout in Multi-Ion Clocks — ●MARIUS SCHULTE¹, NIELS LÖRCH¹, IAN D. LEROUX², PIET O. SCHMIDT^{2,3}, and KLEMENS HAMMERER¹ — ¹Institute for Theoretical Physics and Institute for Gravitational Physics (Albert-Einstein-Institute), Leibniz University Hannover, Callinstrasse 38, 30167 Hannover, Germany — ²QUEST Institut, Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany — ³Institute for Quantum Optics, Leibniz University Hannover, Welfengarten 1, 30167 Hannover, Germany

The methods of quantum information theory have already found many applications in trapped ion technologies. Even today, new generations of ion clocks often rely on quantum logic readouts in order to reference to a specific optical transition. Thereby they use two ion species in the same trap to exploit their different properties. Guided by a quantum algorithm, we present a non-demolition measurement strategy to transfer excitation probabilities among the two species. This method can be used for clocks with larger ion crystals in order to improve their short term stability. Our approach scales favorable in the number of logic ions and entangling-gates needed for the information transfer. We also discuss a possible realization based on a five ion crystal with Al and Ca ions, taking the full normal mode spectrum into account.

Q 44.2 Wed 16:30 Empore Lichthof

The ALPHATRAP g -Factor Experiment — ●ANDREAS WEIGEL^{1,2}, IOANNA ARAPOGLOU^{1,2}, ALEXANDER EGL^{1,2}, HENRIK HIRZLER^{1,2}, SANDRO KRAEMER^{1,2}, TIM SAILER^{1,2}, ROBERT WOLF¹, SVEN STURM¹, and KLAUS BLAUM¹ — ¹Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg — ²Fakultät für Physik und Astronomie, Universität Heidelberg

The Penning-trap based experiment ALPHATRAP is currently being set up at the Max-Planck-Institut für Kernphysik in Heidelberg. It is the follow-up to the Mainz g -factor experiment, which has performed the most sensitive test of bound-state quantum electrodynamics (BS-QED) by measuring the g -factor of the remaining electron bound in hydrogen-like $^{28}\text{Si}^{13+}$ at an uncertainty level of 10^{-11} [1] in a cryogenic double Penning-trap system. ALPHATRAP aims for g -factor measurements on even heavier highly charged ions up to hydrogen-, lithium- and boron- like lead, with simultaneously improved accuracy. To achieve this, the ALPHATRAP experiment, consisting of an improved cryogenic double Penning-trap setup, will be coupled via an ultra-high vacuum beamline to the Heidelberg Electron-Beam Ion Trap, which provides the highly charged ions. In combination with currently conducted BS-QED calculations, the measurements are expected to further contribute to the exploration of the limits of BS-QED

Q 43.10 Wed 16:30 Empore Lichthof

Flexible Rydberg aggregates — ●KARSTEN LEONHARDT, SEBASTIAN WÜSTER, and JAN MICHAEL ROST — Max Planck Institute for the Physics of Complex Systems

Rydberg aggregates [1] are assemblies of highly excited atoms, where all atoms experience strong dipole-dipole interactions. Due to their simple structure and strong interactions, it makes them a fertile platform to study the link between motion, energy and entanglement transport. The transport can be almost coherent, since the quantum properties in Rydberg interacting systems are maintained on the relevant time and length scales. Another feature of Rydberg aggregates is that electronic excitation and atomic motion can propagate as a combined pulse, a so called exciton pulse [2-5]. We identified structural elements in flexible Rydberg aggregates [4,5] that significantly affect exciton dynamics, enabling coherent splitting of an exciton pulse, control of its propagation direction and coherence properties. **References**

- [1] C. Ates, A. Eisfeld, J. M. Rost, NJP **10**, 045030 (2008).
- [2] S. Wüster, C. Ates, A. Eisfeld, J. M. Rost, PRL **105**, 195392 (2010).
- [3] S. Möbius, S. Wüster, C. Ates, A. Eisfeld, J. M. Rost, J. Phys. B. **44**, 184011 (2011).
- [4] K. Leonhardt, S. Wüster, J. M. Rost, PRL **113**, 223001 (2014).
- [5] K. Leonhardt, S. Wüster, J. M. Rost, arXiv:1511.06629 (2015).

and also aim for an independent determination of the fine-structure constant α with high precision. An overview and the current status of the project will be presented.

Q 44.3 Wed 16:30 Empore Lichthof

Metallic Magnetic Calorimeters for high resolution X-ray spectroscopy — ●M. KRANTZ, D. HENGSTLER, C. SCHÖTZ, M. KELLER, J. GEIST, P. SCHNEIDER, S. KEMPF, L. GASTALDO, A. FLEISCHMANN, and C. ENSS — KIP Heidelberg University.

We develop microfabricated, energy dispersive particle detector arrays based on metallic magnetic calorimeters (MMCs) for high resolution x-ray spectroscopy to challenge bound-state QED predictions. Our MMCs are usually operated below 30 mK and use a paramagnetic temperature sensor placed in a weak magnetic field, read-out by a SQUID, to measure the energy deposited by single X-ray photons. MMCs combine the properties of high energy resolution, high energy bandwidth and near perfect linearity in one detector. We discuss the microfabricated devices and performances of three different detector arrays. The maXs-20 is a 1x8 pixel linear array optimized for x-rays up to 20 keV with an achieved energy resolution of 1.6 eV for 6 keV x-rays and experiments with maXs-20 at the MPI-K yielded new reference measurements of V-like and Ti-like tungsten. The maXs-200 is a 1x8 pixel linear array optimized for x-rays up to 200 keV with an achieved energy resolution of 45 eV for 60 keV x-rays. We discuss successfully performed measurements at the Experimental Storage Ring (ESR) at GSI with the maXs-200. Our first 2d prototype with 8x8 pixels, maXs-30, is optimized for x-rays up to 30 keV with an estimated energy resolution below 6 eV.

Q 44.4 Wed 16:30 Empore Lichthof

The new CRYRING facility at GSI / FAIR and experiments with optical ion polarization — ●ZORAN ANDELKOVIC¹, WOLFGANG GEITHNER¹, FRANK HERFURTH¹, MICHAEL LESTINSKY¹, WILFRIED NÖRTERSCHÄUSER², and GLEB VOROBYEV¹ — ¹GSI Darmstadt — ²TU Darmstadt

The CRYRING storage ring, the Swedish in-kind contribution to FAIR, is in the final installation phase. Tests of ion injection from the ESR are foreseen for the upcoming GSI beamtime period, followed by the commissioning of the ring within the following year.

A new transfer line has been designed for the injection from the Experimental Storage Ring (ESR). Thus all ion species presently accessible in ESR can be transferred to CRYRING. In addition, a local injector is available for ring commissioning and first operation. This local injector transfer line has been significantly modified compared to the former Stockholm configuration to meet the requirements at

GSI. It provides stand-alone operation from a 40 kV platform where different ion species can be produced, transported to the RFQ and accelerated to the necessary 300 keV/u for injection into the ring.

One of the first experiments which can be performed with the off-line source and the local injection is the investigation of polarized ion beams inside a storage ring. Recently, in an experiment at the ESR, an indication for optical polarization of an ion beam has been observed. Further systematic tests of optical pumping and polarization conservation of singly charged Mg or Be ions are foreseen at CRYRING.

Q 44.5 Wed 16:30 Empore Lichthof

Laser system for Precise High Voltage measurements — •TIM RATAJCZYK, PHILLIP IMGAM, KRISTIAN KÖNIG, JÖRG KRÄMER, BERNHARD MAASS, JOHANNES ULLMANN, and WILFRIED NÖRTERS-HÄUSER — Institut für Kernphysik, TU Darmstadt

The ALIVE experiment at the TU Darmstadt is a new collinear laser spectroscopy setup. The goal of the experiment is the measurement of high voltages in the range of 10 to 100 kV using precise laser spectroscopy of ions with a well-known transition frequency [1]. The aim is to achieve a precision of at least 1 ppm, which is of interest for many applications.

For first experiments using a $^{40}\text{Ca}^+$ beam, a diode laser based system has been established. The well-known $4s_{1/2} \rightarrow 4p_{3/2}$ transition is used to identify the ion velocity by the Doppler shift. The laser system consists of an external cavity diode laser at 786 nm in combination with a tapered amplifier to provide a narrow bandwidth beam with sufficient power for frequency doubling in an LBO crystal. We present the current status of the experiment and an outlook for the laser system that will be used for spectroscopy on indium.

[1] O. Poulsen, Nuclear Instruments & Methods in Physics Research 202 (1982) 503.

Q 44.6 Wed 16:30 Empore Lichthof

Simulation and characterization of a multiwire backgammon gaseous detector for soft X-ray detection — •MYKHAILO DUMCHEV, JENS OBERRATH, and ANTHIMOS GEORGIADIS — Institut für Produkt- und Processinnovation, Leuphana Universität Lüneburg, Deutschland

To proof the QED corrections of the $1s$ Lamb shift, high precision X-ray spectroscopy of low energetic transitions in high Z-ions is necessary. Since photons will be detected in coincidence with down-charged ions, a time resolution less than 50 ns and spatial resolution less than $100\ \mu\text{m}$ is required.

A promising candidate to meet these requirements is a multiwire backgammon gaseous detector (MWB). It consists of a spacer, an inlet gas plate, an array of seven wires as anode plane, and a cathode plane shaped like a backgammon surface. This anode-cathode arrangement allows for the required spatial resolution in two dimensions as shown by Beyer and Deslattes [1]. To proof that such a detector is able to fulfill the required time resolution, simulations with the software tool Garfield were performed. It turned out that a time resolution of about 26 ns can be reached. Based on these results a MWB is constructed and tested. Within this contribution measurements with this detector will be presented and compared to simulation results.

[1] H. F. Beyer and R. D. Deslattes, GSI Scientific Report 1983, p. 350

Q 44.7 Wed 16:30 Empore Lichthof

Integrated electronic and photonic structures in vapor cells for quantum optics and sensing — •JOHANNES SCHMIDT^{1,2}, RALF RITTER¹, NICO GRUHLER³, PATRICK SCHALBERGER², HOLGER BAUR², HARALD KÜBLER¹, ROBERT LÖW¹, WOLFRAM PERNICE³, NORBERT FRÜHAUF², and TILMAN PFAU¹ — ¹Physikalisches Institut, Universität Stuttgart, Germany — ²Institut für Großflächige Mikroelektronik, Universität Stuttgart, Germany — ³Institute of Nanotechnology, Karlsruhe Institute of Technology, Germany

Rydberg atoms in thermal vapor are discussed as promising candidates for the realization of quantum devices such as single photon sources and sensors [1]. We present a sealing method based on anodic bonding, which is compatible with state of the art thin film technology offering both scalability and miniaturization [2]. We show that we are able to integrate electronic devices ranging from simple electrode structures to complex circuits like operational amplifiers into the vapor cell. Properties of different electrode materials and encapsulation methods are discussed as well.

Furthermore, we can implement integrated optics such as waveguide structures, which offer dozens of applications, like miniaturized atomic vapor spectroscopy, signal processing and sensing [3].

[1] J. A. Sedlacek, et al., Phys. Rev. Lett. 111, 063001 (2013)

[2] R. Daschner, et al., Appl. Phys. Lett. 105, 041107 (2014)

[3] R. Ritter, et al., Appl. Phys. Lett. 107, 041101 (2015)

Q 44.8 Wed 16:30 Empore Lichthof

High precision measurement of the Ho-163 electron capture spectrum — •GASTALDO LOREDANA FOR THE ECHO COLLABORATION — Kirchhoff-Institut für Physik, Universität Heidelberg, INF 227, 69120 Heidelberg, Germany

The sensitivity to the neutrino mass achievable with the analysis of the calorimetrically measured electron capture spectrum of Ho-163 is strongly dependent on the precise understanding of the expected spectral shape. Already at the level of energy resolution that is presently achieved in the ECHO experiment for the Ho-163 spectrum it is obvious that several parameters for the theoretical description of the spectral shape need to be defined with higher accuracy. The determination of higher order processes to the atomic de-excitation within the daughter atom dysprosium might play an important role for achieving sub-eV sensitivity on the electron neutrino mass. We compare the parameters obtained by the analysis of the calorimetrically measured Ho-163 spectrum with the ones available in literature and discuss the discrepancies with present models and available data. We present new experimental methods and discuss recently theoretical models to achieve a better accuracy in the determination of the parameters describing the Ho-163 spectrum.

Q 44.9 Wed 16:30 Empore Lichthof

Towards a quantum logic based CPT test using single trapped (anti-)protons — •TERESA MEINERS¹, MALTE NIEMANN¹, ANNA-GRETA PASCHKE¹, MATTHIAS BORCHERT¹, ALEXANDER IDEL¹, JOHANNES MIELKE¹, AMADO BAUTISTA-SALVADOR^{1,2}, STEFAN ULMER³, and CHRISTIAN OSPELKAUS^{1,2} — ¹Institut für Quantenoptik, Universität Hannover — ²Physikalisch Technische Bundesanstalt, Braunschweig — ³Ulmer Initiative Research Unit, RIKEN

We present sympathetic laser cooling and detection concepts for a CPT test based on a g-factor comparison between single protons and antiprotons in a Penning trap. Following the proposal by Heinzen and Wineland [1] the (anti-)proton can be coupled to a laser-cooled (beryllium) ion to achieve reliable preparation near the motional ground state, reducing systematic uncertainties and difficulties in state detection using the continuous Stern-Gerlach effect. Using sideband cooling techniques to the motional ground state, quantum logic spectroscopy can provide an alternative readout scheme.

We discuss ion trap geometries and state transfer schemes as well as laser systems and optical systems for loading, manipulating and detecting the atomic ion. We acknowledge funding by the ERC (ERC StG QLEDS). This project is supported by the BASE collaboration.

[1] Heinzen and Wineland, PRA 42, 2977 (1990)

Q 44.10 Wed 16:30 Empore Lichthof

Towards a nuclear clock based on ^{229}Th : Internal conversion rates for Th ions — •PAVLO BILOUS and ADRIANA PÁLFFY — Max Planck Institute for Nuclear Physics, Saupfercheckweg 1, D-69117 Heidelberg, Germany

The thorium isotope ^{229}Th bridges atomic and nuclear physics with its unique long-lived nuclear excited state with the energy of 7.8 eV [1]. The advantages of this nuclear transition are its very narrow width, the stability with respect to external perturbations and an accessible frequency within the VUV region, rendering it a candidate for a nuclear clock system. Due to the small excitation energy, typical for outer shell electron transitions, the strongest decay channel of the 7.8 eV nuclear state in a Th atom is internal conversion.

Here we carry out *ab initio* calculations of internal conversion rates for Th using multi-configurational Dirac-Fock wave functions [2] for the bound atomic electron. We consider internal conversion in atoms and ions with charge states Th^+ and Th^{2+} and several ground and excited state configurations. These results are required for a better understanding of the decay properties of the ^{229}Th clock transition in different materials and experimental setups.

[1] B. R. Beck *et al.*, Phys. Rev. Lett. **98**, 142501 (2007).

[2] P. Jönsson *et al.*, Comput. Phys. Commun. **184**, 2197 (2013).

Q 44.11 Wed 16:30 Empore Lichthof

Search for optical excitation of the low-energy nuclear isomer of ^{229}Th — •JOHANNES THIELKING, DAVID-MARCEL MEIER, MAXIM V. OKHAPKIN, and EKKEHARD PEIK — Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany

Direct optical excitation of the nuclear transition between ground state and the 7.8 eV isomer in ^{229}Th is the missing link towards a study of this system as a precise nuclear clock. To excite the nuclear isomer via electronic bridge [1]/NEET processes, we use two-photon laser excitation of high-lying electronic levels in Th^+ within the energy range from 7.3 to 8.3 eV [2,3]. We investigate the hyperfine structure of electronic levels of Th^+ as means for detection of the isomeric state and to examine its nuclear structure. We also study a possible two-photon excitation scheme in Th^{2+} for energies higher than 8.3 eV, since this range is hardly accessible in Th^+ because of resonantly enhanced three-photon ionisation in our experiment.

- [1] S. G. Porsev et al., Phys. Rev. Lett. 105, 182501 (2010)
 [2] O. A. Herrera-Sancho et al., Phys. Rev. A 85, 033402 (2012)
 [3] O. A. Herrera-Sancho et al., Phys. Rev. A 88, 012512 (2013)

Q 44.12 Wed 16:30 Empore Lichthof

The g -factor of the muon bound in a nuclear potential — ●BASTIAN SIKORA, NIKOLAY BELOV, ZOLTÁN HARMAN, and CHRISTOPH H. KEITEL — Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

We present the theory of the g -factor of the muon bound in a nuclear potential. One-loop self-energy and vacuum polarization corrections are included, taking into account the interaction with the nuclear potential exactly. Moreover, we incorporate finite nuclear size and finite nuclear mass corrections.

The theory of the bound-muon g -factor, combined with possible future experiments involving bound muons can be used in principle to test quantum electrodynamics in stronger electric fields than possible with bound electrons. Furthermore, since contributions due to nuclear effects are large for bound muons, nuclear parameters can be determined by comparing the theoretical and experimental bound-muon g -factor.

Q 44.13 Wed 16:30 Empore Lichthof

Investigations of nuclear effects in highly charged ions — ●HENDRIK BEKKER¹, SEBASTIAN KEBRICH¹, KATHRIN KROMER¹, ANDREY V. VOLOTKA², ZOLTÁN HARMAN¹, CHRISTOPH H. KEITEL¹, and JOSÉ R. CRESPO LÓPEZ-URRUTIA¹ — ¹Max-Planck-Institut für Kernphysik, Heidelberg — ²Helmholtz-Institut Jena

Treatment of the interaction between electrons and nucleus beyond the point-like Coulomb potential approximation leads to modification of the energy level structure of bound electrons. Nuclear properties such as its spin, magnetic moment, charge and magnetization distributions can be investigated by measuring how they affect the electronic structure of atoms and ions. Highly charged ions (HCI) belonging to the H-like isoelectronic sequence are specially suitable for this. We aim to measure the hyperfine splitting of the $^2S_{1/2}$, $F = 3 - 2$ ground state in H-like Pr^{58+} , which is predicted to be at approximately 847 nm.

We use the Heidelberg electron beam ion trap to produce, trap, and collisionally excite HCI. Fluorescence light in the optical domain is measured using a grating spectrometer with which a precision of 1 ppm can be reached. Using this setup we have also measured the $J = 2 - 3$ transition in the $3d^4$ ground term of Ti-like Pr^{37+} and Re^{53+} . The many hyperfine levels and the strong magnetic field at the trap center give rise to a complex line shape, which is accurately reproduced by theory. Additionally, we have investigated the *KLL* dielectronic recombination in He- to O-like Pr, which is an important tool for trap optimization. Current efforts are towards the efficient production and trapping of H-like Pr^{58+} .

Q 44.14 Wed 16:30 Empore Lichthof

Spectroscopy of trapped $^{138}\text{Ba}^+$ ions for atomic parity violation and optical clocks — ●ELWIN A. DIJCK, AMITA MOHANTY, NIVEDYA VALAPPOL, J. OLIVIER GRASDIJK, OLIVER BÖLL, ANDREW T. GRIER, KLAUS JUNGSMANN, MAYERLIN NUÑEZ PORTELA, and LORENZ WILLMANN — Van Swinderen Institute, University of Groningen, The Netherlands

The heavy alkaline earth ions Ba^+ and Ra^+ are good candidates for a precision measurement of the weak mixing angle at low energy as well as for building an optical atomic clock. One requirement for these applications is to determine the atomic structure to percent level. We have studied the lifetime of the metastable $5d\ ^2D_{5/2}$ level in $^{138}\text{Ba}^+$ as a benchmark for theory calculations. Systematic effects are investigated by comparing multiple measurement schemes on a single and multiple trapped ions. In addition, we have measured the transition frequencies between the $6s\ ^2S_{1/2}$, $6d\ ^2P_{1/2}$ and $5d\ ^2D_{3/2}$ levels in

$^{138}\text{Ba}^+$ to 100 kHz accuracy [1], improving the knowledge of these frequencies by more than two orders of magnitude.

- [1] E. A. Dijck et al., Phys. Rev. A 91, 060501(R) (2015)

Q 44.15 Wed 16:30 Empore Lichthof

Atomic Parity Violation in Ytterbium — ●ANNE FABRICANT¹, DIONYSIOS ANTYPAS², LYKOURGOS BOUGAS², NATHAN LEEFER², KONSTANTIN TSIGUTKIN³, and DMITRY BUDKER^{1,2} — ¹Johannes Gutenberg Universität-Mainz, Mainz, Germany — ²Helmholtz Institut-Mainz, Mainz, Germany — ³ASML, Veldhoven, The Netherlands

Atomic-parity-violation (APV) experiments enable us to probe fundamental electroweak physics at low energies on a tabletop. Ytterbium (Yb) is a good candidate for APV measurements because of its particularly strong parity-violating effects and the availability of seven stable isotopes. The previous incarnation of the experiment, at UC Berkeley, succeeded in measuring the largest APV effect ever observed. Currently we are developing a new experimental apparatus in Mainz, in order to improve the accuracy of the measurements. This will enable us to investigate neutron distributions in the nucleus (the neutron skin), as well as the anapole moment arising from the weak interaction between nucleons.

Q 44.16 Wed 16:30 Empore Lichthof

Development of a high resolution VUV grating spectrometer — ●STEPAN DOBRODEY¹, MICHAEL A. BLESSENOHL¹, SVEN BERNITT^{1,2}, LAURENT MERCADIER³, CLEMENS WENINGER⁴, NINA ROHRINGER⁴, and JOSÉ R. CRESPO LÓPEZ-URRUTIA¹ — ¹Max-Planck-Institut für Kernphysik, Heidelberg, Germany — ²IOQ, Friedrich-Schiller-Universität, Jena, Germany — ³Centre for Free-Electron Laser Science, Hamburg, Germany — ⁴Max-Planck-Institut für Struktur und Dynamik der Materie, Hamburg, Germany

We present the design and development of a high resolution normal incidence grating spectrometer for the VUV range. First successful measurements have been carried out at the free-electron laser (FEL) FLASH in Hamburg to study the lasing activity of atomic transitions in xenon and krypton after inner-shell excitation with FEL pulses. With an achieved resolving power of 50000 this instrument will be utilized in the near future for observations of transitions in the VUV range in highly charged ions produced in an electron beam ion trap. This will allow for better understanding of astrophysical processes and tests of fundamental theories.

Q 44.17 Wed 16:30 Empore Lichthof

A superconducting resonator-driven linear radio-frequency trap for long-time storage of highly charged ions — ●JULIAN STARK¹, LISA SCHMÖGER^{1,2}, ANDRII BORODIN¹, JANKO NAUTA¹, and JOSÉ R. CRESPO LÓPEZ-URRUTIA¹ — ¹Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg — ²Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig

Cold, strongly localized highly charged ions (HCIs) are particularly interesting candidates for novel frequency standards at a potential 10^{-19} level relative accuracy and searches for physics beyond the Standard Model, such as possible drifts in the value of the fine structure constant α . For sympathetic cooling of HCIs, these are simultaneously trapped with laser-cooled Be^+ ions in a cryogenic linear radio-frequency (RF) Paul trap [1,2]. Stable localization requires a high voltage RF drive with low noise. Currently, a new RF resonator is commissioned which includes the quadrupole trapping electrodes in the cavity. The high quality factor Q of the resonator will drastically reduce Paul trap heating rates as well as improve the overall stability of the trapping conditions. This will render electro-dynamical losses of trapped ions negligible and enables precise localization of HCIs which is needed for high precision laser spectroscopy.

- [1] M. Schwarz et al., Rev. Sci. Instrum. 83, 083115 (2012)
 [2] L. Schmöger et al., Science 347, 6227 (2015)

Q 44.18 Wed 16:30 Empore Lichthof

Line shape of frequency modulation spectroscopy of molecular iodine — ●NIVEDYA VALAPPOL, AMITA MOHANTY, ELWIN A. DIJCK, OLIVER BÖLL, KLAUS JUNGSMANN, and LORENZ WILLMANN — Van Swinderen Institute, FMNS, University of Groningen, The Netherlands

High resolution saturated absorption spectroscopy of $^{127}\text{I}_2$ hyperfine transitions deliver a natural frequency grid in the 500 nm-900 nm range. An external-cavity diode laser system at 650 nm is stabilized to the

frequency modulated absorption signal of the R(25)(6-5) transition in molecular I₂ which is 412 MHz above the 6p²P_{1/2} - 5d²D_{3/2} transition in Ba⁺ ions. The diode laser can be phase locked to a frequency comb which transfers the stability of the GPS disciplined Rb clock of 10⁻¹² optical range. We present a well-defined line shape which permits an accurate description of the observed signals. The stability of the frequency modulated saturated spectroscopy of I₂ lines reaches a precision of kHz level. We find that the residual amplitude modulation, which is inherent in modulation spectroscopy, shifts the zero crossing of the line. The line shape model provides for accurate extraction of density shift, broadening and hyperfine splitting.

Q 44.19 Wed 16:30 Empore Lichthof

Resonant excitation of the 136 eV 2s-2p transition in Li-like Kr³³⁺ at FLASH — ●SVEN BERNITT^{1,2}, GÜNTER BRENNER³, RENÉ STEINBRÜGGE¹, STEPAN DOBRODEY¹, MICHAEL A. BLESSENOHL¹, ANDRÉ CIELUCH¹, ZACHARY HOCKENBERY¹, STEFFEN KÜHN¹, JANKO NAUTA¹, MIGUEL-ANGEL SANCHEZ¹, SASCHA W. EPP⁴, and JOSÉ R. CRESPO LÓPEZ-URRUTIA¹ — ¹Max-Planck-Institut für Kernphysik, Heidelberg, Germany — ²IOQ, Friedrich-Schiller-Universität, Jena, Germany — ³DESY, Hamburg, Germany — ⁴Max-Planck-Institut für Struktur und Dynamik der Materie, Hamburg, Germany

We use the transportable electron beam ion trap FLASH-EBIT to provide a target of Li-like Kr³³⁺ for monochromatized VUV light from the free-electron laser FLASH. By detecting resonantly excited fluorescence as a function of the photon energy, we were able to perform high precision spectroscopic studies of the 1s²2s-1s²2p transition at 136 eV. We reached an accuracy of 6 meV, providing an improvement by a factor of 7 over previous measurements. These results serve as a benchmark for atomic theory and help with the interpretation of VUV spectra from astrophysical and laboratory plasmas. Future work aims at investigations of nuclear size effects which currently impede the full analysis of QED experimental data of H-like systems.

Q 44.20 Wed 16:30 Empore Lichthof

Stopping of highly charged ions in laser-cooled Be⁺ Coulomb crystals — ●LISA SCHMÖGER^{1,2}, MARIA SCHWARZ^{1,2}, THOMAS M. BAUMANN¹, OSCAR O. VERSOLATO^{1,2}, BAPTIST PIEST¹, THOMAS PFEIFER¹, JOACHIM ULLRICH², PIET O. SCHMIDT^{2,3}, and JOSÉ R. CRESPO LÓPEZ-URRUTIA¹ — ¹Max-Planck-Institut für Kernphysik, Heidelberg, Germany — ²Physikalisch-Technische Bundesanstalt, QUEST, Braunschweig, Germany — ³Leibniz Universität Hannover, Germany

Cold highly charged ions (HCIs) are promising candidates for the development of novel ultra-precise clocks and the search for possible variations of fundamental constants. However, in the laboratory HCIs are produced by energetic processes, such as electron impact ionization, leaving the trapped ensemble at translational temperatures on the order of MK. We demonstrate a versatile preparation technique for cold HCIs which are nearly at rest in space. It is based on the generic modular combination of a pulsed HCI source with a cryogenic linear Paul trap [1]. A beamline for deceleration and precooling connects both instruments. Slow HCIs, specifically Ar¹³⁺ ions, are injected into the linear Paul trap where they are forced to perform an oscillatory motion along the trap axis. Finally, the HCIs are stopped by damping this motion through multiple interactions with a prestored and continuously laser-cooled Be⁺ Coulomb crystal.

[1] L. Schmöger, *et al.*, *Rev. Sci. Instrum.* **86**, 103111 (2015)

Q 44.21 Wed 16:30 Empore Lichthof

Coulomb crystallized highly charged ions for fundamental physics research — ●LISA SCHMÖGER^{1,2}, OSCAR O. VERSOLATO^{1,2}, MARIA SCHWARZ^{1,2}, MATTHIAS KOHNEN², ALEXANDER WINDBERGER¹, BAPTIST PIEST¹, STEFANIE FEUCHTENBEINER¹, JOFRE PEDREGOSA-GUTIERREZ⁴, TOBIAS LEOPOLD², THOMAS M. BAUMANN¹, MICHAEL DREWSSEN⁵, JOACHIM ULLRICH^{1,3}, PIET O. SCHMIDT^{2,3}, and JOSÉ R. CRESPO LÓPEZ-URRUTIA¹ — ¹Max-Planck-Institut für Kernphysik, Heidelberg, Germany — ²Physikalisch-Technische Bundesanstalt, QUEST, Braunschweig, Germany — ³Leibniz Universität Hannover, Germany — ⁴Aix-Marseille Université, France — ⁵Aarhus University, Denmark

Production of cold, strongly localized highly charged ions (HCIs) has been an experimental challenge for two decades. We succeeded in re-trapping and sympathetically cooling HCIs [1] - produced with an electron beam ion trap - in our cryogenic radiofrequency linear Paul trap. The strongly suppressed thermal motion (mK scale) of the co-crystallized HCIs will be a great advantage for high precision laser

spectroscopy of forbidden transitions in HCI. Those are particularly interesting both for fundamental research, such as searching for physics beyond the Standard Model, and for technological applications such as high accuracy atomic optical clocks. Our first test experiment will be the study of the ²P_{3/2}-²P_{1/2} M1 transition in Ar¹³⁺ at 441nm.

[1] L. Schmöger, *et al.*, *Science* **347**, 6227 (2015)

Q 44.22 Wed 16:30 Empore Lichthof

High resolution spectroscopy in HCI using High-order Harmonic Generation — ●JANKO NAUTA¹, ANDRII BORODIN¹, PETER MICKÉ^{1,2}, LISA SCHMÖGER^{1,2}, MARIA SCHWARZ^{1,2}, JULIAN STARK¹, JOSÉ R. CRESPO LÓPEZ-URRUTIA¹, and THOMAS PFEIFER¹ — ¹Max-Planck-Institut für Kernphysik — ²Physikalisch-Technische Bundesanstalt, Braunschweig

Highly charged ions (HCI) are atomic systems with a few tightly bound electrons. HCI exhibit much more pronounced quantum-electrodynamics effects than neutrals and singly charged particles, thus allowing accurate tests of fundamental theory to be performed, and high precision determination of values of fundamental constants. Most observations in HCI are made with ions at temperatures of more than 10² eV using electron-beam ion traps. Recent progress in trapping HCI in a cryogenic linear quadrupole trap, and sympathetic cooling with Be⁺ ions [M. Schwarz *et al.*, *Rev. Sci. Instrum.* **83**, pp. 1-10 (2012), L. Schmöger *et al.*, *Science* **347**, pp. 1233-1236 (2015)], opens up the possibility for high-precision laser spectroscopy. Many transitions in HCI have energies of few ten eV. So far, excitation of these transitions required the use of free-electron lasers. The aim of this project is to perform high-resolution spectroscopy of extreme ultraviolet transitions by high-order harmonics generated by femtosecond laser pulses, which are amplified by an enhancement cavity. An experimental scheme for realizing this approach will be presented.

Q 44.23 Wed 16:30 Empore Lichthof

A vibration-free cryogenic system for ion traps — MARIA SCHWARZ^{1,2}, ●PETER MICKÉ^{1,2}, LISA SCHMÖGER^{1,2}, TOBIAS LEOPOLD², THOMAS PFEIFER¹, JOSÉ R. CRESPO LÓPEZ-URRUTIA¹, and PIET O. SCHMIDT^{2,3} — ¹Max-Planck-Institut für Kernphysik, Heidelberg, Germany — ²Physikalisch-Technische Bundesanstalt, QUEST, Braunschweig, Germany — ³Leibniz Universität Hannover, Germany

Cold highly charged ions (HCI) can be sensitive detectors for possible small variations of fundamental constants, e.g. of the fine-structure constant on a level of 10⁻¹⁹ per year. High precision spectroscopy, such as quantum logic spectroscopy, is needed to probe the highly forbidden optical transitions in HCIs. A cryogenic environment is essential to suppress charge exchange with residual gas in order to achieve long HCI storage times. We have set up a cryogenic system based on the one of CryPTE_x [1], using a pulse-tube cryocooler and nested temperature stages. In the upgraded CryPTE_x-II, the cryocooler and the trap are 2 m apart, located in separate rooms for acoustic decoupling, and thermally linked by a vibration-suppression system. Mechanical vibrations due to pumps and the cryocooler are decoupled by means of edge-welded bellows, flexible ultra-pure copper links and a massive inertial pendulum.

[1] M. Schwarz *et al.*, *Rev. Sci. Instrum.* **83**, 083115 (2012)

Q 44.24 Wed 16:30 Empore Lichthof

Polar-maXs: Micro-calorimeter based X-ray polarimeters — ●CHRISTIAN SCHÖTZ¹, DANIEL HENGSTLER¹, LOREDANA GASTALDO¹, SEBASTIAN KEMPF¹, ANDREAS FLEISCHMANN¹, CHRISTIAN ENSS¹, GÜNTER WEBER^{2,3}, and THOMAS STÖHLKER^{2,3,4} — ¹Kirchhoff Institute for Physics, Heidelberg University — ²Helmholtz-Institute Jena — ³GSI Darmstadt — ⁴IOQ, Jena University

We are presently developing the x-ray detector system Polar-maXs, which will combine for the first time the high energy resolution, large dynamic range and excellent linearity of magnetic micro-calorimeters with the sensitivity to polarization caused by polarization-dependent Compton or Rayleigh scattering in an array of scatterers.

Polar-maXs consists of two layers. The first layer comprises a 4 x 4 array of x-ray scatterers behind a corresponding array of collimator holes. Depending on the energy range of interest and whether Compton or Rayleigh scattering is to be used, these scatterers are fabricated from low-Z or high-Z material. The scattered x-rays are detected by an array of 576 x-ray absorbers read-out by paramagnetic temperature sensors as metallic magnetic micro-calorimeters (MMC). Each absorber covers an area of 0.5mm x 0.5mm and is made of 15 micrometer thick gold, to guarantee high stopping power for x-ray with

energies up to 20 keV and an energy resolution of better than 20eV (FWHM) in the complete energy range. We discuss general design considerations as well as the results of Monte-Carlo simulations for a

variety of detector designs. We present micro-fabricated devices and discuss the results of first experimental tests.

Q 45: Ultrashort Laser Pulses I

Time: Thursday 11:00–13:00

Location: a310

Q 45.1 Thu 11:00 a310

Fast-tunable femtosecond broadband ring cavity NOPO with intracavity SFG in visible — ●YULIYA KHANUKAEVA¹, TINO LANG², AYHAN TAJALLI¹, THOMAS BINHAMMER³, and UWE MORGNER¹ — ¹Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, D-30167 Hannover, Germany — ²Deutsches Elektronen-Synchrotron DESY, D-22607 Hamburg, Germany — ³VENTEON Laser Technologies GmbH, D-30419 Hannover, Germany

We present a femtosecond fast tunable source that is able to simultaneously deliver NIR and VIS pulses in the range of 680-950 nm and 400-500 nm correspondingly. The source is based on intracavity sum frequency generation (SFG) in an ultrafast singly-resonant ring cavity non-collinear optical parametric oscillator (NOPO) pumped by the second harmonic of a home-built thin-disk laser. The NOPO employs a BBO crystal as gain medium and a KDP crystal for the intracavity SFG between the signal and remaining IR pump, both in a non-collinear configuration. The tuning concept is based on an ultra-broadband phase-matching that allows tuning the wavelength over the whole range just by varying the cavity length without changing the phase matching angle of the OPO crystal. When both outputs are used at the same time the source provides up to 1 W output at 925 nm and 200 mW of SFG at 485 nm, whereas without IR output coupling up to 450 mW has been recorded in the VIS.

Q 45.2 Thu 11:15 a310

Dual Yb³⁺:Lu₂O₃ thin-disk oscillator with SESAM mode-locking — ●BERNHARD KREIPE, JANA KAMPMANN, LUISE BEICHERT, and UWE MORGNER — Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover

We present a multi-crystal oscillator based on two Yb³⁺:Lu₂O₃ thin-disks in a symmetrically coupled cavity. The multi-pass geometry of the resonator with 16 passes per round trip enables high outcoupling of the intracavity power greater than 25%. By splitting the power of a conventional broadband diode to both thin-disks, we achieve more than 50 W of output power in cw operation at 210 W of pump power with a slope efficiency of 40%. Also the transfer of this power-scaling approach to the pulsed regime in the context of a SESAM mode-locked chirped-pulse oscillator is investigated.

Q 45.3 Thu 11:30 a310

Rapidly, electronically tunable fiber-based optical parametric oscillator — ●MAXIMILIAN BRINKMANN, SARAH JANFRÜCHTE, SVEN DOBNER, and CARSTEN FALLNICH — Institute of Applied Physics, University of Münster, Germany

We present a fiber-based optical parametric oscillator (FOPO) synchronously pumped by an amplified laser diode at a wavelength of 1030 nm, with a repetition rate of about 1 MHz and a pulse duration of 10 ps. The FOPO consisted of 10 cm of highly nonlinear photonic-crystal fiber to frequency-convert the pump pulses via four-wave mixing and about 200 m of single-mode fiber to form the resonator. Due to dispersion in the fiber resonator, the fed back signal pulse was temporarily stretched, such that only a narrow spectral part of it overlapped with the next pump pulse and was amplified. Via this dispersion filtering, output idler pulses with a bandwidth of about 3 nm, a temporal duration of about 5 ps and a pulse energy up to 20 nJ could be produced. By changing the repetition rate of the pump laser diode by about 2 kHz, the wavelength of the output pulses could be tuned between 1130 and 1310 nm. As this tuning mechanism was solely based on electrical means, we were able to tune the FOPO with a speed of 8 μs per wavelength step, independent of the width of the step, which is several orders of magnitude faster than achieved with similar FOPOs tuned via a mechanical delay line or with temperature-controlled OPOs. Due to the rapidly and widely tunable wavelength and the high energy of its output pulses, the FOPO should be well suited for coherent Raman or multi-photon microscopy.

Q 45.4 Thu 11:45 a310

Mode-locking maps for a giant chirp oscillator — ●PAUL REPPEN, FLORIAN SCHEPERS, TIM HELLWIG, and CARSTEN FALLNICH — University of Münster, Institute of Applied Physics, Corrensstraße 2, 48149 Münster

We present a systematic and fully-automated characterization method to analyze the possible output states of a giant chirp oscillator (GCO)¹. Our GCO is a long-cavity (2.6 MHz repetition rate, 6.6 nJ pulse energy) Ytterbium-doped fiber oscillator, mode-locked by a nonlinear amplifying loop mirror (NALM). An approximately 70 m long single-mode fiber in the resonator induces an up-chirp to the pulse due to normal dispersion, resulting in an output pulse with an autocorrelation duration of 133 ps which can be compressed to an autocorrelation duration of 169 fs using an external grating compressor. Within our examination, we scan the pump power of the amplifier fiber as well as the NALM and record the mean power, repetition rate, spectrum, and the pulse energy fluctuations of the different operation states. Based on these data „mode-locking maps“ can be generated that can be subsequently used to directly compare different laser configurations (e.g. after changes of resonator length or output coupler position, etc.) and thereby allow to choose the optimal setup for the desired application.
¹ Erkontalo M., et al., *Opt. Express* **20**, 22669 (2012).

Q 45.5 Thu 12:00 a310

Efficient narrowband terahertz generation in periodically poled lithium niobate — ●FREDERIKE AHR^{1,2}, SERGIO CARBAJO^{1,2,3}, JAN SCHULTE^{1,2}, XIAOJUN WU^{1,3}, KOUSTUBAN RAVI^{1,4}, DAMIAN SCHIMPF^{1,3}, and FRANZ X. KÄRTNER^{1,2,3,4} — ¹Center for Free Electron Laser Science, and Deutsches Elektronen Synchrotron, Notkestraße 85, 22607 Hamburg, Germany — ²Department of Physics, University of Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany — ³The Hamburg Center of Ultrafast Imaging, Luruper Chaussee 149, 22761 Hamburg, Germany — ⁴Department of Electrical and Computer Engineering, and Research Laboratory of Electronics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA

We report a record optical-to-terahertz energy conversion efficiency for narrowband terahertz (THz) radiation in the frequency range of 0.1 to 1 THz via optical rectification in periodically poled lithium niobate (PPLN). The efficiency was optimized by cryogenically cooling the PPLN crystals to reduce THz absorption and by spectrally filtering the pulses from a Ti:sapphire regenerative amplifier. Tuning of the THz frequency was verified by measuring via electro-optic sampling the temporal waveforms and the corresponding spectra of THz pulses generated by PPLNs of different poling periods and corresponding phase-matching conditions. We achieved an energy conversion efficiency of 0.12%, which is two orders of magnitude higher than preceding studies with similar geometries, at a frequency of 560 GHz in a cryogenically cooled PPLN with a domain period of 212 μm.

Q 45.6 Thu 12:15 a310

Resolving the evolution of femtosecond modelocking via real-time spectroscopy at 90 MHz — ●GEORG HERINK^{1,2}, BAHRAM JALALI², CLAUS ROPERS¹, and DANIEL S. SOLLI^{1,2} — ¹IV. Physik, Friedrich Hund Platz 1, 37077 Göttingen — ²Department of Electrical Engineering, University of California, Los Angeles

Kerr-lens mode-locking (KLM) arises from noise and each starting event is highly stochastic and non-repetitive [1]. Conventional forms of time-resolved spectroscopy are incapable to trace the process with single-shot resolution over long record intervals. Here, we present real-time spectroscopy of the mode-locking transition in a KLM oscillator over 900,000 consecutive pulses. This is enabled by the Time-Stretch Dispersive Fourier Transformation (TS-DFT) and real-time electronic sampling [2,3]. We resolve the dynamics over the entire buildup with features on various timescales, i.e., the noisy onset of mode-locking milliseconds before the establishment of a femtosecond pulse, rapid spectral broadening and wavelengths shifts within few hundred roundtrips.

In addition, we identify a previously unreported beating process via the Kerr nonlinearity which governs the spectral broadening. This process can be employed as a time-resolved probe of the intracavity nonlinearity. We expect that the results stimulate further theoretical analysis of mode-locking and establish real-time spectroscopy as a diagnostic tool for novel ultrashort sources and nonlinear systems.

[1] U. Keller, *Nature* 424, 831 (2003). [2] A. Bhushan, F. Coppinger, B. Jalali, *Electronics Letters* 34, 839 (1998). [3] D. Solli, G. Herink, B. Jalali, C. Ropers, *Nature Photonics* 6, 463 (2012).

Q 45.7 Thu 12:30 a310

Full characterization of few-cycle pulses using cross-polarized wave generation d-scan technique — ●AYHAN TAJALLI¹, DAVID ZUBER¹, BRUNO CHANTEAU¹, MARTIN KRETSCHMAR¹, HEIKO KURZ¹, MILUTIN KOVACEV¹, UWE MORGNER^{1,2}, and TAMAS NAGY^{1,3} — ¹Institut Für Quantenoptik, Leibniz Universität Hannover, 30167 Hannover — ²Laserzentrum Hannover e.V., 30419 Hannover — ³Laser Laboratorium Göttingen e.V., 37077 Göttingen

Femtosecond pulse sources are considered as backbone of various fields of fundamental studies and applications e.g. strong field physics, time-resolved optical microscopy and micro-machining. This technology requires the ability for full characterization of the ultrashort pulses. Different techniques such as FROG or SPIDER have been devised in last decades for this purpose; however, they suffer from rather complex setups or accurate calibrations. Here, we demonstrate a new version of dispersion scan (d-scan) pulse characterization scheme for phase retrieval of ultrashort optical pulses based on cross-polarized wave (XPW) generation nonlinearity. Degenerate four wave mixing process relaxes the phase matching constraints and hence is applicable for extremely wide wavelength range. We fully characterize 7-15 fs

pulses in the near-IR region delivered from spectrally broadened amplified pulses in a noble gas-filled hollow-core fiber and compare the results with a state of the art FROG characterization device.

Q 45.8 Thu 12:45 a310

Analysis and measurement of spatiotemporal couplings in noncollinear optical parametric amplifiers — ●ACHUT GIREE^{1,2}, FEDERICO J. FURCH¹, MARK MERO¹, GUNNAR ARISHOLM³, CLAUD PETER SCHULZ¹, and MARC J.J. VRAKING¹ — ¹Max Born Institute, Max-Born-Str. 2A, D12489, Berlin, Germany — ²Amplitude Technologies, 2-4 rue du Bois Chaland CE 2926, 91029 Evry, France — ³Norwegian Defence Research Establishment (FFI), PO Box 25, NO-2027 Kjeller, Norway

Noncollinear optical parametric amplifiers (NOPAs) are capable of delivering high energy, high repetition rate few-cycle pulses and are becoming increasingly more attractive in attosecond science. The high repetition rate ($\gg 10$ kHz) allows a significant increase in data acquisition speed and therefore is particularly important for electron-ion coincidence detection techniques where the necessary event rates are $\ll 1$ per pulse for unambiguous identification of electrons and their ionic partners. However, NOPAs may suffer from unwanted couplings between temporal and spatial coordinates of the electromagnetic field induced by the noncollinear geometry, known as spatiotemporal distortions. This ultimately limits the maximum achievable intensity at focus. In this work, we present a numerical study of spatiotemporal couplings in a NOPA based on the Sisyfos software and discuss possible ways to minimize the distortions. Additionally, we propose a real time technique to measure the spatiotemporal distortions based on spatially resolved spectral interferometry which serves as a tool to reduce them during NOPA alignment.

Q 46: Quantum Gases: Bosons V

Time: Thursday 11:00–12:45

Location: e001

Q 46.1 Thu 11:00 e001

Ground-State Properties of Anyons in a One-Dimensional Lattice — ●GUIXIN TANG¹, SEBASTIAN EGGERT², and AXEL PELSTER² — ¹Physics Department, Harbin Institute of Technology, China — ²Physics Department and Research Center OPTIMAS, Technische Universität Kaiserslautern, Germany

Using the Anyon-Hubbard Hamiltonian, we analyze the ground-state properties of anyons in a one-dimensional lattice [1]. To this end we map the hopping dynamics of correlated anyons to an occupation-dependent hopping Bose-Hubbard model using the fractional Jordan-Wigner transformation. In particular, we calculate the quasi-momentum distribution of anyons, which interpolates between Bose-Einstein and Fermi-Dirac statistics. Analytically, we apply a modified Gutzwiller mean-field approach, which goes beyond a classical one by including the influence of the fractional phase of anyons within the many-body wavefunction. Numerically, we use the density-matrix renormalization group by relying on the ansatz of matrix product states. As a result it turns out that the anyonic quasi-momentum distribution reveals both a peak-shift and an asymmetry which mainly originates from the nonlocal string property. In addition, we determine the corresponding quasi-momentum distribution of the Jordan-Wigner transformed bosons, where, in contrast to the hard-core case, we also observe an asymmetry for the soft-core case, which strongly depends on the particle number density.

[1] G. Tang, S. Eggert, and A. Pelster, *New J. Phys.* (in press), [arXiv:1509.01888](https://arxiv.org/abs/1509.01888)

Q 46.2 Thu 11:15 e001

Anyons in 1D optical lattices by time periodic forcing — ●CHRISTOPH STRÄTER¹, SHASHI C. L. SRIVASTAVA^{1,2}, and ANDRÉ ECKARDT¹ — ¹Max-Planck-Institut für Physik komplexer Systeme, Nöthnitzer Str. 38, 01187 Dresden, Germany — ²Variable Energy Cyclotron Centre, 1/AF Bidhan nagar, Kolkata, India 700 064

Interpolating between bosons and fermions, anyons are particles that pick up a complex phase $0 < \theta < \pi$ upon particle exchange. In one dimensional optical lattices, where anyons can be mapped onto bosons with a density dependent complex hopping element, the possible realization and the physics of anyons has caught a lot of interest recently. Still, the experimental implementation has not yet been achieved. We

propose a simple scheme to realize 1D anyons in optical lattices that relies only on lattice shaking and tilting. Within our proposal, also the on-site interaction of the anyons can be tuned effectively. We analyze the ground state of a chain of finite length, as it can be realized in a quantum gas microscope. With increasing θ the atoms tend to localize and to form a crystal-like structure. This is a signature of the smooth fermionization and can be observed in the density, in two-particle correlations, and in the 2nd Renyi entropy of subsystems.

Q 46.3 Thu 11:30 e001

Spectral characterization of two-dimensional Bose-Hubbard models — ●DAVID FISCHER¹, DARIUS HOFFMANN¹, and SANDRO WIMBERGER^{1,2,3} — ¹Institut für Theoretische Physik, Universität Heidelberg, 69120 Heidelberg, Germany — ²Dipartimento di Fisica e Scienze della Terra, Università degli Studi di Parma, Via G. P. Usberti 7/a, 43124 Parma — ³INFN, Sezione di Milano Bicocca, Gruppo Collegato di Parma, Italy

We study the spectral properties of simple Bose Hubbard models in two dimensions. Small finite size lattices are analyzed for different boundary conditions and different geometries. As we will show, the chosen geometry determines the level-spacing-statistics, which we investigate numerically for all symmetry-reduced subspaces of the Hamiltonian matrix. By comparison of both next-neighbor statistics and long-range spectral correlation functions with the predictions from Random-Matrix Theory (RMT), we find that most setups enjoy quantum chaotic behavior in a certain regime of parameters. This coincides with previous results for one-dimensional systems. Increasing the number of bonds in the lattice results in a smooth transition to a more regular behavior over the whole parameter range. Our spectral results allow us to control the systems' dynamics in a desired way by the choice of the specific form of the lattice and its bonds. Moreover, our investigations may enable further studies of quantum many-body chaos, which is becoming more and more relevant also for state-of-the-art experiments with ultracold bosons in optical lattices.

Q 46.4 Thu 11:45 e001

Quantum transport of ultra-cold bosons in optical lattices — ●URS WALDMANN^{1,2}, ALBERTO RODRIGUEZ¹, SANDRO WIMBERGER^{2,3}, and ANDREAS BUCHLEITNER¹ — ¹Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, 79104 Freiburg, Germany

— ²Dipartimento di Fisica e Scienze della Terra, Università degli Studi di Parma, 43124 Parma, Italy — ³INFN, Sezione di Milano Bicocca, Gruppo Collegato di Parma, Italy

We develop a theoretical framework for the description of experiments on quantum transport of ultra-cold bosons across one-dimensional lattices. We imagine a finite-length lattice connected to reservoirs, which we model by a single-band Bose-Hubbard Hamiltonian with a finite number of sites, connected to some input and output leads. We present first results (obtained by exact diagonalisation) on non-equilibrium dynamics on the closed chain, and on the particle current which can be induced by a finite coupling strength to the leads.

Q 46.5 Thu 12:00 e001

Bose-Einstein condensation in frustrated optical lattices — ●LUDWIG MATHEY¹, PETER JANZEN¹, and WEN-MIN HUANG² — ¹ZOQ/ILP, Universität Hamburg, Hamburg, Germany — ²National Chung-Hsing University, Taichung, Taiwan

We explore the critical behavior of Bose-Einstein condensation in frustrated lattices. In these lattices, an additional, chiral symmetry emerges, which is spontaneously broken at low temperatures. We discuss how this broken symmetry has been experimentally detected via interference of two independent chiral condensates. Furthermore, we present the critical behavior of these systems that are obtained within a renormalization group approach.

Q 46.6 Thu 12:15 e001

Interacting bosons on two-leg ladders in magnetic fields — ●SEBASTIAN GRESCHNER¹, MARIE PIRAUD², FABIAN HEIDRICH-MEISNER², ULRICH SCHOLLWÖCK², IAN MCCULLOCH³, and TEMO VEKUA¹ — ¹Institut für Theoretische Physik, Leibniz Universität Hannover, Germany — ²Arnold Sommerfeld Center for Theoretical Physics, Ludwig-Maximilians-Universität München — ³ARC Centre, University of Queensland

Ultra-cold bosons in ladders with an externally applied synthetic magnetic field exhibit a surprisingly rich physics and a wealth of quantum phases for different interaction strengths. In the regime of hardcore repulsive bosons we observe Meissner and vortex liquid phases both in the superfluid and in the Mott insulator regime [1]. For the case of moderate and weak interaction strengths [2] we show how additionally for certain commensurate vortex-densities vortex-lattice phases form and a superfluid phase with spontaneously imbalanced particle number between the legs of the ladder, the so-called biased leg phase, emerges. The vortex-lattice phases with a spontaneously broken translational symmetry may exhibit a characteristic and counter-intuitive many-body feature: At sufficiently low temperatures for weak interactions strengths the edge current may reverse its direction.

[1] M. Piraud, et al., Phys. Rev. B 91, 140406(R), 2015.

[2] S. Greschner, et al., Phys. Rev. Lett. 115, 190402, 2015.

Q 46.7 Thu 12:30 e001

Effects of multi-color intensity modulations on a 1D optical lattice — ●LORENZO CARDARELLI, SEBASTIAN GRESCHNER, and LUIS SANTOS — Institut für Theoretische Physik, Leibniz Universität Hannover, Appelstr. 2, DE-30167 Hannover, Germany

We study an effective model of a one-dimensional optical lattice loaded with bosonic particles of different spin components, in the presence of a multi-color modulation of the lattice intensity. The modulation opens interesting possibilities of control on the properties of the system, including effective controllable interactions without the need of Feshbach resonances and an effective two-body hard-core constraint. Furthermore, considering a ladder-like lattice in synthetic dimensions, modulation results in a hopping along the real direction (both in amplitude and in phase) that paves the way to the observation of density-dependent synthetic magnetism, along with the generation of inter-site interactions along the real direction without the need of dipolar interactions.

Q 47: Quantum Information: Quantum Computing and Communication I

Time: Thursday 11:00–13:00

Location: e214

Q 47.1 Thu 11:00 e214

Germanium vacancy centres and the "smart search" for perfect diamond qubits — ●LACHLAN J. ROGERS and FEDOR JELEZKO — Institute for Quantum Optics and IQST, Ulm University, Ulm, Germany

Colour centres in diamond are attractive qubit architectures, but the currently available candidates are not perfect. The nitrogen vacancy (NV) centre is famous as an optically addressable electron- and nuclear-spin qubit. However, the NV fluorescence spectrum exhibits a number of undesirable characteristics including a strong phonon sideband and, typically, spectral diffusion of the zero-phonon line (ZPL). More recently the related silicon vacancy (SiV) centre has been shown to have exceptional optical properties, but a fundamentally limited spin coherence time of only 40 ns.

While it is possible to search randomly for attractive spin properties among other reported colour centres, the development in understanding NV and SiV centres over the last decade has begun to enable a "smart search". Here we present germanium vacancy centres as an example of this process. There is a tantalising possibility that germanium vacancies could combine the excellent spin coherence properties of NV with the superb spectral properties of SiV, leading to an almost perfect diamond qubit.

Q 47.2 Thu 11:15 e214

Investigating spectral properties of Silicon-Vacancy centers in Nanodiamonds — ●ANDREA KURZ¹, LACHLAN J. ROGERS¹, DANIEL RUDNICKI², UWE JANTZEN¹, OU WANG¹, VALERY DAVYDOV³, VIATCHESLAV AGAFONOV⁴, ALEXANDER KUBANEK¹, and FEDOR JELEZKO¹ — ¹Institut fuer Quantenoptik, Universitaet Ulm, Deutschland — ²Institute of Physics, Jagiellonian University, Krakow, Poland — ³Institute for High Pressure Physics, Russian Academy of Science, Moscow, Russia — ⁴Greman, Universit F. Rabelais, Tours, France

Over the last decade color centers in diamond have proven to be good candidates for quantum optics applications. One of these color centers, the silicon-vacancy (SiV) center has shown exceptional spectral properties, with more than 70% of the emitted photons contributing

to its strong zero phonon line (ZPL). The strong, sharp and distinct ZPL transitions together with the weak sideband makes the SiV center a promising candidate for single photon generation.

These exceptional properties for centers in bulk are not necessarily preserved in Nanodiamonds (NDs). Even though the SiV fluoresces in NDs as small as 1.7nm, it is not yet known how the center is influenced by strain and the environment that starts to play a more important role at these sizes.

We investigate the properties of NDs grown by High Pressure and High temperature and correlate their size with their spectral behavior at cryogenic temperatures. We see the narrowest spectral lines measured so far in NDs with a width of 344 MHz.

Q 47.3 Thu 11:30 e214

Generation of Entangled Photon strings using Color centers in Diamond — ●DURGA B RAO DASARI^{1,2}, SEN YANG¹, and JÖRG WRACHTRUP^{1,2} — ¹3. Physikalisches Institut, Universität Stuttgart, Stuttgart — ²Max Planck Institute for Solid State Research, Stuttgart

Color centers in diamond make a robust quantum hybrid system comprising different species of quantum bits where, one kind couples strongly to the optical photons and the other has ultra long coherence times. While such hybrid devices can naturally be used as storage units for optical photons in a quantum network [1], they on the otherhand can also be used to mediate entanglement between subsequent photons with which the color center interacts [2].

In this talk I will present a scheme to generate entangled photons using nitrogen vacancy (NV) centers in diamond. We show how the long-lived nuclear spin in diamond can mediate entanglement between multiple photons, thereby increasing the length of the entangled photon string. With the proposed scheme one could generate both n-photon GHZ and cluster states. An experimental scheme realizing the same and estimates for the rate of entanglement generation both in the presence and absence of a cavity will also be shown.

[1]. Sen Yang et al. arXiv:1511.04939 [quant-ph]

[2]. D. D. Bhaktavatsala Rao et al. Phys. Rev. B 92, 081301(2015)(R)

Q 47.4 Thu 11:45 e214

High-rate source of Ca^+ -resonant heralded single photons — ●STEPHAN KUCERA, JAN ARENSKÖTTER, PASCAL EICH, MATTHIAS KREIS, PHILIPP MÜLLER, and JÜRGEN ESCHNER — Experimentalphysik, Universität des Saarlandes, Saarbrücken, Germany

We present a source of heralded single photons for quantum communication experiments with single trapped $^{40}\text{Ca}^+$ ions [1]. The photons are generated at 854 nm wavelength by cavity-enhanced spontaneous parametric down conversion in a doubly resonant bow-tie resonator. In 10 MHz cavity line-width we achieve a fiber-coupled brightness of $4 \cdot 10^4 / (\text{s} \cdot \text{mW})$ ion-resonant photons, about 500 times more than without resonator [2]. Compatibility with the ion resonance is demonstrated by correlation, coherence, and absorption measurements.

- [1] Kurz et al., Nat. Commun. **5**, 5527 (2014)
 [2] Piro et al., Nat. Phys. **7**, 17 (2011)

Q 47.5 Thu 12:00 e214

Programmable atom-photon quantum interface — ●PASCAL EICH, CHRISTOPH KURZ, MICHAEL SCHUG, PHILIPP MÜLLER, MATTHIAS KREIS, and JÜRGEN ESCHNER — Experimentalphysik, Universität des Saarlandes, Saarbrücken, Germany

We report on the implementation of a programmable atom-photon quantum interface, employing a single trapped $^{40}\text{Ca}^+$ ion and single photons. Depending on its mode of operation, the interface serves as a bi-directional atom-photon quantum-state converter [1,2], as a source of entangled atom-photon states, or as a quantum frequency converter of single photons. The interface lends itself particularly to interfacing ions with SPDC-based single-photon sources or entangled-photon-pair sources [3,4]. In the experimental procedure, we generate an initial superposition state in the meta-stable $D_{5/2}$ level of the ion, using a narrow-band laser at 729 nm. Upon the absorption of a single photon at 854 nm, the ion undergoes a Raman transition to its $S_{1/2}$ ground state, emitting a single photon at 393 nm. The coherent evolution from the initial to the final quantum state of atomic superposition and photon polarization is utilized for the interface protocol.

- [1] P. Müller, J. Eschner, Appl. Phys. B **114**, 303 (2014).
 [2] C. Kurz et al., Nat. Commun. **5**, 5527 (2014).
 [3] A. Lenhard et al., arXiv:1504.08303, to appear in Phys. Rev. A.
 [4] J. Brito et al., arXiv:1508.01029, to appear in Appl. Phys. B.

Q 47.6 Thu 12:15 e214

A single ion coupled to UV fiber-cavity — ●TIMOTHY BALLANCE^{1,2}, ASHWIN BODETTI¹, MATTHIAS STEINER⁴, HENDRIK M. MEYER¹, JAKOB REICHEL³, and MICHAEL KÖHL¹ — ¹Physikalisches Institut, Universität Bonn — ²Cavendish Laboratory, University of Cambridge — ³Laboratoire Kastler-Brossel, ENS Paris — ⁴Present Address: Centre for Quantum Technologies, National University of Singapore

We investigate a single trapped ion coupled to an optical fiber-cavity for use as a node in a quantum network. So far ions and fiber-cavities have been successfully combined in the infra-red spectral range. Since the strongest transitions in ions are within the ultra-violet, the extension of ion traps to work with UV fiber-cavities paves the way to larger coupling factors, which are of great interest for single photon production as well as for cavity based state detection. We will present our latest results on trapping Ytterbium ions inside approximately $150 \mu\text{m}$

long fiber-cavities, which are resonant with the $S_{1/2} - P_{1/2}$ electric dipole transition at 370 nm.

Q 47.7 Thu 12:30 e214

Microwave near-field control of $^9\text{Be}^+$ qubits in a surface-electrode ion trap — ●MARTINA WAHNSCHAFFE^{1,2}, HENNING HAHN^{1,2}, GIORGIO ZARANTONELLO^{1,2}, SEBASTIAN GRONDKOWSKI², TIMKO DUBIELZIG², AMADO BAUTISTA-SALVADOR^{1,2}, MATTHIAS KOHNEN^{1,2}, and CHRISTIAN OSPELKAUS^{1,2} — ¹QUEST Institute for Experimental Quantum Metrology, PTB, Bundesallee 100, D-38116 Braunschweig — ²Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, D-30167 Hannover

We describe experiments employing microwave near-fields from conductors embedded in a surface-electrode ion trap [1]. Our optimized trap geometry features a single conductor to induce all the required spin-motional couplings typically used in multi-qubit quantum operations [2]. We load $^9\text{Be}^+$ ions via two-photon ionization from an ablation plume created by single shots of a pulsed laser. Our experiment operates at 22.3 mT where the $|F=2, m_F=1\rangle$ and $|F=1, m_F=1\rangle$ states form a first-order field-independent qubit for long coherence times. We demonstrate initialization and control of the qubit. We perform a spatial characterization of the microwave near-field employing a modified Ramsey / echo sequence with a single ion as a local field probe and find good agreement with full-wave numerical simulations. Using the spatial variation of the microwave near-field, we demonstrate motional sideband transitions on our field-independent qubit as a basic prerequisite for entangling multi-qubit quantum logic gates.

- [1] C. Ospelkaus et al., Phys. Rev. Lett. **101**, 090502 (2008)
 [2] M. Carsjens et al., Appl. Phys. B **114**, 243 (2014)

Q 47.8 Thu 12:45 e214

Quantum Information Processing with Segmented Ion Traps — ●ULRICH POSCHINGER, THOMAS RUSTER, HENNING KAUFMANN, VIDYUT KAUSHAL, JONAS SCHULZ, CHRISTIAN SCHMIEGELOW, and FERDINAND SCHMIDT-KALER — QUANTUM, Universität Mainz

Segmented ion traps offer the possibility to scale up quantum information processing with trapped ion quantum bits via local coherent manipulation of small ion crystals and shuttling of ions within the trap structure. This enables novel schemes for quantum computing, simulation, communication and sensing. We briefly review the current state-of-the-art of the required technology and methods. Our approach to scalability requires ion shuttling operations which do not affect the fidelity of entangling gates. This in turn requires either slow operation times or a substantial control overhead [1,2]. We show how to circumvent this by carrying out entangling gates on radial motional modes of vibration, which are not excited throughout shuttling operations. Furthermore, we demonstrate how entangled ions in conjunction with shuttling operations can be used for sensing inhomogeneous magnetic fields, with nanometer resolution in position and pT field resolution. Finally, we show how shuttling operations can be harnessed to lock the ion position to an optical free-space standing wave [3], which allows for the realization of phase-controlled spin-dependent optical forces. Additional applications of this technique include precise mapping of electric trap potentials and improved addressing of qubit registers.

- [1] H. Kaufmann et al., NJP **16**, 073012 (2014) [2] T. Ruster et al., PRA **90**, 033410 (2014) [3] C. Schmiegelow et al., arXiv:1507.05207

Q 48: Ultra-cold atoms, ions and BEC III (with A)

Time: Thursday 11:00–13:00

Location: f107

Q 48.1 Thu 11:00 f107

Toolbox for tunable ion-ion interactions in a 2D surface trap — ●HENNING KALIS, FREDERICK HAKELBERG, MATTHIAS WITTEMER, MANUEL MIELENZ, ULRICH WARRING, and TOBIAS SCHAEZT — Physikalisches Institut, Albert-Ludwigs-Universität Freiburg

Geometrical frustration has turned out to be a mechanism for inducing exotic quantum disordered phases [1], whose dynamics can not be addressed efficiently on classical computers. To get around this difficulty we follow Feynman's approach of quantum simulations [2]. We chose a bottom up approach based on trapped $^{25}\text{Mg}^+$ ions [3]. Static and real-time control of the motional degrees of freedom has been demonstrated in a triangular surface trap with $80 \mu\text{m}$ inter-ion distance [4]. In our setup we have three distinct trap sites separated by $40 \mu\text{m}$,

arranged in an equilateral triangle. We report on different techniques for analysis of the motional mode orientations, that represent the key ingredient for a tunable ion-ion interaction.

- [1] Moessner, R. & Sondhi, S. L, Phys. Rev. B **63**, 224401 (2001).
 [2] R.P. Feynman, Int. J. Theor. Phys., Vol **21**, Nos. 6/7, (1982).
 [3] Schaezt et al., New J. Phys. **15**, 085009 (2013).
 [4] Mielenz et. al., In Preperation

Q 48.2 Thu 11:15 f107

Purity oscillations in Bose-Einstein condensates with balanced gain and loss — DENNIS DAST, DANIEL HAAG, ●HOLGER CARTARIUS, and GÜNTER WUNNER — 1. Institut für Theoretische Physik, Universität Stuttgart, 70550 Stuttgart, Germany

We present a new generic feature of \mathcal{PT} -symmetric Bose-Einstein condensates by studying the many-particle description of a two-mode condensate with balanced gain and loss. This is achieved using a master equation in Lindblad form whose mean-field limit is a \mathcal{PT} -symmetric Gross-Pitaevskii equation. It is shown that the purity of the condensate's single-particle density matrix periodically drops to small values but then is nearly completely restored. This indicates that during the oscillations the particles leave the single-particle orbital of the condensed phase and return afterwards to an almost perfect mean-field state. We show that this has a direct impact on the average contrast in interference experiments which periodically vanishes and recurs.

Q 48.3 Thu 11:30 f107

Local Ionization of Ultracold Gases by Femtosecond Laser Pulses — ●BERNHARD RUFF^{1,3}, PHILIPP WESSELS^{1,2}, JULIETTE SIMONET^{1,2}, KLAUS SENGSTOCK^{1,2}, and MARKUS DRESCHER^{1,3} — ¹The Hamburg Centre for Ultrafast Imaging, Hamburg, Germany — ²Zentrum für Optische Quantentechnologien, Hamburg, Germany — ³Institut für Experimentalphysik, Hamburg, Germany

The combination of ultracold atomic systems and ultrafast laser pulses promises insight into the coherence properties of macroscopic dissipative quantum systems and enables the preparation of hybrid quantum systems through local ionization of atoms in strong laser fields.

We report on the investigation of ultracold ⁸⁷Rb gas exposed to femtosecond laser pulses at 515 nm wavelength and 290 fs pulse duration. The light pulses ionize atoms of the atomic cloud within the focus region (7 μ m waist) of the beam via two-photon absorption. The number of ions generated can be controlled by tuning the intensity or the wavelength of the laser pulses. The remaining atoms are detected by resonant absorption imaging either in situ or after time of flight.

Atomic losses evident as a hole in the trapped cloud are evaluated and show a non-linear increase with respect to the pulse energy corroborating the generation of ions in a multiphoton process. Additionally results on the relaxation dynamics of thermal clouds and condensates after exposure to a single pulse will be discussed as well as further perspectives on the detection of charged fragments.

Q 48.4 Thu 11:45 f107

Measurements of spectral functions of ultra-cold atoms in a speckle potential — ●VINCENT DENECHAUD, VALENTIN VOLCHKOV, MUKHTAR MUSAWWADAH, JÉRÉMIE RICHARD, ALAIN ASPECT, and VINCENT JOSSE — Laboratoire Charles Fabry - Institut d'Optique, Palaiseau, France

We present a spectroscopic study of ultra-cold atomic states in a disordered potential created by a laser speckle. Atoms are first prepared in a spin state which is insensitive to disorder. In a second step, a radio-frequency spin-flip towards a disorder-sensitive spin state is performed. The transfer rate $A(E, k)$ of such operation is referred to as spectral function, which correspond to the probability of populate an atomic state with a momentum k and an energy E within the disorder [1].

Measurements of such spectral function for various disorder configurations will be presented and discussed. We will highlight two kinds of regimes : the so-called "classical" disorder where the atomic states are shaped by the fluctuations of the random potential, and the "quantum" disorder where the states are dominated by tunnelling effects. We will also explore peculiar features of spectral functions for a repulsive or an attractive speckle potential.

In principle, the spin-flip transfer allows us to create states with narrow energy distributions within the disorder. This paves the way to a precise study of the metal/insulator Anderson phase transition [2].

- [1] M.I. Trappe et al, J.Phys.A: Math.Theor.48, 245102 (2015)
[2] A.Lagendijk et al, Physics Today, 62, 24 (2009)

Q 48.5 Thu 12:00 f107

Dynamics of strongly correlated fermions—first principle results for two and three dimensions — ●NICLAS SCHLÜNZEN, SEBASTIAN HERMANN, JAN-PHILIP JOOST, and MICHAEL BONITZ — CAU Kiel, Germany

Quantum transport of strongly correlated fermions is of central interest in condensed matter physics. While the stationary expansion dynamics have recently been measured with cold atoms in two-dimensional (2D) optical lattices [1], ab initio simulations have been limited, so far, to 1D setups. Using the nonequilibrium Green functions method with the T -matrix approximation [2,3], it becomes possible to precisely predict the fermionic quantum dynamics for 2D and 3D [4]. The simulations give access to the short-time dynamics, including the spatially

resolved build-up of correlations, as well as the long-time limit of the expansion. The latter is investigated concerning the differences between 1D, 2D and 3D and the dependence of the expansion velocity on the particle number N , for which a universal scaling is discovered. These predictions can be verified experimentally using the recently developed fermionic atom microscopes.

- [1] U. Schneider et al., Nat. Phys. **8**, 213 (2012)
[2] K. Balzer and M. Bonitz, *NEGF Approach to Inhomogeneous Systems*, Lecture Notes in Physics (Springer, 2013)
[3] M. P. von Friesen et al., Phys. Rev. B **82**, 155108 (2010)
[4] N. Schlünzen, S. Hermanns, M. Bonitz, and C. Verdozzi, arXiv:1508.02947 (2015)

Q 48.6 Thu 12:15 f107

A High-Speed Single Ion Beam Source using a Cold Atom Beam and Rydberg Blockade — ●BENJAMIN SPARKES, RICHARD TAYLOR, DENE MURPHY, RORY SPEIRS, DAN THOMPSON, JOSHUA TORRANCO, ANDREW MCCULLOCH, and ROBERT SCHOLTEN — School of Physics, University of Melbourne, Melbourne, Australia

We propose a novel single ion source based on Rydberg excitation from a cold atom beam. This source will have the ability to place ions into target surfaces with high precision due to their low temperature, allowing for the possibility of new types of nanofabricated devices and processes in material sciences. For instance, it could be used for ion implantation in solid-state quantum computers, as well as for high-resolution ion microscopy and lithography. The ideal single ion source would be fast, precise and fully deterministic, but current technologies are either slow or stochastic. Combining our second generation cold atom-beam based ion source with the phenomena of Rydberg blockade and stimulated Raman adiabatic passage (STIRAP) will allow us to overcome these issues to create a source that is fast, heralded and quasi-deterministic.

We will present simulations of the proposed single ion beam source as well as our latest experimental results demonstrating high-efficiency excitation using STIRAP in our MOT-based cold atom electron and ion source, with a total efficiency of 60% (peak efficiency of 80%).

Q 48.7 Thu 12:30 f107

Topological bands in cold gases — ●SEBASTIAN WEBER, DAVID PETER, and HANS PETER BÜCHLER — Institute for Theoretical Physics III, University of Stuttgart, 70550 Stuttgart, Germany

Topological band structures are the basis for interesting phenomena like integer and fractional topological insulators that are of high research interest. Recently it has been demonstrated that topological bands characterized by a Chern number can be realized with dipolar exchange interaction [1].

We present a proposal for the implementation of this idea using Rydberg atoms. We analyze finite geometries and investigate the appearance of edge states as a signature of topological bands. In particular, we search for minimal systems that show experimentally accessible edge states.

We study the robustness of edge states to lattice defects. Remarkably, it turns out that their stability allows the realization of interesting systems in optical lattices with slight imperfections. We can increase the robustness further if we use cutoff potentials that suppress the interaction on small length scales. This method paves the way for a novel continuum model that exhibits topological bands.

- [1] D. Peter et al., *Topological flat bands with Chern number $C = 2$ by dipolar exchange interactions*, Phys. Rev. A **91**, 053617 (2015)

Q 48.8 Thu 12:45 f107

Satellite-borne quantum test of the weak equivalence principle — ●NACEUR GAALLOUL, CHRISTIAN SCHUBERT, SINA LORIANI, WOLFGANG ERTMER, and ERNST MARIA RASEL — Leibniz University of Hanover, Germany

The high sensitivity of atom interferometer sensors makes it a promising tool for performing tests of fundamental theories. One timely challenge is to experimentally bound an eventual violation of the weak equivalence principle (WEP), a corner stone of General Relativity, by tracking the trajectories of two different atomic species in free fall. When operating on a satellite, the interferometry time of few seconds would allow to target an inaccuracy of 10^{-15} in differential acceleration between two atomic ensembles of different masses. In this presentation, we present the principle of such a measurement based on the use of a degenerate mixture of potassium and rubidium atoms. Several experimental arrangements have to be made in order to tackle a space operation and mitigate for significant systematic effects. This concept

is proposed as a medium-size mission in the frame of the Cosmic Vision | program of the European Space Agency.

Q 49: Optomechanics I

Time: Thursday 11:00–13:00

Location: f342

Q 49.1 Thu 11:00 f342

Ro-Translational Cavity Cooling of Dielectric Needles and Discs — ●BENJAMIN A. STICKLER¹, LUKAS MARTINETZ¹, STEFAN NIMMRICHTER¹, STEFAN KUHN², MARKUS ARNDT², and KLAUS HORNBERGER¹ — ¹Faculty of Physics, University of Duisburg-Essen, Lotharstraße 1, 47048 Duisburg, Germany — ²Faculty of Physics, VCQ, University of Vienna, Boltzmanngasse 5, 1090 Vienna, Austria

Motivated by recent experiments [1] demonstrating optical manipulation of thin silicon nanorods, we investigate the interaction between dielectric needles or discs and the laser field of a high finesse cavity. We show that such anisotropic nanoparticles can be captured from free flight, at velocities much higher than those required to trap dielectric spheres, and that ro-translational cavity cooling should be achievable. We discuss potential applications of these systems for high mass quantum interference experiments as well as for ro-translational cavity optomechanics.

[1] S. Kuhn, P. Asenbaum, A. Kosloff, M. Sclafani, B.A. Stickler, S. Nimmrichter, K. Hornberger, O. Cheshnovsky, F. Patolsky, and M. Arndt, *Nano Lett.* 15, 5604 (2015).

Q 49.2 Thu 11:15 f342

Feedback Cooling of a Si₃N₄ membrane inside a cryogenic Fiber-Fabry-Pérot cavity — ●PHILIPP CHRISTOPH¹, TOBIAS WAGNER¹, CHRISTINA STAARMANN¹, ANDREAS BICK¹, KLAUS SENGSTOCK¹, CHRISTOPH BECKER¹, HAI ZHONG², ALEXANDER SCHWARZ², and ROLAND WIESENDANGER² — ¹Center for Optical Quantum Technologies, Hamburg, Germany — ²Institute for Applied Physics, Hamburg, Germany

In this talk we present our progress towards a new quantum hybrid system, which aims at coupling ultracold atoms to an ultra-high-Q Si₃N₄ membrane oscillator inside a cryogenic Fiber-Fabry-Pérot cavity. Our approach promises to open new avenues for the manipulation, preparation and detection of the mechanical oscillator.

As an excellent starting point to reach the ground state of the membrane motion we cryogenically cool the membrane-in-the-middle system to a base temperature of 480mK. For further cooling we track the motion of the membrane through balanced homodyne detection and apply a velocity dependent feedback. We observe a substantial further reduction of the fundamental mode temperature, which marks an important step towards the ground state.

This work is supported by the DFG grants no. BE 4793/2-1 and SE 717/9-1.

Q 49.3 Thu 11:30 f342

Optical trapping and control of nanoparticles inside hollow core photonic crystal fibers — ●DAVID GRASS, JULIAN FESEL, NIKOLAI KIESEL, and MARKUS ASPELMAYER — University of Vienna

Optical levitation of nano-particles has attracted significant attention as ultra-high Q mechanical oscillators for room temperature quantum optomechanics, stochastic thermodynamics and force sensing applications. We report an optical conveyor belt for the transport of levitated nano-particles over several centimeters in air or vacuum inside a hollow-core photonic crystal fiber. Detection of the transmitted light field allows three-dimensional read-out of the particles' center of mass motion. An additional laser enables 1-dimensional radiation pressure based feedback cooling over the whole fiber length. Based on the particle motion we characterize the optical intensity distribution inside the HCPCF and measure the local pressure along the fiber when a pressure gradient is applied. A targeted application is the clean and controlled delivery of nanoparticles into a high-finesse optical cavity for levitated cavity optomechanics.

Q 49.4 Thu 11:45 f342

A Hybrid Quantum Architecture Consisting of a Diamond Mechanical Oscillator and Embedded Spins — ●SEYED ALI MOMENZADEH¹, MARCUS W. DOHERTY², FELIPE FAVARO DE OLIVEIRA¹, PHILIPP NEUMANN¹, ANDREJ DENISENKO¹, DURGA B RAO DASARI^{1,3}, and JÖRG WRACHTRUP^{1,3} — ¹3. Physikalisches In-

stitut, Universität Stuttgart, Stuttgart — ²Laser Physics Centre, Research School of Physics and Engineering, Australian National University, Australian Capital Territory 0200, Australia — ³Max Planck Institute for Solid State Research, Stuttgart

Quantum hybrid systems are promising for futuristic quantum technologies [1]. Among others, color centers in diamond, namely nitrogen vacancy centers (NVs), coupled to their mechanical degrees of freedom [2-4] form such a hybrid device. With robust control of the spin properties of the NVs and their coupling to the mechanical modes, they can be used for sensing experiments at the nanoscale and also for scalable quantum information processing. In this talk, I will present our recent progress on the design and fabrication of such hybrid devices. To further demonstrate the robustness of the device, we show how the spin readout could be done through mechanical motion and vice versa.

[1] G. Kurizki et al. *PNAS* 2015, 112, 3866-3873

[2] A. Barfuss et al. *Nat. Phys.* 2015, 11, 820-824

[3] E. R. MacQuarrie et al. *Phys. Rev. Lett.* 2013, 111, 227602

[4] L. M. D. Lepinay et al. *arXiv:1503.03200v1 [quant-ph]*

Q 49.5 Thu 12:00 f342

Light scattering in hybrid optomechanical systems — ●LUIGI GIANNELLI¹, MARC BIENERT^{1,2}, and GIOVANNA MORIGI¹ — ¹Theoretische Physik, Universität des Saarlandes, 66123 Saarbrücken, Germany — ²Hohenzollern Gymnasium, 72488 Sigmaringen, Germany

Nitrogen-vacancy (NV) centers in Diamond are a promising platform for quantum technological realizations. We investigate hybrid quantum systems based on a NV-center coupled to a vibrating structure which is also a light resonator (cavity). The NV center interacts with the strain field associated to a high Q vibrational mode of the structure and with the cavity photon field. The mechanical resonator and the cavity also interact via radiation pressure coupling. We discuss the cooling dynamics of the mechanical resonator in these settings. The cooling regime, the stationary temperatures, the cooling rate, and the resonance fluorescence spectrum are theoretically evaluated. The features associated with the cooling dynamics are identified in the spectrum of resonance fluorescence.

Q 49.6 Thu 12:15 f342

Position-Squared Coupling in a Tunable Optomechanical Cavity — ●TAOFIQ PARAISSO¹, MAHMOUD KALAEI³, LEYUN ZANG¹, HANNES PFEIFER¹, FLORIAN MARQUARDT², and OSKAR PAINTER³ — ¹MPI for the Science of Light, Germany — ²FAU Erlangen-Nürnberg, Germany — ³Caltech, Pasadena, CA, USA

Position-squared optomechanical coupling has been proposed as a means of performing the long-sought-after continuous quantum non-demolition (QND) measurements of a mechanical field. The stored energy in a mechanical resonator, proportional to its average squared displacement (x^2), can be used to infer quantum jumps of photons or phonons. Despite significant technical advances made in recent years, achieving a x^2 coupling large enough for preparing non-classical quantum states of mesoscopic mechanical resonators remains an open challenge. Here we demonstrate giant x^2 coupling in a multimoded optomechanical resonator [1]. The device is a double-slotted quasi-2D photonic crystal cavity supporting a pair of optical resonances that both couple to the motion of the structure. Integrated capacitors are used to drive the system from the linear regime into the x^2 coupling regime and to tune the optical normal mode splitting to arbitrarily small values. From independent measurements of the avoided crossing of the optical modes and of the static and dynamical spring effects, we measure a vacuum x^2 coupling rate up to 5 orders of magnitudes larger than in conventional systems. We anticipate these novel platforms to enable the demonstration of quantum nonlinearities in optomechanics.

[1] T. Paraiso et al., *Phys. Rev. X* 5, 041024 (2015)

Q 49.7 Thu 12:30 f342

Phononic bandgap membranes for high quantum cooperativity optomechanics — YEGHISHE TSATURYAN, ANDREAS BARG, WILLIAM NIELSEN, CHRISTOFFER MOLLER, EUGENE POLZIK, and

•ALBERT SCHLIESSER — Niels Bohr Institute, Copenhagen, Denmark

We combine an engineered phononic density of states with stress-induced mechanical dissipation dilution to obtain nanomechanical membrane resonators with Qf -products exceeding $k_B T/h$ already at room temperature. At moderate (^4He) cryogenic temperatures, these devices feature quantum cooperativities well above unity when combined with a compact Fabry-Perot resonator, enabling the observation of quantum backaction, optomechanical light squeezing and preparation of the quantum ground state with high probability ($\bar{n} \lesssim 1$). In addition, the intrinsic multi-mode nature of the Fabry-Perot cavity, and the relatively open access to the membrane lend itself to multi-mode entanglement and quantum coherent conversion schemes both in the optical-optical and electro-optical domains.

Q 49.8 Thu 12:45 f342

Optimizing electro-optomechanical transduction using equivalent circuits — •EMIL ZEUTHEN¹, ALBERT SCHLIESSER¹, JACOB M. TAYLOR², and ANDERS S. SØRENSEN¹ — ¹Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark — ²Joint Quantum Institute & Joint Center for Quantum Information and Computer Science, National Institute of Standards and Technology and the

University of Maryland, College Park, Maryland 20742 USA

A mechanical oscillator can serve as an efficient link between electromagnetic modes of different frequencies. We find that such a transducer can be characterized by two key parameters, the signal transfer efficiency and added noise temperature. In terms of these, we evaluate its performance in various tasks ranging from classical signal detection to quantum state conversion between, e.g., superconducting circuitry and traveling optical signals. Having established the requirements for efficient performance, we turn to the question of optimization. We address this by developing a unifying equivalent-circuit formalism for electro-optomechanical transducers. This approach accommodates arbitrary linear circuits and integrates the novel optomechanical transduction functionality into the well-established framework of electrical engineering, thereby facilitating its implementation in potential applications such as nuclear magnetic resonance imaging and radio astronomy. We consider such optomechanical sensing of weak electrical signals and discuss how the equivalent circuit formalism can be used to optimize the electrical circuit design. We also discuss the parameter requirements for transducing microwave photons in the quantum regime.

Q 50: Precision spectroscopy of atoms and ions II (with A)

Time: Thursday 11:00–13:00

Location: f428

Invited Talk

Q 50.1 Thu 11:00 f428

The magnetic moment of the antiproton — •STEFAN SELLNER¹, KLAUS BLAUM², MATTHIAS BORCHERT³, TAKASHI HIGUCHI^{1,4}, NATHAN LEEFER⁵, YASUYUKI MATSUDA⁴, ANDREAS MOOSER¹, HIROKI NAGAHAMA^{1,4}, CHRISTIAN OSPELKAUS³, WOLFGANG QUINT⁶, GEORG SCHNEIDER⁷, CHRISTIAN SMORRA^{1,8}, TOYA TANAKA⁴, JOCHEN WALZ^{5,7}, YASUNORI YAMAZAKI⁹, and STEFAN ULMER¹ — ¹Ulmer Initiative Research Unit, RIKEN, Wako, Japan — ²Max-Planck-Institut für Kernphysik, Heidelberg, Germany — ³Institut für Quantenoptik, Leibniz Universität Hannover, Hannover, Germany — ⁴Graduate School of Arts and Sciences, University of Tokyo, Tokyo, Japan — ⁵Helmholtz-Institut Mainz, Mainz, Germany — ⁶GSI-Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany — ⁷Institut für Physik, Johannes Gutenberg-Universität Mainz, Mainz, Germany — ⁸CERN, Geneva, Switzerland — ⁹Atomic Physics Laboratory, RIKEN, Wako, Japan

The Standard Model describes the fundamental interactions and properties of elementary particles. Being a Lorentz-invariant theory, the absolute values of the properties like charge, mass, and magnetic moment, of matter and antimatter-conjugates, are invariant under the combined charge, parity, and time transformation. Any violation of this CPT symmetry would indicate new physics. The BASE experiment tests this symmetry at lowest energy and with highest precision. We use an advanced multi-Penning trap system to compare charge-to-mass ratios and magnetic moments of single protons and antiprotons, respectively.

Our aimed relative precision is 1 ppb (10^{-9}) for the magnetic moment measurement. Last year, we succeeded in measuring the charge-to-mass ratio of the antiproton and the proton [1], confirming CPT invariance down to the atto-electron volt scale with a measurement precision of 69 parts per trillion. Next, we will focus on magnetic moment measurements.

In my talk, I will present the techniques and recent results of our measurements at BASE and give an outlook on future improvements.

[1] S. Ulmer et al, Nature 524, p. 196-199 (2015)

Q 50.2 Thu 11:30 f428

RIS studies of high-lying energy levels in erbium for the determination of the first ionization potential — •DOMINIK STUDER¹, PATRICK DYRAUF¹, PASCAL NAUBEREIT¹, MATSUI DAIKI², and KLAUS WENDT¹ — ¹Institute of Physics, Johannes Gutenberg-University Mainz — ²Department of Physics, Nagoya University

For most lanthanides, the extremely rich atomic spectrum is not completely known and proper level identification is still a challenge. Theoretical approaches are often incapable to deconvolute the stuffed structures, as obtained from atomic spectroscopy in particular for higher excitation energies, due to missing level assignments. In addition, precise and meaningful experimental data is still lacking in that range.

Correspondingly, the ionization potentials of a number of lanthanide elements were determined with an insufficient precision of a few cm^{-1} . Here, we report on two-step resonance ionization spectroscopy in the spectrum of erbium. The accurate measurement of energy positions of a multitude of high-lying Rydberg-states in the range of principal quantum number $15 < n < 60$ was performed. To account for perturbations of the observed Rydberg-series from interloper states, an extension of the conventional Rydberg-Ritz formalism is required for a correct description of the observed s, d and g series. It allows for a determination of the ionization potential with a precision of better than $0,1 \text{ cm}^{-1}$. This talk presents the spectroscopic data and discusses the analysis of the Rydberg-series comparing two different approaches for the evaluation of perturbed Rydberg-series.

Q 50.3 Thu 11:45 f428

Laser spectroscopy of the element Nobelium — •FELIX LAUTENSCHLÄGER FOR THE RADRIIS COLLABORATION — Technische Universität Darmstadt

Laser spectroscopy is one of the most powerful tools to investigate the atomic properties of transfermium elements ($Z \geq 100$). In particular, finding atomic levels in such elements allows to benchmark theoretical predictions and to understand the influence of relativistic- and QED-effects on their shell structure. To this end, we employ the Radiation Detected Resonance Ionisation Spectroscopy (RADRIIS) [1].

The latter method is well suited to reveal the atomic properties of such elements, which can be only artificially produced in a complete fusion reaction at on-line facilities such as GSI in Darmstadt.

In my talk I will introduce this technique and report on laser spectroscopy of the element nobelium ($Z=102$).

[1]: H.Backe et al., Eur. Phys. J. D 45, 99-106 (2007).

Q 50.4 Thu 12:00 f428

Mass measurements of neutron-rich copper isotopes and technical developments at ISOLTRAP — •ANDREE WELKER¹ and ISOLTRAP COLLABORATION² — ¹Institut für Kern- und Teilchenphysik, Technische Universität Dresden, 01069 Dresden, Germany — ²CERN

We present very recent results from ISOLTRAP [1] measurements of neutron rich copper isotopes, where - with the help of the multi-reflection time-of-flight mass spectrometer (MR-ToF) [2] - ^{79}Cu was reached for the first time. With the gained knowledge of the copper binding energies, which are a really sensitive probe for the evolution of shell structure, we are only one proton above the $Z = 28$ core, close to the doubly-magic ^{78}Ni isotope. These measurements belong to an extended ISOLTRAP campaign on very neutron-rich nuclides for nuclear-structure and astrophysical cases. To be able to reach out even further exotic nuclides at very high precision, a position-sensitive ion detector

was installed behind the precision Penning trap. This major step will allow the application of the Phase-Imaging Ion-Cyclotron-Resonance (PI-ICR) [3] method, which was developed at SHIPTRAP/GSI. The new technique offers higher precision in less measurement time as well as a much higher resolving power, and thus the ability to resolve low-lying isomers, compared to the present Time-of-Flight Ion-Cyclotron-Resonance (ToF-ICR) technique [4]. The current status and an outlook on the implementation of the PI-ICR technique at ISOLTRAP will be presented.

Q 50.5 Thu 12:15 f428

The high-precision Penning-trap mass spectrometer PENTATRAP — ●ALEXANDER RISCHKA¹, HENDRIK BEKKER¹, CHRISTINE BÖHM¹, JOSÉ RAMÓN CRESPO LÓPEZ-URRUTIA¹, ANDREAS DÖRR¹, SERGEY ELISEEV¹, MIKHAIL GONCHAROV¹, PAVEL FILIANIN¹, YURI NOVIKOV², RIMA SCHÜSSLER^{1,3}, SVEN STURM¹, STEFAN ULMER⁴, and KLAUS BLAUM¹ — ¹Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany — ²Petersburg Nuclear Physics Institute, 188300 Gatchina, Russia — ³Universität Heidelberg, Fakultät für Physik und Astronomie, 69120 Heidelberg, Germany — ⁴RIKEN, Ulmer Initiative Research Unit, Japan

The Penning-trap mass spectrometer PENTATRAP is currently in the commissioning phase at the Max-Planck-Institute for Nuclear Physics in Heidelberg. We are aiming at measurements of mass ratios using highly charged ions with a relative uncertainty of better than 10^{-11} . This allows, among others, contributions to neutrino physics research by a sub-eV measurement of the Q -value of $^{163}\text{Ho}/^{163}\text{Dy}$. Furthermore, for a precision test of the energy-mass equivalence $E = mc^2$ and thus of special relativity, the Q -value of $^{35}\text{Cl}/^{36}\text{Cl}$ and the sum of energies of the gamma-rays emitted after the neutron capture in ^{35}Cl are needed. Former one will be measured at PENTATRAP and the latter one at ILL Grenoble. To reach trapping times of weeks for the highly charged ions and to perform a full characterization of the Penning-trap system in order to start first precision measurements, a major revision of the cryogenic setup and the ion transfer beamline is presently prepared and will be commissioned soon.

Q 50.6 Thu 12:30 f428

A large array of microcalorimeters for high-precision X-ray spectroscopy — ●PASCAL SCHOLZ¹, VICTOR ANDRIANOV², and SASKIA KRAFT-BERMUTH¹ — ¹Justus-Liebig-Universität, Gießen,

Germany — ²Lomonosov Moscow State University, Moscow, Russia

High-precision X-ray spectroscopy of highly-charged heavy ions, commonly performed at storage rings, provides a sensitive test of quantum electrodynamics. Silicon microcalorimeters, which detect the X-ray energy as heat rather than by charge production, have already demonstrated their potential to improve the precision of such experiments due to their excellent energy resolution for X-ray energies around 100 keV.

To improve their performance with respect to statistical as well as systematic uncertainties, a large array of silicon microcalorimeters for high-precision X-ray spectroscopy, especially optimized for experiments at storage rings, has now been designed. With an active area of about 100 mm^2 , it will be the largest microcalorimeter array currently available for storage ring experiments. In addition, the large dynamic range will allow the intrinsic determination of the Doppler correction, which is a prominent source of systematic uncertainty in such experiments. The presentation will introduce the detection principle, present the new detector design as well as first tests of performance, and discuss potential applications.

Q 50.7 Thu 12:45 f428

Precise high voltage measurements based on laser spectroscopy — ●KRISTIAN KÖNIG, PHILLIP IMGAM, JÖRG KRÄMER, BERNHARD MAASS, TIM RATAJCZYK, JOHANNES ULLMANN, and WILFRIED NÖRTERSCHÄUSER — Institut für Kernphysik, TU Darmstadt

The ALIVE experiment at the TU Darmstadt is a new collinear laser spectroscopy setup. The goal of the experiment is the measurement of high voltages in the range of 10 to 100 kV using precise laser spectroscopy of ions with a well-known transition frequency [1]. The aim is to achieve a precision of at least 1 ppm, which is of interest for many applications.

The setup consists of an ion source that provides $^{40}\text{Ca}^+$ ions and an acceleration region between two chambers of which one is equipped with a fluorescence detection. The well-known $4s_{1/2} \rightarrow 4p_{3/2}$ and the $3d_{3/2} \rightarrow 4p_{3/2}$ transitions are used to identify the ion velocities before and after acceleration based on the Doppler shift as proposed in [2]. In order to obtain the targeted accuracy, precise control and knowledge of the ion beam properties is required. We present the current status of the experiment.

[1] O. Poulsen, Nucl. Instr. Meth. Phys. Res. 202 (1982) 503.

[2] S. Götze, et al., Rev. Sci. Instrum. 75 (2004) 1039.

Q 51: Quantum Effects: QED I

Time: Thursday 11:00–13:00

Location: f442

Q 51.1 Thu 11:00 f442

Prefactor in the dynamically assisted Sauter-Schwinger effect — ●CHRISTIAN SCHNEIDER and RALF SCHÜTZHOLD — Universität Duisburg-Essen

The dynamically assisted Sauter-Schwinger effect exhibits significant, qualitative differences between, for example, a Sauter pulse $1/\cosh(\omega t)^2$ and a Gaussian $\exp(-\omega^2 t^2)$ [1]. So far, only the exponent of the pair creation rate has been calculated, these results are now extended to include the subleading fluctuation prefactor.

Additionally, possible influences of spatial inhomogeneities are discussed. For example, a longitudinal spatial dependence modifies the exponent of the pair production probability [2], while a transversal dependence only affects the prefactor.

[1] M. F. Linder, C. Schneider, J. Sicking, N. Szpak, and R. Schützhold. *Phys. Rev. D* **92**, 85009 (2015).

[2] C. Schneider and R. Schützhold, arXiv:1407.3584 [hep-th]

Q 51.2 Thu 11:15 f442

WKB-like approach to Sauter-Schwinger pair production in spacetime-dependent fields — ●JOHANNES OERTEL and RALF SCHÜTZHOLD — Universität Duisburg-Essen

A well-known method for calculating an approximation to the pair creation rate in the Sauter-Schwinger effect is based on approximating solutions of the Riccati equation. Although several interesting field configurations can be examined in this formalism (see e.g. [1]), its application is fundamentally restricted to the case of solely time-dependent electromagnetic fields. We propose a new WKB-like technique for approximating the pair creation rate in the presence of spacetime-

dependent fields.

[1] M. F. Linder et al., *Phys. Rev. D* **92**, 085009 (2015)

Q 51.3 Thu 11:30 f442

Simulating the Dirac equation in spacetime-dependent electric fields in band insulators — ●MALTE F. LINDER and RALF SCHÜTZHOLD — Fakultät für Physik, Universität Duisburg-Essen, Lotharstr. 1, 47057 Duisburg, Germany

The relativistic and quantum-theoretic description of electrons and positrons via the Dirac equation gives rise to many interesting phenomena. One prominent example is the Sauter-Schwinger effect, which is the nonperturbative pair creation in strong classical electric fields. However, this high-energy quantum effect is difficult to observe experimentally due to the largeness of the critical field strength $E_S \approx 10^{18}\text{ V/m}$. Analogs of the Dirac equation can be found in condensed matter physics such as in band and Mott insulators, for example. These systems are well accessible in the laboratory and typically exhibit critical field strengths for the Sauter-Schwinger effect (one mechanism of dielectric breakdown) much smaller than E_S . In this talk, we derive a 1+1-dimensional analog of the Dirac equation for conduction electrons in a band insulator from the underlying (nonrelativistic) physics. We especially point out in how far the (quantitative) analogy holds if the external electric field depends on time as well as on the space coordinate in a nontrivial way.

Q 51.4 Thu 11:45 f442

The classical-quantum transition in the theory of free-electron lasers — ●PETER KLING^{1,2}, ENNO GIESE², RAINER

ENDRICH², ROLAND SAUERBREY¹, and WOLFGANG P. SCHLEICH^{2,3} — ¹Helmholtz-Zentrum Dresden-Rossendorf, D-01314 Dresden — ²Universität Ulm, D-89069 Ulm — ³Texas A & M University, College Station, Texas 77843, USA

The free-electron laser (FEL) is the best known example for a ‘Classical Laser’ [1]. However, there exists a regime where quantum mechanics is relevant and at some point even dominates the dynamics [2,3]. In this talk we pursue the goal to calculate the corrections to the classical FEL when quantum effects start to become perceivable.

Employing the formalism of the Wigner distribution function we find the quantum corrections to the gain of the FEL in the low-gain, small-signal regime. We demonstrate that these corrections scale with powers of the quantum mechanical recoil the electron experiences when it scatters off the photons of the wiggler and the laser field. Moreover, the width of the initial momentum distribution of the electron has to be small enough to ensure for quantum corrections to be visible.

- [1] M. Borenstein and W. E. Lamb, *Phys. Rev. A* **5**, 1298–1311 (1972).
- [2] R. Bonifacio, N. Piovello and G. R. M. Robb, *Fortschr. Phys.* **57**, 1041–1051 (2009).
- [3] P. Kling, E. Giese, R. Endrich, P. Preiss, R. Sauerbrey and W. P. Schleich; accepted for *New J. Phys.* (Oct. 2015).

Q 51.5 Thu 12:00 f442

stopping x-ray pulses in a thin-film cavity — ●XIANGJIN KONG and ADRIANA PÁLFFY — Max Planck Institute for Nuclear Physics, Saupfercheckweg 1, D-69117 Heidelberg, Germany

Recent years have witnessed the commissioning of coherent x-ray sources opening the new field of x-ray quantum optics [1]. While not yet as advanced as its optical counterpart, x-ray quantum optics may enable coherent control of x-rays, with potential applications for the fields of metrology, material science, quantum information, biology and chemistry. The desirable properties of x-rays are deeper penetration, better focus, no longer limited by an inconvenient diffraction limit as for optical photons, correspondingly spatial resolution, robustness, and the large momentum transfer they may produce. A promising platform for x-ray control are thin-film planar x-ray cavities [2] with embedded layers containing nuclei with a transition resonant to the x-ray pulse.

Here, we demonstrate from the theory side that a spectrally narrow x-ray pulse can be mapped and stored as nuclear coherence through a mechanism reminding of electromagnetically induced transparency in a thin film planar x-ray cavity. The storage time can reach approximate hundred nanoseconds [3]. We anticipate this setup can become a versatile tool for control of spectrally narrow x-ray pulses.

- [1] B. W. Adams, et al., *Journal of Modern Optics* **60.2** (2013)
- [2] R. Röhlsberger et al., *Nature* **482**, 199 (2012)
- [3] X. Kong, and A. Pálffy, arXiv:1508.06762 (2015)

Q 51.6 Thu 12:15 f442

Design and control of quantum optical schemes at x-ray energies — PAOLO LONGO, KILIAN P. HEEG, CHRISTOPH H. KEITEL, and ●JÖRG EVERS — Max Planck Institute for Nuclear Physics, Heidelberg

Modern synchrotron light sources and x-ray free electron lasers strive to continue the success story of optical lasers at hard x-ray energies. However, in contrast to the broad capabilities available in labs operating at optical frequencies, the implementation of laser-coupled quantum systems in the x-ray domain remains a challenge due to basic experimental limitations. In recent years, first steps to circumvent these limitations were taken by few experiments which demonstrated basic quantum optical effects at x-ray energies. However, systematic approaches to implement advanced quantum optical level schemes at

x-ray energies are currently lacking, impeding further progress in the field.

Here, we present our progress towards such a systematic approach. Our basic idea is to tailor cooperative effects in large ensembles of nuclei in such a way that effectively, a single artificial quantum system is simulated with the desired properties. To achieve this goal, we consider nuclear ensembles embedded in an x-ray cavity as our model system.

Q 51.7 Thu 12:30 f442

Optimisation of energy transfer processes to increase upconversion luminescence in multi-layered photonic structures — ●FABIAN SPALLEK, ANDREAS BUCHLEITNER, and THOMAS WELLENS — Institute of Physics, University of Freiburg, Germany

Upconversion materials, which convert two low-energy photons into one photon with higher energy, in combination with photonic structures give promising possibilities to improve the efficiency of silicon solar cells by utilising the full range of the solar spectrum [1]. We analyse the influence of photonic structures on energy transfer processes between active charged centers within the upconverter material. Using the framework of macroscopic quantum electrodynamics, the dependence of energy transfer rates can be derived in the presence of arbitrarily shaped dispersing and absorbing material bodies [2]. We calculate the relevant energy transfer rates for multi-layered photonic structures with the goal to optimise the energy transfer properties for the upconversion process.

- [1] B. Herter, S. Wolf, S. Fischer, J. Gutmann, B. Blasi, and J.C. Goldschmidt, *Increased upconversion quantum yield in photonic structures due to local field enhancement and modification of the local density of states - a simulation-based analysis*, *Opt. Express* **21**, A883 (2013)
- [2] H.T. Dung, L. Knöll, and D.-G. Welsch, *Intermolecular energy transfer in the presence of dispersing and absorbing media*, *Phys. Rev. A* **65**, 043813 (2002)

Q 51.8 Thu 12:45 f442

Exploring quantum interference at x-ray nuclear interfaces — ●JONAS GUNST and ADRIANA PÁLFFY — Max-Planck-Institut für Kernphysik, Heidelberg

The concept of interference lies at the heart of quantum physics. Already in its beginnings, a number of gedankenexperiments have been proposed to better understand the origin and controllability of interference phenomena. Along with the great success of quantum optics, it has been shown that coherent control schemes can be employed to gain and subsequently remove again the which-way information in a double-slit scenario, known as the ‘‘quantum eraser’’ [1].

Here, we propose a quantum eraser setup with x-ray quanta, potentially extending time-energy complementarity tests into the so far unexplored parameter regime of x-ray energies. In the course of nuclear forward scattering (NFS) with synchrotron radiation on ensembles of Mössbauer ⁵⁷Fe nuclei generally more than one hyperfine transition can be driven at once. Since the scattering paths remain unresolved, the interference leads to the so called quantum beat characteristic for the time spectrum of NFS in an external magnetic field [2]. We show that it is possible to mark the individual paths by orthogonal polarizations such that the quantum beat pattern disappears in the time spectrum. Moreover, we put forward how to recover the interference by erasing the which-way information stored in the x-ray polarization.

- [1] M. O. Scully *et al.*, *Nature* **351**, 111 (1991).
- [2] J. Hannon and G. Trammell, *Hyperfine Interact.* **123-124**, 127 (1999).

Q 52: Ultrashort Laser Pulses II

Time: Thursday 14:30–16:30

Location: a310

Q 52.1 Thu 14:30 a310

Elements of a Dielectric Laser Accelerator Beamline: Staging, Focusing, and Tapering — ●JOSHUA MCNEUR, MARTIN KOZAK, NORBERT SCHÖNENBERGER, ALEXANDER TAFEL, ANG LI, and PETER HOMMELHOFF — Department Physik, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Staudtstrasse 1, 91058 Erlangen

Dielectric laser accelerators (DLAs) provide an attractive alternative

to the high-cost radio frequency accelerators that currently define the high energy particle physics landscape. Their orders-of-magnitude smaller footprints and larger acceleration gradients potentially enable University-lab scale (and smaller) high energy electron sources with a wide range of applications. However, to progress from the proof of principle DLA experiments [1,2] to a DLA-based accelerator beamline, many challenges need to be addressed. Here, we report on first evidence of DLA-based staging, focusing, and compensation for elec-

tron dephasing. All of these results are crucial towards the realization of a multi-stage DLA that can generate a collimated high brightness relativistic electron beam.

1. Peralta, E. A. et al. Demonstration of electron acceleration in a laser-driven dielectric microstructure *Nature* 503, 91-94 (2013).

2. Breuer, J. & Hommelhoff, P. Laser-Based Acceleration of Nonrelativistic Electrons at a Dielectric Structure. *Phys. Rev. Lett.* 111, 134803 (2013).

Q 52.2 Thu 14:45 a310

Attosecond electron gating and streaking by optical fields — •MARTIN KOZÁK, JOSHUA MCNEUR, NORBERT SCHÖNENBERGER, ALEXANDER TAFEL, ANG LI, and PETER HOMMELHOFF — Department Physik, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Staudtstrasse 1, 91058 Erlangen

We report on recent experimental results of sub-optical cycle temporal gating and streaking of free electrons at sub-relativistic energies (25-30 keV). In our experiments, the energy and transverse momentum of a DC electron beam is modulated in time by the interaction with the optical near-fields of a dielectric nanostructure utilizing the inverse Smith-Purcell effect [1,2]. As this interaction is linear with the electric field, the sub-cycle temporal structure of the femtosecond laser pulse is imprinted to the electron beam with very high precision (200 attoseconds in our experiment). Combined with a high-pass energy filter for accelerated electrons, this technique will enable sub-cycle temporal resolution in ultrafast electron diffraction and microscopy experiments (1.3 fs demonstrated). Moreover, the simple variation of the setup will serve as an attosecond streak camera for charged particle beams, potentially offering 10 as temporal resolution.

[1] J. Breuer, and P. Hommelhoff, *Phys. Rev. Lett.* 111, 134803 (2013).

[2] E. A. Peralta, et al. *Nature* 503, 91-94 (2013).

Q 52.3 Thu 15:00 a310

Ultrafast streaking of photo-electric emission from tungsten nanotips — •THOMAS JUFFMANN¹, BRANNON KLOPPER¹, GUNNAR SKULASON¹, CATHERINE KEALHOFER¹, FAN XIAO¹, SETH FOREMAN², and MARK KASEVICH¹ — ¹Stanford University, California 94305, USA — ²University of San Francisco, California 94117, USA

We present a new technique to study the photo-electric effect with femtosecond resolution. Laser-triggered electrons emitted from a tungsten nanotip interact with a cavity enhanced radiofrequency field. The final kinetic energy of the electrons depends on the phase of the RF field at the time of emission. We reach femtosecond resolution and a dynamic range of tens of picoseconds. Our results have implications for ultrafast electron microscopy and diffraction.

Q 52.4 Thu 15:15 a310

Charge transfer between unbiased metallic nanocontacts illuminated by phase-controlled ultrashort light pulses — •ANDREY S. MOSKALENKO, DANIELE BRIDA, TOBIAS RYBKA, ALFRED LEITENSTORFER, and GUIDO BURKARD — Department of Physics and Center for Applied Photonics, University of Konstanz, Germany

We theoretically investigate tunneling through free space nanogaps, which are formed between metallic nanocontacts, driven by few-fs broadband light pulses. Since the seminal work of Keldysh [1], it is known that the tunneling process can be significantly influenced by the energy gain as the electron moves in the classically forbidden region. In the past, this was demonstrated theoretically for atomic ionization by ultrashort light pulses [2]. We argue that the analogous regime is realizable for experimentally available nanocontacts and light pulses. In a certain range of parameters, a decrease of the pulse duration leads to a drastic increase of the tunneling probability.

Taking realistic pulse profiles and nanostructure configurations and using a time-dependent quasiclassical approach, we demonstrate that the preferred direction of the electron transport through the nanogap can be controlled by changing the carrier-envelope phase of the pulse, in agreement with our recent experimental findings. We calculate the tunneling probability and estimate the amount of transferred electrons per pulse in dependence on the parameters of the pulse and nanogap.

[1] L.V. Keldysh, *Sov. Phys. JETP* 20, 1307 (1965).

[2] V.S. Popov, *Phys. Usp.* 47, 855 (2004).

Q 52.5 Thu 15:30 a310

Theoretical modeling of light-field control of photocurrent in graphene — •TAKUYA HIGUCHI, CHRISTIAN HEIDE, KONRAD ULLMANN, HEIKO B. WEBER, and PETER HOMMELHOFF — De-

partment Physik, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), 91058 Erlangen

Under an intense electric field ($> 1 \text{ V/\AA}$) of a focused pulsed laser, electrons in solids undergo both inter- and intra-band motions driven by the field [1,2]. In this presentation, we discuss theoretically how the interplay of these two dynamics of electrons contributes to the generation of photocurrent in graphene. Numerical simulation suggests that the excitation from the valence band to the conduction band is well described as a result of interference of electron wave packets generated by tunneling within subcycles of the oscillating field. This interference is sensitive to the temporal evolution of the electric field, which explains the experimentally observed carrier-envelope-phase dependence of the photocurrent under few-cycle laser pulse illumination.

[1] M. Hohenleutner *et al.*, *Nature* 523, 573 (2015).

[2] T. Higuchi *et al.*, *Phys. Rev. Lett.*, 113, 213901 (2014).

Q 52.6 Thu 15:45 a310

Experimental observation of light-field controlled current in graphene — •CHRISTIAN HEIDE, TAKUYA HIGUCHI, KONRAD ULLMANN, HEIKO B. WEBER, and PETER HOMMELHOFF — Department Physik, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU) 91058 Erlangen

Here, we show experimental data of photocurrent generation in an epitaxially grown monolayer graphene ribbon under the illumination of few-cycle laser pulses. Thereby, we control the carrier-envelope-phase (CEP) of the pulses to change the carrier waveform, maintaining the temporal intensity envelope and the spectrum. We observed a dependence of the induced photocurrent on the CEP and the polarization of the laser. Both strongly suggest that the electrons are directly steered by the electric field within subcycles of the laser pulse. To explain the experimental findings we numerically simulate the population transfer from the valence band to the conduction band, which persists after the pulse is gone.

Q 52.7 Thu 16:00 a310

Effect of multiphoton resonances on femtosecond filaments in gaseous media — •CARSTEN BREE^{1,2} and MICHAEL HOFMANN^{1,3} — ¹Weierstraß-Institut für Angewandte Analysis und Stochastik — ²Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie — ³Institut für Theoretische Physik, Technische Universität Berlin

A femtosecond filament is a longitudinally extended channel of intense laser radiation and plasma which appears to be diffraction-free. Theoretically, it is described by assuming a phenomenological model of the optical response which consists of the all-optical Kerr effect and the Drude model accounting for ionization effects due to the high field-strength. However, recent research indicates that one has to go beyond this phenomenological description and resort to full quantum calculations of the optical response [1]. By solving the time-dependent Schrödinger equation, we obtain the atomic dipole response and conclude that multiphoton resonances strongly influence the field-induced nonlinear refractive index Δn . Plugging the calculated Δn into a propagation equation for the optical field enables us to observe the impact of multiphoton resonances on filamentary propagation [2].

[1] M. Kolesik *et al.*, *Optica* 1, 323(2014).

[2] M. Hofmann and C. Brée, *Phys. Rev. A* 92, 013813(2015).

Q 52.8 Thu 16:15 a310

Two-color multi-photon photoemission from a tungsten nanotip: Time-resolved dynamics — •TIMO PASCHEN¹, MICHAEL FÖRSTER^{1,2}, MICHAEL KRÜGER^{1,2}, FLORIAN LIBISCH³, CHRISTOPH LEMELL³, GEORG WACHTER³, THOMAS MADLENER³, JOACHIM BURGDÖRFER³, and PETER HOMMELHOFF^{1,2,4} — ¹Department Physik, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Staudtstrasse 1, 91058 Erlangen — ²Max-Planck Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching — ³Institute for Theoretical Physics, Vienna University of Technology, Wiedner Hauptstr. 8-10/E136, 1040 Wien — ⁴Max-Planck Institut für die Physik des Lichts, Günther-Scharowsky-Str. 1/Geb. 24, 91058 Erlangen

By superimposing a fundamental laser pulse and a perturbative second harmonic admixture on a nanometric metal tip we coherently control multi-photon photoemission. We show that the photo-induced electron emission is dependent on the phase of the two light fields. By using a single solid state nanoemitter, contrast values of the phase-dependent electron signal of more than 90 per cent are reached, which is among the highest reported values for two-color coherent control measurements

[1]. The experimentally observed phase-dependent electron emission is explained via quantum pathway interference and is compared to time-dependent density functional theory (TDDFT) and DFT simulations

[2].

- [1] P. Ackermann et al., Phys. Rev. A, 89, 063804 (2014).
 [2] M. Förster et al., manuscript in preparation.

Q 53: Quantum Gases: Fermions I

Time: Thursday 14:30–16:45

Location: e001

Q 53.1 Thu 14:30 e001

Exploring a Strongly Interacting Fermi gas in a 2D lattice — ●LUCA BAYHA, RALF KLEMT, PUNEET MURTHY, MATHIAS NEIDIG, MARTIN RIES, GERHARD ZÜRN, and SELIM JOCHIM — Physikalisches Institut, Universität Heidelberg

In this talk we will present our current progress and ideas on exploring a two-component Fermi gas in the BEC-BCS crossover in a 2D square lattice.

Our starting point is a quasi-2D gas of deeply bound bosonic Li₆ dimers, which are cooled to the superfluid phase. This sample is then loaded into a superimposed square lattice, where at shallow lattice depths we observe the appearance of additional peaks in the momentum distribution indicating superfluidity. For deeper lattices and low enough temperatures this system becomes insulating. By tuning the scattering length the type of this insulator can be smoothly changed from a band insulator of free fermions to a Mott insulator of repulsively interacting bosonic molecules. This change manifests itself in the different correlations between the particles, in both the spin and spatial degrees of freedom. These correlations can be accessed from atomic fluctuations in the momentum distribution. Thus we plan to investigate the (anti)correlations of atom shot-noise in the momentum distribution to reveal the character of the different insulating states.

Q 53.2 Thu 14:45 e001

Antiferromagnetic Heisenberg Spin Chain of a Few Cold Atoms in a One-Dimensional Trap — SIMON MURMANN¹, ●FRANK DEURETZBACHER², GERHARD ZÜRN¹, JOHANNES BJERLIN³, DANIEL BECKER⁴, STEPHANIE REIMANN³, LUIS SANTOS², THOMAS LOMPE¹, and SELIM JOCHIM¹ — ¹Physikalisches Institut der Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg — ²Institut für Theoretische Physik, Leibniz Universität Hannover, Appelstraße 2, 30167 Hannover — ³Mathematical Physics and NanoLund, LTH, Lund University, SE-22100 Lund, Sweden — ⁴I. Institut für Theoretische Physik, Universität Hamburg, Jungiusstr. 9, 20355 Hamburg

We report on the deterministic preparation of antiferromagnetic Heisenberg spin chains consisting of up to four fermionic atoms in a one-dimensional trap [1]. These chains are stabilized by strong repulsive interactions between the two spin components without the need for an external periodic potential [2]. We independently characterize the spin configuration of the chains by measuring the spin orientation of the outermost particle in the trap and by projecting the spatial wave function of one spin component on single-particle trap levels. Our results are in good agreement with a spin-chain model for fermionized particles and with numerically exact diagonalizations of the full few-fermion system.

- [1] S. Murmann et al., PRL 115, 215301 (2015)
 [2] F. Deuretzbacher et al., PRA 90, 013611 (2014)

Q 53.3 Thu 15:00 e001

Imaging transport of neutral atoms using a scanning probe microscope — ●SAMUEL HÄUSLER¹, SEBASTIAN KRINNER¹, DOMINIK HUSMANN¹, MARTIN LEBRAT¹, CHARLES GRENIER², SHUTA NAKAJIMA³, JEAN-PHILIPPE BRANTUT¹, and TILMAN ESSLINGER¹ — ¹Institute for Quantum Electronics, ETH Zürich, 8093 Zürich, Switzerland — ²Laboratoire de Physique, ENS de Lyon, 69364 Lyon, France — ³Department of Physics, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan

We implement a scanning probe technique to image the transport of ultracold fermions through a quantum point contact. A “tip” is created with a tightly focused, repulsive laser beam, and moved and shaped using a Digital Mirror Device. By scanning its position and monitoring the subsequent variations of conductance, we retrieve spatially resolved information on the transport, like in scanning gate microscopy applied to solid state devices [1].

The scanning gate pictures are compared with ab-initio simulations

for a non-interacting Fermi gas. The method is readily extended to strongly interacting fermions where superfluidity enhances the contrast.

- [1] M.A. Eriksson, et al. Appl. Phys. Lett. 69 671 (1996)

Q 53.4 Thu 15:15 e001

Spin transport of ultracold fermions through a quantum point contact — ●MARTIN LEBRAT¹, SEBASTIAN KRINNER¹, DOMINIK HUSMANN¹, SAMUEL HÄUSLER¹, CHARLES GRENIER², JEAN-PHILIPPE BRANTUT¹, and TILMAN ESSLINGER¹ — ¹Institute for Quantum Electronics, ETH Zürich, 8093 Zürich, Switzerland — ²Laboratoire de Physique, ENS de Lyon, 69364 Lyon, France

We report on the first measurement of spin conductance through a quantum point contact (QPC) with ultracold fermions. Experimentally, we prepare two clouds of ⁶Li atoms with opposite populations in two different hyperfine states, connect them by a narrow, optically-shaped constriction, and monitor the atomic flow in a spin-resolved way to infer spin conductance. In absence of interactions, conductance is expected to reach a quantum of 1/h whenever the Fermi wavelength is comparable to the transverse dimensions of the constriction.

As attractive interactions are increased towards the BEC-BCS crossover, we observe a non-monotonic behaviour of the spin conductance as a function of atomic density around the QPC, which is consistent with the appearance of a superfluid gap. For weaker interactions in the normal phase, we measure a reduction of conductance from the conductance quantum 1/h, that can be attributed to one-dimensional scattering within the QPC between excitations of opposite spins.

Q 53.5 Thu 15:30 e001

Formation and dynamics of anti-ferromagnetic correlations in tunable optical lattices — ●MICHAEL MESSER¹, DANIEL GREIF^{1,2}, GREGOR JOTZU¹, FREDERIK GÖRG¹, RÉMI DESBUQUOIS¹, and TILMAN ESSLINGER¹ — ¹Institute for Quantum Electronics, ETH Zurich, 8093 Zurich, Switzerland — ²Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

Ultracold fermions in optical lattices are an ideal toolbox for studying quantum magnetism in the Hubbard model. In this model many questions on the low-temperature phase diagram still remain open, both for simple cubic and square configurations, as well as for more complex lattice geometries. Besides a highly controlled approach to studying the thermodynamic properties cold atoms can also give insight into the dynamic properties of the system in the low entropy regime.

In our experiment we load a two-component, repulsively interacting fermionic quantum gas of K-40 into a tunable-geometry optical lattice. We observe anti-ferromagnetic spin correlations on neighboring sites in both isotropic 3D cubic and more complex lattice geometries for very low temperatures. In addition we study the strength of the spin correlations in a crossover between distinct geometries. Furthermore, we investigate the formation and redistribution time of spin correlations by dynamically changing the lattice geometry.

Q 53.6 Thu 15:45 e001

Persistent currents of massless Dirac fermions with interactions — ●JOHANNES JÜNEMANN^{1,2} and MATTEO RIZZI¹ — ¹Johannes Gutenberg-Universität, 55099 Mainz, Germany — ²Graduate School Materials Science in Mainz, 55128 Mainz, Germany

The persistent current response of ring-shaped materials to a piercing magnetic flux is a traditional topic in condensed matter: the effect of impurities/disorder and/or interactions have been thoroughly studied. Little attention has been however devoted to systems with Dirac-cone dispersion relation at the Fermi-level, and the few available results are focused on the non-interacting case. Here we investigate the scaling of the current and its response (the so-called orbital magnetic response or Drude weight) with respect to system-size and interaction-strength in a (quasi-)1D ring filled with massless Dirac fermions. We present both analytical results and numerical results obtained using so-called binary tree-tensor networks. We envisage an implementation via a Creutz lad-

der Hamiltonian with periodic boundary conditions, as made possible in cold-atomic setups by laser-assisted transfer processes (spin-flips, complex hopping, spin-orbit coupling) and recent progresses in shaping trapping potentials.

Q 53.7 Thu 16:00 e001

Quench Dynamics in Spin Chains from Discrete Truncated Wigner Approximations — ●STEFANIE CZISCHEK¹, HALIL ÇAKIR¹, MARKUS KARL¹, MICHAEL KASTNER², MARKUS K. OBERTHALER¹, and THOMAS GASENZER¹ — ¹Kirchhoff-Institut für Physik, INF 227, 69120 Heidelberg, Germany — ²Institute of Theoretical Physics, University of Stellenbosch, Stellenbosch 7600, South Africa

We study the dynamical build-up of correlations after sudden quenches in spin chains using the novel discrete truncated Wigner approximation. In particular, we consider quenches from large external fields to the vicinity of the quantum critical point within the paramagnetic phase. We calculate correlation lengths and regard their time evolution at different distances from the critical point. For the transverse field Ising chain, we find that the discrete truncated Wigner approximation is in good agreement with exact analytical and numerical results. Furthermore, our results show that the correlation function takes the form given by a generalized Gibbs ensemble already after short times and small relative distances. Since the generalized Gibbs ensemble usually describes the behaviour for asymptotically large times and distances, this is in contrast to expectations. Thus, our results suggests that the effects of universal dynamics are accessible on experimentally realizable timescales.

Q 53.8 Thu 16:15 e001

Measuring the scaling exponent of strongly interacting 2D gases — ●JONAS SIEGL, NICLAS LUICK, KLAUS HUECK, WOLF WEIMER, KAI MORGNER, THOMAS LOMPE, and HENNING MORITZ — Institut für Laserphysik, Hamburg, Deutschland

The critical behaviour exhibited by two-dimensional systems has profound impact on phenomena ranging from superfluidity in liquid helium films to high temperature superconductivity. It is intriguing that 2D systems with a continuous symmetry can become superfluid at all, since true long-range order is precluded by thermal fluctuations.

Instead, the celebrated Berezinskii, Kosterlitz and Thouless (BKT) theory predicts that below the superfluid transition the first order coherence decays algebraically with no characteristic length scale. Such scale free behaviour is typically only encountered at the critical point, whereas in 2D systems it is predicted to persist down to zero temperature, making them critical throughout.

Here, we locally probe the phase fluctuations of strongly correlated 2D gases of composite bosons. We determine the scaling exponent characterising the algebraic decay as a function of phase space density: during a short expansion along the strongly confined direction the phase fluctuations responsible for the algebraic decay are transformed into density fluctuations. We image the resulting density distribution and extract the scaling exponent from the power spectrum. The results are in excellent agreement with BKT theory, from which we can deduce the superfluid density locally. Our results extend the study of BKT theory towards the strongly interacting regime of fermionic superfluidity.

Q 53.9 Thu 16:30 e001

Observation of the Berezinskii-Kosterlitz-Thouless transition in an ultracold Fermi gas — ●PUNEET MURTHY¹, IGOR BOETTCHER², LUCA BAYHA¹, DHRUV KEDAR¹, MATHIAS NEIDIG¹, MARTIN RUES¹, ANDRE WENZ¹, GERHARD ZÜRN¹, and SERLIM JOCHIM¹ — ¹Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, 69120 Heidelberg — ²Institut für Theoretische Physik, Ruprecht-Karls-Universität Heidelberg, 69120 Heidelberg

We report on the experimental investigation of the first-order correlation function of a trapped Fermi gas across the quasi-two-dimensional BEC-BCS crossover. We demonstrate that even in the inhomogeneous trapped system, the correlation function shows a qualitative change in behavior from an exponential to power law decay. The extracted scaling exponents show substantial deviations from BKT theory for homogeneous systems. Furthermore, we find the maximal scaling exponent at the transition to show no dependence on interaction strength, suggesting that the corresponding phase transitions lie in the same universality class. On the BEC side, our findings are validated by Quantum Monte Carlo computations for bosons. Near the resonance, the observed algebraic decay is not captured by the bosonic picture, indicating the crossover to a fermionic superfluid.

Q 54: Quantum Information: Quantum Computing and Communication II

Time: Thursday 14:30–16:30

Location: e214

Q 54.1 Thu 14:30 e214

Measurement-device-independent randomness generation — ●FELIX BISCHOF, HERMANN KAMPERMANN, and DAGMAR BRUSS — Institut für Theoretische Physik III, Heinrich-Heine-Universität Düsseldorf, Universitätsstraße 1, D-40225 Düsseldorf, Germany

The inherent unpredictability of quantum measurements provides a way to generate true objective randomness. However, the presence of unavoidable noise in any realistic setting requires careful separation of quantum randomness from classical pseudo-randomness. At the same time, the number of assumptions and explicit modelling of the devices should be low for any safe and practical scheme.

We introduce and analyze a measurement-device-independent scheme to generate true randomness with few assumptions: trusted sending devices send out qubit signals inside a secure laboratory. Upon receiving the signals, an uncharacterized measurement apparatus outputs classical bits, the raw random numbers. The observed measurement statistics is then used to quantify the amount of true randomness, independent of the inner working of the measurement device.

Q 54.2 Thu 14:45 e214

Randomized Benchmarking protocol accounting for leakage and gate dependent errors — ●TOBIAS CHASSEUR and FRANK WILHELM — Theoretical Physics, Saarland University, 66123 Saarbrücken, Germany

In the wake of recent advances in experimental implementations of quantum gates on physical qubits characterizing the fidelity of those gates efficiently and accurately becomes increasingly important. The Randomized Benchmarking protocol allows to do so for specific sets of quantum gates such as the Clifford group in a way that is scalable in the number of qubits and robust against state preparation and

measurements errors. It however suffers from several assumptions and restrictions which are typically not given for physical systems. We investigate the effect of leakage errors induced from an additional level per physical qubit on Randomized Benchmarking and provide a modified protocol that allows to derive reliable estimates for the average error per gate in their presence. Our protocol allows for gate dependent error channels without the unphysical restriction to small perturbations. We show that our protocol is compatible with Interleaved Randomized Benchmarking and expand to benchmarking of arbitrary gates. This setting is relevant for superconducting transmon qubits, among other systems.

Q 54.3 Thu 15:00 e214

Randomized benchmarking of one-qubit and two-qubit operations in an ion-trap quantum computer — ●ALEXANDER ERHARD, ROMAN STRICKER, DANIEL NIGG, ESTEBAN MARTINEZ, PHILIPP SCHINDLER, and RAINER BLATT — Institute for Experimental Physics, University of Innsbruck, Austria

Randomized benchmarking provides a platform independent approach to characterize the performance of a quantum computer. Large scale quantum computers require quantum error correction, which can be realized using operations from the Clifford group. Hence we investigate the fidelity of our quantum computer using only operations from the Clifford group. We present randomized benchmarking experiments on a single qubit and on two qubits. We estimate the fidelity of a single Clifford gate from the decay of the fidelity with increasing gate sequence length.

Q 54.4 Thu 15:15 e214

Consistency test for quantum process tomography — ●SABINE WÖLK — Department Physik, Universität Siegen, 57068 Siegen, Ger-

many

Quantum channels are in general described by completely-positive maps \mathcal{E} . However, when performing quantum process tomography, often non-positive maps appear.

There exist several reasons for the emersion of non-positive maps in quantum process tomography: (i) statistical errors due to the limited number of measurements, or systematic errors such as e.g. (ii) misaligned measurements or (iii) initial correlation of the system and the environment [1,2].

In this talk we will discuss the reasons for the appearance of not completely-positive maps. Furthermore, we introduce methods to distinguish statistical and systematic errors in process tomography based on methods from state tomography [3].

[1] P. Pechukas, Phys. Rev. Lett. **73**, 1060 (1994).

[2] C. Wood, Honours thesis, Macquarie University, Sydney, Australia (2009), arXiv:0911.3199.

[3] T. Moroder, M. Kleinmann, P. Schindler, T. Monz, O. Gühne, and R. Blatt, Phys. Rev. Lett. **110**, 180401 (2013).

Q 54.5 Thu 15:30 e214

Contextuality as a resource for qubit quantum computation

— ROBERT RAUSSENDORF¹, DAN E. BROWNE², NICOLAS DELFOSSE^{3,4,5}, CIHAN OKAY⁶, and JUAN BERMEJO-VEGA^{7,8}

— ¹Department of Physics and Astronomy, University of British Columbia, Vancouver, BC, Canada — ²Department of Physics and Astronomy, University College London, Gower Street, London, UK

— ³Departement de Physique, Université de Sherbrooke, Sherbrooke, Quebec, Canada — ⁴IQIM, California Institute of Technology, Pasadena, CA, USA — ⁵Department of Physics and Astronomy, University of California, Riverside, California, 92521, USA —

⁶Department of Mathematics, University of Western Ontario, London, Ontario, Canada — ⁷Max-Planck Institut fuer Quantum Optics, Theory Division, Garching, Germany — ⁸Dahlem Center for Complex Quantum Systems, Freie Universitaet Berlin, Berlin, Germany

We describe a scheme of quantum computation with magic states on qubits for which contextuality is a necessary resource possessed by the magic states. More generally, we establish contextuality as a necessary resource for all schemes of quantum computation with magic states on qubits that satisfy three simple postulates. Furthermore, we identify stringent consistency conditions on such computational schemes, revealing the general structure by which negativity of Wigner functions, hardness of classical simulation of the computation, and contextuality are connected.

Based on <http://arxiv.org/abs/1511.08506>

Q 54.6 Thu 15:45 e214

Atomic two-qubit quantum operations assisted by multiphoton states

— JUAN MAURICIO TORRES, JÓZSEF ZSOLT BERNÁD, LUD-

WIG KUNZ, and GERNOT ALBER — Institut für Angewandte Physik, Technische Universität Darmstadt, D-64289 Germany

We compare two schemes to implement quantum operations on atomic qubits. In one of them two two-level atoms interact one after the other with the electromagnetic field inside an optical resonator. In the second scheme, the two atoms interact simultaneously with the optical field. We show that in both cases, two-qubit entangling operations can be performed by measuring the field state inside the resonator with a balanced homodyne detection. To complete the description we analyze the effects of photon losses in the performance of the protocol.

Q 54.7 Thu 16:00 e214

Performance analysis of large-scale quantum networks based on graphs

— MICHAEL EPPING, HERMANN KAMPERMANN, and DAGMAR BRUSS — Heinrich-Heine-Universität Düsseldorf, Institut für Theoretische Physik III, Düsseldorf

Quantum repeaters effectively reduce the error rates (i.e. the noise and erasures) of transmission channels, which is a necessary prerequisite of any long distance quantum communication protocol. A quantum network, containing such channels to connect the participants, can be associated with a mathematical graph. Here, each vertex corresponds to a party and each edge to a line of repeater stations.

We analyze the propagation of errors in a quantum network [1]. In particular we focus on the production of graph states shared by all parties - a natural resource of multipartite entanglement in a quantum network. Finally we show how our approach leads to schemes which efficiently employ the infrastructure of a given quantum network.

[1] M.E., H.K., and D.B., arXiv:1508.02185 [quant-ph]

Q 54.8 Thu 16:15 e214

Quantum state merging with bound entanglement

— ALEXANDER STRELTSOV — Freie Universität Berlin

Quantum state merging is one of the most important protocols in quantum information theory. In this task two parties aim to merge their parts of a pure tripartite state by making use of additional singlets while preserving coherence with a third party. We study a variation of this scenario where the merging parties have free access to PPT entangled states, and the total quantum state shared by all three parties is not necessarily pure. We provide general conditions for a state to admit perfect merging, and present a family of fully separable states which cannot be perfectly merged if the merging parties have no access to additional singlets. We also show that for pure states the conditional entropy plays the same role as in standard quantum state merging, quantifying the amount of quantum communication needed to perfectly merge the state. While the question whether the protocol considered here exhibits the strong converse property is left open, it is shown that for a significant amount of quantum states the merging fidelity vanishes asymptotically.

Q 55: Ultra-cold atoms, ions and BEC IV (with A)

Time: Thursday 14:30–16:30

Location: f303

Q 55.1 Thu 14:30 f303

Spectroscopy of Topological Defects in Coulomb Crystals

— PHILIP KIEFER¹, JONATHAN BROX¹, MIRIAM BUJAK¹, ISABELLE SCHMAGER¹, HAGGAI LANDA², and TOBIAS SCHAETZ¹ — ¹Atom-, Molekül- und optische Physik, Physikalisches Institut, Universität Freiburg, Hermann-Herder-Str. 3, 79104 Freiburg — ²LPTMS, Université Paris Sud, Orsay, France

We study structural defects (kinks) experimentally, which we form during two related phase-transitions in Coulomb crystals. A cloud of ²⁴Mg-ions is frozen into a crystalline structure, consisting of several tens of ions in a linear radiofrequency trap [1]. We observe the formation of topological defects with a structural phase transition from a linear chain to a 2D-zig-zag configuration. Numerical simulations predict a strong anharmonicity of the kink's internal mode of vibration [2].

We observe the defects' experimental occurrence, lifetime and annihilation due to controlled motional excitation of the localized mode. We reveal evidence for the (gapped) localized mode and present first data of spectroscopy results. Furthermore, the formation of kink configurations and the transformation of kinks between different structures in dependence on the trapping parameters are investigated.

[1] M. Mielenz et al., Phys. Rev. Lett. **110**, 133004 (2013)

[2] H. Landa et al., New J. Phys. **15**, 093003 (2013)

Q 55.2 Thu 14:45 f303

Quantum phases of ultracold dipolar bosons in a highly anisotropic trap

— FLORIAN CARTARIUS^{1,2}, ANNA MINGUZZI², and GIOVANNA MORIGI¹ — ¹Theoretische Physik, Universität des Saarlandes, 66123 Saarbrücken, Germany — ²Laboratoire de Physique et Modélisation des Milieux Condensés, Université-Grenoble Alpes and CNRS, 25 avenue des martyrs, F-38042 Grenoble, France

We study two dimensional dipolar bosons in an optical lattice, tightly confined to a string by a highly anisotropic harmonic potential. The bosons are polarized perpendicular to the plane by an external field, so that they interact via the repulsive part of the dipolar potential. For very strong harmonic confinements, the dipoles are in the lowest energy state of the transverse harmonic oscillator. This breaks down when the transverse confinement frequency is decreased below a critical value. In this regime, we show that the system can be mapped onto several coupled extended Bose-Hubbard Hamiltonians, where the coefficients can be determined by means of a low energy theory [1]. We determine the ground state of this Bose-Hubbard Hamiltonian as

a function of the trap aspect ratio and of the strength of the dipolar potential, and analyse the conditions under which Haldane-like phases and pair-superfluidity can occur.

[1] F. Cartarius, G. Morigi, and A. Minguzzi, *Phys. Rev. A* 90, 053601 (2014)

Q 55.3 Thu 15:00 f303

On the heteronuclear Efimov effect with van der Waals interactions — ●JURIS ULMANIS¹, STEPHAN HÄFNER¹, RICO PIRES¹, YUJUN WANG², CHRIS H. GREENE³, EVA D. KUHNLE¹, and MATTHIAS WEIDEMÜLLER¹ — ¹Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany — ²Department of Physics, Kansas State University, 116 Cardwell Hall, Manhattan, KS 66506, USA — ³Department of Physics, Purdue University, West Lafayette, Indiana, 47907-2036, USA

Ultracold Bose-Fermi mixture of ¹³³Cs and ⁶Li atoms constitutes a prototypical system with mass imbalance that allows thorough exploration of the heteronuclear Efimov effect – the formation of an infinite geometrical series of bound three-body states for resonant two-body interactions. Here we present our measurements and analysis of three-body recombination spectra of Li+Cs+Cs close to two broad Li-Cs Feshbach resonances. Two series of consecutive Efimov resonances, each characterized by different sign and magnitude of Cs-Cs s-wave scattering length, are observed, showing deviations from the geometric scaling law. For positive Cs-Cs scattering lengths the three-body resonance that is associated to the Efimov ground state is missing. This is in agreement with the spinless van der Waals theory that predicts the transformation of the Efimov ground state into the Li + Cs₂ scattering channel, and modification of the scaling factors via short-range effects. These findings provide a comprehensive picture of universal and non-universal features in the heteronuclear Efimov scenario.

Q 55.4 Thu 15:15 f303

Sympathetic cooling of ions inside a radio frequency trap — ●BASTIAN HÖLTKEMEIER¹, PASCAL WECKESSER¹, HENRY LOPEZ¹, ANDRE DE OLIVEIRA^{1,2}, JI LUO¹, ERIC ENDRES³, ROLAND WESTER³, and MATTHIAS WEIDEMÜLLER¹ — ¹Physikalisches Institut, Universität Heidelberg, INF 226, 69120 Heidelberg — ²Departamento de Física, Universidade do Estado de Santa Catarina-Joinville, SC, Brazil — ³Institut f. Ionenphysik und angewandte Physik, Universität Innsbruck, Technikerstraße 25/3, 6020 Innsbruck

Sympathetic cooling has become a powerful and universal method for preparing ultracold ions confined in radio frequency traps. We theoretically investigate the possibility of using laser-cooled atoms as a buffer gas. Recent theories indicate that cooling of ions in radio frequency traps is limited to atom-to-ion mass ratios below unity. Using a localized buffer gas cloud and/or a higher order radio frequency trap this limitation can be overcome. A description of our model and the corresponding cooling limit for experimental applications will be presented. We show how the ion's final temperature can be tuned by adjusting the appropriate experimental parameters, such as the rf-voltage or the atom cloud size (Forced Sympathetic Cooling).

Q 55.5 Thu 15:30 f303

Single particle dynamics in an ultracold environment: From superfluidity to finite size reheating — ●PAULA OSTMANN and WALTER STRUNZ — TU Dresden, Inst. f. Theor. Physik, Zellescher Weg 17, 01062 Dresden

We investigate the quantum dynamics of a single ion which is immersed into a Bose-Einstein condensate. The ultracold environment acts as a refrigerator, and thus, the influence on the motion of the ion is dissipative. For a theoretical description, simple phenomenological master equation approaches are widely used to describe the ensuing damped quantum dynamics. Instead of calculating the particle dynamics itself, our focus lies on a more detailed description of the environment and the particle-environment interaction. We aim to describe the effective dynamics of the damped particle dynamics using the full bath correlation function instead of a simple damping rate. In this way we gain a more thorough theoretical understanding of properties of quantum matter, such as superfluidity, when acting as an environment.

We find that we can divide the dynamical effect of the BEC on the ion into two parts: The initial energy loss and the return of energy to

the ion dynamics. By considering just the initial decay we effectively study an ion coupled to an infinitely large environment and are able to identify a Landau Criterion for a quantum particle in a harmonic trap. Secondly we see that the finite size of the condensate causes the return of the energy, which results in a periodically reheating of the ion, which could be used as an additional cooling mechanism as well.

Q 55.6 Thu 15:45 f303

Radio-frequency dressed detection of atomic clock states — ●SINDHU JAMMI, TADAS PYRAGIUS, MARK BASON, and THOMAS FERNHOLZ — School of Physics and Astronomy, University of Nottingham

We introduce a new method to dispersively measure population and population difference of alkali atoms prepared in their two clock states ($m=0$). Linear birefringence of the atomic medium allows atom number detection via polarisation homodyning, i.e. common path interferometry. In order to achieve low technical noise levels, we perform sideband detection after adiabatically transforming the atomic states via radio-frequency dressing. The balanced homodyne signal then oscillates at twice the dressing frequency, independent of field fluctuations, thus allowing for robust, phase-locked detection that circumvents low-frequency noise. Using probe pulses of two optical frequencies consecutively, we can detect both atomic states separately and obtain population difference as well as total atom number in a single experimental cycle. Simultaneously pulsed detection can be used for direct subtraction of the homodyne signals, which we expect to enable quantum noise limited measurements and preparation of spin squeezed states. The method can thus be used in atomic clocks and atom interferometric measurements.

Q 55.7 Thu 16:00 f303

Development of a deterministic ion source based on ultracold atoms — ●CIHAN SAHIN, ANDREAS MÜLLERS, JENS BENARY, and HERWIG OTT — Technische Universität Kaiserslautern

A deterministic ion source using ultracold atoms can provide ions with low energy spread at high repetition rates. These properties are beneficial for experiments on ion interferometry or semiconductor doping.

In our experiment, a magneto optical trap (MOT) storing ⁸⁷Rb atoms acts as an ion source. The atoms are photoionized from the $5P_{3/2}$ state with a 405 nm laser. Both electrons and ions are detected with channel electron multipliers (CEM). The electrons serve as triggers for the ions, which would enable us to predict and control the ions.

As a next step, the ions will be detected with a position sensitive multi channel plate (MCP) with a delay line detector (DLD) to characterize their energy spread and position resolution.

We discuss the status of the experiment and present results obtained so far.

Q 55.8 Thu 16:15 f303

Dimensional phase transition from 1D behavior to a 3D Bose-Einstein condensate — DENIS MORATH, ●DOMINIK STRASSEL, AXEL PELSTER, and SEBASTIAN EGGERT — Department of Physics and Research Center Optimas, University Kaiserslautern, 67663 Kaiserslautern, Germany

The emergence of new properties from low-dimensional building blocks is a universal theme in different areas in physics. The investigation of transitions between isolated and coupled low-dimensional systems promises to reveal new phenomena and exotic phases. Interacting 1D bosons, which are coupled in a two-dimensional array, are maybe the most fundamental example of a system which illustrates the concept of a dimensional phase transition. However, recent experiments using ultracold gases have shown a surprising discrepancy between theory and experiment [1] and it is far from obvious if the power laws from the underlying 1D theory can predict the transition temperature and order parameter correctly for all interaction strengths. Using a combination of large-scale Quantum Monte-Carlo simulations and chain mean-field calculations, we show that the behavior of the ordering temperature as a function of inter-chain coupling strength does not follow a universal powerlaw, but also depends strongly on the filling.

[1] A. Vogler, R. Labouvie, G. Barontini, S. Eggert, V. Guarrera, and H. Ott, *Phys. Rev. Lett.* 113, 215301 (2014)

Q 56: Optomechanics II

Time: Thursday 14:30–15:45

Location: f342

Q 56.1 Thu 14:30 f342

Photon-Phonon Interactions in Nano-Photonic Waveguides — ●HASHEM ZOUBI and KLEMENS HAMMERER — Institute for Theoretical Physics, Leibniz University Hannover

Stimulated Brillouin Scattering (SBS), i.e. the scattering of photons from acoustic phonons in dielectric materials, is induced mainly by electrostriction phenomena in bulk media. It was shown recently that SBS can be enhanced by orders of magnitudes when approaching the nanoscale regime due to radiation pressure. We develop a microscopic quantum theory that includes electrostriction and radiation pressure on the same footing. We derive the photon-phonon coupling parameter, which combines SBS and quantum optomechanical processes. We present the results by giving detailed calculations for the case of a nanoscale waveguide of circular cross section. We extract an effective photon-photon interaction which is a step toward many-body physics of photons.

Q 56.2 Thu 14:45 f342

Measurement-induced long-distance entanglement of superconducting qubits with optomechanical transducers — ●ONDREJ CERNOTIK and KLEMENS HAMMERER — Institute for Theoretical Physics, Institute for Gravitational Physics (Albert Einstein Institute), Leibniz University Hannover, Germany

While superconducting systems provide a promising platform for quantum computing, their networking poses a considerable challenge as they cannot be interfaced directly to light—the natural carrier for transmission of quantum signals through channels at room temperature. Here, we show that remote superconducting qubits can be prepared in entangled states by coupling them to mechanical oscillators whose positions are monitored with optical fields. Continuous homodyne detection of light provides information on the total spin of the two qubits such that entangled qubit states can be post-selected. Entanglement generation is possible without ground state cooling of the mechanical oscillators for systems with an optomechanical cooperativity moderately larger than unity; in addition, our setup tolerates a substantial loss of photons in transmission. The approach is scalable to generation of multipartite entanglement and represents a crucial step towards quantum networks with nodes using superconducting circuits.

Q 56.3 Thu 15:00 f342

Optomechanical multistability in the quantum regime — ●ANDREAS ALVERMANN, CHRISTIAN SCHULZ, and HOLGER FEHSKE — Institut für Physik, Universität Greifswald

Classical optomechanical systems feature self-sustained oscillations, where multiple stable periodic orbits at different amplitudes coexist. While these orbits persist in the quantum dynamics sufficiently close to the classical limit, a new dynamical pattern emerges as one moves deeper into the quantum regime: Transitions between different orbits are induced by the spreading of the quantum state in phase space, and the stability of orbits changes in a predictable way.

We explain the resulting dynamical patterns from the point of view

of phase space dynamics, and derive a Langevin equation with a specific quantum noise term that comes into play only through the deviation of quantum states from classical states. We also discuss to which extent the transition to chaos observed in the classical dynamics survives in this context, and point out in which way the Langevin description is of general relevance for dissipative quantum systems in the vicinity of—but not arbitrarily close to—the classical limit.

Q 56.4 Thu 15:15 f342

An optomechanical interface bridging x-ray and optical photons — WEN-TE LIAO^{1,2} and ●ADRIANA PÁLFFY¹ — ¹Max-Planck-Institut für Kernphysik, Heidelberg — ²National Central University, Taoyuan City, Taiwan

Future photonic quantum networks will require interfaces between different photon frequency regimes. So far, conversion experiments bridged the visible with telecommunication bands in infrared [1,2]. Going towards shorter wavelengths bears however certain advantages: x-rays are better focusable, are more robust and penetrate deeper through materials than visible or IR photons. They also carry much larger momenta, potentially facilitating the entanglement of light and matter at a single-photon level.

Here we envisage for the first time an optomechanical system that bridges optical photons and x-rays. The x-ray-optical interface system comprises of an optomechanical cavity and a movable microlever interacting with both an optical laser and with x-rays via resonant nuclear scattering. We develop a theoretical model for this system and show that x-ray absorption spectra of nuclei can be tuned optomechanically [3]. In particular, our theoretical simulations predict optomechanically induced transparency of x-rays, which can be used for metrology-relevant applications.

[1] M. T. Rakher *et al.*, Nature Photon. **4**, 786 (2010)

[2] A. G. Radnaev *et al.*, Nature Phys. **6**, 894 (2010)

[3] W.-T. Liao and A. Pálffy, arXiv:1508.06769

Q 56.5 Thu 15:30 f342

Optomechanics in the time domain — ●RALF RIEDINGER¹, SINGKUN HONG¹, ALEX KRAUSE^{2,3}, TIM BLASIUS^{2,3}, OSKAR PAINTER^{2,3}, SIMON GRÖBLACHER⁴, and MARKUS ASPELMEYER¹ — ¹Universität Wien, Vienna, Austria — ²Kavli Nanoscience Institute and Thomas J. Watson, Sr., Laboratory of Applied Physics, California Institute of Technology, Pasadena CA, USA — ³Institute for Quantum Information and Matter, California Institute of Technology, Pasadena CA, USA — ⁴Kavli Institute of Nanoscience, Delft University of Technology, Delft, Netherlands

Optomechanical systems suffer from noise associated with continuous optical drives, e.g. absorption heating or parametric instabilities. Recently, it was proposed to use short optical pulses to circumvent these problems. Optical time domain probes can be used e.g. to realize quantum non-demolition measurements of mechanical positions. We report recent progress on time domain measurements on photonic crystal based mechanical resonators.

Q 57: Quantum Effects: QED II

Time: Thursday 14:30–16:30

Location: f442

Group Report

Q 57.1 Thu 14:30 f442

Interference and dynamics of light from a distance-controlled atom pair in an optical cavity — ●OLIVIER MORIN, ANDREAS NEUZNER, MATTHIAS KÖRBER, STEPHAN RITTER, and GERHARD REMPE — Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 85748 Garching

A single atom in a cavity is the most simple system of cavity QED. Reaching control over the internal and external degrees of freedom of the atom has enabled novel quantum physical applications. Similarly, research with atomic many-body systems has led to many new insights into complex quantum systems. However, only a few experiments have attempted to bridge the two areas of research.

We report recent results in this direction by extending our system from one to two atoms in regimes typically associated with super- and

sub-radiance. As for the paradigmatic double-slit experiment, we observe the fundamental role of the relative phase between possible optical paths determined by the atoms' positions. This new degree of freedom introduces non-trivial effects based on the cavity-mediated long-range interaction between the atoms. A plethora of counter-intuitive phenomena in the intensity and the photon statistics of the light emitted from the atom-driven system is observed. The reported amount of control opens up a unique way to connect cavity QED and many-body physics.

Q 57.2 Thu 15:00 f442

Nonclassical light from an incoherently pumped quantum dot in a microcavity — ●LUCAS TEUBER, PETER GRÜNWARD, and WERNER VOGEL — Institut für Physik, Universität Rostock, D-18055

Rostock, Germany

Quantum dots in semiconductor microcavities have become one of the backbones of semiconductor quantum optics. However, technical and physical issues often limit the study of optical fields to incoherently excited systems. For incoherently driven two-level systems, we derive steady-state solutions for the correlation of intracavity field and the quantum dot by means of recurrence relations [1]. With these correlations, different nonclassicality criteria based on moments [2] are analyzed. Realistic cavity systems from previous experiments [3] show nonclassicality in terms of lower-order moments for moderate quantum-dot-cavity coupling. Our method also allows to compute the characteristic function [4] in order to prove that the intracavity field is always nonclassical.

[1] L. Teuber, P. Grünwald, and W. Vogel, *Phys. Rev. A* **92**, 053857 (2015).

[2] E. Shchukin, Th. Richter, and W. Vogel, *Phys. Rev. A* **71**, 011802(R) (2005).

[3] G. Khitrova, H. M. Gibbs, M. Kira, S. W. Koch, and A. Scherrer, *Nature Phys.* **2**, 81 (2006).

[4] W. Vogel, *Phys. Rev. Lett.* **84**, 1849 (2000).

Q 57.3 Thu 15:15 f442

Quantum decoherence of a single-ion qubit induced by single optical photons — MOONJOO LEE¹, KONSTANTIN FRIEBE¹, FLORIAN R. ONG¹, ●DARIO A. FIORETTO¹, BERNARDO CASABONE¹, KLEMENS SCHUEPPERT¹, RAINER BLATT^{1,2}, and TRACY E. NORTHUP¹ — ¹Institute of Experimental Physics, University of Innsbruck, Austria — ²Institute of Quantum Optics and Quantum Information, Austria

Quantum measurement is based on the interaction between a quantum object and a meter entangled with the object. While the information stored in the object is being extracted by the interaction, the measurement leads to decoherence of the object due to the intrinsic quantum fluctuations of the meter. Here, we report the observation of measurement-induced dephasing of a single-ion qubit with single optical photons. We employ a single ⁴⁰Ca⁺ ion that is dispersively coupled to a high-finesse cavity. The cavity is driven by a weak laser field to populate the cavity with mean photon numbers up to five. Spectroscopy is performed on the 729 nm qubit transition to identify the shift and broadening of the atomic energy levels. The information stored in the qubit is extracted by photons escaping the cavity, which, in turn, leads to dephasing of the qubit owing to photon-number fluctuations. This measurement represents the first demonstration of such quantum decoherence effects in the optical domain. Furthermore, heterodyne measurements of the cavity output photons will make it possible to probe quantum trajectories of the qubit nondestructively.

Q 57.4 Thu 15:30 f442

Enhanced Nonlinearity in an Atom-Driven Cavity QED System — ●CHRISTOPH HAMSEN, KARL NICOLAS TOLAZZI, HAYTHAM CHIBANI, TATJANA WILK, and GERHARD REMPE — Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, D-85748 Garching

Optical nonlinearities at the single- to few-photon level are an essential ingredient to quantum optics and quantum information processing. An atom strongly coupled to the light field of an optical cavity provides such a nonlinearity. As described by the Jaynes-Cummings model, the system's eigenstates form an anharmonic ladder of doublets for each excitation number giving rise to nonlinearities strong enough to enable single- or multi-photon effects [1,2].

Here we investigate a system composed of a single ⁸⁷Rb atom strongly coupled to a cavity where the coherent drive resonantly excites the quantum emitter instead of the resonator. Compared to the cavity-driven case, we expect an enhanced nonlinearity since the transition elements from the first to higher manifolds are reduced. This in turn has distinct implications on the photon statistics of the cavity emission, as demonstrated experimentally: First, driving the emitter on the normal modes yields an improved photon-blockade effect. In contrast, resonant driving to the second manifold leads to a novel nonclassical photon-concatenation effect reflecting the internal dynamics of the system.

[1] K. M. Birnbaum et al., *Nature* **436**, 87 (2005).

[2] A. Kubanek et al., *Phys. Rev. Lett.* **101**, 203602(2008).

Q 57.5 Thu 15:45 f442

Injection locking of a self-sustained cQED oscillator — ●WOLTERS JANIK^{1,2}, ELISABETH SCHLOTTMANN², STEFFEN HOLZINGER², BENJAMIN LINGNAU³, KATHY LÜDGE³, CHRISTIAN SCHNEIDER⁴, MARTIN KAMP⁴, SVEN HÖFLING⁴, and STEPHAN REITZENSTEIN² — ¹Universität Basel, Departement Physik, CH-4056 Basel — ²Institut für Festkörperphysik, Quantum Devices Group, Technische Universität Berlin, Hardenbergstrasse 36, EW 5-3, 10623 Berlin, Germany — ³Institut für Theoretische Physik, AG Nichtlineare Laserdynamik, Technische Universität Berlin, Hardenbergstrasse 36, EW 7-1, 10623 Berlin, Germany — ⁴Technische Physik, Universität Würzburg, Am Hubland, 97074 Würzburg, Germany

We report on a comprehensive study of external control of a self-sustained cQED oscillator, namely a microscopic laser operating in the weak coupling regime with a few tens of photons in the cavity. Where perfect synchronization or chaotic dynamics are expected for its conventional macroscopic counterparts, stationary oscillation synchronized to the external signal and oscillation at the solitary frequency is observed to occur simultaneously. The experimental findings are quantitatively supported and explained by modeling the cQED oscillator under study. As indicated by the theoretical analysis, the observed partial injection is a phenomenon unique to cQED enhanced oscillators excited with a few tens of quanta. Our studies are a landmark for future experiments on external (quantum) control of optical, opto-mechanical or electronic oscillators exhibiting complex dynamics in the quantum regime.

Q 57.6 Thu 16:00 f442

Mean-field analysis of synchronization-induced cooling — ●SIMON B. JÄGER¹, MINGHUI XU², STEFAN SCHÜTZ¹, GIOVANNA MORIGI¹, and MURRAY HOLLAND² — ¹Theoretische Physik, Universität des Saarlandes, D-66123 Saarbrücken, Germany — ²JILA, National Institute of Standards and Technology and Department of Physics, University of Colorado, Boulder, Colorado 80309-0440, USA

We discuss the cavity cooling dynamics which accompanies synchronization of dipoles in a resonator. The atomic transitions are incoherently driven by an external pump and strongly coupled to a cavity. Friction forces and diffusion depend critically on the external parameters, and can lead to recoil temperatures in the synchronization regime. By means of a mean-field analysis we show that this is accompanied by an onset of correlations between internal and external degrees of freedom and determine the phase diagram for the stationary state as a function of the external pump strength and of the superradiant linewidth.

Q 57.7 Thu 16:15 f442

Thermodynamics and relaxation in a system of photon-mediated long-range interactions — ●STEFAN SCHÜTZ, SIMON BALTHASAR JÄGER, and GIOVANNA MORIGI — Theoretische Physik, Universität des Saarlandes, D-66123 Saarbrücken, Germany

We study the steady-state properties and relaxation dynamics of atoms in the quantum field of an optical cavity and which are driven by a laser. In a semiclassical limit we show that the steady state is a thermal distribution whose temperature is solely controlled by the detuning between laser and cavity. The laser intensity, on the other hand, determines the onset of selforganized Bragg gratings. We evaluate the free energy and demonstrate that the selforganization transition is a second-order phase transition described by Landau's model: the control field is the laser intensity and the order parameter is the cavity field amplitude. We then discuss the dynamics following a sudden quench across the phase transition, and report the observation of metastable spatial patterns, whose lifetime can be several resonator lifetimes. These metastable patterns are nonthermal and result from the interplay between the dispersive and the dissipative mechanical forces of the resonator.

[1] S. Schütz, H. Habibian, and G. Morigi, *Phys. Rev. A* **88**, 033427 (2013)

[2] S. Schütz, S. B. Jäger, and G. Morigi, arXiv 1508.06606v1, PRA in press.

[3] S. Schütz and G. Morigi, *Phys. Rev. Lett.* **113**, 203002 (2014)

Q 58: Poster: Quantum Optics and Photonics IV

Time: Thursday 16:30–19:00

Location: Empore Lichthof

Q 58.1 Thu 16:30 Empore Lichthof

Quantum Friction and Markovianity — •JULIANE KLATT¹, STEFAN YOSHI BUHMANN¹, and DIEGO A.R. DALVIT² — ¹Albert-Ludwig University, Freiburg, Germany — ²LANL, Los Alamos, NM, USA

Quantum friction is the velocity-dependent force between two polarizable objects in relative motion, resulting from quantum-fluctuation mediated transfer of energy and momentum. Due to its short-ranged nature it has proven difficult to observe.

Attempts to determine the velocity-dependence of the drag experienced by an atom moving parallel to a surface have arrived at contradicting results. Scheel and Buhmann¹ predict a force linear in relative velocity v by employing the quantum regression theorem (QRT). Intravaia², however, predicts a v^3 power-law starting from a non-equilibrium fluctuation-dissipation theorem (FDT). The QRT approach assumes Markovianity, whereas the FDT does not but is restricted to stationary systems instead.

We employ the time-convolutionless expansion (TCL) for probing Markovianity and then study an atom flying towards a surface. We derive signatures of the relative motion in the atom's decay rates and level shifts, calculate the friction experienced by the atom and compare both to results obtained from time-dependent perturbation theory.

- [1] S. Scheel and S. Y. Buhmann, Phys. Rev. A **80** (2009)
- [2] F. Intravaia et al., Phys. Rev. A **89** (2014)

Q 58.2 Thu 16:30 Empore Lichthof

Casimir-Polder Interaction and Matter Wave Scattering — •JOSHUA HEMMERICH and STEFAN BUHMANN — Physikalisches Institut Universität Freiburg, Germany

The interaction between electromagnetically neutral objects, atoms or molecules, has been a subject of study for more than a century. Often known as van der Waals force, this interaction can be formally understood within the context of quantum fluctuations of the electromagnetic field. We review the perturbative calculation of a general expression for the attractive Casimir-Polder potential for an atom interacting with an arbitrarily shaped dielectric body and apply it to the case of a dielectric sphere. The asymptotic behavior of this expression in the nonretarded and retarded limits, for small and large sphere radii and for a perfectly conducting sphere agrees with well-known historical results. We present numerical results for the interaction between a ground-state indium atom and a silicon-dioxide sphere. The results are used to study the impact of the Casimir-Polder force on matter-wave scattering. We are specifically interested in observations regarding the Poisson spot, where precise experiments are shown to lead to direct evidence of such an attractive Casimir-Polder potential.

Q 58.3 Thu 16:30 Empore Lichthof

Casimir-Polder Interaction and Matter Wave Scattering — •JOSHUA HEMMERICH and STEFAN YOSHI BUHMANN — Freiburg University, Freiburg, Germany

The interaction between electromagnetically neutral objects, atoms or molecules, has been a subject of study for more than a century. Often known as van der Waals force, this interaction can be formally understood within the context of quantum fluctuations of the electromagnetic field. We review the perturbative calculation of a general expression for the attractive Casimir-Polder potential for an atom interacting with an arbitrarily shaped dielectric body and apply it to the case of a dielectric sphere. The asymptotic behavior of this expression in the nonretarded and retarded limits, for small and large sphere radii and for a perfectly conducting sphere agrees with well-known historical results. We present numerical results for the interaction between a ground-state indium atom and a silicon-dioxide sphere. The results are used to study the impact of the Casimir-Polder force on matter-wave scattering. We are specifically interested in observations regarding the Poisson spot, where precise experiments are shown to lead to direct evidence of such an attractive Casimir-Polder potential.

Q 58.4 Thu 16:30 Empore Lichthof

Van der Waals interaction of Rydberg atoms in hollow-core fibers — •HELGE DOBBERTIN¹, HARALD R. HAAKH², and STEFAN SCHEEL¹ — ¹Universität Rostock, Rostock, Germany — ²Max Planck Institute for the Science of Light, Erlangen, Germany

The presence of material boundaries modifies the van der Waals inter-

actions between atoms and molecules [1]. In hollow-core fibers, it has been shown that there exist regimes in which the (nonresonant) interaction between ground-state atoms can be exponentially suppressed due to the lack of available waveguide modes [2]. Conversely, the presence of such modes for the relevant atomic transition frequencies may lead to an extended interaction range. Due to their extreme polarizability, Rydberg atoms are ideal candidates for strong dispersion interactions. The appearance of resonant contributions to the van der Waals interaction for excited atoms at their resonance frequencies provides an additional handle [3]. Here, we show how the waveguide modes in a cylindrical hollow-core fiber affect the van der Waals potential between highly-excited Rydberg atoms and, as a result, their Rydberg blockade.

- [1] H. Safari *et al.*, Phys. Rev. A **74**, 042101 (2006).
- [2] H.R. Haakh and S. Scheel, Phys. Rev. A **91**, 052707 (2015).
- [3] H. Safari and M.R. Karimpour, Phys. Rev. Lett. **114**, 013201 (2015).

Q 58.5 Thu 16:30 Empore Lichthof

Magnetic Casimir-Polder Interaction and the Influence of Foucault currents — •DANIEL REICHE^{1,2}, FRANCESCO INTRAIVAIA², and KURT BUSCH^{1,2} — ¹Humboldt-Universität zu Berlin, Institut für Physik, AG Theoretische Optik & Photonik, Newtonstr. 15, 12489 Berlin, Germany — ²Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy, Max-Born-Str. 2A, 12489 Berlin, Germany

Miniaturization is a major task for modern physics and for this atomic systems are promising candidates, e.g. for the implementation of quantum technologies. However, as atoms are trapped in a confined volume near macroscopic objects, phenomena like Casimir-Polder forces become important. In recent years, progress in experimental methods has revealed some not yet understood behaviors of these interactions, especially with respect to dissipation in material composing the macroscopic body.

To gain more insight we investigate the contribution of the Foucault current modes on the magnetic Casimir-Polder interaction for a two-level atom in front of a conducting half-space. Both, a local Drude model and a non-local material model are considered for the description of the half-space's permittivity. We analyze in detail the temperature dependence of some relevant thermodynamical properties of this contribution.

Q 58.6 Thu 16:30 Empore Lichthof

Decay properties of an atom coupled to a disordered 1D waveguide — •MICHAEL P. SCHNEIDER¹, CHRISTOPH MARTENS¹, TOBIAS SPROLL¹, and KURT BUSCH^{1,2} — ¹Max-Born-Institut, Max-Born-Str. 2A, 12489 Berlin, Germany — ²Humboldt-Universität zu Berlin, Institut für Physik, AG Theoretische Optik & Photonik, Newtonstr. 15, 12489 Berlin

Single atoms coupled to one-dimensional (1D) waveguides are systems that are experiencing growing interest over the last years. They can be thought of as building blocks for quantum networks, where the entanglement between the atoms is distributed by means of single photons. These systems can be combined with structured waveguides, which exhibit a nonlinear dispersion relation, including band edges. In this case, the coupled atom-waveguide system supports an atom-photon bound state in the band gap. This is a polaritonic eigenstate of the system, which can be used for example to trap light.

We analyze the decay properties of a two-level system (TLS) coupled to a 1D waveguide with (fabricational) disorder. With the help of disorder-averaged Green's functions, also backed up by numerical calculations, we find that the atom-photon bound state is unstable for large enough disorder. Within the framework of a newly developed formalism we associate this effect to the disorder-induced smearing of the waveguides density of states. Additionally, we identify a special set of diagrams which are dominant for energies far away from the band edge. These diagrams introduce a new timescale in the decay process and thus render the system non-Markovian.

Q 58.7 Thu 16:30 Empore Lichthof

Atomic population transfer in integrated 1-D photonic structures — •TOBIAS SPROLL¹, CHRISTOPH MARTENS¹, FRANCESCO INTRAIVAIA¹, and KURT BUSCH^{1,2} — ¹Max-Born-Institut, Berlin, Germany — ²Humboldt University, Berlin, Germany

As an important mechanism of population transfer, we discuss Förster resonance energy transfer (FRET) which has found wide applications in chemistry and biology. For example, FRET is used to measure interactions between proteins or distances inside them. Furthermore it is hoped that this effect leads to new opportunities for manipulating and storing information in optical circuits.

We analyze FRET in a model system consisting of a 1D optical wire and two atoms, modeled as 2-level systems. We analyze the spectrum of the problem using tools from Quantum Field Theory. From this results we argue that there are very general reasons that FRET in 1D is a truly non-Markovian effect and is mediated by the polaritonic eigenmodes of our model system which occurrence strongly depends on the curvature and boundedness of the dispersion relation of the waveguide. This shows that linearization of the spectra may be insufficient to catch essential physical features of these systems.

A possible interesting application of our result could be in light harvesting complexes which are important for the design of organic solar cells.

Q 58.8 Thu 16:30 Empore Lichthof

Dynamics and interaction of two emitters embedded in a one-dimensional waveguide — ●CHRISTOPH MARTENS¹, TOBIAS SPROLL¹, MICHAEL PETER SCHNEIDER¹, FRANCESCO INTRAVAIA¹, and KURT BUSCH^{1,2} — ¹Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy, Max-Born-Str. 2a, 12489 Berlin, Germany — ²Humboldt-Universität zu Berlin, Institut für Physik, AG Theoretische Optik & Photonik, Newtonstr. 15, 12489 Berlin, Germany

Integrated, low-dimensional waveguiding structures with embedded emitters are promising candidates to form the basic building blocks of quantum-information processing networks. On this account, it is vital to study and understand the light-matter interactions within these structures on the quantum level.

In this contribution, we analyze the interaction of two two-level emitters embedded in a one-dimensional waveguide. We show how the dynamics of light emission and absorption is influenced by both polaritonic and cavity-like eigenstates of the whole system as well as by the mode structure of the waveguiding continuum. Furthermore, we reveal super- and subradiant states of the system.

Q 58.9 Thu 16:30 Empore Lichthof

Circuit-QED with left-handed superlattice metamaterials — ●ANETTE MESSINGER, BRUNO TAKETANI, and FRANK K. WILHELM — Theoretical Physics, Saarland University, 66123 Saarbrücken, Germany

Circuit QED deals with quantum phenomena in superconducting circuits, in which photons can interact with artificial qubits. With new circuit architectures one can reach new optical properties like nonlinear effects and left-handedness with promising applications for quantum computers. Recently, a quantum mechanical phase transition of the qubit's tunneling probability was predicted in a transmission line coupled to a left-handed circuit [1].

In this work, we investigate a superlattice of two alternating left-handed circuit cells instead of a normal left-handed circuit. This gives rise to a new energy band in which the density of modes can reach extremely high values, and with that, strong multimode coupling of the qubit is possible. Furthermore, we use adiabatic renormalization to find the effective tunneling element of the qubit. While in the previously proposed system one phase transition from delocalization of the qubit to quasi-localization was observed, here we will show two additional phases of partial localization appearing.

References:

[1] D. J. Egger and F. K. Wilhelm, Phys. Rev. Lett. 111, 163601 (2013)

Q 58.10 Thu 16:30 Empore Lichthof

Superballistic center-of-mass motion in one-dimensional attractive Bose gases: Decoherence-induced Gaussian random walks in velocity space — ●CHRISTOPH WEISS¹, SIMON CORNISH¹, SIMON GARDINER¹, and HEINZ-PETER BREUER² — ¹Joint Quantum Centre (JQC) Durham–Newcastle, Department of Physics, Durham University, United Kingdom — ²Physikalisches Institut, Univ. Freiburg, Germany

We show that the center-of-mass motion of ultracold attractively interacting bosons can become superballistic in the presence of decoherence, via single-, two- and/or three-body losses. In the limit of weak decoherence, we analytically solve the numerical model introduced in [1]. The analytical predictions allow us to identify experimentally accessible pa-

rameter regimes for which we predict superballistic motion of the center of mass. Ultracold attractive Bose gases form weakly bound molecules, quantum matter-wave bright solitons. Our computer-simulations combine ideas from classical field methods ("truncated Wigner") and piecewise deterministic stochastic processes. While the truncated Wigner approach to use an average over classical paths as a substitute for a quantum superposition often is an uncontrolled approximation, here it predicts the exact root-mean-square width when modeling an expanding Gaussian wave packet. In the superballistic regime, the leading-order of the motion can thus be modeled as a quantum superposition of classical Gaussian random walks in velocity space.

[1] C. Weiss et al., Phys. Rev. A 91, 063616 (2015).

[2] C. Weiss et al., arXiv:1510.05204

Q 58.11 Thu 16:30 Empore Lichthof

Resonance fluorescence spectrum of a laser-cooled atom trapped in a non-harmonic potential — ●RALF BETZHOLZ and MARC BIENERT — Theoretische Physik, Universität des Saarlandes, D-66123 Saarbrücken, Germany

Single trapped atoms open the possibility of realizing well controlled quantum interfaces. When the atom, trapped in a non-harmonic potential, is cooled by a laser the spectral sidebands of the emitted light allow to monitor the dynamics of the motional degrees of freedom and the readout of the thermal distribution. We evaluate the laser cooling and the spectrum of resonance fluorescence for two exemplary trapping potentials: an infinite square well potential and the Morse potential.

Q 58.12 Thu 16:30 Empore Lichthof

Efficient coupling of a trapped moving atom to a single photon in free space — ●THORSTEN HAASE, NILS TRAUTMANN, and GERNOT ALBER — Institut für Angewandte Physik, Technische Universität Darmstadt

The efficiency of the coupling of a single trapped two-level-system to a single photon in free space is strongly affected by the two level system's center of mass motion, especially if no sub-Doppler cooling techniques are applied [1]. By squeezing the center of mass state, the coupling efficiency of the two level system to a single photon can be greatly enhanced. Squeezing can be induced by parametric amplification due to a time dependent modulation of a harmonic trapping potential which can be realized even in cases of a weak trapping potential. We investigate the dynamics of the center of mass motion in the modulated trapping potential by taking dissipative processes into account which are induced by Doppler cooling.

[1] M. Fischer, M. Bader, R. Maiwald, A. Golla, M. Sondermann, and G. Leuchs, Applied Physics B 117, 797 (2014).

Q 58.13 Thu 16:30 Empore Lichthof

Light-light interaction in strong plane-wave laser fields — SEBASTIAN MEUREN, ●SERGEY BRAGIN, RASHID SHAISULTANOV, CHRISTOPH H. KEITEL, and ANTONINO DI PIAZZA — Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg

While according to classical electrodynamics the superposition principle holds in vacuum, in quantum field theory light interacts with a background electromagnetic field via virtual charged particles. If the field is effectively of the order of the critical field of QED, also the transformation of a photon into a real electron-positron pair becomes sizable (nonlinear Breit-Wheeler process). These light-light interaction effects could be measurable at upcoming laser facilities like Vulcan 10P, ELI and XCELS [1]. Here, we present the momentum distribution of Breit-Wheeler electron-positron pairs in detail and introduce an intuitive semiclassical model which explains all qualitative features of the corresponding spectrum [2]. Also, we study the exact photon propagator inside a plane-wave laser field [3]. Due to light-light interaction the propagation of a photon through the background field is modified in a nontrivial way. By solving the Dyson-Schwinger equations we obtain a compact expression valid to one-loop order and discuss possible applications of our finding.

[1] A. Di Piazza et al., Rev. Mod. Phys. 84, 1177–1228 (2012)

[2] S. Meuren, C. H. Keitel, and A. Di Piazza, arXiv:1503.03271 (2015)

[3] S. Bragin et al., in preparation.

Q 58.14 Thu 16:30 Empore Lichthof

Analytical tools for investigating strong-field QED processes in tightly focused laser fields — ANTONINO DI PIAZZA and ●ALESSANDRO ANGIOI — Max-Planck-Institut für Kernphysik,

Saupfercheckweg 1, D-69117 Heidelberg

The theoretical analysis of QED processes in intense laser fields has been limited to within the plane-wave approximation [1], even if the very high intensities considered in those analysis are, as of today, only reachable by focusing the laser energy almost to diffraction limit. Here we construct single-particle fermion states in the presence of a background electromagnetic field of general space-time structure within the WKB approximation [2]. Our main assumption is the realistic one that the initial energy of the electron is the largest dynamical energy scale in the problem. A substitution rule is found that allows these states to be obtained from the well-known Volkov wave functions in a plane-wave field [3]. Moreover, scalar and spinor propagators are constructed under the same approximations. The development of these tools opens in particular the possibility of investigating strong field QED processes in the presence of tightly focused strong fields analytically.

- [1] A. Di Piazza et al., *Rev. Mod. Phys.* **84**, 1177 (2012).
 [2] A. Di Piazza, *Phys. Rev. Lett.* **113**, 040402 (2014).
 [3] A. Di Piazza, *Phys. Rev. A* **91**, 042118 (2015).

Q 58.15 Thu 16:30 Empore Lichthof

Many-body phases emerging from the competition between long-range and short-range potentials — ●REBECCA KRAUS¹, KATHARINA ROJAN¹, HESSAM HABIBIAN^{2,3}, and GIOVANNA MORIGI¹ — ¹Theoretische Physik, Universität des Saarlandes, D-66123 Saarbrücken, Germany — ²Departament de Física, Universitat Autònoma de Barcelona, E-08193 Bellaterra, Spain — ³Institut de Ciències Fotòniques (ICFO), Mediterranean Technology Park, E-08860 Castelldefels (Barcelona), Spain

We consider the Bose-Hubbard model for ultracold bosonic atoms confined by an optical lattice inside an optical resonator. The atoms interact with a cavity mode whose wavelength is incommensurate with the spatial periodicity of the confining potential, as considered in [1]. We consider a two-dimensional gas and identify the parameter tuning the strength of the long-range cavity mediated potential and the onsite interaction. In absence of the cavity, the second incommensurate potential is absent and the well-known Superfluid-Mott insulator transition is found. For small cavity fields, the cavity potential stabilizes glassy phases at sufficiently small kinetic energy [1]. We complete the diagram by analysing the situation, when the cavity potential is dominant over the onsite interaction and discuss the nature of the phases we identify.

- [1] H.Habibian et al., *Phys. Rev. Lett.* **110**, 075304 (2013)

Q 58.16 Thu 16:30 Empore Lichthof

Realizations of non-linear quantum maps in the one-atom maser model — ●FELIX WEBER, ZSOLT BERNÁD, and GERNOT ALBER — Institut für Angewandte Physik, Technische Universität Darmstadt, D-64289 Darmstadt

We investigate the iterative behavior of a single mode cavity field which interacts repeatedly with two-level atoms. In our scenario two-level atoms are successively inserted into the cavity containing a superposition of Fock states and interact with this field. Subsequently, the atoms leaving the cavity are postselected. We study the behavior of the photonic state resulting from many iterations of this postselection process. For arbitrary initial conditions and interaction times the fixed points of this transformation and the state to which the field converges after many iterations are determined.

Q 58.17 Thu 16:30 Empore Lichthof

Towards Cavity QED with N-type atoms — ●KARL NICOLAS TOLAZZI, CHRISTOPH HAMSEN, HAYTHAM CHIBANI, TATJANA WILK, and GERHARD REMPE — Max Planck Institute of Quantum Optics, Hans-Kopfermann-Str. 1, 85748 Garching, Germany

The combination of electromagnetically induced transparency (EIT) and cavity QED leads to an interesting new regime with large light-light coupling [1]. This can be realized by a single atom with a lambda-type level scheme where one atomic transition (probe) is strongly coupled to an optical cavity. The second transition (control) in the lambda scheme can then be used to control the properties of the probe light field. Extending this scheme to an atom with a N-type level scheme where an additional transition (signal) is also strongly coupled to the cavity enables control of the EIT resonance [2,3]. This is due to the cavity-enhanced ac-Stark shift of the atomic levels by the signal light

field. Thus even single photons in the signal field result in a detuning of the narrow EIT window which leads to considerable phase shifts in the probe beam [4]. This so called cross-phase modulation (XPM) can be understood as a strong effective Kerr nonlinearity which can be engineered on demand. We present first steps towards an experimental realization of this scheme with single ⁸⁷Rb atoms trapped inside a high finesse optical Fabry-Perot resonator of variable length.

- [1] M. Mücke et al., *Nature* **465**, 7299 (2010).
 [2] A. İmamoğlu et al., *Physical Review Letters*, **79**, 8 (1997).
 [3] S. Rebić et al., *Journal of Optics B* **1**, 4 (1999).
 [4] A. Feizpour et al., *Nature Physics* **11**, 11 (2015).

Q 58.18 Thu 16:30 Empore Lichthof

Quantum dynamics in spatially resolved two-atom cavity-QED — ●MATTHIAS KÖRBER, ANDREAS NEUZNER, OLIVIER MORIN, STEPHAN RITTER, and GERHARD REMPE — Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching

Embedding an optical emitter in a Fabry-Perot-type optical cavity has become a well-established technique to study the interaction of matter with a single mode of the light field. By extending this system to multiple atoms coupling to the same cavity mode, novel effects and degrees of freedom emerge compared to the single atom case: When an atom pair is driven with a laser transversal to the cavity axis, the difference position of the atoms defines the relative phase with which the atoms couple to the driving laser and the cavity mode. To achieve experimental control over this new degree of freedom, we pin two atoms to the sites of a two-dimensional optical lattice in the plane spanned by the cavity axis and the direction of the driving laser. The relative distance between the occupied lattice sites is determined via fluorescence imaging with single-site resolution. Thereby, the phase difference of the two atoms can be resolved. We show that the intensity and the correlation properties of the light scattered into the cavity strongly depend on this relative phase, and foresee further studies of fundamental aspects of light-matter interaction enabled by our experimental setting.

Q 58.19 Thu 16:30 Empore Lichthof

Strong optical nonlinearity induced by weakly interacting ions — ●ROBERT JOHNE and THOMAS POHL — Max Planck Institute for the Physics of Complex Systems, Nöthnitzer Straße 38, 01187 Dresden, Germany

The generation of strong optical nonlinearities at smaller and smaller pump powers is a long-standing goal of technological and fundamental significance. The ultimate challenge is a single-photon nonlinearity, where a single light quantum is sufficient to drastically alter the system response for subsequent ones. Here we show that such a strong optical nonlinearity can be generated by weakly interacting ions placed in a cavity. In contrast to the conventional photon blockade based on the Jaynes-Cummings nonlinearity, the present system does not require ultrahigh quality cavities since the nonlinearity is induced by ion-ion interactions. We theoretically analyse in detail the system dynamics in dependence on various parameters and show that a strong nonlinear response is maintained although the ion-ion interaction strength is orders of magnitude smaller than all other parameters such as the cavity loss rate. The system holds great promise for advanced applications in quantum information processing e.g. single photon switches as well as for the deterministic generation of photon Fock states.

Q 58.20 Thu 16:30 Empore Lichthof

Long high finesse fiber Fabry-Pérot resonators — KONSTANTIN OTT^{1,2}, SÉBASTIEN GARCIA¹, FRANCESCO FERRI¹, ●TORBEN PÖPPLAU¹, RALF KOHLHAAS¹, KLEMENS SCHÜPPERT³, ROMAIN LONG¹, and JAKOB REICHEL¹ — ¹Laboratoire Kastler Brossel, ENS/CNRS/UPMC, Paris (France) — ²LNE-SYRTE, Observatoire de Paris/CNRS/UPMC, Paris (France) — ³Institute for Experimental Physics, University Innsbruck, Austria

We present the realization of millimeter-long fiber coupled open Fabry-Pérot resonators with a finesse of 46.000. Deterioration of the finesse with increasing resonator length observed in previous experiments could be suppressed by advances in the CO₂ laser-based fabrication process of the fiber micro mirrors. In this way, resonator lengths up to 1.4 mm could be realized, corresponding to a free spectral range of 107 GHz and linewidths of 2.2 MHz.

Fiber-based micro-cavities are of great use in experimental quantum information science, as they have many application benefits. The reduced apparatus size and direct fiber coupling lead to an increased stability. Beyond concave mirror structures, the novel multi-pulse laser fabrication technique further allows to enlarge the range of accessi-

ble structures, including asymmetric mirror profiles, convex shapes on fiber tips and on macroscopic fused silica substrates.

Q 58.21 Thu 16:30 Empore Lichthof

3D motional ground state cooling and collective scattering of two atoms inside a high-finesse cavity — •NATALIE THAU, WOLFGANG ALT, TOBIAS MACHA, LOTHAR RATSCHBACHER, RENÉ REIMANN, SEOKCHAN YOON, and DIETER MESCHDE — Institut für Angewandte Physik der Universität Bonn, Wegelerstr. 8, 53115 Bonn
Tight control and knowledge of the motional states of single atoms are a prerequisite for many cavity-QED experiments. In our system single cesium atoms coupled to a high finesse optical cavity are cooled close to the 3D motional ground state by means of resolved Raman sideband cooling. Two Raman beams are formed by a blue detuned dipole trap and a perpendicularly adjusted running wave driving Raman transitions between two hyperfine ground states. Thereby we strongly suppress motional carrier transitions along the dipole trap axis [1]. Efficient cooling along all three dimensions is implemented with a second pair of Raman beams using the intracavity dipole trap. Driving two atoms with a probe beam from the side we measure super- and subradiant Rayleigh scattering into the cavity depending on the relative distance between the two atoms [2]. The information on the relative phase of the driving and cavity light fields at the atom positions and efficient pinning of the atoms in their 3D optical lattice due to two Raman cooling are important for the implementation of two-atom entanglement schemes [3].

- [1] R. Reimann *et al.*, New J. Phys. **16**, 113042 (2014)
[2] R. Reimann *et al.*, Phys. Rev. Lett. **114**, 023601 (2015)
[3] F. Reiter *et al.*, New J. Phys. **14**, 053022 (2012)

Q 58.22 Thu 16:30 Empore Lichthof

Fabrication and characterization of Fabry-Pérot microcavities — •FELIX GLÖCKLER, ANDREA KURZ, ANDREAS DIETRICH, FEDOR JELEZKO, and ALEXANDER KUBANEK — University Ulm, Institute for Quantum Optics, Germany

Starting with the question whether the excited-state lifetime of an atom can be modified, many experiments have been performed in order to engineer the properties of quantum emitters. The change of spontaneous emission is typically associated with Purcell's prediction that the radiation of a dipolar transition can be accelerated with a cavity by the Purcell factor $F_P = \frac{3\lambda^3 Q}{4\pi^2 V}$ which is mainly dependent on the quality factor Q and the Volume V of the cavity. Realizing high Purcell factors via the recipe high Q low V is non-trivial. Open Fabry-Pérot cavities are particularly attractive to achieve this goal since they are easily tunable and compatible with different kinds of emitters. In this work we will concentrate on achieving sizable F_P by optimizing the Q/V ratio.

Q 58.23 Thu 16:30 Empore Lichthof

Many-Body Dynamics Through Measurement and Feedback — •JONAS LAMMERS^{1,2}, HENDRIK WEIMER¹, and KLEMENS HAMMERER^{1,2} — ¹Institut für Theoretische Physik, Leibniz Universität Hannover — ²Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut), Hannover

Time-continuous homodyne measurements and feedback allow for efficient quantum control of a broad range of systems, such as cavity and circuit QED, atomic ensembles, or optomechanics. Here we consider interferometric measurements on an array of such systems. We derive the corresponding feedback master equation, and apply it for the generation of many-particle entangled, stationary states (such as Bell, GHZ, and W states), and for the engineering of non-equilibrium dynamics of many-body systems (such as dissipative Ising models).

Q 58.24 Thu 16:30 Empore Lichthof

Ion-ion entanglement with large numerical aperture optics — •DANIEL HIGGINBOTTOM^{1,2}, GABRIEL ARANEDA², LUKÁŠ SLODIČKA^{2,3}, LUKAS LACHMAN³, RADIM FILIP³, YVES COLOMBE², and RAINER BLATT² — ¹ANU, Australia — ²Universität Innsbruck, Österreich — ³Palacký University, Czech Republic

We trap short strings of ions at the focus of large numerical aperture optics as a means of generating quantum optical fields and ion-ion entanglement. We generate single photon Fock states and demonstrate their purity by measuring violations of a non-Gaussian field witness [1]. We then entangle two trapped ions with a single-photon herald by indistinguishably coupling the ions to a single detection mode [2]. Parity measurements characterize the bipartite entanglement and we

describe an additional entanglement signature measured by scattering a second photon from the entangled state. The collection efficiency of the lenses used in these experiments limits the single-photon source efficiency and the entanglement fidelity and generation rate. We present the fabrication and characterization of hemispheric mirrors for stronger atom-light coupling and outline how such a mirror may be used to enhance or suppress the spontaneous emission of an ion trapped at the mirror's centre of curvature [3].

- [1] R. Filip, L. Mišta, Phys. Rev. Lett. **106**, 200401 (2011). [2] L. Slodička, G. Hétet, N. Röck, P. Schindler, M. Hennrich, R. Blatt, Phys. Rev. Lett. **110**, 083603 (2013). [3] G. Hétet, L. Slodička, A. Glätzle, M. Hennrich, R. Blatt, Phys. Rev. A **82**, 63812 (2010).

Q 58.25 Thu 16:30 Empore Lichthof

Entanglement of Polarization and Orbital Angular Momentum — •DANIEL BHATTI^{1,3}, JOACHIM VON ZANTHIER^{1,3}, and GIRISH S. AGARWAL² — ¹Institut für Optik, Information und Photonik, Universität Erlangen-Nürnberg, 91058 Erlangen, Germany — ²Department of Physics, Oklahoma State University, Stillwater, OK, USA — ³Erlangen Graduate School in Advanced Optical Technologies (SAOT), Universität Erlangen-Nürnberg, 91052 Erlangen, Germany

It is known that for identical particles entangled states can be constructed using different degrees of freedom, e.g., linear momentum and polarization. Recently it was shown that also orbital angular momentum (OAM), another degree of freedom of the radiation field, can be employed for entanglement generation [1]. We discuss the particular case of two photons with the same linear momentum but entangled in polarization and OAM degrees of freedom [2]. We show how to produce such entangled states and use the recently introduced concept of duality [3,4] to perform entanglement sorting. Here, the entangled character can be detected by studying either polarization variables or OAM variables using appropriate witnesses. In both cases identical information is obtained if the particles are indistinguishable. We also present generalizations to three- and four-photon entangled states.

- [1] A. Mair, et al., Nature **412**, 313 (2001).
[2] D. Bhatti, J. von Zanthier, G. S. Agarwal, Phys. Rev. A **91**, 062303 (2015).
[3] S. Bose, D. Home, Phys. Rev. Lett. **110**, 140404 (2013).
[4] J.-J. Ma, et al., New Journal of Physics **16**, 083011 (2014).

Q 58.26 Thu 16:30 Empore Lichthof

Entanglement of an open quantum system with its environment — •NINA MEGIER¹, ANSGAR PERNICE¹, FRANZISKA PETER², and WALTER T. STRUNZ¹ — ¹TU Dresden — ²Universität Potsdam

To investigate entanglement of an open quantum system with its environment the description using the reduced density matrix is not sufficient. By a linear coupling to the bath of harmonic oscillators the partial P-representation allows to efficiently determine the total state of system and environment. We use this approach in a Markov approximation. With the Peres-Horodecki separability criterion we study system - environment entanglement.

Q 58.27 Thu 16:30 Empore Lichthof

exact entanglement dynamics under the influence of a common structured environment using HOPS — •RICHARD HARTMANN and WALTER T. STRUNZ — Institut für Theoretische Physik, Technische Universität Dresden, D-01062 Dresden, Germany

Open quantum systems have to be considered as the general case when examining quantum mechanics experimentally or its technical applications. Therefore the computation of the so called reduced dynamics gains interest in many areas of physics, although no exact and efficient method has been developed yet. Especially when dealing with strong system-bath interactions the "hierarchy of pure states" (HOPS) [1] promises an interesting approach to estimate the exact non Markovian reduced dynamics.

Motivated by the vast progress in implementing qubits in solid state nano devices, we focus in this work on the entanglement dynamics of two non interacting qubits coupled to a common sub-ohmic bosonic bath. Questions such as entanglement decay and sudden death of entanglement as well as entanglement creation are addressed by comparing the exact numeric results gained using HOPS with approximative results employing the Redfield master equation and a second order weak coupling expansion of the non Markovian quantum state diffusion equation [2].

- [1] D. Süß, A. Eisfeld, and W.T. Strunz, Phys. Rev. Lett. **113**, 150403 (2014).
[2] L. Diósi, N. Gisin, W.T. Strunz, Phys. Rev. A **58**, 1699–1712

(1998).

Q 58.28 Thu 16:30 Empore Lichthof

Collisional decoherence of polar molecules — •KAI WALTER, BENJAMIN A. STICKLER, and KLAUS HORNBERGER — Faculty of Physics, University of Duisburg-Essen, Germany

Collisions with background gases are an important source of environmental decoherence in interference experiments with molecular matter waves [1]. So far, the theoretical description of this effect is limited to the case of isotropic interactions between the colliding pair [2]. However, the large molecules envisioned for future experiments [3] are typically characterized by a permanent dipole moment, implying an orientation-dependent interaction. We present a theoretical description of the decoherence of polar molecules due to collisions with environmental gas atoms. The result is discussed by considering a concrete far-field setup.

- [1] Hornberger et al., Phys. Rev. Lett. 90, 160401 (2003)
- [2] Hornberger et al., Phys. Rev. A, 70, 053608 (2004)
- [3] Arndt et al., Nat. Phys. 10, 271 (2014)

Q 58.29 Thu 16:30 Empore Lichthof

Towards a Lorentz-invariant quantum master equation — •MARDUK BOLANOS and KLAUS HORNBERGER — Fakultät für Physik, Universität Duisburg-Essen

There is an ongoing effort to test the predictions of quantum theory in systems involving a large number of particles. The experiments performed in the last decade have motivated several measures of the macroscopic character of the systems under study. The empirical measure in [1] is based on a minimal modification to the von Neumann equation, that is invariant under *Galilean transformations* and induces the quantum-classical transition.

In this project we aim to develop an extension of the method presented in [1], that allows us to analyze on empirical grounds the macroscopic character of photonic experiments described by a *Lorentz-invariant* theory. As a starting point, in this work we develop a classical master equation with the required invariance property. This result will provide a useful reference when we consider the quantum-classical transition in a relativistic setting.

- [1] Nimmrichter and Hornberger, PRL 110, 160403 (2013).

Q 58.30 Thu 16:30 Empore Lichthof

Attractor Spaces of Dissipatively Dephased Random Unitary Evolution and Quantum Darwinism — •NENAD BALANESKOVIC¹, GERNOT ALBER¹, and JAROSLAV NOVOTNY² — ¹Institut für Angewandte Physik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany — ²Department of Physics, FNSPE, Czech Technical University in Prague, 11519 Praha 1 - Stare Mesto, Czech Republic

We discuss characteristic properties of Quantum Darwinism (QD) [1] involving pure decoherence [4], dissipation and dephasing [3]. In particular, we reconstruct and derive the structure of the corresponding dissipatively dephased attractor spaces of our random unitary qubit-model of QD [2] and investigate whether QD appears with respect to evolution based on non-Controlled-NOT (non-CNOT) unitary operations. We identify those attractor space structures that allow the most efficient storage of classical information about a system into its environment. Furthermore, we conclude that CNOT-type unitary operations appear to be well suited copy-machines when it comes to efficiently store the information about a system's pointer basis into the environment. [1] W. H. Zurek, Nature Physics 5, 181-188 (2009). [2] Novotny, J., Alber, G., I Jex, I., J. Phys A 45, 485301 (2012). [3] V. Scarani et al., Phys. Rev. Lett. 88, 097905 (2002). [4] N. Balaneskovic, EPJD 69, 232 (2015).

Q 58.31 Thu 16:30 Empore Lichthof

Detecting the Berry curvature in photonic graphene — •HOLGER FEHSKE and RAFAEL L. HEINISCH — Institut für Physik, Universität Greifswald, Greifswald, Germany

We propose a method for measuring the Berry curvature from the wave-packet dynamics in perturbed arrays of evanescently coupled optical waveguides with honeycomb lattice structure. To disentangle the effects of the Berry curvature and the energy dispersion we suggest a difference measurement by propagating the wave packet under the influence of a constant external force back and forth. In this way a non-vanishing Berry curvature is obtained for photonic graphene with small sublattice bias or strain, where the relative error between the exact Berry curvature and the one derived from the semiclassical dy-

namics is largely negligible. For the strained lattice we demonstrate the robustness of the Berry curvature texture over the Brillouin zone compared to the energy dispersion.

Q 58.32 Thu 16:30 Empore Lichthof

Symmetry transtion in a periodic parity-time-symmetric potential induced in an atomic sytem — •LIDA ZHANG and JÖRG EVERS — Max Planck Institute for Nuclear Physics, 69117 Heidelberg

We propose a feasible scheme to produce a periodic parity-time (PT) symmetric potential using standing-wave laser fields in an atomic system which combines two different physical processes, i.e., electromagnetically induced transparency and active Raman gain. The resulting band structure of the system shows completely real eigenvalues when the imaginary part of the potential is below a certain limit, corresponding an unbroken PT phase. However, as exceeding this limit, pairs of complex eigenvalues start to enter in the band edge, referring to a broken PT phase. The transition between unbroken and broken PT symmetry can be further characterized by an order parameter. Under two-level approximation, we obtain analytical expressions for the eigenvalues, with which we understand the emergence of complex eigenvalues in a deeper physical level. Moreover, we find a simple analytical solution for the order parameter, which agrees perfectly well with numerical results. Finally, additional nonlocal nonlinear effects is addressed by introducing Rydberg-Rydberg interactions. We find the symmetry transition can be either broken or recovered by the nonlocal nonlinear effects.

Q 58.33 Thu 16:30 Empore Lichthof

Lasing Without Inversion in Quecksilber bei 253,7 nm — BENJAMIN REIN, •JOCHEN SCHMITT und THOMAS WALTHER — TU Darmstadt, Institut für Angewandte Physik, AG Laser und Quantenoptik, Schlossgartenstr. 7, D-64289 Darmstadt

Mit herkömmlichen Lasersystemen werden Wellenlängen im ultravioletten Bereich im Dauerbetrieb in der Regel mittels Frequenzverdopplung bzw. -vervierfachung erreicht. Einen weiteren Ansatz, um in diesen Frequenzbereich vorzudringen, bietet Lasing Without Inversion (LWI), welches die Anregung atomarer Kohärenzen ausnutzt, um die Absorption des unteren Laserniveaus zu unterdrücken, also folglich ohne Besetzungsinversion funktionieren kann. Als Medium wird im gezeigten Experiment Quecksilber verwendet, welches durch die vorhandenen Niveaus Laserübergänge bei 253,7 nm und 185 nm ermöglicht. Für die Anregung der atomaren Kohärenzen werden Laser der Wellenlänge 435,8 nm und 546,1 nm benötigt, in dieser Konstellation kann LWI bei der Wellenlänge 253,7 nm realisiert werden. Der aktuelle Stand des Forschungsprojekts wird diskutiert.

Q 58.34 Thu 16:30 Empore Lichthof

Ein Titan:Saphir Lasersystem zur Erzeugung von ns-Pulsen bei 420 nm und 1995 nm — •TOBIAS EGGERT¹, VINCENZO TALLUTO¹, THOMAS WALTHER¹, LUKAS MADER¹ und THOMAS BLOCHOWICZ² — ¹Institut für Angewandte Physik, Technische Universität Darmstadt, Schlossgartenstr. 7, 64289 Darmstadt — ²Institut für Festkörperphysik, Technische Universität Darmstadt, Hochschulstr. 8, 64289 Darmstadt

Wir stellen ein gepulstes Titan:Saphir Lasersystem bei 840 nm vor, das durch nichtlineare Frequenzkonversionsprozesse ns-Pulse bei 420 nm und 1995 nm erzeugt. Durch Injection-Seeding und einer kompakten Bauweise bietet das System sehr stabile und kurze Buildup Zeiten. Dies ermöglicht neben der Differenzfrequenzmischung des frequenzverdoppelten Titan:Saphir Pulses mit dem Pumpimpuls auch die Synchronisation mehrerer Lasersysteme.

Q 58.35 Thu 16:30 Empore Lichthof

Photon statistics of quantum-dot superluminescent diodes — •FRANZISKA FRIEDRICH and REINHOLD WALSER — Institut für Angewandte Physik, Darmstadt, Germany

Commercial devices for optical coherence tomography greatly benefit from the appealing features of broadband light emitting quantum-dot superluminescent diodes (QDSLs), where light is generated in the regime of amplified spontaneous emission (ASE). But also from the fundamental point of view, these devices exhibit uncommon properties considering field and intensity correlations, $g^{(1)}(\tau)$ and $g^{(2)}(\tau)$: a reduction of $g^{(2)}(0)$ from 2 to 1.33 at $T = 190$ K was observed in the lab in 2011 [1]. The understanding of these hybrid coherent light states, which are simultaneously incoherent in $g^{(1)}(\tau)$ and coherent in $g^{(2)}(\tau)$, represents an interesting and challenging topic of research.

In a previous study [2], we assumed that the quantum state of the emitted diode light is well described by a multimode phase-randomized Gaussian (PRAG) state. Amongst sundry results, the experiment measured time resolved $g^{(2)}(\tau)$ in the fs time scale using modern fast two-photon detectors. It turned out that the assumption of PRAG states agrees with experimental findings. In the present contribution, we will discuss a model of the QDSL and study the generation of the amplified spontaneous emission on a microscopic level [3].

[1] M. Blazek, W. Elsässer, Phys. Rev. A **84**, 063840 (2011)

[2] S. Hartmann et al., New J. Phys. **17**, 043039 (2015)

[3] to be published

Q 58.36 Thu 16:30 Empore Lichthof

Potassium Spectroscopy on a Sounding Rocket — ●KAI LAMPMANN¹, ORTWIN HELLMIG⁵, MARKUS KRUTZIK², ACHIM PETERS^{2,3}, ANDRÉ WENZLAWSKI¹, PATRICK WINDPASSINGER^{1,5}, and THE KALEXUS TEAM^{1,2,3,4} — ¹Johannes Gutenberg-Universität, Mainz — ²Humboldt-Universität zu Berlin — ³Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik, Berlin — ⁴Leibniz Universität Hannover — ⁵Universität Hamburg

We present the laser system of the sounding rocket experiment KALEXUS. This mission is scheduled to be launched in spring 2016 and should demonstrate the fully autonomous operation of a system for laser frequency stabilization, which is required e.g. for quantum gas experiments in space. The whole system is designed to meet the stringent requirements of a sounding rocket launch and to provide redundancy options to handle possible system failures.

The spectroscopy module for absolute frequency stabilization to the potassium D2 line consists of special monolithic Zerodur components for guiding and overlapping the beams. A fiber based splitting module connects the different functional units of the system and provides a beat note detection for offset frequency stabilization. We show ground based characterization measurements of the spectroscopy system and tests for space qualification.

The KALEXUS project is led by the Humboldt-Universität zu Berlin and supported by the German Space Agency DLR with funds provided by the Federal Ministry for Economic Affairs and Energy (BMWi) under grant number 50 WM 1345.

Q 58.37 Thu 16:30 Empore Lichthof

Laser system technology for rubidium atom interferometry aboard sounding rockets — ●VLADIMIR SCHKOLNIK¹, MARKUS KRUTZIK¹, ACHIM PETERS^{1,2}, THE MAIUS TEAM^{1,2,3,4,5}, and THE FOKUS TEAM^{1,2,3,4} — ¹Institut für Physik, Humboldt-Universität zu Berlin — ²Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik, Berlin — ³ILP, Universität Hamburg — ⁴Institut für Physik, JGU Mainz — ⁵IQO, Leibniz Universität Hannover

Laser systems with precise and accurate frequencies are one of the key elements in modern precision experiments such as atom interferometers and atomic clocks. Future space missions including quantum interferometry based gravity mapping, tests of the equivalence principle or the detection of gravitational waves will need robust and compact lasers with high mechanical and frequency stability.

We present a new generation of compact diode laser systems optimized for precision measurement applications with ultra-cold atoms aboard sounding rockets. Design, assembly and qualification of the laser system for the MAIUS mission, an atom interferometer with degenerate ⁸⁷Rb scheduled for launch 2016 is discussed.

All key technologies have already been successfully tested on a separate sounding rocket mission in 2015 by performing precision Doppler free spectroscopy in space on the TEXUS 51 mission. The payload and the experimental results are presented.

This work is supported by the German Space Agency DLR with funds provided by the Federal Ministry for Economic Affairs and Energy under grant numbers DLR 50WM 1237-1240, and 1345.

Q 58.38 Thu 16:30 Empore Lichthof

Automated experiment control and laser frequency stabilization of the KALEXUS experiment on a sounding rocket. — ●ALINE DINKELAKER¹, ANDREW KENYON¹, MAX SCHIEMANGK¹, VLADIMIR SCHKOLNIK¹, MARKUS KRUTZIK¹, ACHIM PETERS^{1,2}, and THE KALEXUS TEAM^{1,2,3,4,5} — ¹Institut für Physik, Humboldt-Universität zu Berlin — ²FBH Berlin — ³JGU Mainz — ⁴LU Hannover — ⁵Menlo Systems GmbH

To demonstrate the functionality of a laser system for atomic physics experiments in space, the KALEXUS experiment tests the performance

of two frequency stabilized micro-integrated extended cavity diode lasers (ECDLs) on a sounding rocket for the first time. Most challenging is the sensitivity of ECDLs to vibrational and thermal effects as locking parameters can change throughout launch and flight, while real-time communication to adjust these parameters is not possible in our mission. Therefore we developed automated control software with a state machine to regulate the experiment during its sequence and perform absorption spectroscopy and different functional tests, including tests of fallback options and redundancy equipment. The experiment is autonomous from first switch-on and requires no manual control. We present the structure of the experimental control, focusing on the implementation of several layers of auto-detection for autonomous frequency stabilization in the changing environment of a sounding rocket.

The KALEXUS project is supported by the German Space Agency DLR with funds provided by the Federal Ministry for Economic Affairs and Energy (BMWi) under grant number 50 WM 1345.

Q 58.39 Thu 16:30 Empore Lichthof

Noncollinear optical parametric oscillators for Raman Spectroscopy — ●LUISE BEICHERT¹, YULIYA KHANUKAEVA¹, and UWE MORGNER^{1,2,3} — ¹Institute of Quantum Optics, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany — ²Centre for Quantum Engineering and Space-Time Research (QUEST), Welfengarten 1, 30167 Hannover, Germany — ³Laser Zentrum Hannover (LZH), Hollerithallee 8, 30419 Hannover, Germany

Meanwhile microplastics can be detected at an increasing rate in our oceans as well as in our drinking water. We present new light sources with a high bandwidth and high output power for detecting these particles via simulated Raman scattering.

Noncollinear optical parametric oscillators (NOPOs) provide a good scalability in terms of power, repetition rate and pulse energy. The instantaneous broadband frequency conversion combined with the special phase matching geometry in the nonlinear crystal enables a fast tunability of the spectrum without readjustment.

We show the concept of a multi-colour NOPO for the Raman spectroscopy. Using the frequency-doubled radiation of an infrared pump laser will lead to an IR-NOPO, tunable from 650 to 950 nm. With help of the third harmonic the spectrum will be shifted to the visible spectral regime. Introducing a second focus with an additional sum frequency process in the VIS-NOPO will even generate UV-radiation about 350 nm.

Q 58.40 Thu 16:30 Empore Lichthof

Two-color spectroscopy for laser stabilization to the ytterbium 1S0-3P1 intercombination line — ●CHRISTIAN HALTER, BASTIAN POLLKENESER, KAPILAN PARAMASIVAM, BASTIAN SCHEPERS, TOBIAS FRANZEN, GREGOR MURA, and AXEL GÖRLITZ — Institut für Experimentalphysik, HHU Düsseldorf, 40225 Düsseldorf

We present a scheme for frequency stabilization of multiple lasers that are resonant to transitions and originating from a common ground state. For the detection of weaker transitions we are harnessing the high signal to noise ratio provided by a strong transition. Doppler reduced spectroscopy is performed on an atomic beam by detecting the fluorescence of a strong dipole allowed transition. Individual error signals for this transition as well as additional weaker transitions are recovered from the strong fluorescence signal using lock-in techniques. We demonstrate the application to strong 1S0-1P1 transition and the 1S0-3P1 intercombination line of ytterbium in the context of MOT.

Q 58.41 Thu 16:30 Empore Lichthof

Electromagnetic wave propagation in time-dependent Hermitian and non-Hermitian structures — ●ARMEN HAYRAPETYAN¹, JÖRG GÖTTE², SANDRA KLEVANSKY³, STEPHAN FRITZSCHE⁴, KAREN GRIGORYAN⁵, and RUBIK PETROSYAN⁵ — ¹Max-Planck-Institut für Physik komplexer Systeme, Dresden, Germany — ²School of Physics and Astronomy, University of Glasgow, U.K. — ³Institut für Theoretische Physik, Universität Heidelberg, Germany — ⁴Helmholtz-Institut Jena, Germany — ⁵Yerevan State University, Armenia

We study the impact of a spatially homogeneous yet non-stationary dielectric permittivity on the dynamical and spectral properties of light. We focus on two distinct scenarios in which time-dependent dielectric structures experience either Hermitian or non-Hermitian change. In the Hermitian case, a smoothly time-varying modification of the medium is considered in order to demonstrate the possibility of amplification and attenuation of waves associated with the decrease and increase of the permittivity. In the non-Hermitian case, using a complex-valued permittivity with parity-time symmetry, modulations of light

amplification and attenuation are shown correspondingly linked to the well-defined regions of gain and loss. While real-valued permittivities give rise to either the conversion or the time-dependent modulation of the frequency, the parity-time symmetric permittivity, beyond some threshold, leads to the splitting of extrema in the frequency modulation and to a reduction of the modulation period. Our results may pave the way towards controllable light-matter interaction in time-varying structures.

Q 58.42 Thu 16:30 Empore Lichthof

Rydberg excitons in artificially grown cuprous oxide — ●MORITZ FISCHER — 4th Physics Institute and Research Center SCOPE, Stuttgart, Germany

We investigate the yellow exciton series in an artificially grown crystal of cuprous oxide (chemical formula Cu_2O) at low temperatures (1.9 K). The yellow green light (close to 571 nm) is generated by a combination of an external cavity diode laser and second-harmonic generation in a waveguide of lithium niobate. To our knowledge it is the first time that yellow excitons are observed in an artificially grown crystal of cuprous oxide. We achieved excitons with principal quantum numbers from $n=4$ to $n=9$. From the transmission spectrum we calculated the band gap to 2.172 04 eV of cuprous oxide and the Rydberg energy of the yellow excitons to 94.75 meV. The current limitation is the phonon-assisted absorption in lower excitonic states. We further investigate the opportunities of fiber-based measurement techniques in reflection in order to reach lower temperatures (50 mK) and overcome the critical issue of the sample thickness.

Q 58.43 Thu 16:30 Empore Lichthof

Edge diffraction of optical-vortex beams formed by means of a "fork" hologram — ALEKSEY CHERNYKH¹, ALEKSANDR BEKSHAEV², and ●ANNA KHOROSHUN¹ — ¹East Ukrainian National University, Severodonetsk, Ukraine — ²I.I. Mechnikov National University, Odessa, Ukraine

We present experimental and numerical studies of a transverse profile for a beam obtained by the screen-edge diffraction of optical-vortex (OV) Kummer beams with different topological charges generated by means of a "fork" hologram. Our main results concern the behavior of secondary OVs formed in the diffracted beam due to splitting of the incident multi-charged OV into a set of single-charged ones. When the screen edge moves across the incident beam, OVs in every cross section of the diffracted beam describe complicated spiral-like trajectories which distinctly manifest the screw-like nature and the energy circulation in the OV beam. The trajectories contain fine structure details that reflect the nature and peculiar spatial configuration of the diffracting beam. For the Kummer beams' diffraction, the trajectories contain self-crossings and regions of "backward" rotation (loops). In the case of Laguerre-Gaussian beams, the trajectories are smoother. At certain conditions, positions of separate OVs as well as their mutual configuration (a singular skeleton of the diffracted beam) demonstrate high sensitivity to the screen edge dislocation with respect to the incident beam axis. This effect can be used for remote measurements of small displacements and deformations.

Q 58.44 Thu 16:30 Empore Lichthof

Determination of the relative emitter phases in an external-cavity diode laser array — ●MARIO NIEBUHR and AXEL HEUER — Institut für Physik und Astronomie, Universität Potsdam, 14476 Potsdam-Golm

Laser diodes (LD) with simultaneous high output power and good beam quality (BQ) are still a matter of ongoing research. One Ansatz which could enable LDs in corresponding applications is the coherent combination of multiple low power, good BQ emitters [1]. The emitters unfortunately tend to de-phase at high pump/output powers and the array loses coherence even when exposed to external seed or feedback.

We intend to investigate the cause of de-phasing by adapting a spatial light modulator based measurement method [2] to determine the relative phase difference between all emitters in an LD array. Measurements were done with an exemplary 9 emitter array radiating at 980nm and forced into coupled operation using an external cavity. Our method allowed for an accurate determination of the preset supermode phase relations as well as a convincing reconstruction of the emitted far field power distribution. Ideas will be presented on how to obtain an understanding of the possible de-phasing mechanisms.

[1] Fan et al, IEEE J. Sel. Top. Quantum Electron., 11, 567 (2005)

[2] Partanen et al., Fringe 2013. Springer Berlin Heidelberg, 879 (2014)

Q 58.45 Thu 16:30 Empore Lichthof

Quantum-inspired sensing of trapped particle kinematics — ●STEFAN BERG-JOHANSEN^{1,2}, MARTIN NEUGEBAUER^{1,2}, PETER BANZER^{1,2,3}, ANDREA AIELLO^{1,2}, CHRISTOPH MARQUARDT^{1,2}, and GERD LEUCHS^{1,2,3} — ¹Max Planck Institute for the Science of Light, Guenther-Scharowsky-Str. 1/Bldg. 24, D-91058 Erlangen, Germany — ²Institute of Optics, Information and Photonics, University of Erlangen-Nuremberg, Staudtstr. 7/B2, D-91058 Erlangen, Germany — ³Department of Physics, University of Ottawa, 25 Templeton, Ottawa, Ontario, K1N 6N5 Canada

Recently, it was demonstrated that the inseparable mode structure of radially polarized beams of light can be used for kinematic sensing with gigahertz temporal bandwidth [1]. The technique relies on the intrinsic correlations existing between the transverse spatial and polarisation degrees of freedom of vector beams, having a mathematical structure similar to that of entangled quantum systems [2]. The high temporal resolution made possible by the method becomes particularly valuable when investigating phenomena occurring at comparatively short length scales, such as the Brownian motion of a microparticle.

Here, we report on progress in applying the new method to measurements on microparticles suspended in liquid and trapped by an optical tweezer.

[1] S. Berg-Johansen, F. Töppel *et al.*, *Optica* **2**(10), 864 (2015).

[2] R. J. C. Spreeuw, *Phys. Rev. A* **63**, 062302 (2001).

Q 58.46 Thu 16:30 Empore Lichthof

Diode laser pumped molecular lasers — ●BERND WELLEGEHAUSEN¹ and WALTER LUHS² — ¹Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany — ²Photonic Engineering Office, Herbert-Hellmann Allee 57, 79189 Bad Krozingen, Germany

In the past, lasers with diatomic molecules as Na_2 , Te_2 , Se_2 and I_2 have been realized by optical pumping with argon and krypton ion lasers. Available powerful blue emitting laser diodes now open new possibilities for the generation of compact, low cost molecular laser systems. We report on first operation of lasers with Na_2 and Te_2 molecules on lines in the range of 535 nm to 636 nm, pumped by standard diode lasers at 461 nm and 445 nm. Investigations on the spectral narrowing of the diode lasers and features of the molecular lasers will be presented and discussed.

Q 58.47 Thu 16:30 Empore Lichthof

Zerodur-based optical systems for precision measurements in space — ●ANDRÉ WENZLAWSKI¹, MORITZ MIHM¹, KAI LAMPMANN¹, ORTWIN HELLMIG², KLAUS SENGSTOCK², PATRICK WINDPASSINGER¹, and THE MAIUS TEAM^{1,2,3,4,5,6} — ¹Johannes Gutenberg-Universität Mainz — ²ILP, Universität Hamburg — ³Institut für Physik, HU-Berlin — ⁴IQO, Leibniz Universität Hannover — ⁵ZARM, Universität Bremen — ⁶FBH, Berlin

Stable and robust optical systems are a key technology for high precision experiments such as atom interferometers or atomic clocks. Future space missions which allow for key improvements in these fields additionally require a high degree of thermal and mechanical robustness for the individual components.

To fulfill these requirements we developed a number of optical systems based on the glass ceramic Zerodur, a material which excels in having a very low coefficient of thermal expansion (CTE) over a very broad temperature range.

We present different fiber-coupled modules whose functionalities range from spectroscopy of Rubidium or Potassium to intensity control and pulse shaping for the MAIUS-experiments realizing a BEC-based atom interferometer.

MAIUS is part of the QUANTUS project, which is supported by the German Space Agency DLR with funds provided by the Federal Ministry of Economics and Technology (BMW) under grant numbers DLR 50 WM 1131 - 1137 and DLR 50 WP 1431 - 1435.

Q 58.48 Thu 16:30 Empore Lichthof

Temperature and frequency stabilisation in a cryogenic confocal microscope for single-site experiments — ●JAN M. BINDER, LACHLAN J. ROGERS, and FEDOR JELEZKO — Institute for Quantum Optics and IQST, Ulm University, Albert-Einstein-Allee 11, D-89081 Ulm, Germany

During our experiments on single-site crystal defects at liquid helium temperatures we have noticed that the spatial stability of our cryogenic

confocal microscope is influenced significantly by the temperature of the surrounding laboratory. To a lesser extent this also applies to the frequency stability of the associated laser system.

We present a solution to the temperature stability problem in the form of a cost-effective high current PID controller and thermoelectric temperature regulation.

We also show an approach to laser stabilisation combining multiple feedback signals of different inherent accuracy and sampling rates with the goal of enabling multi-hour measurements of fluorescence signals at low excitation power.

Q 58.49 Thu 16:30 Empore Lichthof

Field test of a Brillouin-LIDAR for temperature profiles of the ocean — ●SONJA FRIMAN¹, DAVID RUPP¹, ANDREAS RUDOLF¹, CHARLES TREES², and THOMAS WALTHER¹ — ¹TU Darmstadt, Institut für Angewandte Physik, 64289 Darmstadt — ²CMRE, 19136 La Spezia, Italy

In our group, a Brillouin-LIDAR for the measurement of temperature profiles of the ocean up to 100 m depths is being developed. It is meant to work as a flexible alternative to contact-based techniques. The temperature information is deduced from the Brillouin backscatter, which shows a temperature dependent spectral shift with respect to the incident laser frequency.

The LIDAR consists of a pulsed fiber amplifier as the beam source and an atomic edge filter as the detector. After frequency doubling, the ytterbium-doped fiber amplifier emits 10 ns pulses with a repetition rate of 1 kHz and a pulse energy of 0.5 mJ. The emission wavelength of 543.3 nm is set by the rubidium-based components of the setup: the absorption filter, which eliminates the elastic scattering from the signal, and the rubidium edge filter (ESFADOF).

The setup has successfully been tested under laboratory conditions, resulting in a temperature accuracy of up to 0.07°C and a depth resolution of 1 m. Recently, a field test was conducted in the Mediterranean.

The setup, its functionality and the preliminary results from the field test are presented.

Q 58.50 Thu 16:30 Empore Lichthof

Femtosecond pulse shaping of Laguerre-Gaussian laser pulses — ●TOM BOLZE and PATRICK NUERNBERGER — Physikalische Chemie II, Ruhr-Universität Bochum, Universitätsstraße 150, 44801 Bochum

The temporal shaping of femtosecond laser pulses is widely used and well explored. A number of schemes have been demonstrated to achieve fast, stable and precise shaping of incident laser pulses. However the Hermite-Gaussian HG₀₀ mode is almost exclusively used.

We present our results for shaping femtosecond Laguerre-Gaussian (LG) laser pulses with a pulse shaper. We employ a 128-pixel LCD in the common 4f geometry of a pulse shaper, a spiral phase plate (SPP) is used to transform the HG₀₀ mode into the LG₀₁ mode. Upon changing the spectral phase of the pulse we investigate the variations in the temporal shape of the pulse using a FROG-device and the spatial shape using a CCD-camera. The Orbital Angular Momentum (OAM) of the shaped pulse is determined in dependence on the applied spectral phase, hence we investigate whether complex spectral phases distort the spatial beam profile of femtosecond LG beams.

Q 58.51 Thu 16:30 Empore Lichthof

Design and implementation of a Kerr lens mode-locked air operated high-power thin disk oscillator — ●JOSÉ RICARDO ANDRADE, BERNHARD KREIPE, and UWE MORGNER — Leibniz Universität Hannover, Institute for Quantum Optics, Welfengarten 1, 30167 Hannover, Germany

In this work we present some theoretical considerations and experimental evidence of how to design and operate a Kerr lens mode-locked thin disk laser in the high power regime (hundreds of Watt) in ambient air. This technology enables scaling down the size of high-power systems with the added benefit of not needing to reduce the repetition rate. In contrast to high-power thin disk lasers mode-locked by semiconductor saturable absorber mirrors, operation in air is feasible and the gain-bandwidth of the gain material is more properly exploited, making this type of systems better contenders for up-scaling.

Q 58.52 Thu 16:30 Empore Lichthof

Generation of sub 10 fs UV pulses with MHz repetition rate — ●SVEN KLEINERT¹, AYHAN TAJALLI¹, BERNHARD KREIPE¹, YULIYA KHANUKAEVA¹, TAMAS NAGY^{1,3}, and UWE MORGNER^{1,2} — ¹Institut für Quantenoptik, Leibniz Universität Hannover, 30167 Hannover — ²Laserzentrum Hannover e.V., 30419 Hannover — ³Laser-

Laboratorium Göttingen e.V., 37077 Göttingen

Energetic ultrashort UV pulses at high repetition rates are essential for wide fields of applications e.g. nonlinear imaging and ultrafast spectroscopy. A well-established technique for generation of such pulses is optical parametric amplification (OPA). However, the lack of proper nonlinear media as well as pump and seed sources make them difficult for UV pulse generation. One possible solution to this problem is a frequency conversion of these sources. Here, we present a broadband OPA in the visible region with a repetition rate of 1MHz which is used for generation of UV pulses with duration of sub 10fs via frequency doubling process. The driving laser source for this experiment is an Ytterbium-doped rod-type-fiber amplifier system delivering 600fs IR pulses with pulse energy of 50μJ. This source is used for generation of pump and seed for the OPA via third harmonic and supercontinuum generation processes in BBO and YAG crystals respectively. This very compact setup supports the generation of sub 9fs pulses in the visible range with pulse energy of more than 700nJ. The generation of sub 10fs UV pulses with pulse energy of more than 40nJ at 1MHz repetition rate is then guaranteed via second harmonic generation of the output.

Q 58.53 Thu 16:30 Empore Lichthof

Sub two-cycle optical pulse compression from Ti:sapphire oscillators — ●PHILIP DIENSTBIER¹, TAKUYA HIGUCHI¹, JOHN TRAVERS², FRANCESCO TANI², MICHAEL FROSZ², PHILIP ST. J. RUSSELL², and PETER HOMMELHOFF^{1,2} — ¹Department Physik, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Staudtstrasse 1, 91058 Erlangen — ²Max Planck Institute for the Science of Light, Günther-Scharowsky-Str. 1, Erlangen, Germany

Ultrashort pulsed lasers with a duration of a single oscillation of the electric field are an ideal tool to investigate the sub-cycle dynamics of electrons under an intense field [1]. Recent observation of rescattering physics at a nanotip with the aid of optical field enhancement suggests that such a strong-field sub-cycle regime can be reached with much lower pulse energy (< 1 nJ) [2]. However, for such small pulse energy, difficulty in spectral broadening involving nonlinear optics hindered generation of sub two-cycle pulses. Here, we discuss how to broaden the spectrum of Ti:sapphire oscillator output by a customized solid core photonic crystal fiber and compress it back to its shortest pulse duration.

[1] M. T. Hassan *et al.*, Rev. Sci. Instrum. **83**, 111301 (2012).

[2] M. Krüger *et al.*, Nature **475**, 78 (2011).

Q 58.54 Thu 16:30 Empore Lichthof

Nanostructured laser-driven dielectric structures for electron focusing — ●ALEXANDER TAFEL, JOSHUA MCNEUR, MARTIN KOZÁK, ANG LI, NORBERT SCHÖNENBERGER, and PETER HOMMELHOFF — Friedrich-Alexander-Universität

By combining the strong fields of ultrashort laser pulses and the large damage thresholds of dielectrics, dielectric laser accelerators (DLAs) hold great potential to reduce the size and cost of existant accelerators dramatically. Acceleration and deflection have already been demonstrated in several proof of principle experiments in a single stage [1,2,3]. To extend the interaction between electrons and the laser-induced fields, however, focusing elements must be introduced to counteract the divergence of the electron beam. Here, we present two candidates for this role: dielectric laser quadrupole structures - a setup of two 2D gratings - which work analogously to radio frequency quadrupoles and single-grating based electron lenses. The former can be used for strong focusing and simultaneous acceleration, microbunching and/or guiding of the beam. The latter have already shown to be effective electron focusing elements with focal distances on the order of 100 microns [4].

[1] J. Breuer and P. Hommelhoff, Phys. Rev. Lett. **111**, 134803 (2013).

[2] E. A. Peralta *et al.* Nature **503**, 91-94 (2013).

[3] M. Kozak, J. McNeur *et al.*, submitted

[4] J. McNeur, M. Kozak *et al.*, submitted

Q 58.55 Thu 16:30 Empore Lichthof

Nanoscale vacuum-tube electronic devices triggered by few-cycle laser pulses — ●CONSTANZE STURM, TAKUYA HIGUCHI, PEYMAN YOUSEFI, CHRISTIAN HEIDE, KRISTOF KREMER, and PETER HOMMELHOFF — Department Physik, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Staudtstrasse 1, 91058 Erlangen

Electron pulses from a sharp metal nanotip triggered by ultrashort laser pulses via multiphoton and above-threshold photoemission are

extremely confined both in space and time. Employing such short-pulsed electrons as charge carriers in electronic devices may drastically improve their operation speed. As a first step, we demonstrate a nanoscale diode device triggered by few-cycle laser pulses [1]. While focusing the laser on two tips facing each other and separated by a few hundreds of nanometers, we exploit the dependence of the near-field optical enhancement on the tip radius. This dependence results in a photoemission yield that is larger for the sharper tip compared to the blunter one. As a consequence the laser-triggered current between two tips exhibits a rectifying behavior. For a systematic variation of the tip radii and a reliable control of the distance between the tips, we lithographically fabricated tips on top of a substrate. The current status of the experiments will be presented.

[1] T. Higuchi et al., *Appl. Phys. Lett.*, 106, 051109 (2015).

Q 58.56 Thu 16:30 Empore Lichthof

A scanning tunneling microscope joined with few-cycle laser pulses — ●MICHAL HAMKALO, TAKUYA HIGUCHI, M. ALEXANDER SCHNEIDER, and PETER HOMMELHOFF — Department Physik, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), 91058 Erlangen

Sharp metal tips are not only essential to perform scanning tunneling microscopy (STM), but also extremely interesting from the point of view of strong field physics as the apex of such a tip exhibits a large optical field enhancement. Due to this feature it is possible to achieve electric fields of the order of 1 V/Å and to enter the light-field-induced tunneling photoemission regime. Electrons resulting from this process rescatter at a distance of a few nanometers from tip surface [1]. When the tip apex is approached to another surface within such a distance, electrons are expected to tunnel in between the tip and the surface within a subcycle of the oscillating field. A tip-to-tip interface is an attracting playground for seeking such optical-field driven tunneling over a gap, but the mechanical instability of the previous setup hindered to reach this tunneling regime [2]. In this study, a STM-based setup with optical access was built and used to investigate tip-to-tip and tip-to-surface interfaces illuminated with few-cycle laser pulses.

1. M. Krüger, M. Schenk and P. Hommelhoff, *Nature* 475, 78 (2011).
2. T. Higuchi et al., *Appl. Phys. Lett.* 106, 051109 (2015).

Q 58.57 Thu 16:30 Empore Lichthof

Attosecond gating and streaking of free electrons via interaction with laser-induced optical fields — ●NORBERT SCHÖNENBERGER, MARTIN KOZAK, JOSHUA MCNEUR, and PETER HOMMELHOFF — Department Physik, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Staudtstr. 1, 91058 Erlangen

The recent successful demonstrations of dielectric laser acceleration have opened up the possibility of more advanced experiments and setups [1,2]. The experimental results presented here demonstrate optical gating and streaking of 28 keV free electrons with a precision of 1.3 fs [3]. This is achieved via the linear interaction of the light's electric field with the energy and transverse momentum of an electron beam near a dielectric grating. Furthermore, we discuss the potential applications of the demonstrated gating and streaking. The optical gating demonstrated here can be used for a wide range of ultrafast electron diffraction experiments that require sub-fs free electron probes. Moreover, a dielectric-laser based streak camera based off of this scheme could allow for temporal characterization of electron bunches with 10 attosecond precision. [1] J. Breuer, and P. Hommelhoff, *Phys. Rev. Lett.* 111, 134803 (2013). [2] E. A. Peralta, et al. *Nature* 503, 91-94 (2013). [3] M. Kozak, J. McNeur et al., submitted.

Q 58.58 Thu 16:30 Empore Lichthof

A Miniaturized Electron Source Based on Dielectric Laser Accelerator Operation at Higher Spatial Harmonics and a Nanotip Photoemitter — ●ANG LI, JOSHUA MCNEUR, MARTIN KOZAK, DOMINIK EHBERGER, and PETER HOMMELHOFF — Department Physik, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Staudtstr. 1, 91058 Erlangen

Dielectric Laser Acceleration, a novel accelerator concept based on micron-scale dielectric grating structures driven by the high peak field of short laser pulses, can exceed the performance of RF-based accelerators. Recent experimental progress on dielectric laser acceleration of electrons with energies below 10 keV via interaction with high spatial harmonics of a DLA is discussed. Further, laser-triggered coherent electron emission from tungsten nanotips is discussed in the context of a novel DLA-based miniaturized electron gun[1]. The photoemitted low-emittance electron bunches suggests incorporation with sub-

relativistic dielectric laser accelerators (DLAs). On tapered silicon grating structures, experimental results show an acceleration gradient (energy gain/interaction length) already analogous to the electron injectors in rf-based accelerators. The combination of the nanotip emitter with sub-relativistic DLAs to construct a mm-scale electron injector capable of producing arbitrary energies will be discussed.

[1] J. McNeur, D. Ehberger et al., *J. Phys. B*, accepted

Q 58.59 Thu 16:30 Empore Lichthof

Nano-structured chips for dielectric laser accelerators and laser triggered electron emission — ●PEYMAN YOUSEFI, JOSHUA MCNEUR, MARTIN KOZAK, and PETER HOMMELHOFF — Department Physik, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Staudtstr. 1, 91058 Erlangen, Germany

Laser-driven dielectric accelerators (DLAs) are based on the synchronicity of laser-induced electromagnetic fields and charged particles traversing nano-structured chips. Proof of principle experiments have shown efficient acceleration with energy gradients already exceeding those of RF accelerators [1,2]. To improve upon these gradients, new dielectric structures composed of varying materials must be built. Different techniques can be utilized to fabricate such structures depending on the material properties and the desired geometries. Electron beam lithography with spatial resolution of 2-5 nm enables us to pattern such structures down to 50 nm feature size. Depending on the geometry of the desired structure we use either reactive ion etching tool enhanced by inductive coupled plasma or deep reactive ion etching tool to etch different substrates (Si, SiO₂, SiC, Al₂O₃ etc.). Furthermore, we report on recent results of the fabrication of an on chip electron source appropriate for integration with DLAs. An apex radius of about 30 nm and a cathode to anode gap of around 30 nm were achieved using focused ion beam (FIB) on a thin film of gold on a fused silica substrate. [1] J. Breuer, and P. Hommelhoff, *Phys. Rev. Lett.* 111, 134803 (2013). [2] E. A. Peralta, et al. *Nature* 503, 91-94 (2013).

Q 58.60 Thu 16:30 Empore Lichthof

Experimental study of photoelectronic angular distributions using velocity map imaging: Intensity and CEP effects — ●EIKE LÜBKING¹, THOMAS GAUMNITZ², CHRISTOPH VORNDAMME¹, TAMAS NAGY¹, TORSTEN HARTMANN¹, UWE MORGNER¹, THORSTEN UPHUES², and MILUTIN KOVACEV¹ — ¹Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany — ²Center for Free-Electron Laser Science, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany

A Velocity Map Imaging Spectrometer (VMIS) was used to study the angular and energy distributions of photoelectrons created in the ultrashort-pulse ionization of xenon and argon.

The intensity dependence of these distributions can be utilised to gain insight into the diverse participating processes, e.g. channel switching and resonant and non-resonant ionization.

By using a CEP-stabilized laser source generating few-cycle pulses, we were also able to study the influence of the carrier-envelope phase (CEP) on the photoelectronic angular distributions.

Q 58.61 Thu 16:30 Empore Lichthof

Selective etching of fs-laser structured crystalline YAG — ●KORE HASSE^{1,2}, CHRISTIAN KRÄNKEL^{1,2}, and THOMAS CALMANO^{1,2} — ¹Institut für Laser-Physik, Universität Hamburg — ²The Hamburg Centre for Ultrafast Imaging, Universität Hamburg

The etching rate of fs-laser structured dielectric materials is increased within the modified region by order of magnitude. This enables the fabrication of narrow hollow structures with dimensions comparable to those of the fs-inscribed structures of a few micrometers. In future this may allow modifying active laser and amplifier materials and influence their transversal mode profile or suppress amplified spontaneous emission (ASE).

Here we report on preliminary investigations on selective etching of fs-laser structured wedges in undoped YAG-samples. We present etching rates of unmodified YAG and those of YAG crystals modified with different fs-laser pulse parameters. Furthermore, we compare roughness and scattering losses of fs-laser assisted etched surfaces and surfaces resulting from direct laser ablation.

Q 58.62 Thu 16:30 Empore Lichthof

Few-cycle pulse conversion by soliton implosion — ●JAN-HENDRIK OELMANN¹, IHAR BABUSHKIN^{1,2}, AYHAN TAJALLI¹, HAKAN SAYINC³, UWE MORGNER^{1,3,4}, GÜNTER STEINMEYER², and AYHAN DEMIRCAN^{1,4} — ¹Institute of Quantum Optics, Leibniz University

Hannover, Welfengarten 1, 30167 Hannover — ²Max-Born-Institute (MBI), Max-Born-Str. 2a, 12489 Berlin, Germany — ³Laser Zentrum Hannover e. V., Hollerithallee 8, 30419 Hannover, Germany — ⁴Hannover Centre for Optical Technologies, Nienburger Str. 17, 30167 Hannover, Germany

We predict a new regime of coherent supercontinuum generation in photonic-crystal fibers based on few-cycle higher order soliton dynamics. Instead of using the standard soliton fission process, we exploit dramatic shock formation dynamics of a higher-order soliton, which completely converts the input solitonic radiation to different wavelength regions in the normal dispersion regime. This enables the transfer of energy to coherent radiation in the visible as well as the ultraviolet spectral range. The scheme is simple, very effective and completely deterministic, which suggests the possibility to compress the pulses down to the sub-cycle level and thus hold a new way to directly generate attosecond pulses well outside the vacuum ultraviolet. We present numerical simulations for commercially available fibers with realistic pulse parameters and present preliminary experimental results, supporting the theoretical prediction.

Q 58.63 Thu 16:30 Empore Lichthof

Exploiting optical event horizon concept in microstructured optical fibers to manipulate higher order soliton trajectories

— ●AYHAN TAJALI¹, ALEXANDER PAPE¹, IHAR BABUSHKIN^{1,2}, GÜNTER STEINMEYER², UWE MORGNER^{1,3}, and AYHAN DEMIRCAN^{1,4} — ¹Institut Für Quantenoptik, Leibniz Universität Hannover, 30167 Hannover — ²Max-Born-Institut (MBI), 12489 Berlin — ³Laserzentrum Hannover e.V., 30419 Hannover — ⁴Hannover Centre for Optical Technologies, 30167 Hannover

Supercontinuum generation in photonic crystal fibers has been of great interest to optical scientists since its discovery. More interestingly, it has recently revealed some unexpected analogy to different areas of physics including event horizon and rogue waves. The concept of event horizon in supercontinuum generation relies on enhanced interaction between a signal and a phase velocity matched control pulse which results in mutual frequency change of both pulses. Here, we experimentally demonstrate the possibility of accelerating or decelerating of ejected fundamental solitons in the supercontinuum generation. By choosing an appropriate choice of the initial conditions including fiber parameters, wavelength, energy and temporal delay of the weaker control pulse we verify the strong all optical controlling possibility of this interaction

Q 58.64 Thu 16:30 Empore Lichthof

Floquet-engineering topological and spin-dependent bands with ultracold fermions

— ●GREGOR JOTZU, MICHAEL MESSER, FREDERIK GÖRG, DANIEL GREIF, RÉMI DESBUQUOIS, MARTIN LEBRAT, THOMAS UEHLINGER, and TILMAN ESSLINGER — Institute for Quantum Electronics, ETH Zurich, 8093 Zurich, Switzerland

Periodically driven quantum systems, when observed on time-scales longer than one modulation period, can be described by effective Floquet Hamiltonians that show qualitatively new features. Using a magnetic field gradient, we apply an oscillating force to ultracold fermions in an optical lattice. The resulting effective energy bands then become spin dependent, allowing for a tunable ratio of the effective mass for each internal state, also giving access to the regime where one spin is completely localized whilst the other remains itinerant.

In a honeycomb lattice, circular modulation leads to the appearance of complex next-nearest neighbour tunnelling. This corresponds to a staggered magnetic flux in the lattice, allowing for the realisation of Haldane's model of a topological Chern insulator. When spin dependence is included, time-reversal symmetry can be restored giving rise to the Kane-Mele model.

A crucial question is whether Floquet engineering can be extended to interacting systems, and how the resulting Hamiltonians are modified. In particular, we study how heating in the system depends on the modulation and interaction parameters and identify regimes where it becomes negligible.

Q 58.65 Thu 16:30 Empore Lichthof

Connecting strongly correlated superfluids by a quantum point contact

— ●MARTIN LEBRAT¹, SAMUEL HÄUSLER¹, DOMINIK HUSMANN¹, SEBASTIAN KRINNER¹, JEAN-PHILIPPE BRANTUT¹, SHUN UCHINO², THIERRY GIAMARCHI³, and TILMAN ESSLINGER¹ — ¹Institute for Quantum Electronics, ETH Zürich, 8093 Zürich, Switzerland — ²Center for Emergent Matter Science, RIKEN, Saitama 351-0198, Japan — ³Department of Quantum Matter Physics, University

of Geneva, 1211 Geneva, Switzerland

We study strongly interacting Fermi gases connected by a tunable, ballistic constriction and measure a non-linear current-bias relation, reminiscent of superconducting weak links. We prepare an elongated cloud of ultracold ⁶Li at unitarity by tuning its scattering length close to a Feshbach resonance. The cloud is then pinched off at its center using repulsive laser beams, effectively splitting it into two macroscopic reservoirs connected by a one-dimensional constriction, a quantum point contact (QPC).

By imposing an atom number imbalance between the two clouds and observing the dynamics of particle flow, we analyse the current-bias characteristics of our system and find nonlinear behaviour indicating superfluid behaviour. The results agree quantitatively with a biased superfluid point contact model treated with the Keldysh formalism, suggesting that the supercurrent originates from multiple Andreev reflections. We study how the current-bias characteristics depend on the density in the QPC and finite temperature.

Q 58.66 Thu 16:30 Empore Lichthof

Anti-ferromagnetic correlations with ultracold fermions on optical lattices

— DANIEL GREIF^{1,2}, GREGOR JOTZU¹, MICHAEL MESSER¹, FREDERIK GÖRG¹, ●RÉMI DESBUQUOIS¹, and TILMAN ESSLINGER¹ — ¹Institute for Quantum Electronics, ETH Zurich, 8093 Zurich, Switzerland — ²Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

The observation of anti-ferromagnetic spin correlations of ultracold fermions in optical lattices is an important milestone towards an experimental study of the Hubbard model. In this model many questions on the low-temperature phase diagram still remain open, both for simple cubic and square configurations, as well as for more complex lattice geometries. Additionally, for creating an equilibrated low-temperature state and a successful implementation of advanced cooling schemes based on entropy redistribution, an understanding of the formation time for spin correlations is of paramount importance.

In our experiment we load a two-component, repulsively interacting fermionic quantum gas into an optical lattice of tunable geometry. For very low temperatures we observe anti-ferromagnetic correlations on neighbouring sites in many different lattice geometries. Furthermore, we investigate the characteristic formation time of spin correlations in optical lattices by changing the lattice geometry on variable timescales.

Q 58.67 Thu 16:30 Empore Lichthof

Realization of the ionic Hubbard model with ultracold fermions on optical lattices

— MICHAEL MESSER¹, ●RÉMI DESBUQUOIS¹, THOMAS UEHLINGER¹, GREGOR JOTZU¹, FREDERIK GÖRG¹, SEBASTIAN HUBER², DANIEL GREIF^{1,3}, and TILMAN ESSLINGER¹ — ¹Institute for Quantum Electronics, ETH Zurich, 8093 Zurich, Switzerland — ²Institute for Theoretical Physics, ETH Zurich, 8093 Zurich, Switzerland — ³Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

Ultracold atoms in optical lattices constitute a tool of choice to realize the Fermi-Hubbard model. Previous experiment showed that, by increasing the on-site repulsive interactions, a gap opens in the excitation spectrum and the system becomes progressively a Mott insulator. A more simple band insulator appears in half filled lattices when a staggered energy offset is introduced. There, the ground state possesses charge density-wave ordering. The competition of both phenomena constitute the ionic Hubbard model, which we experimentally realize by loading a two-component interacting Fermi gas into an optical lattice with a staggered energy offset on alternating sites. The underlying density order of the ground state is revealed through the correlations in the noise of the measured momentum distribution. For a large energy offset, we observe a charge density-wave ordering, which is suppressed as the on-site interactions are increased. To further elucidate the nature of the ground state, we measure the double occupancy of lattice sites and show a gapped charge excitation spectrum for a wide range of parameters.

Q 58.68 Thu 16:30 Empore Lichthof

The quasi-particle residue in the crossover from few to many particles

— ●MICHAEL DEHABE, ANDREA BERGSCHNEIDER, SIMON MURMANN, VINCENT M. KLINKHAMER, JAN-HENDRIK BECHER, GERHARD ZÜRN, and SELIM JOCHIM — Physikalisches Institut, Universität Heidelberg, Heidelberg, Germany

In one dimension, the ground-state wave function of an impurity particle interacting with a Fermi sea is orthogonal to the ground-state

wave function in the non-interacting case. Hence, the squared overlap of these two wave functions, which is known as quasi-particle residue, is zero.

By measuring the quasi-particle residue of a single impurity atom and an increasing number of majority atoms we want to study the emergence of orthogonality in the system. We deterministically prepare these few-fermion systems in a cigar-shaped optical dipole trap in their motional ground state. This system can be considered as quasi one-dimensional, if the atom number is smaller than the aspect ratio of the trap. For each specific number of majority particles, we determine the quasi-particle residue by flipping the spin of the impurity particle using a resonant RF pulse and measuring the Rabi frequency.

In our current experimental setup, the aspect ratio limits the number of majority particles to values smaller than five. We will present our latest results on increasing the aspect ratio of the trap while keeping full control over the quantum state of the few-atom system. This will allow us to study the quasi-particle residue in the crossover to the many-body limit.

Q 58.69 Thu 16:30 Empore Lichthof

Deterministic Preparation of Few-Fermion Systems in Actively Stabilized Potential Wells — •VINCENT M. KLINKHAMER, JAN-HENDRIK BECHER, ANDREA BERGSCHNEIDER, MICHAEL DEHABE, SIMON MURMANN, GERHARD ZÜRN, and SELIM JOCHIM — Physikalisches Institut der Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany

In our experiment we control the total wave function of several interacting ${}^6\text{Li}$ atoms trapped in multiple coupled dimple traps. In our previous experiments with a double-well potential, we were able to prepare two-particle eigenstates by adiabatically tuning the depth of the two wells with an acousto-optic deflector (AOD). However, the ramps of the optical potential had to be optimized experimentally and we also observed drifts on the scale of the superexchange energy J^2/U . This inhibited our progress towards larger systems.

Here we present the first results of our new stabilization setup for the optical potential. It can directly produce potential landscapes and ramps by monitoring the potential on a camera in real time. At the same time, it provides a relative stability of 5×10^{-4} . This will allow us to conveniently create potentials with multiple sites. We are going to deterministically prepare, e.g., one-dimensional Hubbard chains and four-site plaquettes. Thanks to the control over the preparation, it will also be possible to introduce various amounts of doping into our system.

Q 58.70 Thu 16:30 Empore Lichthof

Spin Resolved Imaging of an Ultracold Fermi Gas in a 2D Optical Lattice — •RALF KLEMT, LUCA BAYHA, PUNEET MURTHY, MATHIAS NEIDIG, MARTIN RIES, GERHARD ZÜRN, and SELIM JOCHIM — Physikalisches Institut, Universität Heidelberg, Germany

We report on the current status of our experiment investigating an ultracold, two-component ${}^6\text{Li}$ Fermi gas in the BEC-BCS crossover, which is trapped in a 2D optical lattice. By using a matterwave focusing technique, we measure the momentum distribution which allows access to spatial coherence information. We realize both a transition from the normal to the superfluid phase and from the superfluid to an insulating phase by tuning the temperature and the lattice depth, respectively. For the insulating phase a loss of first-order correlations and phase coherence is expected. Probing the type of this insulating phase as well as observing spin-ordering requires to measure second-order, i.e. atom-noise, correlations.

Therefore a spin resolved two-state imaging has been implemented, which allows for recording both hyperfine states of the ${}^6\text{Li}$ gas within a single experimental cycle. This was achieved combining fast current modulation of a diode laser and the interline transfer mode of a CCD camera. Hence the density profile of both spin components can be measured within $100\mu\text{s}$, keeping the distortion between the images at a minimum. With this tool at hand the spatial atom-noise correlations between the different spin components can be obtained in addition to single spin correlations.

Q 58.71 Thu 16:30 Empore Lichthof

Strongly interacting ultracold quantum gases of fermionic Ytterbium-173 — •LUIS RIEGGER^{1,2}, DIOGO RIO FERNANDES^{1,2}, MORITZ HÖFER^{1,2}, CHRISTIAN HOFRICHTER^{1,2}, FRANCESCO SCAZZA^{1,2}, IMMANUEL BLOCH^{1,2}, and SIMON FÖLLING^{1,2} — ¹Ludwig-Maximilians-Universität, Schellingstraße 4, 80799 München, Germany — ²Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße

1, 85748 Garching, Germany

Degenerate ensembles of ytterbium and alkaline-earth atoms allow novel many-body systems to be implemented due to their extended $SU(N)$ -symmetry and the existence of a metastable internal “clock” state, introducing a yet unexplored orbital degree of freedom. Motivated by the possibility of simulating two-orbitals physics with cold atoms, we investigate the coupling of the clock state to external degrees of freedom via state-dependent potentials. In addition we characterize strongly interacting $SU(N)$ -symmetric Fermi gases of ${}^{173}\text{Yb}$ in the 3D lattice by probing the equation of state in the trap.

Q 58.72 Thu 16:30 Empore Lichthof

Probing Many-Body Localization With a Gas of Ultracold Fermions in Optical Lattices — •PRANJAL BORDIA^{1,2}, HENRIK LÜSCHEN^{1,2}, SEAN HODGMAN^{1,2,3}, MICHAEL SCHREIBER^{1,2}, IMMANUEL BLOCH^{1,2}, and ULRICH SCHNEIDER^{1,2,4} — ¹Fakultät für Physik, Ludwig-Maximilians-Universität München, Schellingstr. 4, 80799 Munich, Germany — ²Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching, Germany — ³Research School of Physics and Engineering, Australian National University, Canberra ACT 0200, Australia — ⁴Cavendish Laboratory, University of Cambridge, J. J. Thomson Avenue, Cambridge CB3 0HE, United Kingdom

Many Body Localization (MBL) offers a generic alternative to thermalization in isolated quantum systems in which a many-body system fails to act as its own heat bath, even at finite energy densities. However, it is crucial for such a phenomenon that the system undergoes strictly closed system dynamics.

We present our recent work on probing MBL with ultra-cold fermions loaded in optical lattices by preparing an out of equilibrium change density wave and monitoring the relaxation dynamics. We will describe two experiments where we studied the effects of taking the system controllably away from the ideal isolated 1D case and describe how it influences the many-body state.

Q 58.73 Thu 16:30 Empore Lichthof

Microscopic Observations in Degenerate Fermionic Lattice Gases — •MARTIN BOLL¹, TIMON HILKER¹, AHMED OMRAN¹, KATHARINA KLEINLEIN¹, GUILAUME SALOMON¹, IMMANUEL BLOCH^{1,2}, and CHRISTIAN GROSS¹ — ¹Max-Planck Institute of Quantum Optics — ²Faculty of Physics, LMU Munich

Ultracold atoms in optical lattices provide a powerful platform for the controlled study of quantum many-body physics. We present here the first studies of a Fermi gas with a new generation quantum gas microscope, which allows to observe the full atom number statistics on every site. The common problem of light induced losses is avoided by an additional small scale “pinning lattice” for Raman sideband cooling during the imaging.

We report the local observation of Pauli’s exclusion principle in a spin-polarized degenerate gas of ${}^6\text{Li}$ fermions in an optical lattice. In the band insulating regime, we measure a strong local suppression of particle number fluctuations and we extract a local entropy as low as $0.3 k_B$ per atom. In addition we present our progress studying the metal to Mott-insulating transition. Our work opens an avenue for studying local density and even magnetic correlations in fermionic quantum matter both in and out of equilibrium.

Q 58.74 Thu 16:30 Empore Lichthof

Goldstone mode in the quench dynamics of an ultracold BCS Fermi gas — •PETER KETTMANN¹, SIMON HANNIBAL¹, MIHAIL CROITORU², VOLLRATH MARTIN AXT³, and TILMANN KUHN¹ — ¹Institute of Solid State Theory, University of Münster — ²Condensed Matter Theory, University of Antwerp — ³Theoretical Physics III, University of Bayreuth

Ultracold Fermi gases are a convenient system to probe and study the properties of phases like the BEC and the BCS phase and the crossover in between those regimes. In particular, ultracold Fermi gases can be used as a test bed to study the two fundamental dynamical modes –the Higgs and the Goldstone mode– which result from spontaneous symmetry breaking in these phases.

We investigate the Goldstone mode in the dynamics of a cigar-shaped ultracold ${}^6\text{Li}$ gas after an interaction quench on the BCS side of the BCS-BEC crossover. To this end, we numerically solve Heisenberg’s equations of motion for the Bogoliubov single-particle excitations in the framework of the Bogoliubov-de Gennes formalism. In

doing so, we find that the single-particle occupations oscillate in time with one dominant low-frequency component. We identify this frequency as the frequency of the Goldstone mode of the BCS gap [1]. Furthermore, we investigate the Goldstone mode over a wide range of parameters and show that the size-dependent superfluid resonances [2] have a strong impact on this mode.

- [1] Kettmann et al., arXiv preprint arXiv:1511.04239 (2015)
 [2] Shanenko et al., PRA 86, 033612 (2012)

Q 58.75 Thu 16:30 Empore Lichthof

Confinement-induced effects on the Higgs mode of an ultracold Fermi gas after a quench — ●SIMON HANNIBAL¹, PETER KETTMANN¹, MIHAIL CROITORU², VOLLRATH MARTIN AXT³, and TILMANN KUHN¹ — ¹Institute of Solid State Theory, University of Münster — ²Condensed Matter Theory, University of Antwerp — ³Theoretical Physics III, University of Bayreuth

Ultracold Fermi gases in optical traps provide a unique system to study the many body physics of systems composed of fermionic constituents. Both, the BEC and the BCS superfluid state are observed in these systems. Furthermore, the transition between these two states is well controllable by means of a Feshbach resonance, which allows one to tune the interaction strength over a wide range from negative to positive scattering lengths.

We employ an inhomogeneous BCS mean field theory and calculate the dynamics of the BCS gap of a confined ultracold Fermi gas after a quantum quench, i.e., a sudden change of the coupling constant. Due to the spontaneously broken U(1) symmetry in the superfluid phase two fundamental modes of the BCS gap evolve, i.e., the amplitude (Higgs) and phase (Goldstone) mode. Here we focus on the Higgs mode on the BCS side of the BCS-BEC crossover regime.

We find damped collective amplitude oscillations of the gap breaking down after a certain time. Depending on the quench parameters we investigate the damping and fragmentation of the Higgs mode exploiting a set of linearized equations of motions. Thereby, we illuminate the impact of the confinement on the dynamics of a BCS-BEC system.

Q 58.76 Thu 16:30 Empore Lichthof

Towards a 2D gas of Fermions in an optical lattice — ●THOMAS PAINTNER, DANIEL HOFFMANN, STEFAN HÄUSSLER, STEPHAN MAIER, WLADIMIR SCHOCH, WOLFGANG LIMMER, and JOHANNES HECKER DENSCHLAG — Institut für Quantenmaterie, Universität Ulm, Ulm, Deutschland

Fermions in optical lattices increasingly gain attention, because they represent a promising model system to simulate interesting solid-state phenomena. We are currently setting up a quantum gas microscope experiment for an ultracold 2D fermionic Lithium gas. We plan to expose the 2D gas to a honeycomb type optical potential which is projected on the atomic layer by a high resolution objective. The atoms inside this lattice will be cooled down using the Raman sideband cooling technique. In the future we want to implement single atom detection with single site resolution. We present a progress report of our set up.

Q 58.77 Thu 16:30 Empore Lichthof

Towards single site single atom imaging of ⁶Li atoms in an optical honeycomb potential — ●STEFAN HÄUSSLER, THOMAS PAINTNER, DANIEL HOFFMANN, WLADIMIR SCHOCH, WOLFGANG LIMMER, and JOHANNES HECKER DENSCHLAG — Institute for Quantum Matter, Ulm University, Albert-Einstein-Allee 45, 89081, Ulm, Germany

We are setting up a fermionic quantum gas experiment with ultracold ⁶Li atoms in the quasi two-dimensional regime. The gas will be structured with an optical honeycomb potential, projected with a high resolution objective. Such a system should enable us to investigate interesting phases of the fermionic ensemble at different lattice parameters and interaction strengths. For detection we will implement single site fluorescence imaging of the particles.

Since the fluorescence detection leads to heating of the atoms due to light scattering, thermal hopping of the atoms in the lattice can occur. To suppress this effect during detection, we will make use of a Raman sideband cooling technique as shown in [1].

The Raman cooling scheme, which is used to reduce the thermal energy of the particles in the honeycomb potential and simultaneously delivers the spontaneously emitted photons for the fluorescence imaging is presented here, as well as the required laser setup, which includes a 10 GHz offset frequency locking scheme and a digital feedback control based on a wavelengthmeter. Using this locking scheme first experimental results on Raman spectroscopy are presented.

- [1] M. Greiner: Phys. Rev. Let. 114, Nr. 213002 (2015)

Q 58.78 Thu 16:30 Empore Lichthof

Setup of a new lithium quantum gas microscope — ●MICHAEL HAGEMANN, ANDREAS KERKMANN, YANN KIEFER, NIELS ROHWEDER, BENNO REM, CHRISTOF WEITENBERG, and KLAUS SENGSTOCK — Institut für Laserphysik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany

We are setting up a new quantum gas machine for the preparation of small degenerate samples of 6Li atoms with single atom resolved detection and manipulation. We use a compact 2D-MOT/3D-MOT setup and plan to create the degenerate gases in a glass cell at the position of the 3D-MOT. After a lambda-bda-enhanced grey molasses phase, we want to directly load into a crossed optical dipole trap at 1070 nm. We will present the current status of the experiment including the setup of the laser system and its locking scheme, the design of the magnetic field coils, and the interferometer for testing the deformation of the glass cell.

Q 58.79 Thu 16:30 Empore Lichthof

Probing Open Quantum Systems Using Ultracold Yb in Optical Lattices — ●ANDRÉ KOCHANKE, BASTIAN HUNDT, THOMAS PONATH, BENJAMIN ABELN, ANNA SKOTTKE, LUKAS HEINZE, KLAUS SENGSTOCK, and CHRISTOPH BECKER — Zentrum für Optische Quantentechnologien, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg

Open quantum systems are an important and active field of research and highly relevant for applications like quantum information processing as well as fundamental questions in many body systems. Ultracold Ytterbium (Yb) gases are an ideal candidate to simulate these phenomena. With its unique atomic structure, Yb offers meta-stable, excited states which are subject to very strong two-body losses. These loss channels are the origin for many quantum effects like entanglement or the “Quantum-Zeno” effect. Here we present our latest results concerning these model systems. In a 3-D optical lattice we selectively prepare single-spin or spin-mixture gases of ¹⁷³Yb. Starting with a Band- or Mott-Insulator, we collectively populate the meta-stable ³P₀ state by means of Rapid-Adiabatic-Passage to measure and characterize the losses for different lattice configurations and extract information about the underlying time evolution. Further, we present details of our experimental setup used to perform these measurements. This work is supported by the DFG within the SFB 925 and the Marie Curie Initial Training Network QTea, financed by the FP7 of the European Commission (contract-no. MCITN-317485).

Q 58.80 Thu 16:30 Empore Lichthof

Using Raman sideband cooling to build Fermi-Hubbard systems atom by atom — ●PHILLIP WIEBURG, CHRISTIAN DARSOW-FROMM, LENNART SOBIREY, THOMAS LOMPE, and HENNING MORITZ — Institut für Laserphysik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany

Investigating the Fermi-Hubbard model with cold atoms is typically done by evaporatively cooling an ultracold Fermi gas and loading it into a large optical lattice. In contrast, we plan to build up a Fermi-Hubbard system site by site using optical microtraps. Each microtrap will contain a single atom cooled to the vibrational ground state by Raman-sideband cooling. This technique combines fast experimental cycle times with single site addressability and detection, which allows to study the fundamental processes governing the Fermi-Hubbard model in a bottom-up approach.

Here we present the design of this new experiment, which is going to be able to cool a gas of 40K to quantum degeneracy as well as to directly lasercool single atoms into optical microtraps. To achieve loading of single atoms with high fidelity, we can exploit light-assisted collisions as described in [1]. The cooling of the atoms will be performed using a Raman-sideband cooling techniques similar to the one described in [2]. In order to image and to manipulate the atoms with high spatial resolution, our setup will be equipped with a novel achromatic imaging system located inside the vacuum chamber.

- [1] T. Grünzweig et al., Nature Physics 6 951 (2010).
 [2] A.M. Kaufman et al., Physical Review X 2 041014 (2012).

Q 58.81 Thu 16:30 Empore Lichthof

Modulation spectroscopy of ultracold fermions in optical superlattices — ●KARLA LOIDA, JEAN-SÉBASTIEN BERNIER, and CORINNA KOLLATH — HISKP, Universität Bonn, Nussallee 14-16,

53115 Bonn

We study the excitation spectrum of the ionic Hubbard model. The ionic Hubbard model consists of three terms: a nearest-neighbor tunneling, an onsite interaction and an alternating energy offset between even and odd sites. It was originally introduced for the description of condensed matter systems, e.g. mixed stacked organic compounds, and can be cleanly realized by ultracold fermionic atoms confined to an optical superlattice. Its phase diagram in one dimension has attracted considerable theoretical interest. In the limits of predominating energy offset or onsite interaction strength, the ground state is a band insulator or Mott insulator, respectively. In between a narrow so-called bond-ordered wave phase has been predicted which spontaneously breaks site-inversion symmetry. The excitation spectrum of the ionic Hubbard model has attracted much less attention so far. We exert a time-periodic modulation of the superlattice amplitude and study the exact time-dependence within the time-dependent density matrix renormalization group method. Our study is motivated by the possibilities of experimental probing in cold atomic gas experiments where our choice of perturbation corresponds to lattice amplitude modulation spectroscopy of superlattice geometry.

Q 58.82 Thu 16:30 Empore Lichthof

A Laser System for Cooling of Yb Atoms — •BENJAMIN NAGLER, TOBIAS EUL, CARSTEN LIPPE, BENJAMIN GÄNGER, JAN PHIELER, THOMAS PINNEL, CHRISTINA WEIRICH, and ARTUR WIDERA — Technische Universität Kaiserslautern, Fachbereich Physik und Landesforschungszentrum Optimas, Erwin-Schrödinger-Str. 46, 67663 Kaiserslautern, Germany

Quantum gases have proven useful tools to gain insight into fundamental phenomena of quantum physics. The working horse for preparation of these systems is laser cooling of dilute atomic gases. Here we report on the current state of preparing an ultracold gas of Ytterbium atoms, focusing on the laser system developed. This features blue light generation by second harmonic generation several hundreds of MHz detuned from the atomic transition for operating a Zeeman slower, stabilized onto an atomic resonance. We will show key features of the laser system and present measurements of the system characteristics.

Q 58.83 Thu 16:30 Empore Lichthof

Fermionic many-body states under the microscope — •DANIEL GREIF¹, MAXWELL F. PARSONS¹, ANTON MAZURENKO¹, CHRISTIE S. CHIU¹, SEBASTIAN BLATT^{1,2}, FLORIAN HUBER¹, GEOFFREY JI¹, and MARKUS GREINER¹ — ¹Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA — ²Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany

We report on site-resolved imaging of various fermionic many-body states of ultracold Li-6 in a square optical lattice, including metallic, Mott-insulating and band-insulating phases. The insulating states show a suppression in the single-site occupation variance and a spatially constant filling fraction. A comparison to theory shows that the system is in global thermal equilibrium with fitted global entropies of $1.0 k_B$. We also report on our most recent progress towards probing magnetically ordered quantum states with the quantum gas microscope.

Q 58.84 Thu 16:30 Empore Lichthof

Cloud Shape of Dipolar Fermi Gases — •VLADIMIR VELJIC¹, ANTUN BALAZ¹, ARISTEU R. P. LIMA², and AXEL PELSTER³ — ¹Scientific Computing Laboratory, Institute of Physics Belgrade, University of Belgrade, Serbia — ²UNILAB, Brazil — ³Physics Department and Research Center OPTIMAS, Technical University of Kaiserslautern, Germany

In a recent time-of-flight (TOF) expansion experiment for ultracold polarized fermionic erbium atoms it was shown that the Fermi surface has an ellipsoidal shape [1]. It was also observed that the Fermi surface follows a rotation of the dipoles, which is induced by changing the direction of the external magnetic field, keeping the major axis always parallel to the direction of maximal attraction of the dipole-dipole interaction. Here we present a theory for determining the cloud shape in both real and momentum space by extending the work of Ref. [2], where the magnetic field is oriented along one of the harmonic trap axes, to an arbitrary orientation of the magnetic field. In order to analyze the cloud shape within TOF dynamics, we solve analytically the corresponding Boltzmann-Vlasov equation by using a suitable rescaling of the equilibrium distribution [3]. The resulting ordinary differential equations of motion for the scaling parameters are solved numerically

in the collisionless regime at zero temperature and turn out to agree with the observations in the Innsbruck experiment [1].

[1] K. Aikawa, et al., *Science* **345**, 1484 (2014).[2] F. Wächtler, A. R. P. Lima, and A. Pelster, *arXiv:1311.5100*.[3] P. Pedri, et al., *Phys. Rev. A* **68**, 043608 (2003).

Q 58.85 Thu 16:30 Empore Lichthof

Development of a digital phase lock for optical lattices — •DOMINIK VOGEL, NICK FLÄSCHNER, MATTHIAS TARNOWSKI, BENNO REM, CHRISTOF WEITENBERG, and KLAUS SENGSTOCK — Universität Hamburg, Germany

Non-separable optical lattices feature new physics as for example Dirac cones and Berry phases in the case of the hexagonal lattice, which is formed by three interfering beams. Usually, the lattice beams pass through optical fibers for optimal beam profiles and therefore pick up independent phases, which translate the lattice potential and thus couple acoustic noise to the ensemble of ultra cold atoms, leading to heating.

In this poster, we present a digital phase locked loop that fixes those phases by controlling the laser frequencies via AOMs. The loop features a 800 kS/s bipolar analog to digital converter, a real time processor and a DDS frequency source. Our setup enables a total feedback signal delay under 2 micro seconds, while providing the high linewidth quality of a DDS-source, which is superior to conventional analog phase locks. In closed loop, we achieve a significant reduction of the phase noise, which is expected to increase the atomic life time in the optical lattice and thus provides access to new temperature regimes.

Q 58.86 Thu 16:30 Empore Lichthof

Towards quantum gas microscopy of ultracold potassium atoms — •TOBIAS WINTERMANTEL, EMIL PAVLOV, ALDA ARIAS, STEPHAN HELMRICH, and SHANNON WHITLOCK — Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg

Ultracold quantum gases in optical lattices are a versatile model system for engineering many-body quantum systems. Additionally, the advent of single-atom-resolution imaging techniques enables one to extract an unprecedented degree of information on the spatial correlations.

We are constructing a new experiment featuring fermionic or bosonic potassium atoms in optical lattices with reduced dimensional confinement. A special aspect will be the ability to introduce and control long-range interactions between the atoms via optical dressing of Rydberg states. A high-resolution imaging setup for probing these quantum gases, mainly consisting of an in-vacuum high-NA objective lens and a high quantum efficiency EMCCD camera, is currently under construction. The expected imaging quality depends, on the one hand, on the constraints of the imaging system (numerical aperture, aberrations and detector noise) and on the other hand, on physical constraints such as the number of photons which can be scattered before the atoms are heated and lost out of the microtraps. We present our progress in quantifying these effects for imaging Rydberg-dressed quantum fluids.

Q 58.87 Thu 16:30 Empore Lichthof

Density dependent synthetic magnetism — •SEBASTIAN GRESCHNER¹, DANIEL HUERGA², GAOYONG SUN¹, DARIO POLETTI³, and LUIS SANTOS¹ — ¹Institut für Theoretische Physik, Leibniz Universität Hannover, Germany — ²Institut für Theoretische Physik III, Stuttgart — ³Engineering Product Development, Singapore University of Technology and Design

Raman-assisted hopping can allow for the creation of density-dependent synthetic magnetism for ultracold neutral gases in optical lattices. In 1D the density-dependent Peierls phases can be mapped the anyon Hubbard model which exhibits a rich groundstate physics including unconventional two-component superfluid phases and statistically driven phase transitions [1]. In 2D square lattices we observe a non-trivial interplay between density modulations and effective magnetic fluxes as well as intriguing dynamical properties [2].

[1] S. Greschner and L. Santos, *Phys. Rev. Lett.* **115**, 053002, 2015[2] S. Greschner, D. Huerga, G. Sun, D. Poletti, and L. Santos, *Phys. Rev. B* **92**, 115120, 2015

Q 58.88 Thu 16:30 Empore Lichthof

Heteronuclear Spin-Changing-Collisions in Li-Na mixtures — •ARNO TRAUTMANN, FABIÁN OLIVARES, MARCELL GALL, FRED JENDRZEJEWSKI, and MARKUS K. OBERTHALER — Kirchhoff-Institut für Physik, Im Neuenheimer Feld 227, 69120 Heidelberg

Homonuclear Spin-Changing-Collisions are a well-known tool in ultracold atomic samples to study entanglement, magnetism and the rich field of both bosonic and fermionic spinor physics. Spin-Changing-Collisions of atoms with different species can extend these tools even further to investigate collective effects of spinor mixtures. We present first results on heteronuclear Bose-Bose Spin-Dynamics in the $^7\text{Li-Na}$ mixtures as well as in the Fermi-Bose $^6\text{Li-Na}$ mixture. The heteronuclear Bose-Bose system has the advantage that no dressing is needed to achieve energetic degeneracy due to the different quadratic Zeeman shift. The Fermi-Bose case, however, poses large experimental challenges since the energy-dependence on the magnetic field is of linear order, which requires high stability of magnetic fields.

Since the spin-exchange term for all these processes depends on the scattering lengths of the molecular states, we also present the first measurement of the Feshbach spectrum of $^7\text{Li-Na}$ which reveals a 1 G broad resonance at 150 G.

Q 59: Poster: Symposium Biomedical Optics (SYBO)

Time: Thursday 16:30–19:00

Location: Empore Lichthof

Q 59.1 Thu 16:30 Empore Lichthof

Determination of absorption and effective scattering in three-layered biological tissue using the diffusion and P_3 approximation — ●SIMEON MÜLLER, DOMINIK REITZLE, ANDRÉ LIEMERT, and ALWIN KIENLE — Institut für Lasertechnologien in der Medizin und Meßtechnik, Helmholtzstr. 12, 89081 Ulm, Germany

Clinically relevant parameters can be deduced from the scattering and absorption properties of tissue. The radiative transfer equation (RTE) describes light propagation in biological tissue. Solutions are obtained applying different approximations. The most widely used one is the diffusion approximation. It has been solved for infinite, half space and layered geometries but has limitations for short times and small source-detector separations. The spherical harmonic (P_n) approximation approaches the exact solution to the RTE for high orders n . It has recently been solved by our group for the above mentioned geometries.

One way to determine the optical properties of scattering media are time domain measurements. A short pulsed laser beam is targeted on the medium and the time resolved reflectance signal from the surface is measured at a certain distance. Determination of the optical properties is then accomplished by fitting the mentioned models to the measured signal.

With simulated time domain measurements, the determination of the optical properties in three-layered media is investigated, comparing the different approximations. It is shown that already P_3 offers a significant improvement to the diffusion theory for optical properties in the typical range of biological tissue.

Q 59.2 Thu 16:30 Empore Lichthof

Separation of absorption and reduced scattering by multi-spectral Spatial Frequency Domain Imaging utilizing analytical solutions of the RTE — ●STEFFEN NOTHELFER, DOMINIK REITZLE, FLORIAN FOSCHUM, PHILIPP KRAUTER, ANDRÉ LIEMERT, and ALWIN KIENLE — Institut für Lasertechnologien in der Medizin und Meßtechnik, Helmholtzstr. 12, D-89081 Ulm, Germany

Extensive investigations on Spatial Frequency Domain Imaging (SFDI) are done for separation of absorption (μ_a) and reduced scattering coefficient (μ'_s). However, for an accurate and absolute determination of e.g. drug concentrations, spectrally resolved measurements are generally inevitable. Moreover, structural and morphological changes of tissue or other substances mostly result in a change of the reduced scattering spectra. A new contact free and rapid method for measuring absorption and the reduced scattering coefficient spectra from 500 nm to 1000 nm is presented. Therefore a push broom spectral imager (InnoSpec, Germany) is used to map each point of a line parallel to a sinusoidal spatial intensity modulation spectrally resolved onto a CCD sensor. These images are post-processed with a special FFT algorithm to obtain the spectral resolved reflectance in the spatial frequency domain. To solve the inverse problem of separating absorption and reduced scattering, a nonlinear least squares regression is used, which applies analytical solutions of the Radiative Transfer Equation (RTE).

Q 58.89 Thu 16:30 Empore Lichthof

Spin phonon dynamics with classical statistical methods — ●ASIER PIÑEIRO ORIOLI^{1,2}, ARGHAVAN SAFAVI-NAINI², MICHAEL WALL², JOHANNES SCHACHENMAYER², and ANA MARÍA REY² — ¹Institute for Theoretical Physics, Heidelberg, Germany — ²JILA, NIST and University of Colorado, Boulder, Colorado, USA

Systems with both spin and phonon degrees of freedom are ubiquitous in physical fields ranging from condensed matter to biophysics. However, methods to compute the dynamics of such systems are scarce, especially in high dimensions. In this work, we combine the Truncated Wigner Approximation (TWA) for bosons with its recently developed discrete version (dTWA) for spins to describe the dynamics of coupled spin-phonon systems. We benchmark the method by comparing to exact results and discuss applications to trapped-ion and cavity experiments.

Q 59.3 Thu 16:30 Empore Lichthof

Angular resolved light scattering microscopy on human chromosomes — ●DENNIS MÜLLER, JULIAN STARK, and ALWIN KIENLE — Institute for Lasertechnologies in Medicine and Metrology at Ulm University

Common optical methods to karyotype human chromosomes rely on marker substances. Scattering light microscopy promises to be a method to distinguish human chromosomes marker-free, when supported with suitable theoretical models.

The scattering light microscope setup consists of an inverse microscope with an AOTF - supercontinuum laser combination as source, providing collimated broadband light and monochromatic light with a tuneable wavelength at high intensities. The backscattered light can be sampled with a spectrometer or angular resolved via a CCD camera, positioned in the Fourier plane [1].

With this setup, the angular resolved scattering pattern of human chromosomes were measured. The measurement conditions were modelled using the Amsterdam Discrete Dipole Approximation (ADDA), an open source light scattering simulation software based on Maxwell's equations. Measurement and simulation results show a high correlation with a strong sensibility to the chromosome's geometrical properties. Hence, this method promises to become a powerful, marker-free tool in measuring geometrical features of organic samples well below the resolution limit of common light microscopy.

[1] M. Schmitz, T. Rothe, A. Kienle, Biomed. Opt. Express, Vol.2, No. 9, p.2665-2678 (2011)

Q 59.4 Thu 16:30 Empore Lichthof

Separation of the reduced scattering and absorption coefficients of layered media using an enhanced integrating sphere setup — ●FLORIAN BERGMANN, FLORIAN FOSCHUM, and ALWIN KIENLE — Institut für Lasertechnologien in der Medizin und Meßtechnik, Ulm, Deutschland

The integrating sphere is a well-known "golden standard method" to estimate optical properties of biological tissue. In contrast to other standard methods like spatially resolved-, time resolved- or temporal frequency resolved reflectance the integrating sphere setup allows the study of samples having small volumes.

Our enhanced integrating sphere setup using a layered GPU Monte Carlo simulation of light propagation for evaluation enables the separation of the reduced scattering μ'_s and absorption μ_a coefficients in a spectral range of 400 to 1700 nm. Validation of the setup was done by preparation of epoxy resin phantom slabs with well-known optical properties in a range of $0.5 \text{ mm}^{-1} < \mu'_s < 30 \text{ mm}^{-1}$ and $10^{-3} \text{ mm}^{-1} < \mu_a < 10 \text{ mm}^{-1}$. The results were compared with semi-infinite phantoms having the same properties as the slabs using other standard methods.

The next step is to separate the reduced scattering and absorption coefficients of layered biological samples like tissue.

Q 60: Laser Applications I

Time: Friday 11:00–13:00

Location: a310

Q 60.1 Fri 11:00 a310

Evidence for influence of the final-state bandstructure on attosecond photoemission from metals — ●MARTIN SCHÄFFER — Max-Planck-Institut für Quantumoptik, 85748 Garching — Department für Physik, TUM, 85748 Garching

Since 2007, time-resolved photoemission from metals has been studied on the attosecond time-scale. Photoemission is triggered by sub-femtosecond XUV photons, and the momentum and energy of the emitted photoelectron is then modulated by the vector potential of an synchronized femtosecond few-cycle NIR-laser-field (streaking). Temporal information of the photoemission can then be extracted with attosecond precision from the resulting spectrogram (electron energy vs. XUV-NIR delay). A lot of experimental results have been obtained, and variety of theoretical treatments aiming at the explanation of these results. However, clear discrimination of the distinct theories in experiment has not been possible till recently.

Here, we focus on the possible influence of the final-state bandstructure. In fact, in an streaking experiment from Magnesium at high XUV photon energies, we have obtained clear evidence that the final-state bandstructure has an effect on the delay in photoemission between electrons emerging from localized core states and from delocalized valence states. This is remarkable because this result clearly supports one of the theories in favor of the other approaches, namely the model of resonant and non-resonant emission. Hence, we made serious progress towards a better understanding of the photoemission process in the time domain.

Q 60.2 Fri 11:15 a310

Wavelength tunable high speed femtosecond pump probe spectroscopy based on supercontinuum generation — ●LUKAS EBNER, NICO KRAUSS, and THOMAS DEKORSY — Universität Konstanz

Asynchronous optical sampling (ASOPS) based on two synchronized GHz repetition rate oscillators allows performing pump-probe measurements over a time-delay window of 1ns with a signal sensitivity and temporal resolution limited only by shot noise and the pulse duration, respectively [1-3]. Here, we extend the ASOPS scheme towards wavelength tunability by spectral broadening of a GHz repetition rate Ti:sapphire oscillator in a photonic crystal fiber. The resulting supercontinuum supports ultrashort pulses with central wavelengths around 550 nm and 850-1100 nm. First two-colour ASOPS measurements with a pump wavelength of 800 nm and a continuously tunable probe wavelength are demonstrated.

1. Bartels, A. et al., Rev. Sci. Instrum. 78, 035107 (2007). 2. Gebbs, R. et al., Opt. Express 18, 5974-5983 (2010) 3. Krauß, N. et al., Opt. Express 23, 18288-18299 (2015)

Q 60.3 Fri 11:30 a310

Femtosecond Yb:KYW laser and applications in time-resolved spectroscopy — NICO KRAUSS, GERHARD SCHÄFFER, ●CHANGXIU LI, and THOMAS DEKORSY — Department of Physics and Center of Applied Photonics, University of Konstanz, D-78457 Konstanz, Germany

High speed asynchronous optical sampling (ASOPS) is an important method for pump-probe experiments based on two femtosecond lasers without a mechanical delay line. An ASOPS system based on a GHz Yb:KYW oscillator and a Ti:sapphire oscillator is reported. The repetition rate offset between two oscillators is stabilized by a phase-locked loop to permit multi-kHz scanning rates. The GHz diode-pumped Kerr-lens mode-locked Yb:KYW oscillator with optical-to-optical efficiency of more than 45% is demonstrated. The time resolution of this system within 1 ns time window is below 350 fs and noise floor below 10^{-6} close to the shot-noise level within an acquisition time of 5 s can be achieved. We discuss applications of this two-colour pump-probe system.

Q 60.4 Fri 11:45 a310

Absolute frequency measurement and phase-locking of a THz quantum cascade laser with 10 GHz Ti:sapphire frequency combs — ●OLIVER KLIEBISCH¹, DIRK HEINECKE¹, THOMAS DEKORSY¹, HUA LI², CARLO SIRTORI², GIORGIO SANTARELLI³, and STEFANO BARBIERI² — ¹Center for Applied Photonics, University of

Konstanz, Konstanz — ²Laboratoire Matériaux et Phénomènes Quantiques, Université Paris Diderot, France — ³Laboratoire Photonique, Numérique et Nanosciences, Université Bordeaux, France

Terahertz quantum cascade lasers (QCLs) play an important role as THz sources for high resolution spectroscopy [1] and frequency metrology. The challenge is to determine the absolute frequency of the QCL. With a dual-comb sampling technique using high repetition rate femtosecond lasers this can be accomplished without using additional frequency references for calibration. The QCL operates at 2.5 THz [2] and is injection locked at 9.72 GHz repetition rate. The femtosecond laser used for electro-optic sampling of the THz QCL electric field is a stabilized 10 GHz repetition rate Ti:sapphire laser [3] which is also used for phase locking the QCL by drive current modulation. Dual-comb spectroscopy is employed by sampling the phase-locked QCL with a second Ti:sapphire laser which is offset locked to the first Ti:sapphire laser. The two down-converted QCL spectra allow the determination of the absolute QCL frequency only limited by the stability and measurement precision of the RF beat mode. [1] L. Consolino et. al., Nat. Commun., 3, 1040 (2012). [2] S. Barbieri, et. al., App. Phys. Lett 85 1674 (2004). [3] A. Bartels, et. al., Science, 326, 681 (2009).

Q 60.5 Fri 12:00 a310

Lasertätigkeit von Nd:Lu₂O₃ auf den Übergängen ⁴F_{3/2} → ⁴I_{13/2}, ⁴I_{11/2} und ⁴I_{9/2} im nahen infraroten Spektralbereich — ●PATRICK VON BRUNN^{1,2}, ALEXANDER HEUER^{1,2} und CHRISTIAN KRÄNKEL^{1,2} — ¹Institut für Laser-Physik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg — ²The Hamburg Centre for Ultrafast Imaging, Luruper Chaussee 149, 22761 Hamburg

Lu₂O₃ eignet sich hervorragend als Wirtsmaterial für Seltenerd-dotierte Festkörperlaser. Während mit Yb³⁺-, Ho³⁺-, Tm³⁺- und Er³⁺-dotiertem Lu₂O₃ bereits ausgezeichnete Laserresultate erzielt wurden, erfolgte bisher keine detaillierte Charakterisierung der Lasereigenschaften von Nd³⁺-dotiertem Lu₂O₃. Hier berichten wir über unsere Ergebnisse zur Untersuchung der Lasertätigkeit von Nd:Lu₂O₃. Unter Ti:Saphir-Laser-Pumpen wurde Lasertätigkeit auf sechs Übergängen mit Wellenlängen zwischen 951 nm und 1463 nm mit differentiellen Wirkungsgraden von bis zu 65% realisiert. Die Wellenlänge von 1463 nm gehört dabei zu den längsten Wellenlängen, die jemals mit einem Nd-dotierten Kristall demonstriert wurden.

Q 60.6 Fri 12:15 a310

Anregung der Rydbergzustände n = 22, 51, 52 und 64 von ⁴⁰Ca⁺ mit Vakuum-Ultraviolettem-Laserlicht — ●PATRICK BACHOR^{1,2}, MATTHIAS STAPPEL^{1,2}, JOCHEN WALZ^{1,2}, THOMAS FELDKER¹ und FERDINAND SCHMIDT-KALER¹ — ¹Quantum, Institut für Physik, Universität Mainz, 55099 Mainz — ²Helmholtz-Institut Mainz, 55099 Mainz

Ein vielversprechender Ansatz für zukünftige Anwendungen in der Quanteninformation sind in Rydbergzustände angeregte Ionen, die in einer Paulfalle gezielt manipuliert werden können. Zum einen können so, aufgrund des für Rydbergzustände modifizierten Fallenpotentials, spezielle Vibrationsmoden designt werden. Zum anderen sind schnelle Verschränkungsoperationen mittels der großen Dipol-Dipol-Wechselwirkung möglich. Wir konnten bisher Anregungen von ⁴⁰Ca⁺ Ionen in die Niveaus n = 51F, 52F und 64F [1] sowie in das Niveau 22F beobachten.

Eine Herausforderung ist die Erzeugung des benötigten Lichtfeldes im Vakuum-Ultravioletten (VUV) bei 122 nm, die hier erläutert werden soll. Zudem werden die Fortschritte der Rydbergspektroskopie, die Zuordnung der Niveaus, sowie die Linienform in oszillierendem Feld der Paulfalle diskutiert.

[1] Phys.Rev.Lett. 115, 173001 (2015)

Q 60.7 Fri 12:30 a310

Measurement of the nonlinear refractive index of noble gases — ANDREAS BLUMENSTEIN¹, MILUTIN KOVACEV², UWE MORGNER^{2,3}, PETER SIMON¹, and ●TAMAS NAGY^{1,2} — ¹Laser-Laboratorium Göttingen e.V., Hans-Adolf-Krebs-Weg 1, 37077 Göttingen — ²Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover — ³Laser Zentrum Hannover e.V., Hollerithallee 8, 30419 Hannover

The nonlinear refractive index of rare gases were measured with high precision by characterizing the spectral broadening of short laser pulses

during propagation in a long hollow waveguide. In this way two common problems of nonlinearity measurements could be overcome: the precise determination of the actual light intensity and the accumulation of sufficiently large nonlinearity by using a well-defined geometry and large interaction length. As a result, reliable values could be extracted also for helium and neon which are notoriously difficult to measure due to their very low nonlinearity.

Q 60.8 Fri 12:45 a310

Driving circular currents in super atomic molecular orbitals of fullerenes by light carrying orbital angular momentum — ●JONAS WÄTZEL, YAROSLAV PAVLYUKH, ALEXANDER SCHÄFFER, and JAMAL BERAKDAR — Institut für Physik, Martin-Luther Universität Halle-Wittenberg, Karl-Freiherr-von-Fritsch-Str. 3, 06120 Halle/Saale
Endohedral molecular magnets are promising candidates for molecular electronics and quantum information processing. For utilization

an ultrafast control of the local magnetization is inevitable. We suggest exploiting in Fullerenes the virtual, (super) atomic-like molecular orbitals (SAMOs) to photo-trigger current loops and hence localized magnetic pulses for magnetization

An effective method to steer magnetism is to use inhomogeneous, light carrying orbital angular momentum (OAM). In principle in presence of spin-orbital coupling one may drive the spin directly with such a beam but here we generate surface orbital moment that Zeeman-couples to the well isolated spin active states associated with the endohedral structure.

We found that the generated current is controllable by the frequency, the topological charge, and the intensity of the light. Utilizing Numerical and analytic calculations we find that a UV OAM fs pulse with an intensity 10^{13} W/cm² generates nA currents with an associated magnetic field on the scale of few hundreds μ T in the centre of the fullerene.

Q 61: Quantum Gases: Fermions II

Time: Friday 11:00–13:15

Location: e001

Q 61.1 Fri 11:00 e001

Realizing state-dependent optical lattices for ultracold fermions by periodic driving — ●FREDERIK GÖRG¹, GREGOR JOTZU¹, MICHAEL MESSER¹, DANIEL GREIF^{1,2}, RÉMI DESBUQUOIS¹, and TILMAN ESSLINGER¹ — ¹Institute for Quantum Electronics, ETH Zurich, 8093 Zurich, Switzerland — ²Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

Ultracold atoms in optical lattices offer the possibility to engineer specific Hamiltonians with widely tunable properties. Recently, time-modulated optical lattices have been used to dynamically control the atomic tunnelling and to realize effective Floquet lattice Hamiltonians with a non-trivial topological band structure. While previous implementations relied on the physical motion of the lattice potential, this effect can also be realized by a periodic modulation of a magnetic field gradient. As the coupling of an atom to this magnetic field gradient depends on its magnetic moment and therefore its internal state, the effective Hamiltonian is spin-dependent.

We realize a state-dependent lattice for fermionic potassium atoms and characterize the different band structures for each internal state by measuring the expansion rate of an atomic cloud in the lattice and the effective mass through dipole oscillations. Furthermore, we study the heating caused by the periodic driving in an interacting fermionic spin mixture and how it can be suppressed. This method of creating spin-dependent optical lattices can be used to create novel situations, such as systems where one fermionic spin state is pinned to the lattice, while the other remains itinerant.

Q 61.2 Fri 11:15 e001

Experimental reconstruction of the Berry curvature in a topological Bloch band — ●NICK FLÄSCHNER, BENNO REM, MATTHIAS TARNOWSKI, DOMINIK VOGEL, DIRK-SÖREN LÜHMANN, KLAUS SENGSTOCK, and CHRISTOF WEITENBERG — Institut für Laserphysik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany

Topological properties lie at the heart of many fascinating phenomena in solid state systems such as quantum Hall systems or Chern insulators. The topology can be captured by the distribution of Berry curvature, which describes the geometry of the eigenstates across the Brillouin zone. Employing fermionic ultracold atoms in a hexagonal optical lattice, we generate topological bands using resonant driving and show a full momentum-resolved measurement of the ensuing Berry curvature. Our results pave the way to explore intriguing phases of matter with interactions in topological band structures.

Q 61.3 Fri 11:30 e001

Detecting the BCS order parameter in the dephasing of collective oscillations after a sudden ramp of the lattice depth in a honeycomb lattice — ●MARLON NUSKE¹, EITE TIESINGA², and LUDWIG MATHEY¹ — ¹Zentrum für Optische Quantentechnologien and Institut für Laserphysik, Universität Hamburg, 22761 Hamburg, Germany — ²Joint Quantum Institute and Center for Quantum Information and Computer Science, National Institute of Standards and Technology and University of Maryland, Gaithersburg, Maryland

20899, USA

We obtain the exact time evolution for a mean-field Bardeen-Cooper-Schrieffer (BCS) state after a sudden quench to a large lattice depth, where the dynamics is dominated by interactions between atoms. The quench initiates collective oscillations with frequency $U_f/(2\pi)$ of the momentum occupation numbers and imprints a phase oscillating with the same frequency on the order parameter. Finite hopping after the quench leads to dephasing of the different momentum modes and a subsequent damping of the oscillations. Even for finite temperatures this occurs for a mean-field BCS state, but not for a non-interacting Fermi gas. Measuring the dephasing of collective oscillations of occupation numbers may therefore be used as a signature to detect the BCS order parameter Δ . Finally, we investigate the time evolution of the density-density correlations.

Q 61.4 Fri 11:45 e001

Floquet-Boltzmann equation for periodically driven Fermi systems — ●MAXIMILIAN GENSKE and ACHIM ROSCH — Institut für Theoretische Physik, Universität zu Köln, D-50937 Cologne, Germany

Periodically driven quantum systems can be used to realize quantum pumps, ratchets, artificial gauge fields and novel topological states of matter. Starting from the Keldysh approach, we develop a formalism, the Floquet-Boltzmann equation, to describe the dynamics and the scattering of quasiparticles in such systems. The theory builds on a separation of time-scales. Rapid, periodic oscillations occurring on a time scale $T_0 = 2\pi/\Omega$, are treated using the Floquet formalism and quasiparticles are defined as eigenstates of a non-interacting Floquet Hamiltonian. The dynamics on much longer time scales, however, is modeled by a Boltzmann equation which describes the semiclassical dynamics of the Floquet-quasiparticles and their scattering processes. As the energy is conserved only modulo $\hbar\Omega$, the interacting system heats up in the long-time limit. As a first application of this approach, we compute the heating rate for a cold-atom system, where a periodic shaking of the lattice was used to realize the Haldane model [G. Jotzu *et al.*, Nature **515**, 237 (2014)].

Q 61.5 Fri 12:00 e001

Dynamics of Trapped Dipolar Fermi Gases: From Collisionless to Hydrodynamic Regime — ●VLADIMIR VELJIC¹, AN-TUN BALAZ¹, and AXEL PELSTER² — ¹Scientific Computing Laboratory, Institute of Physics Belgrade, University of Belgrade, Serbia — ²Physics Department and Research Center OPTIMAS, Technical University of Kaiserslautern, Germany

A recent time-of-flight expansion experiment has now unambiguously detected a Fermi surface deformation in a dipolar quantum gas of fermionic erbium atoms in the collisionless regime [1]. Here we follow Ref. [2] and perform a systematic study of a time-of-flight expansion for trapped dipolar Fermi gases ranging from the collisionless to the hydrodynamic regime at zero temperature. To this end we solve analytically the underlying Boltzmann-Vlasov equation in the vicinity of equilibrium by using a suitable rescaling of the equilibrium distribution [3], where the collision integral is simplified within a relaxation time approximation. We also analyze the quench dynamics, which is in-

duced by a sudden rotation of the polarization of the atomic magnetic moments and show that it can be understood in terms of a superposition of the low-lying collective modes. All presented analytical and numerical calculations are relevant for understanding quantitatively ongoing experiments with ultracold fermionic dipolar atoms.

[1] K. Aikawa, et al., *Science* **345**, 1484 (2014).

[2] F. Wächtler, A. R. P. Lima, and A. Pelster, [arXiv:1311.5100](https://arxiv.org/abs/1311.5100).

[3] P. Pedri, D. Guery-Odelin, and S. Stringari, *Phys. Rev. A* **68**, 043608 (2003).

Q 61.6 Fri 12:15 e001

Emergence of orthogonality in the Fermi impurity problem — ●ANDREA BERGSCHNEIDER, MICHAEL DEHABE, JAN HENDRIK BECHER, VINCENT M. KLINKHAMER, SIMON MURMANN, GERHARD ZÜRN, and SELIM JOCHIM — Physikalisches Institut der Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany

In quasi-one-dimensional systems, the ground-state wave function of an impurity particle interacting with a Fermi sea is orthogonal to the wave function of the non-interacting system. In this case the squared overlap between the interacting and the non-interacting systems, which is defined as the quasiparticle residue, is zero.

Here, we report on measurements of the residue of a single fermionic impurity particle interacting with an increasing number of majority particles. To probe the system, we flip the spin of the impurity particle by driving a radio frequency (RF) transition. In a previous experiment we used RF spectroscopy to measure the interaction energy in this system while increasing the number of majority particles one atom at a time and thereby observed the crossover from few to many-body physics [1]. Now, we measure how the wave function overlap between initial and final states changes both as a function of interaction strength and the number of majority particles. Our goal is to extend these measurements into the crossover region between few and many-body physics by increasing the number of majority particles and thereby observe the emergence of the orthogonality catastrophe.

[1] Wenz et al. *Science* 342, 457 (2013)

Q 61.7 Fri 12:30 e001

Many-body localization in the presence of photon scattering — ●HENRIK LUESCHEN^{1,2}, PRANJAL BORDIA^{1,2}, SEAN HODGMAN^{1,2}, MICHAEL SCHREIBER^{1,2,3}, IMMANUEL BLOCH^{1,2}, and ULRICH SCHNEIDER^{1,2,3} — ¹Max-Planck-Institut für Quantenoptik, Garching — ²Ludwig-Maximilians-Universität, München — ³Cavendish Laboratory, Cambridge

In recent years, disordered systems have been the subject of great interest. Especially, Many-Body Localization (MBL) has emerged as a new paradigm for ergodicity breaking robust to interactions in closed quantum systems. While any coupling of an MBL system to an ex-

ternal bath is expected to restore ergodicity, it is still unclear to what extent the dynamics are affected by the proximity of the MBL phase.

Here, we investigate a fermionic, quasi-disordered MBL system in the presence of weak photon scattering. This introduces non-unitary measurement processes, acting as an infinite bandwidth bath, and particle loss. We monitor the transient behaviour of our system and find a strong dependence on both the disorder strength and interactions.

Q 61.8 Fri 12:45 e001

Observation of an orbital interaction-induced Feshbach resonance in ¹⁷³Yb — MORITZ HÖFER^{1,2}, ●LUIS RIEGGER^{1,2}, FRANCESCO SCAZZA^{1,2}, CHRISTIAN HOFRICHTER^{1,2}, DIOGO RIO FERNANDES^{1,2}, IMMANUEL BLOCH^{1,2}, MEERA M. PARISH³, JESPER LEVINSSEN³, and SIMON FÖLLING^{1,2} — ¹Ludwig-Maximilians-Universität, Schellingstraße 4, 80799 München, Germany — ²Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany — ³School of Physics and Astronomy, Monash University, Victoria 3800, Australia

We report on the experimental observation of a novel inter-orbital Feshbach resonance in ultracold ¹⁷³Yb atoms, which opens the possibility of tuning the interactions between the ¹S₀ and ³P₀ metastable state, both possessing vanishing total electronic angular momentum. The resonance is observed at experimentally accessible magnetic field strengths and occurs universally for all hyperfine state combinations. We characterize the resonance in the bulk via inter-orbital cross-thermalization as well as in a three-dimensional lattice using high-resolution clock-line spectroscopy.

Q 61.9 Fri 13:00 e001

Pair Production and String Breaking with Cold Atoms — ●VALENTIN KASPER¹, FLORIAN HEBENSTREIT², FRED JENDRZEJSKI³, MARKUS OBERHALER³, and JUERGEN BERGES¹ — ¹Institut für Theoretische Physik, Philosophenweg 16, 69120 Heidelberg, Germany — ²Universität Bern, Albert Einstein Center for Fundamental Physics, Sidlerstrasse 5, CH-3012 Bern — ³Kirchhoff-Institut für Physik, Im Neuenheimer Feld 227, 69120 Heidelberg

We consider a system of ultracold atoms in an optical lattice as a quantum simulator for electron-positron pair production and string breaking in quantum electrodynamics (QED). For a setup in one spatial dimension, we investigate the non-equilibrium dynamics of both phenomena. Moreover, we discuss the experimental realization of this model in one dimension. In particular this will allow us to study quantum link models in a yet unexplored parameter regime. The result suggests that depending on the theoretical question at hand, the quantum simulator has to employ coherent samples of a localized bose gas instead of single particles.

Q 62: Quantum Information: Quantum Computing and Communication III

Time: Friday 11:00–12:45

Location: e214

Q 62.1 Fri 11:00 e214

Ultrafast Fault-Tolerant Long-Distance Quantum Communication with Static Linear Optics — ●FABIAN EWERT and PETER VAN LOOCK — Institut für Physik, Johannes Gutenberg-Universität, Staudingerweg 7, D-55128 Mainz

We present an all-optical, ultrafast scheme for long-distance quantum communication that can handle both photon losses and various depolarizing errors, e.g., caused by faulty detectors and resource states. The scheme is based on quantum parity encoded qubits and static linear optics. Nonlinear effects are only required for the generation of encoded qubits and Bell states where we propose to use coherent photon conversion which also allows for a static setup and, in principle, an on-chip integration.

Q 62.2 Fri 11:15 e214

Upgrading existing Laser Communication Terminals for Satellite Quantum Communication — ●DOMINIQUE ELSER¹, KEVIN GÜNTNER¹, IMRAN KHAN¹, BIRGIT STILLER¹, CHRISTOPH MARQUARDT¹, GERD LEUCHS¹, KAREN SAUCKE², DANIEL TRÖNDLE², FRANK HEINE², STEFAN SEEL², PETER GREULICH², HERWIG ZECH², BJÖRN GÜTLICH³, INES RICHTER³, and ROLF MEYER³ — ¹Max Planck Institute for the Science of Light, Erlangen, Germany and

Institute of Optics, Information and Photonics, Friedrich-Alexander University Erlangen-Nürnberg (FAU), Erlangen, Germany — ²Tesat-Spacecom GmbH & Co. KG, Backnang, Germany — ³Space Administration, German Aerospace Center (DLR), Bonn, Germany

By harnessing quantum effects, we nowadays can use encryption that is information-theoretically secure. These fascinating quantum features have been implemented in metropolitan quantum networks around the world. In order to interconnect such metropolitan networks over long distances, optical satellite communication is the method of choice. Standard telecommunication components allow one to efficiently implement quantum communication by measuring field quadratures (continuous variables). This opens the possibility to upgrade the existing Laser Communication Terminals (LCTs) to quantum key distribution (QKD). First satellite measurement campaigns are currently validating our approach [1].

[1] D. Elser *et al.*, International Conference on Space Optical Systems and Applications (IEEE ICSOS 2015), October 27 and 28, 2015, New Orleans, USA, [arXiv:1510.04507](https://arxiv.org/abs/1510.04507) [quant-ph] (2015).

Q 62.3 Fri 11:30 e214

Atmospheric Quantum Key Distribution with Squeezed States — ●KEVIN GÜNTNER¹, CHRISTIAN PEUNTINGER¹, CHRISTIAN S. JACOBSEN², DOMINIQUE ELSER¹, VLADYSLAV C. USENKO³,

RADIM FILIP³, ULRIK L. ANDERSEN², CHRISTOPH MARQUARDT¹, and GERD LEUCHS¹ — ¹Max Planck Institute for the Science of Light (MPL), Erlangen, Germany and Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU) — ²Department of Physics, Technical University of Denmark, Kongens Lyngby, Denmark — ³Department of Optics, Palacký University, Olomouc, Czech Republic

In Continuous Variable Quantum Key Distribution, Gaussian quantum states and homodyne detection are used to distribute a secret key between two parties.

Recently it was shown that — in comparison to coherent states — squeezed states can provide higher key rates in presence of channel noise and realistic reconciliation efficiency [1].

This protocol was already successfully implemented in laboratory conditions [2]. Now we verify the feasibility of this approach with an urban free-space channel. We eliminate atmospheric phase noise by using polarization squeezed states benefiting from a decoherence free subspace [3].

[1] V. C. Usenko and R. Filip, *New J. Phys.* **13**, 113007 (2011).

[2] C. S. Jacobsen *et al.*, arXiv:1408.4566 (2014).

[3] C. Peuntinger *et al.*, *Phys. Rev. Lett.* **113**, 060502 (2014).

Q 62.4 Fri 11:45 e214

Towards practical device-independent quantum key distribution with spontaneous parametric downconversion sources, on-off photodetectors and entanglement swapping —

•KAUSHIK SESHADREESAN^{1,2}, MASAHIRO TAKEOKA², and MASAHIDE SASAKI² — ¹Max Planck Institute for the Science of Light, Guenther-Scharowsky-Str. 1/Bldg. 24, D-91058 Erlangen, Germany — ²National Institute of Information and Communications Technology, Koganei, Tokyo 184-8795, Japan

Device-independent quantum key distribution (DIQKD) guarantees unconditional security of secret key without making assumptions about the internal workings of the devices used. The security of DIQKD relies on the verification of nonlocal correlations via the violation of a Bell's inequality in a loophole-free test. The primary challenge in realizing DIQKD in practice is the detection loophole problem associated with optical tests of Bell's inequalities over long distances. We revisit a proposal [1] to use a linear optics-based entanglement swapping relay to counter this problem by considering realistic models for the entanglement sources and photodetectors. More precisely, we consider (a) polarization-entangled states based on a pair of pulsed SPDCs that have infinitely higher order multiphoton components and multimode spectral structure, and (b) on-off photodetectors that have non-unit efficiencies and non-zero dark count probabilities. Our results show that the imperfect entanglement swapping relay-based scheme can still enable positive secret key rates at distances of about a 100 kilometers. [1] Curty and Moroder, *Phys. Rev. A* **84**, 010304(R) (2011).

Q 62.5 Fri 12:00 e214

Continuous-variable high-speed quantum key distribution compatible with telecom networks —

•IMRAN KHAN^{1,2}, BIRGIT STILLER^{1,2,3}, KEVIN JAKSCH^{1,2}, CHRISTIAN PEUNTINGER^{1,2}, KEVIN GÜNTHER^{1,2}, JONAS GEYER-RAMSTECK^{1,2}, NITIN JAIN^{1,2,4}, DOMINIQUE ELSER^{1,2}, CHRISTOPH MARQUARDT^{1,2}, and GERD LEUCHS^{1,2,5} — ¹Max Planck Institute for the Science of Light, 91058 Erlangen Germany — ²Institute of Optics, Information and Photonics, University of Erlangen-Nuernberg, 91058 Erlangen, Germany — ³Centre for Ultrahigh bandwidth Devices for Optical Systems (CUDOS), School of Physics, University of Sydney, NSW 2006, Australia — ⁴Center for Photonic Communication and Computing, EECS Department, Northwestern University, Evanston, Illinois 60208, USA —

⁵Department of Physics, University of Ottawa, 25 Templeton, Ottawa, ON, Canada

The ability to securely distribute keys at high rates is of crucial importance for the future of practical quantum key distribution (QKD). In this work, we show our progress on implementing a GHz rate continuous-variable QKD setup in a realistic telecom environment, employing wavelength-division multiplexing. We discuss how these high transmission rates increase the robustness against finite-size effects and realistic noise sources (e. g. in the low frequency regime; also relevant for free-space channels with fluctuating transmission). We also show the experimental status on implementing a local oscillator, which is situated at the receiver.

Q 62.6 Fri 12:15 e214

Large-Alphabet Time-Frequency Quantum Key Distribution —

•JASPER RÖDIGER^{1,2}, NICOLAS PERLOT¹, MATTHIAS LEIFGEN², ROBERT ELSCHNER¹, ROBERTO MOTTOLA², OLIVER BENSON², and RONALD FREUND¹ — ¹Fraunhofer Heinrich-Hertz Institut, Berlin, Germany — ²Nanooptik AG, Humboldt-Universität zu Berlin, Berlin, Germany

We investigate a quantum key distribution (QKD) scheme, referred to as time-frequency (TF-) QKD, based on the time-frequency uncertainty relation. It is a BB84-like QKD protocol with the two bases being modulations in time and frequency, namely the pulse position modulation (PPM) and frequency shift keying (FSK). Assuming one photon per pulse, measuring in one of the bases increases the measurement uncertainty in the other and thus destroys most information encoded there, similar to BB84.

TF-QKD is mostly compatible to classical communication technologies. Since PPM is a well-established coding technique in free-space communication and polarization is free for duplexing, TF-QKD is very well suited for free-space communication. In addition it is possible to use a large alphabet, thus to send a high number of bits per photon.

With a proof-of-principle experiment, using two symbols per basis, it was possible to distribute a key with a sifted key rate of 12 kbit/s. More symbols per basis and a higher key-rate are the subjects of current investigation. Numerical simulations identified optimal pulse relations and showed that a larger alphabet increases the secret key rate.

Q 62.7 Fri 12:30 e214

Dissipation enabled efficient excitation transfer from a single photon to a single quantum emitter —

•NILS TRAUTMANN and GERNOT ALBER — Institut für Angewandte Physik, Technische Universität Darmstadt

We propose a scheme for triggering a dissipation dominated highly efficient excitation transfer from a single photon wave packet to a single quantum emitter. This single photon induced optical pumping turns dominant dissipative processes, such as spontaneous photon emission by the emitter or cavity decay, into valuable tools for quantum information processing and quantum communication. It works for an arbitrarily shaped single photon wave packet with sufficiently small bandwidth provided a matching condition is satisfied which balances the dissipative rates involved. Our scheme does not require additional laser pulses or quantum feedback and is not restricted to highly mode selective cavity quantum electrodynamical architectures. In particular, it can be used to enhance significantly the coupling of a single photon to a single quantum emitter implanted in a one dimensional waveguide or even in a free space scenario. We demonstrate the usefulness of our scheme for building a deterministic quantum memory and a deterministic frequency converter between photonic qubits of different wavelengths.

Q 63: Ultra-cold atoms, ions and BEC V (with A)

Time: Friday 11:00–13:00

Location: f107

Q 63.1 Fri 11:00 f107

Production of ultracold atomic clouds at the shot noise limit through feedback —

•ANDREW HILLIARD, MIROSLAV GAJDACZ, MICK KRISTENSEN, JACOB SHERSON, and JAN ARLT — Institute for Physics and Astronomy, Ny Munkegade 120, 8000, Aarhus C, Denmark

The reliable production of cold atomic clouds with well-defined properties is a notoriously difficult task. Variations in the atom number and temperature typically arise due to technical fluctuations during

the experimental sequence. However, non-destructive measurements of the ensemble properties during an experimental sequence allow for an active adjustment of the cooling procedure to obtain the desired outcome.

To achieve this, we use a dispersive imaging technique based on Faraday rotation combined with on-line digital image evaluation to provide feedback to the evaporative cooling sequence. Our imaging technique achieves a relative precision below 10^{-3} and thus allows for

active feedback that can beat the atomic shot noise limit. We have implemented feedback based on the Faraday rotation signal and thus achieved run-to-run stability at the shot noise limit.

Q 63.2 Fri 11:15 f107

Box traps for 2D Bose gases — ●SAINT-JALM RAPHAËL¹, VILLE JEAN-LOUP¹, CORMAN LAURA¹, BIENAIMÉ TOM^{1,2}, NASCIMBENE SYLVAIN¹, BEUGNON JÉRÔME¹, and DALIBARD JEAN¹ — ¹Laboratoire Kastler-Brossel, Collège de France — ²INO-CNR BEC Center and Dipartimento di Fisica, Università di Trento

I will present a new experimental setup designed to investigate properties of ultracold bosons in low dimensions. In this setup, we produce a degenerate gas of rubidium atoms vertically confined into a single plane in an optical accordion. In the horizontal plane, we are able to engineer a flat-bottom potential whose shape can be chosen at will (disc, square, rings, boxes) by imaging the surface of a Digital Mirror Device (DMD). Thanks to this versatile system we aim at studying bosonic transport as well as implementing artificial gauge fields. I will present the first results that we have obtained in these directions.

Q 63.3 Fri 11:30 f107

Topological Bogoliubov excitations of weakly interacting Bose-Einstein condensates — ●GEORG ENGELHARDT and TOBIAS BRANDES — Institut für Theoretische Physik, Technische Universität Berlin, Hardenbergstr. 36, 10623 Berlin

Topological band structures have been mostly investigated for fermionic systems. In our talk, we explain how to generalize the notion of topology to Bogoliubov excitations on top of a Bose-Einstein condensate. We investigate the topology of these Bogoliubov excitations in inversion-invariant systems of weakly interacting bosons.

The excitations of the corresponding Bogoliubov Hamiltonian have to be diagonalized in a symplectic manner. Analogously to the fermionic case, we here establish a symplectic extension of the polarization characterizing the topology of the Bogoliubov excitations and link it to the eigenvalues of the inversion operator at the inversion-invariant momenta.

We show that the interaction of the particles influences the topology of the Bogoliubov excitations. Additionally, we demonstrate that this quantity is related to edge states in the excitation spectrum of a finite-size system with boundaries.

Q 63.4 Fri 11:45 f107

Tuning Static and Dynamic Properties of a Quasi One-Dimensional Bose-Einstein Condensate — ●JAVED AKRAM¹ and AXEL PELSTER² — ¹Physics Department, Freie Universität Berlin, Germany — ²Physics Department and Research Center OPTIMAS, Technische Universität Kaiserslautern, Germany

Here we provide a detailed theoretical investigation in view of how to tune both static and dynamic properties of quasi one-dimensional confined Bose-Einstein condensates (BECs). At first we study ⁸⁷Rb atoms in a quasi one-dimensional trap geometry, which consists of a harmonic trap together with a red or blue-detuned Gaussian (Hermite-Gaussian) dimple trap [1,2]. After having switched off the dimple trap, shockwaves or gray pair-soliton (bi-)trains emerge, which oscillate with a characteristic frequency in the remaining harmonic trap. Afterwards, we analyze a quasi one-dimensional BEC in a nonlinear gravito-optical surface trap [3]. Studying a non-ballistic expansion of the BEC cloud, when the confining evanescent laser beam is shut off, turns out to agree quite well with results from a previous Innsbruck experiment. Finally, we investigate how the wave function of a trapped ⁸⁷Rb BEC changes due to the presence of a single ¹³³Cs impurity [4]. To this end, we determine the equilibrium phase diagram, which is spanned by the intra- and inter-species coupling strengths.

[1] J. Akram and A. Pelster, [arXiv:1508.05482](#).

[2] J. Akram and A. Pelster, [arXiv:1509.03826](#).

[3] J. Akram and A. Pelster, [arXiv:1509.05987](#).

[4] J. Akram and A. Pelster, [arXiv:1510.07138](#).

Q 63.5 Fri 12:00 f107

Physical realization of third-order exceptional points — ●JAN SCHNABEL, HOLGER CARTARIUS, and GÜNTER WUNNER — 1. Institut für Theoretische Physik, Universität Stuttgart

Exceptional points are characterized by the coalescence of two or even more eigenstates in non-Hermitian quantum systems. While second-order exceptional points (EP2) have already been realized in experiments, an experimental observation of a third-order exceptional point (EP3) is still lacking. Encouraging systems for such an observation could be a setup of three coupled waveguides as proposed in [1] or \mathcal{PT} -symmetric Bose-Einstein condensates (BEC) in a triple-well trap. We investigate a realistic optical setup by numerically exact calculations, which shows the appearance of an EP3. Due to a formal analogy between the Schrödinger and the Helmholtz equation the same potential can also be realized in quantum mechanics. We introduce a realistic quantum system made up of a BEC in a three-dimensional potential, which should exhibit the characteristic behaviour of an EP3.

[1] E-M. Graefe, *J. Phys. A*: **45**, 2 (2012)

Q 63.6 Fri 12:15 f107

Levy flight and Anderson localization of polar molecules — ●XIAOLONG DENG¹, BORIS ALTSHULER², GORA SHLYAPNIKOV³, and LUIS SANTOS¹ — ¹ITP, Uni. Hannover — ²Physics Dept, Columbia Uni., USA — ³LPTMS, CNRS, France

Rotational excitations in polar molecules in deep optical lattices realize a quantum percolation model with long-range hops, whose properties depend on both lattice filling and dimensionality. Using spectral and multi-fractal analysis, we show that whereas in 1D and 2D all eigenstates are localized, while in 3D all are delocalized.

Q 63.7 Fri 12:30 f107

Photodetachment spectroscopy of OH- in a Hybrid Atom Ion Trap — ●HENRY LOPEZ¹, BASTIAN HÖLTKEMEIER¹, JI LUO¹, ANDRE DE OLIVEIRA², ERIC ENDRES³, ROLAND WESTER³, and MATTHIAS WEIDEMÜLLER¹ — ¹Physikalisches Institut, Universität Heidelberg, INF 226, 69120 Heidelberg, Germany — ²Departamento de Física, Universidade do Estado de Santa Catarina-Joinville, SC, Brazil — ³Institut für Ionenphysik und angewandte Physik, Universität Innsbruck, Technikerstraße 25/3, 6020 Innsbruck, Austria

We report on the current status of our experiment, which combines an 8-pole radio-frequency trap for OH- anions and a dark-spontaneous-force optical trap for rubidium atoms. The laser-cooled atoms serve as an ultracold buffer gas for the trapped anions. The anions final internal state is probed by means of electron photodetachment spectroscopy (PDS). We further discuss how PDS can be used for determining the final translational temperature of the anions.

Q 63.8 Fri 12:45 f107

Coupling Identical 1D Many-Body Localized Systems — ●PRANJAL BORDIA^{1,2}, HENRIK LÜSCHEN^{1,2}, SEAN HODGMAN^{1,2}, MICHAEL SCHREIBER^{1,2}, IMMANUEL BLOCH^{1,2}, and ULRICH SCHNEIDER^{1,2} — ¹Facultät für Physik, LMU, München — ²Max-Planck Institut für QuantenOptik

Many-Body Localization (MBL) marks a new paradigm in condensed matter and statistical physics. It describes a generic insulating phase in which an interacting many-body system fails to serve as its own heat bath and thermalization fails even in excited many-body states.

We experimentally study the dynamics of coupling identically disordered 1D MBL systems. Using a gas of ultracold fermions loaded in optical lattices, we prepare an out-of-equilibrium density wave and monitor its relaxation. We find striking difference between Anderson and MBL systems. While the Anderson case remains localized, coupling MBL systems with each other shows slow glassy relaxation and de-localizes the entire system.

Q 64: Nano-Optics III

Time: Friday 11:00–12:30

Location: f342

Q 64.1 Fri 11:00 f342

Enhancing the spontaneous emission rate of a single emitter by a gold nanocone antenna — ●KORENOBU MATSUZAKI¹, HSUAN-WEI LIU¹, BJÖRN HOFFMANN¹, SILKE CHRISTIANSEN^{1,2}, ANKE DUTSCHKE^{1,3}, STEPHAN GÖTZINGER^{4,1}, and VAHID SANDOGHDAR^{1,4} — ¹Max Planck Institute for the Science of Light, Erlangen, Germany — ²Helmholtz Centre for Materials and Energy, Berlin, Germany — ³Carl Zeiss, Oberkochen, Germany — ⁴Friedrich Alexander University of Erlangen-Nürnberg, Erlangen, Germany

In a recent theoretical work, we have suggested that a gold nanocone can be an ideal plasmonic antenna, which allows one to modify the radiative decay rate of a single emitter by several thousand times while keeping its quantum efficiency high [1]. Here, we report on the first experimental realisation of this concept. The gold nanocones were fabricated by focussed ion beam milling on a glass substrate [2]. As an emitter, we used a colloidal quantum dot, which we attached to the glass tip of a near-field microscope. This configuration allowed us to position the quantum dot with nanometer precision with respect to the nanocone. We will report a reduction of the radiative lifetime by the order of one hundred times. Furthermore, we present a method to extract the radiative decay rate enhancement factor and the antenna efficiency from the experimental data by taking the photophysics of quantum dots into account. [1] Chen, Agio, and Sandoghdar, *Phys. Rev. Lett.* **108**, 233001 (2012). [2] Hoffmann, Vassant, Chen, Götzinger, Sandoghdar, and Christiansen, *Nanotechnology* **26**, 404001 (2015).

Q 64.2 Fri 11:15 f342

Few-cycle sub-10 femtosecond electron point source driven by nanofocused surface plasmon polaritons — ●MELANIE MÜLLER¹, VASILY KRAVTSOV², MARKUS RASCHKE², and RALPH ERNSTORFER¹ — ¹Fritz-Haber-Institut der MPG, Berlin, Germany — ²University of Colorado, Boulder, Colorado 80309, USA

We report the nonlocal excitation of sub-10 femtosecond electron pulses triggered by nanofocused surface plasmon polaritons (SPPs) from the apex of a gold nanotip. Few-cycle SPPs are launched 20 μm away from the apex by broadband grating coupling of 5 fs laser pulses at 800 nm. Nanolocalized photoemission from the apex is verified by the specific focusing conditions of the electron beam inside an electrostatic lens. We measure a pulse duration of 7-8 fs of the plasmonic near field, triggering multiphoton photoemission within a time window of 5 fs. We employ this conceptually new ultrafast electron source for plasmon-triggered femtosecond point-projection microscopy (fsPPM) at a tip-sample distance of 3 μm with a geometric magnification $>30,000$ and image the nanoscale field distribution along the surface of a doped semiconductor nanowire. The remote excitation scheme allows for a significant reduction of the tip-sample distance compared to conventional far-field illumination of the apex, promising few nanometer spatial and few femtosecond temporal resolution in fsPPM as well as the implementation of time-resolved low-energy electron holography.

Q 64.3 Fri 11:30 f342

Above threshold ionization of Rydberg electrons localized to a gold nanotip — ●JÖRG ROBIN¹, JAN VOGELSANG¹, BENEDEK J. NAGY², PETRA GROSS¹, and CHRISTOPH LIENAU¹ — ¹Carl von Ossietzky Universität, 26129 Oldenburg — ²Wigner Research Centre for Physics, H-1121 Budapest

Metallic nanotips are model systems to study nanometre and femtosecond electron dynamics and provide the possibility for ultrafast electron microscopy. Evidence of strong-field phenomena has been observed by one-colour photoemission of electrons from metallic nanotips [1-3], while two-colour photoemission has established the existence of surface states on metallic films [4]. Here, we report femtosecond two-colour photoemission of electrons from a gold nanotip. We observe long-lived wave packets of Rydberg electrons bound to their own image potential. These intermediate bound states facilitate above-threshold ionization similar to atomic systems and give access to a cold, ultrafast, nanolocalized electron source. [1] Krüger, M. et al. *Nature* **475**, 78 (2011) [2] Herink, G. et al. *Nature* **483**, 190 (2012) [3] Piglosiewicz, B. et al. *Nat. Photon.* **9**, 37 (2014) [4] Höfer, U. et al. *Science* **277**, 1480 (1997)

Q 64.4 Fri 11:45 f342

Quantum coherent Ramsey-type interactions of free elec-

trons with spatially separated near-fields — ●KATHARINA E. ECHTERNKAMP, ARMIN FEIST, SASCHA SCHÄFER, and CLAUS ROPPERS — 4th Physical Institute, University of Göttingen, Göttingen, Germany

A few years ago, inelastic interactions of free electrons with optical near-fields, i.e., the absorption and emission of multiple photons, were observed for the first time [1]. Recently, we experimentally demonstrated the quantum coherent nature of this interaction by measuring multilevel Rabi oscillations in the sideband populations of the electron energy spectra [2].

Here, we employ an ultrafast transmission electron microscope (UTEM) to realize a novel type of electron-light interferometer, in which free electron momentum superposition states are manipulated in a quantum coherent manner by two spatially separated optical near-fields. In the experiments, the electron beam passes a specially designed gold nanostructure, which enables precise amplitude and phase control of the two subsequent interactions. In some analogy to the Ramsey method of separated oscillatory fields [3], the relative phase between these interactions governs the total transition amplitude.

[1] B. Barwick *et al.*, *Nature*, **462**,902 (2009).[2] A. Feist *et al.*, *Nature*, **521**,200-203 (2015).[3] N. F. Ramsey, *Rev. Mod. Phys.* **62** (3), 541-552 (1990).

Q 64.5 Fri 12:00 f342

On the existence of TE resonances in graphene-dielectric structures — ●JULIA F. M. WERRA¹, FRANCESCO INTRAVAIA², and KURT BUSCH^{1,2} — ¹Humboldt-Universität zu Berlin, Institut für Physik, AG Theoretische Optik & Photonik, 12489Berlin, Germany — ²Max Born Institute, 12489 Berlin, Germany

In this talk, we discuss the existence and the properties of TE resonances in graphene-dielectric structures. In our description we assume that the contact with the dielectric does alter graphene's properties by inducing a bandgap in its electric bandstructure [1]. In contrast to previous results [2], we show that in this case the TE-plasmon resonance do not cease to exist.

Additionally, we show that, when graphene is in contact with a dielectric slab with finite thickness, it introduces a frequency cutoff for the slab's waveguide modes. This is a pure quantomechanical effect closely related to the pair-creation threshold in graphene [3].

These results do not only offer new ways of designing waveguides but they also provide a basis to understand the behavior and lifetime of, e.g. emitters, in the proximity of such graphene-dielectric structures.

[1] J. Jung, A. M. DaSilva, A. H. MacDonald, and S. Adam, *Nat. Commun.* **6**, 6308 (2015).[2] O. Kotov, M. Kol'chenko, and Y. E. Lozovik, *Opt. Expr.* **21**, 13533 (2013).

[3] J. F. M. Werra, F. Intravaia, and K. Busch, arXiv:1511.00408 (2015).

Q 64.6 Fri 12:15 f342

Hyperbolic plasmons and Dyakonov waves in the topological insulator Bi₂Se₃ unravelled by swift electrons — ●NAHID TALEBI¹, CIGDEM ÖZSOY KESKINBORA¹, HADJ MOHAMED BENIA¹, CHRISTOPH T. KOCH², and PETER A. VAN AKEN¹ — ¹Max Planck Institute for Solid State Research, Heisenbergstr. 1, 70569 Stuttgart, Germany — ²Institut für Experimentelle Physik Universität Ulm Albert-Einstein-Allee 11, D-89081 Ulm

Materials crystallizing in tetradymite structure are fascinating, since at their bandgap just near to the Fermi level they sustain time-reversal-invariant topological effects. Another characteristic of tetradymites is caused by the huge uniaxial electric anisotropic behaviour of the material. Due to the interplay between the metallic and dielectric response, Bi₂Se₃ can be a proper case for studying the plasmonic excitations in hyperbolic materials with different bulk dispersion characteristics.

Here, utilizing electron energy-loss spectroscopy, we experimentally investigate plasmonic modes of Bi₂Se₃ nanostructures. Very interesting observations are the high intensities for the EELS signal almost all energies ranging from 0.8 eV up to 4 eV, while at higher energies the contribution of surface plasmon modes is more evident. Interestingly, even at the energy loss of E=0.8 eV in which the material is totally dielectric, the excitation of an edge mode is apparent, and can be explained by the excitation of Dyakonov waves. We furthermore investi-

gate the surface waves and edge plasmon dispersions, both analytically and numerically, in order to obtain an improved understanding of our

experimental observations.

Q 65: Precision spectroscopy of atoms and ions III (with A)

Time: Friday 11:00–12:45

Location: f428

Q 65.1 Fri 11:00 f428

Spectroscopy of hyperfine structures and isotope shifts in the sequence of 97-99 technetium — ●TOBIAS KRON¹, REINHARD HEINKE¹, SEBASTIAN RAEDER², TOBIAS REICH³, PASCAL SCHÖNBERG³, and KLAUS WENDT¹ — ¹Institute of Physics, Mainz University — ²GSF Helmholtzzentrum für Schwerionenforschung, Darmstadt — ³Institute of Nuclear Chemistry, Mainz University

One of the dominant fission products of uranium is technetium-99, which is generally extremely rare in nature, due to the fact that all isotopes are unstable. With a long half-life and its strong β^- -radioactivity, ⁹⁹Tc is one of the major radiotoxic long-term remnants of nuclear reactors and atomic bombs. On the other hand, knowledge on atomic and nuclear properties of technetium isotopes is rather scarce due to their rare occurrence. Both, ultra-trace determination as well as investigations of nuclear structure are of relevance and require extensive atomic spectroscopy as input.

This talk presents first results of high resolution resonance ionization spectroscopy on the isotopes ^{97–99}Tc. Measurements were carried out on smallest samples in the order of 10^{12} atoms or less, using a high repetition rate laser system. The hyperfine structures and isotope shifts of several transitions were investigated, giving new information on nuclear structure and deriving the so-far unclear nuclear spin of ⁹⁸Tc. Experimental linewidths around 100 MHz were achieved by using a frequency-doubled pulsed injection-locked titanium:sapphire laser in combination with a newly developed ion source with a perpendicular laser-atom beam geometry in a radiofrequency quadrupole structure.

Q 65.2 Fri 11:15 f428

Identification of the splitting and sequence of closely-spaced energy levels by analyzing the angle-resolved fluorescence light — ●ZHONGWEN WU^{1,2}, ANDREY SURZHYKOV¹, ANDREY VOLOTKA¹, and STEPHAN FRITZSCHE^{1,3} — ¹Helmholtz Institute Jena, Germany — ²Northwest Normal University, China — ³University of Jena, Germany

The energy-dependent photoexcitation and subsequent fluorescence radiation of atoms have been investigated within the framework of second-order perturbation theory and the density matrix theory. Special attention has been paid to the angular distribution of the characteristic x-rays from (partial) overlapping resonances and how they are affected by the level splitting and the sequence of these resonances, if analyzed as a function of the photon energy of the exciting light. Detailed computations within the multiconfiguration Dirac-Fock method were carried out for the $1s^2 2s^2 2p^6 3s$ $J_0 = 1/2 + \gamma_1(\hbar\omega) \rightarrow (1s^2 2s 2p^6 3s)_{13p_{3/2}}$ $J = 1/2, 3/2 \rightarrow 1s^2 2s^2 2p^6 3s$ $J_f = 1/2 + \gamma_2$ excitation and decay of neutral sodium atoms. A remarkably strong dependence of the angular distribution of these x-rays upon the level splitting and even the sequence was found by crossing the resonances. This dependence arises from the finite lifetime of the overlapping resonances. We therefore suggest that accurate measurements of x-ray angular distribution could be used to identify the level splitting and sequence of closely-spaced atomic resonances following inner-shell excitations.

Q 65.3 Fri 11:30 f428

Precision isotope shift measurements of calcium ions using photon recoil spectroscopy — FLORIAN GEBERT¹, YONG WAN¹, FABIAN WOLF¹, JAN-CHRISTOPHE HEIP¹, ●CHUNYAN SHI¹, CHRISTIAN GORGES², SIMON KAUFMANN², WILFRIED NÖRTERSHÄUSER², and PIET O. SCHMIDT^{1,3} — ¹QUEST Institut, PTB, Braunschweig, Germany — ²Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt, Germany — ³Institut für Quantenoptik, Leibniz Universität Hannover, Hannover, Germany

In photon recoil spectroscopy (PRS), recoil kicks from photon absorption near a dipole-allowed transition in a single trapped ion are detected via motional coupling to a co-trapped cooling ion [1].

We present isotope shift measurements of the $^2S_{1/2} \rightarrow ^2P_{1/2}$ (D1 line), $^2D_{3/2} \rightarrow ^2P_{1/2}$ (non-closed transition) [2] and $^2S_{1/2} \rightarrow ^2P_{3/2}$

(D2 line) transitions in the calcium isotopes ⁴⁰Ca⁺, ⁴²Ca⁺, ⁴⁴Ca⁺ and ⁴⁸Ca⁺ with an accuracy better than 100 kHz by employing the PRS technique. Furthermore, the isotope shift difference between the D1 and D2 line of calcium ions has been resolved for the first time. As a result from the precision isotope shift measurements, the uncertainties of the relative field and mass shift constants in the respective transitions as well as the mean square nuclear charge radii of these calcium isotopes have been improved.

[1] Y. Wan et al. Nat. Commun **5**, 4096 (2014)

[2] F. Gebert et al. Phys. Rev. Lett. **115**, 053003(2015)

Q 65.4 Fri 11:45 f428

A tunable laser with a drift <100 kHz through stabilization to the Rb D2 line — ●TOBIAS LEOPOLD¹, LISA SCHMÖGER^{1,2}, STEFANIE FEUCHTENBEINER², NILS SCHARNHORST¹, IAN D. LEROUX¹, JOSÉ R. CRESPO LÓPEZ-URRUTIA², and PIET O. SCHMIDT^{1,3} — ¹Physikalisch-Technische Bundesanstalt, 38116 Braunschweig — ²Max-Planck-Institut für Kernphysik, 69117 Heidelberg — ³Institut für Quantenoptik, Universität Hannover

Stable lasers with a narrow linewidth are an important tool for precision spectroscopy. Here, we present a simple and versatile laser system for spectroscopy of trapped highly charged ions at sub-Kelvin temperatures. While covering the wavelength range from 780 - 890 nm we reach a linewidth and longterm frequency drift on the 50 kHz level, corresponding to a fractional instability of $< 1 \times 10^{-10}$.

As frequency reference we use a low-cost 780 nm DFB-laser stabilized to a hyperfine transition of the rubidium D2 line by modulation transfer spectroscopy. The stability of this laser is transferred to the spectroscopy laser by use of an optical reference cavity. Tunability over 1.5 GHz in closed-loop operation is possible by means of the offset sideband locking technique. We measure the instability of both reference and spectroscopy laser against a Maser-stabilized frequency comb.

The laser system presented here will be used for spectroscopy of the $1s^2 2s^2 2p^2 \ ^2P_{1/2} - ^2P_{3/2}$ transition in trapped Ar¹³⁺ ions at 441 nm. Sympathetically cooled in a laser cooled cloud of beryllium ions the 100 Hz natural linewidth is expected to be Doppler broadened to several 100 kHz.

Q 65.5 Fri 12:00 f428

The ALPHATRAP double Penning-trap experiment — ●IOANNA ARAPOGLOU^{1,2}, ALEXANDER EGL^{1,2}, HENRIK HIRZLER^{1,2}, SANDRO KRAEMER^{1,2}, TIM SAILER^{1,2}, ANDREAS WEIGEL^{1,2}, ROBERT WOLF¹, SVEN STURM¹, and KLAUS BLAUM¹ — ¹Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg — ²Fakultät für Physik und Astronomie, Universität Heidelberg

The ALPHATRAP experiment, being a follow-up of the g -factor experiment at Mainz, aims for high-precision tests of bound-state quantum electrodynamics in electric fields with strengths in the order of 10^{16} V/cm. These fields are provided by heavy highly charged ions, such as hydrogen-like ²⁰⁸Pb⁸¹⁺. Furthermore, via the high-precision determination of the bound electron g -factor, fundamental constants such as the fine-structure constant α can be determined. The Heidelberg Electron-Beam Ion Trap delivers the desired heavy highly charged ions, which are injected into and manipulated by means of the ALPHATRAP cryogenic double Penning-trap system. The latter is optimised for heavy highly charged ions and consists of a 7-pole and a 5-pole cylindrical Penning trap that are used for high-precision measurements and spin orientation detection, respectively. This configuration together with the measurement principle and the current status of the experiment will be presented.

Q 65.6 Fri 12:15 f428

Towards Electron Affinity Measurements of Radioactive Elements: Laser Photodetachment of Negative Ions at CERN/ISOLDE — SEBASTIAN ROTHE^{2,3,5}, ●REINHARD HEINKE¹, VALENTIN FEDOSSEEV², THOMAS DAY GOODACRE^{2,5}, DAG HANSTORP³, TOBIAS KRON¹, YUAN LIU⁴, BRUCE MARSH², AN-

NIE RINGWALL-MOBERG³, RALF ERIK ROSSEL², JULIA SUNDBERG³, JAKOB WELANDER³, and KLAUS WENDT¹ — ¹JGU Mainz — ²EN Department, CERN — ³University of Gothenburg — ⁴Oak Ridge National Laboratory — ⁵University of Manchester

Modern on-line isotope separators such as ISOLDE at CERN yield access to a wide variety of exotic nuclei. Besides investigations on nuclear properties of rare isotopes, these facilities allow for detailed studies on the fundamental atomic structures of the few all-radioactive elements across the Periodic Table. In this respect, two values are of elementary importance: (a) The first ionization potential (IP), i.e. the required energy to remove an electron from the neutral atom and produce a positively charged ion, and (b) the electron affinity (EA), i.e. the binding energy of an extra electron to form a negatively charged ion. For all-radioactive elements, their knowledge is even more relevant, as they are required as input for quantum chemical calculations on the behaviour within chemical compounds. Whereas the IPs of the all-radioactive elements Polonium and Astatine were precisely measured at ISOLDE via Rydberg spectroscopy recently, the EAs of these elements are still under investigation.

The talk will give an overview of the experimental setup as well as on the measurement technique, applying laser photodetachment spectroscopy with a high performance, high repetition rate tuneable laser system. First results on iodine carried out on a negative ion beam at ISOLDE are discussed together with alternatives for negative ion production at ISOLDE and an outlook on the envisaged experiments.

Q 65.7 Fri 12:30 f428

Resonance ionization studies in holmium and a redetermination of its ionization potential — ●PASCAL NAUBEREIT¹, YUAN LIU², TINA GOTTWALD¹, and KLAUS WENDT¹ — ¹Institute of Physics, Mainz University, D-55128 Mainz, Germany — ²Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

The first ionization potential of Holmium as well as many other lanthanides was measured around 1978 with rather big uncertainties in the order of 5 cm⁻¹ using early methods of laser spectroscopy. Values that are much more precise are obtained by using two or three step resonance ionization spectroscopy via high lying Rydberg states and applying detailed analyses of convergence limits of different Rydberg series.

Here we report on three step resonance ionization measurements into 6snp levels with principal quantum numbers 17 < n < 59 converging towards the two lowest members of the ionic ground state configuration. Strong interactions with interloper states, well known for most of the lanthanides, perturb the Rydberg series below the first IP for Ho. In contrary the auto-ionizing Rydberg series, observed just above the first ionization potential, exhibits a smooth behavior in the studied range from 33 < n < 57. Correspondingly, the latter was used to reevaluate the first ionization potential of Holmium with an uncertainty of better than 0.1 cm⁻¹. The spectroscopic measurements, which also led to the identification of a new efficient resonant excitation scheme for holmium isotope implantation within the ECHo project, as well as the Rydberg analysis are discussed.

Q 66: Quantum Effects: QED III

Time: Friday 11:00–12:45

Location: f442

Group Report

Q 66.1 Fri 11:00 f442

High finesse Fabry-Perot fiber resonators for efficient photonic interfacing: optimal mode-matching and stabilization — JOSE GALLEGU, SUTAPA GHOSH, SEYED KHALIL ALAVI, WOLFGANG ALT, MIGUEL MARTINEZ-DORANTES, DIETER MESCHEDER, and ●LOTHAR RATSCHBACHER — University of Bonn

In recent years optical Fabry-Perot fiber resonators have been used in an increasing number of scientific applications. Due to their small resonator mode volume and their intrinsic fiber coupling these resonators, for example, are employed as efficient interfaces between single optical photons and a wide range of quantum systems, including cold atoms, ions and solid state emitters, as well as in quantum opto-mechanical experiments. Here we address some important practical questions that arise during the experimental implementation of high finesse fiber cavities: How can optimal fiber cavity alignment be achieved and how can the individual mode matching efficiencies be characterized? How should optical fiber cavities be constructed and to fulfill their potential for miniaturization and integration into robust devices? To answer the first question, we present an analytic mode matching calculation that relates the alignment dependent fiber-to-cavity mode-matching efficiency to the dip in the reflected light power at the cavity resonance. The latter question we explore by investigating a novel, intrinsically rigid fiber cavity design that makes use of the high passive stability of a monolithic cavity spacer and employs thermal self-locking and external temperature tuning. Finally, we also discuss the issue of fiber-generated background photons in fiber Fabry-Perot cavities.

Q 66.2 Fri 11:30 f442

Nonreciprocal light propagation based on chiral interaction of light and matter — ●ADÈLE HILICO, ELISA WILL, MICHAEL SCHEUCHER, JÜRGEN VOLZ, and ARNO RAUSCHENBEUTEL — Vienna Center for Quantum Science and Technology, Atominstitut, TU Wien
Nanophotonic components confine light at the wavelength scale and enable the control of the flow of light in an integrated optical environment. Such strong confinement leads to an inherent link between the local polarization of the light and its propagation direction and fundamentally alters the physics of light-matter interaction [1]. We employ this effect to demonstrate low-loss nonreciprocal transmission of light at the single-photon level through a silica nanofiber. For this purpose, we use a single spin-polarized atom that is strongly coupled to the nanofiber via a whispering-gallery-mode resonator [1]. These resonators provide very long photon lifetimes and near lossless in- and

out-coupling of light via tapered fiber couplers. This renders them ideal for the investigation of nonreciprocal light propagation based on chiral light-matter interaction. In a first experiment, we study the on-resonance performance of the system and observe a strong imbalance between the transmissions in forward and reverse direction of 13 dB while the forward transmission still exceeds 70% [2]. The resulting optical isolator exemplifies a new class of nanophotonic devices based on chiral interaction of light and matter, where the state of single quantum emitters defines the directional behavior.

[1] C. Junge et al., Phys. Rev. Lett. 110, 213604 (2013).

[2] C. Sayrin et al., arXiv 1502.01549 (2015).

Q 66.3 Fri 11:45 f442

Towards strong ion-photon coupling in an ion-trap fiber-cavity apparatus — KLEMENS SCHUEPPERT¹, FLORIAN ONG¹, BERNARDO CASABONE¹, KONSTANTIN FRIEBE¹, DARIO A. FIORETTO¹, MOONJOO LEE^{1,2}, KONSTANTIN OTT³, JAKOB REICHEL³, TRACY NORTHUP¹, and ●RAINER BLATT^{1,2} — ¹Institute for Experimental Physics, University Innsbruck, Austria — ²Institute for Quantum Optics and Quantum Information, Austria — ³Laboratoire Kastler Brossel, ENS/CNRS/UPMC/CdF Paris, France

Quantum networks offer a compelling solution to the challenge of scalability in quantum computing. With atoms coupled to optical cavities it is possible to build up quantum interfaces between stationary and flying qubits in a quantum network. By using fiber-based optical cavities, we expect to reach the strong coupling regime of cavity quantum electrodynamics with single trapped ions. This regime allows higher fidelity and efficiency in protocols for quantum interfaces.

The challenge in integrating fiber cavities with ion traps is that the dielectric fibers should be far enough from the ions so that they do not significantly alter the trap potential. However, with our previous fiber-mirror machining process, cavity lengths were limited to about 250 μm due to deviations from the mirrors' ideal spherical shape. Therefore, we have developed new CO₂-laser ablation techniques for the fiber facets. With the resulting fibers, we have constructed fiber cavities with finesse up to 70,000 at a length of 550 μm. To integrate these fiber cavities with ions, we have built a new miniaturized calcium ion trap in the "Innsbruck" linear design.

Q 66.4 Fri 12:00 f442

Collective behaviour of spins in waveguide networks — ●SEBEM GÜNES SÖYLER, JIŘÍ MÍNÁŘ, and IGOR LESANOVSKY — School of Physics and Astronomy, University of Nottingham, Univer-

sity Park, NG7 2RD, Nottingham, United Kingdom

We investigate a strongly correlated system of light and matter inside a two dimensional array of optical waveguides. We formulate an effective Hamiltonian for two-level atoms coupled to cavity modes and sourced by an external laser field. We perform large scale quantum Monte Carlo simulations and analytical calculations of the ground state properties of the system. We show the phase diagram for interacting atomic spins and cavity modes together with results obtained in a dispersive regime where the cavity field has been eliminated, leading to an effective spin-spin Hamiltonian. We also discuss the properties of the system in geometries with frustrated interactions.

Q 66.5 Fri 12:15 f442

Localization transition in presence of cavity backaction — ●KATHARINA ROJAN¹, REBECCA KRAUS¹, THOMÁS FOGARTY¹, HESAM HABIBIAN^{2,3}, ANNA MINGUZZI⁴, and GIOVANNA MORIGI¹ — ¹Theoretische Physik, Universität des Saarlandes, D-66123 Saarbrücken, Germany — ²Departament de Física, Universitat Autònoma de Barcelona, E-08193 Bellaterra, Spain — ³Institut de Ciències Fotòniques (ICFO), Mediterranean Technology Park, E-08860 Castelldefels (Barcelona), Spain — ⁴Laboratoire de Physique et Modélisation des Milieux Condensés, C.N.R.S, B.P. 166, 38042 Grenoble, France

We study the localization transition of an atom in a bichromatic lattice, when the depth of the second, incommensurate lattice depends on the spatial wave function of the atoms. This situation can be realised when the second potential is the standing wave of a high-finesse cavity, which strongly couples with the atom in the dispersive regime and whose wavelength is incommensurate with the wavelength of the confining optical lattice. By means of a mapping to a Hubbard type

Hamiltonian, we identify the extended and the localised phases of the atom as a function of the strength of the cavity nonlinearity and of the depth of the second lattice, and show that the cavity nonlinearity preserves the main properties of the localization transition. We discuss possible experimental realizations in recent cavity electrodynamics experiments.

Q 66.6 Fri 12:30 f442

Nanofriction and cooling in cavity QED — ●THOMAS FOGARTY¹, HAGGAI LANDA², CECILIA CORMICK³, and GIOVANNA MORIGI¹ — ¹Theoretische Physik, Universität des Saarlandes, Saarbrücken, Germany — ²LPTMS, CNRS, Univ. Paris-Sud, Université Paris-Saclay, France — ³IFEG, CONICET and Universidad Nacional de Córdoba, Ciudad Universitaria, Córdoba, Argentina

I will describe the process of self-organisation of ions in an optical cavity due to the interplay between the Coulomb forces of the ions and the optical forces from the cavity. This can be described in the language of the well known Frenkel-Kontorova model whereby tuning the depth of the cavity lattice one can realise structural transitions. As the depth of this lattice is increased the ions undergo a transition, from a sliding frictionless phase to a pinned phase with increasing static friction, once the strength of the lattice exceeds a critical point. As a consequence of the ion-cavity coupling there is an associated back-action of the ions on the cavity field which establishes a long range interaction between the ions changing the nature of the transition. The cavity field can also act as a tunable reservoir which may cool the ion chain through the coupling of the cavity and ion fluctuations. We show how this can be tuned by changing the cavity detuning and the structural phase of the crystal to achieve sub-Doppler cooling of the chain. Observation of these effects is proposed by utilising the spectrum of the cavity output field.

Q 67: Laser Applications II

Time: Friday 14:30–15:15

Location: a310

Q 67.1 Fri 14:30 a310

KALEXUS - a potassium laser system with autonomous frequency stabilization on a sounding rocket. — ●ALINE DINKELAKER¹, MAX SCHIEMANGK¹, VLADIMIR SCHKOLNIK¹, ANDREW KENYON¹, MARKUS KRUTZIK¹, ACHIM PETERS^{1,2}, and THE KALEXUS TEAM^{1,2,3,4,5} — ¹Institut für Physik, Humboldt-Universität zu Berlin — ²FBH Berlin — ³JGU Mainz — ⁴LU Hannover — ⁵Menlo Systems GmbH

Atomic physics experiments on space-borne microgravity platforms require robust laser systems that can be frequency stabilized for applications such as laser cooling or atom interferometry. Additionally, the systems should work autonomously as access and communication are usually limited. Sounding rockets provide a suitable test environment for such technologies. With the KALEXUS experiment we have created a compact, robust and modular system that includes two extended cavity diode lasers (ECDLs) with an optical switch, an absorption spectroscopy setup and its own on-board computer and control electronics. The system is designed to autonomously perform absorption spectroscopy, frequency stabilization and tests of redundancy components on-board the TEXUS 53 sounding rocket. KALEXUS specifically tests the performance of two micro-integrated ECDLs with one laser stabilized to ³⁹K and a second, offset locked laser. We present an overview of the experiment, its components and operation.

The KALEXUS project is supported by the German Space Agency DLR with funds provided by the Federal Ministry for Economic Affairs and Energy (BMWi) under grant number 50 WM 1345.

Q 67.2 Fri 14:45 a310

Experimental research on tilt-to-length coupling for future geodesy mission — ●YONG HO LEE^{1,2}, SÖNKE SCHUSTER^{1,2}, DANIEL SCHÜTZE^{1,2}, MICHAEL TRÖBS^{1,2}, GUDRUN WANNER^{1,2}, GERHARD HEINZEL^{1,2}, and KASTEN DANZMANN^{1,2} — ¹Max Planck Institute for Gravitational Physics (Albert Einstein Institute) — ²Leibniz Universität Hannover

The GRACE satellites measure Earth's gravity field very successfully since 2002, but will soon reach the end of their lifetime. The next generation Earth gravity observer - GRACE Follow-On - will be launched

in 2017 and will carry for the first time a Laser Ranging Interferometer (LRI) to validate that laser interferometry can significantly enhance the measurement precision. We are already now preparing for future geodesy missions beyond GRACE Follow-On, by addressing the main noise sources of the LRI. Roughly 50% of the LRI noise are allocated to tilt-to-length (TTL) coupling noise, which results from the coupling of angular satellite jitter into the interferometer phase readout.

In this talk, we will introduce the characteristics of TTL coupling noise. In addition, our theoretical and experimental work for suppressing the TTL noise will be explained.

Q 67.3 Fri 15:00 a310

Brillouin-LIDAR zur Messung von Temperaturprofilen im Ozean: Umbau für ersten Feldtest — ●DAVID RUPP¹, SONJA FRIMAN¹, ANDREAS RUDOLF¹, CHARLES TREES² und THOMAS WALTHER¹ — ¹TU Darmstadt, Institut für Angewandte Physik, 64289 Darmstadt — ²CMRE, 19126 La Spezia, Italien

Die Entwicklung eines flugtauglichen LIDAR-Systems zur Messung von Wassertemperaturen im Ozean geht in die nächste Phase. Das LIDAR-System soll es ermöglichen, Temperaturprofile bis zu 100 m Tiefe bei einer Ortsauflösung von 1 m in quasi Echtzeit zu ermitteln. Dazu werden mit Hilfe von mehreren Faserverstärkerstufen Laserpulse mit einer Pulsdauer von 10 ns und einer Repetitionsrate von 1 kHz erzeugt. Diese werden anschließend frequenzverdoppelt. Das ins Wasser eingestrahlte Licht hat dann eine Wellenlänge von 543 nm, abgestimmt auf den Detektor. Die Temperaturinformation wird aus der spektralen Verschiebung des rückwärtig Brillouin-gestreuten Lichts gewonnen. Der Detektor besteht im wesentlichen aus einem atomaren Absorptionsfilter und einem atomaren Kantenfilter (ESFADOF), beide auf Rubidium basierend. Der Absorptionsfilter eliminiert das elastisch gestreute Licht und der Kantenfilter hat eine von der spektralen Verschiebung abhängige Transmission. Die Transmission wird gemessen und kann einer Temperatur zugeordnet werden. Im Labor wurde die Funktion des Systems bereits demonstriert. Für den ersten Feldtest im echten Ozean wurden diverse Änderungen am System vorgenommen. Die Funktionsweise des Systems, die Änderungen im Vergleich zur Labordemonstration und vorläufige Ergebnisse des ersten Feldtests werden präsentiert.

Q 68: Quantum Gases: Fermions III

Time: Friday 14:30–16:30

Location: e001

Q 68.1 Fri 14:30 e001

Quantum many body physics using strontium atoms — ●RODRIGO GONZALEZ — Max Planck Institute of Quantum Optics Garching

In the last few years alkaline earth atoms have become the most precise tools for metrology and time measurement available. It is due to their rich internal atomic structure and high controllability what makes them ideal for this area of research.

On the other hand, quantum gas microscopes present themselves as one of the most powerful tools for understanding the dynamics of electrons in solids. However, the complexity of this systems makes a precise mathematical description impossible.

The extension of the Quantum Gas microscope technique to fermionic isotopes of alkaline atoms represents already an important milestone in the development and understanding of this systems

In this context, we report the very first stages of a new experiment witch aims to create a Quantum Gas microscope of Strontium atoms at the Max Planck Institute of Quantum Optics.

Q 68.2 Fri 14:45 e001

Site-resolved imaging of a fermionic Mott insulator — ●DANIEL GREIF¹, MAXWELL F. PARSONS¹, ANTON MAZURENKO¹, CHRISTIE S. CHIU¹, SEBASTIAN BLATT^{1,2}, FLORIAN HUBER¹, GEOFFREY JI¹, and MARKUS GREINER¹ — ¹Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA — ²Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany

Probing quantum many-body systems on a microscopic level with single-site resolution offers unique insight with unprecedented control and level of detail. We report site-resolved imaging of two-component fermionic Mott insulators, metals, and band insulators with ultracold Li-6 atoms in a square lattice. We observe large, defect-free 2D Mott insulators for strong repulsive interactions, which are characterized by a constant single-site occupation and strongly reduced variance. For intermediate interactions we observe a coexistence of phases. From comparison to theory we find trap-averaged entropies per particle of $1.0 k_B$ and local entropies as low as $0.5 k_B$. This experiment is a vital step towards probing quantum-mechanical models in regimes inaccessible by modern theoretical methods.

Q 68.3 Fri 15:00 e001

Direct probing of the Mott crossover in the SU(N) Fermi-Hubbard model — CHRISTIAN HOFRICHTER^{1,2}, LUIS RIEGGER^{1,2}, FRANCESCO SCAZZA^{1,2}, MORITZ HÖFER^{1,2}, ●DIOGO RIO FERNANDES^{1,2}, IMMANUEL BLOCH^{1,2}, and SIMON FÖLLING^{1,2} — ¹Ludwig-Maximilians-Universität, Schellingstraße 4, 80799 München, Germany — ²Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany

The Fermi-Hubbard model (FHM) is a cornerstone of modern condensed matter theory. Developed for interacting electrons in solids, which typically exhibit SU(2) symmetry, it describes a wide range of phenomena, such as metal to insulator transitions and magnetic order. Its generalized SU(N)-symmetric form, originally applied to multi-orbital materials such as transition-metal oxides, has recently attracted much interest owing to the availability of ultracold atomic gases with unbroken SU(N)-symmetry. In this talk we report on a detailed experimental investigation of the SU(N)-symmetric FHM using local probing of an atomic gas of ytterbium in an optical lattice. We prepare a low-temperature SU(N)-symmetric Mott insulator and characterize the Mott crossover by directly determining the equation of state of the gas, giving model-free access to density and compressibility.

Q 68.4 Fri 15:15 e001

Local probing of the equation of states in two-dimensional Fermi Hubbard Model — ●CHUN FAI CHAN¹, EUGENIO COCCHI^{1,2}, LUKE MILLER^{1,2}, JAN HENNING DREWES¹, DANIEL PERTOT¹, FERDINAND BRENNECKE¹, and MICHAEL KÖHL^{1,2} — ¹Physikalisches Institut, Universität Bonn, Wegelerstrasse 8, 53115 Bonn, Germany — ²Cavendish Laboratory, University of Cambridge, JJ Thomson Avenue, Cambridge CB3 0HE, United Kingdom

Ultracold fermions in optical lattices are promising candidate for simulating the Hubbard model. The Hubbard model contains various inter-

esting phases, such as the Mott insulating phase, spin-ordered states and possibly d-wave superconductivity. Using 40K atoms in optical lattices, we perform high-resolution imaging and radio-frequency spectroscopy to probe the two-dimensional Hubbard model. Here we report on the experimental determination of the equation of state, which enables us to fully characterize the thermodynamics of the Hubbard model in the charge sector.

Q 68.5 Fri 15:30 e001

Microscopic Observation of Pauli Blocking in Degenerate Fermionic Lattice Gases — ●TIMON HILKER, AHMED OMRAN, MARTIN BOLL, KATHARINA KLEINLEIN, GUILLAUME SALOMON, IMMANUEL BLOCH, and CHRISTIAN GROSS — Max-Planck-Institute für Quantenoptik

Ultracold atoms in optical lattices provide a powerful platform for the controlled study of quantum many-body physics. We present here the first studies of a Fermi gas with a new generation quantum gas microscope, which allows to observe the full atom number statistics on every site. The common problem of light induced losses is avoided by an additional small scale "pinning lattice" for Raman sideband cooling during the imaging.

We report the local observation of Pauli's exclusion principle in a spin-polarized degenerate gas of ⁶Li fermions in an optical lattice. In the band insulating regime, we measure a strong local suppression of particle number fluctuations and we extract a local entropy as low as $0.3 k_B$ per atom. Our work opens an avenue for studying local density and even magnetic correlations in fermionic quantum matter both in and out of equilibrium.

Q 68.6 Fri 15:45 e001

Fluctuations and correlations in the two-dimensional Hubbard Model — ●JAN HENNING DREWES¹, LUKE MILLER^{1,2}, EUGENIO COCCHI^{1,2}, CHUN FAI CHAN¹, DANIEL PERTOT¹, FERDINAND BRENNECKE¹, and MICHAEL KÖHL¹ — ¹Physikalisches Institut, University of Bonn, Wegelerstrasse 8, 53115 Bonn, Germany — ²Cavendish Laboratory, University of Cambridge, JJ Thomson Avenue, Cambridge CB3 0HE, United Kingdom

Quantum gases of interacting fermionic atoms in optical lattices promise to shed new light on the low-temperature phases of the Hubbard model such as spin-ordered phases, or in particular, on possible d-wave superconductivity. In this context it remains challenging to access the correlation functions underlying strongly-correlated many-body states. We experimentally realise the two-dimensional Hubbard model by loading a quantum degenerate Fermi gas of 40K atoms into a three-dimensional optical lattice geometry. High resolution absorption imaging in combination with radio-frequency spectroscopy is applied to spatially resolve the atomic distribution in a single layer in the vertical direction. We focus on local measurements of fluctuations of the density of singly- and doubly occupied lattice sites as well as of the local spin-imbalance. Our measurements allow for thermometry using the fluctuation-dissipation theorem and provide information about spatial spin-correlations.

Q 68.7 Fri 16:00 e001

Studying the interplay of order and geometry in the Hubbard model with ultracold fermions — RÉMI DESBUQUOIS¹, ●GREGOR JOTZU¹, MICHAEL MESSER¹, THOMAS UEHLINGER¹, FREDERIK GÖRG¹, SEBASTIAN HUBER², DANIEL GREIF¹, and TILMAN ESSLINGER¹ — ¹Institute for Quantum Electronics, ETH Zurich, 8093 Zurich, Switzerland — ²Institute for Theoretical Physics, ETH Zurich, 8093 Zurich, Switzerland

The geometry of a lattice plays a crucial role in determining the order which can form therein. This shows up in the types of spin-correlations supported by a particular lattice, but can even play a role in the charge/density degree of freedom. In particular, when a symmetry of the system is broken by the lattice, the resulting quantum state is expected to display this broken symmetry.

For example, in the ionic Hubbard model, an energy-offset between neighbouring sites breaks inversion symmetry leading to a charge-density wave. However, strong repulsive interactions can drive the system into a Mott-insulating regime, where the broken symmetry is suppressed in the density-distribution.

Ultracold atoms in optical lattices are well suited for studying the effects of varying the lattice geometry, as both local observables such as the double-occupancy, and long-range observables such as noise-correlations are accessible. In addition, the excitation spectrum of the system can be probed by dynamically modulating the lattice parameters.

Q 68.8 Fri 16:15 e001

Multiple particle-hole pair creation in the Fermi-Hubbard model by a pump laser — •NICOLAI TEN BRINKE and RALF SCHÜTZHOLD — Fakultät für Physik, Universität Duisburg-Essen, Lotharstraße 1, D-47057 Duisburg, Germany

We study the Fermi-Hubbard model in the strongly correlated Mott

regime under the influence of a harmonically oscillating electric field created by a pump laser. Using a Peierls transformation, the pump field can be represented as an effective, oscillating hopping rate in terms of the Fermi-Hubbard Hamiltonian. As the oscillation leads to a reduction in the effective time-averaged hopping rate, a sudden switch of the pump laser is analogous to a quantum quench in the lattice parameters. Apart from that, particle-hole pairs can be created via the oscillating components of the effective hopping rate, when the pump frequency is in resonance with the Mott gap. Further, it should be possible to create multiple particle-hole pairs if the pump frequency is an integer multiple of the Mott gap. These findings should be relevant for pump-probe experiments.

Q 69: Quantum Information: Quantum Computing and Communication IV

Time: Friday 14:30–16:00

Location: e214

Q 69.1 Fri 14:30 e214

Quantum correlations in microwave frequency combs — •THOMAS WEISSL¹, ERIK THOLÉN², DANIEL FORCHHEIMER^{1,2}, and DAVID B. HAVILAND¹ — ¹KTH- Royal Institute of Technology, 106 91 Stockholm, Sweden — ²Intermodulation Products AB, 823 93 Segersta Sweden

Multipartite entangled states in frequency combs have possible application as a universal resource for continuous wave quantum computation. In the optical frequency range, bipartite entanglement between different frequencies in frequency combs generated by parametric down-conversion has been demonstrated [1,2]. In comparison with optical systems, superconducting microwave circuits can be designed with much stronger coupling strength between (artificial) atoms and the electromagnetic field, as well as much stronger non-linearity that couple the various tones of a frequency comb. We present a method to create and to measure quadrature response of a microwave frequency comb, based on up- and down-conversion of a digitally synthesized and digitally demodulated low-frequency comb. The method works with as many as 42 frequencies. When a non-linear superconducting resonator is pumped with the GHz comb, the tones in the comb become correlated due to the strong non-linearity. We show preliminary results on the analysis of these correlations. [1] J. Roslund et al., Nature Photonics 8, 109-112 (2014) [2] M. Chen et al., PRL 112, 120505 (2014)

Q 69.2 Fri 14:45 e214

A two-photon quantum gate — •BASTIAN HACKER, STEPHAN WELTE, STEPHAN RITTER, and GERHARD REMPE — Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching

Optical photons are excellent carriers of quantum information with well established technologies for their creation, manipulation and detection. For the purpose of photonic quantum information processing, it is essential to achieve non-linear interactions between them. Unfortunately, the non-linearities in conventional optical materials are too weak for this at the low light powers of single photons. A way to mediate strong interactions is to use a single atom inside a high-finesse cavity, which couples to the light field of impinging photons. According to an old but not yet implemented proposal [1] this can be employed to realize a two-photon quantum gate between successively reflected photons. Our current setup is well-suited to achieve this long-standing goal. We will discuss a potential implementation in our setup and will report on the current status of the experiment.

[1] L.-M. Duan and H. J. Kimble, Phys. Rev. Lett. 92, 127902 (2004)

Q 69.3 Fri 15:00 e214

Higher-efficiency lower-noise Raman quantum memory — SARAH THOMAS^{1,2}, JOSEPH MUNNS^{1,2}, •BENJAMIN BRECHT¹, PATRICK M. LEDINGHAM¹, DYLAN J. SAUNDERS¹, JOSHUA NUNN¹, and IAN A. WALMSLEY¹ — ¹Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, UK — ²QOLS, Blackett Laboratory, Imperial College London, London SW7 2BW, UK

Raman quantum memories in warm atomic vapour promise excellent applicability in future quantum networks, owing to their experimental simplicity and large time-bandwidth product. However, they suffered from intrinsic four-wave noise and moderate efficiencies, which ultimately limited their usefulness.

Here, we report on experimental progress that allowed us to demonstrate on the one hand high noise suppression with only 0.015 noise photons per pulse, and on the other hand high memory efficiency of up to 60% in a warm Cs vapour Raman memory. These steps facilitate the future realization of a genuine quantum memory operating on single photons.

Q 69.4 Fri 15:15 e214

A quantum repeater scheme with single atoms in telecom-wavelength cavities — •MANUEL UPHOFF, MANUEL BREKENFELD, DOMINIK NIEMIETZ, STEPHAN RITTER, and GERHARD REMPE — Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching

Single atoms in optical cavities are a promising system to implement a quantum repeater, which can overcome the limitations arising from the exponential decrease of transmission with distance in optical fibers. For such a repeater to be useful, the entanglement generation between remote nodes must be mediated by photons at a telecom wavelength. Unfortunately, the ground states of easily laser cooled atoms show no suitable transitions at these wavelengths. As a solution, we propose a scheme for entanglement generation between a single atom and a telecom photon based on cascaded transitions from higher excited states of alkali atoms [1]. Owing to a modification of the atomic emission by means of crossed cavities, the telecom photons are heralded and highly indistinguishable. This is essential for a high-fidelity photonic Bell state measurement performed to provide entanglement between remote nodes. We will also discuss the prospects of extending this scheme to a simple quantum repeater that can generate entangled pairs faster than using direct transmission using state-of-the-art technology. [1] Uphoff *et al.*, arXiv:1507.07849 (2015)

Q 69.5 Fri 15:30 e214

A two-color polarization-entangled photon pair source for applications in hybrid quantum architectures — •CHRIS MÜLLER, OTTO DIETZ, TIM KROH, THOMAS KREISSL, and OLIVER BENSON — AG Nanooptik, Institut für Physik, Humboldt-Universität zu Berlin

Entangled photon pairs can be exploited to realize a quantum repeater [1] which is crucial for a long distant quantum communication. However, entangled photon pairs can also be used for establishing entanglement between dissimilar systems to create quantum hybrid structures.

We set up a two-color polarization-entangled parametric down conversion source in a folded-sandwich geometry [2] to create entangled photon pairs. This setup can generate highly non-degenerate photons with wavelengths at the Cs D1 line (894.3 nm) and the telecom O-band (1313.1 nm), while obtaining an entanglement fidelity of $F = (75 \pm 2)\%$ [3].

The long term goal is to establish a hybrid quantum interface where the photon pair source is used to demonstrate teleportation [1] of the electronic state of a semiconductor quantum dot [4] to photons at telecom wavelength.

- [1] Bussi eres F., et al. Nature Photonics 8, 775-778 (2014)
- [2] Steinlechner F., et al. Optics Express 21, 11943 (2013)
- [3] Dietz O., et al. Applied Physics B accepted
- [4] Gao W.B., et al. Nature Comm. 4, 2744 (2013)

Q 69.6 Fri 15:45 e214

Parsing Squeezed Light into Polarization Manifolds — ●CHRISTIAN R. MÜLLER^{1,2,3}, LARS S. MADSEN³, ANDREI KLIMOV⁴, LUIS L. SÁNCHEZ-SOTO^{5,1,2}, GERD LEUCHS^{1,2}, CHRISTOPH MARQUARDT^{1,2,3}, and ULRİK L. ANDERSEN^{3,1} — ¹Max Planck Institute for the Science of Light, Erlangen, Germany. — ²Department of Physics, University of Erlangen-Nuremberg (FAU), Germany. — ³Department of Physics, Technical University of Denmark, Lyngby, Denmark. — ⁴Departamento de Física, Universidad de Guadalajara, Mexico. — ⁵Departamento de Óptica, Facultad de Física, Universidad Complutense, Madrid, Spain.

We investigate polarization squeezing in squeezed coherent states with different amplitudes [1]. In contrast to the traditional characterization

based on the full Stokes parameters [2,3], we experimentally characterize the polarization properties of each photon number manifold individually. This method provides a substantially richer description and allows to investigate the otherwise separate regimes of spin squeezing, of quadrature squeezing as well as of the intermediate regime in a single experiment. Intuitive insight into the nature of the different regimes is given via the Husimi Q function [4,5] of the polarization states with different coherent amplitudes.

- [1] C. R. Müller et al., arXiv:1511.03553 [quant-ph] (2015)
- [2] Ch. Marquardt et al., Phys. Rev. Lett. 99, 220401 (2007)
- [3] C. R. Müller et al., New J. Phys. 14, 085002 (2012)
- [4] L. L. Sánchez-Soto et al., J. Phys. B 46, 104011 (2013)
- [5] P. de la Hoz et al., Phys. Rev. A 88, 063803 (2013).

Q 70: Quantum Gases: Bosons VI

Time: Friday 14:30–16:00

Location: f342

Q 70.1 Fri 14:30 f342

Non-equilibrium steady-states in a driven dissipative superfluid — ●BODHADITYA SANTRA, RALF LABOUVIE, SIMON HEUN, and HERWIG OTT — Research Center OPTIMAS and Fachbereich Physik, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany

Non-equilibrium steady-states constitute fix points of the phase space dynamics of classical and quantum systems. They emerge under the presence of a driving force and lie at the heart of transport phenomena such as heat conduction or current flow.

We experimentally study the steady-states of a driven-dissipative Josephson junction array, realized with a weakly interacting Bose Einstein condensate residing in a one-dimensional optical lattice [1]. Engineered losses on one site act as a local dissipative process, while tunneling from the neighboring sites constitutes the driving force. We characterize the emerging steady-states of this atomtronic device. With increasing dissipation strength the system crosses from a superfluid state, characterized by a coherent DC Josephson current into the lossy site to a resistive state, characterized by an incoherent hopping transport. For intermediate values of the dissipation, the system exhibits bistability, where a superfluid and a resistive branch coexist. We also study the relaxation dynamics towards the steady-state, where we find a critical slowing down, indicating the presence of a non-equilibrium phase transition.

- [1] R. Labouvie, B. Santra, S. Heun, H. Ott, arXiv:1507.05007

Q 70.2 Fri 14:45 f342

Studying quench dynamics in an ultracold quantum gas by near-field interferometry — ●CHRISTIAN BAALS, BODHADITYA SANTRA, RALF LABOUVIE, and HERWIG OTT — Research Center OPTIMAS and Fachbereich Physik, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany

The effect of interferometric self-imaging in the near-field, also known as Talbot effect, has been exploited in many areas of research since its discovery in the 19th century. In our experiment the temporal Talbot effect is used to measure the coherence length of a matter-wave field. A Bose-Einstein condensate of Rb-87 is loaded adiabatically into a 1D or a 3D optical lattice. Subsequently, the lattice potential is switched off and on again for a short time. The momentum distribution is observed in absorption images after time-of-flight where the width of the central peak serves as a measure of coherence. For a superfluid this width shows oscillations where the period corresponds to the Talbot time. In the Mott-insulating regime these oscillations disappear but can be restored by quenching the system to the superfluid regime before the pulse is applied. With increasing waiting time between the quench and the pulse the coherence length increases which can directly be seen by the appearance of oscillations in the measurement signal.

Q 70.3 Fri 15:00 f342

Observation of symmetry-broken momentum distributions: matter-wave diffraction during time-of-flight expansion — ●CHRISTOPH ÖLSCHLÄGER, MALTE WEINBERG, OLE JÜRGENSEN, DIRK-SÖREN LÜHMANN, JULIETTE SIMONET, and KLAUS SENGSTOCK — Institut für Laserphysik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg

The information about quantum gas systems is still commonly inferred from time-of-flight measurements.

Here, we demonstrate that interaction during the time-of-flight expansion can strongly alter the measurement of the initial atomic momentum distribution. We discuss the observation of symmetry-broken momentum distributions for bosonic mixtures in state-dependent honeycomb lattices due to scattering processes within the first milliseconds of the expansion time.

These findings play an inevitable role in a broad range of systems, including state-dependent lattices and superlattices, where the lattice symmetry does not cancel the influence of the scattering processes on the interference pattern. In addition, the interactions during a free expansion can indeed be used as an interferometric probe to reveal novel quantum phases, such as supersolids.

Q 70.4 Fri 15:15 f342

Topological edge state with ultracold atoms in a spatially variable lattice potential — ●MARTIN LEDER¹, CHRISTOPHER GROSSERT¹, TILL OCKENFELS¹, MAXIMILIAN GENSKE², ACHIM ROSCH², and MARTIN WEITZ¹ — ¹Institut für Angewandte Physik, Universität Bonn — ²Institut für Theoretische Physik, Universität zu Koeln

An electronic topological insulator has a bulk energy band gap like an ordinary insulator, but conducting edge states on the surface that are insensitive to material impurities [1]. We report on the observation of a topological edge state located between two spatial regions with different topological phases in an atomic physics experiment. Our experiment is built upon a one-dimensional geometry, and uses four-photon lattice potentials which are realized in an atomic three-level system with two ground states of different spin projections and one spontaneously excited state [2]. Using an additional combination of a magnetic field gradient and a careful momentum preparation of an ultracold rubidium atomic wave packet allows to simulate an effective Dirac equation with a spatially varying mass term. We experimentally observe the trapping of the atoms in a bound state locked to the position of the band crossing between of two spatial regions of different topology in the lattice. Our real space observations give a direct link to the SSH model of the electrical conductance of polyacetylene [3].

- [1] M. Z. Hasan and C. L. Kane, Rev. Mod. Phys. 82, 3045 (2010).
- [2] G. Ritt *et al.*, Phys. Rev. A 74, 063622 (2006).
- [3] W. P. Su *et al.*, Phys. Rev. Lett. 42, 1698 (1979).

Q 70.5 Fri 15:30 f342

Phase diagrams of ultra cold selforganized structures in cavity QED potentials — ●ASTRID ELISA NIEDERLE, HEIKO RIEGER, and GIOVANNA MORIGI — Theoretische Physik, Universität des Saarlandes, D-66123 Saarbrücken, Germany

Scattering of photons into an optical resonator by laser-driven atoms can give rise to atomic structures, which emerge from the interplay between drive and cavity losses. These structures match an underlying Bragg order, thus maximizing the number of intracavity photons which in turn mechanically stabilize the atomic density distribution. We analyse the phases of bosonic atoms confined on a plane by an external optical lattice, whose periodicity is commensurate and incommensurate with the wavelength of a cavity mode. This system can be described by a Bose-Hubbard model with a specific dynamical on-site potential [1]. We determine the ground state properties using local mean field theory complemented by a cluster analysis [2].

We identify the parameter regimes for which this underlying order emerges and show that it can exhibit nontrivial features, to which quantitatively different patterns correspond. In the incommensurate case these phases are all compressible, and for given atomic densities can exhibit superfluidity even at vanishing tunneling. We discuss the corresponding observables and show that these predictions could be tested in existing experiments [3].

[1] Phys. Rev. A **81** (2010) 043407 and Phys. Rev. A **88** (2013) 043618, [2] New. J. Physics **15** (2013) 075029, [3] Nature **464** (2010) 1301

Q 70.6 Fri 15:45 f342

Q 71: Quantum Effects: QED IV

Time: Friday 14:30–16:30

Location: f442

Group Report

Q 71.1 Fri 14:30 f442

New effects in surface-dependent vacuum QED — ●ROBERT BENNETT¹, JULIANE KLATT¹, ADAM STOKES², STEFAN BUHMANN¹, and CLAUDIA EBERLEIN³ — ¹University of Freiburg, Germany — ²University of Leeds, United Kingdom — ³University of Sussex, Brighton, United Kingdom

Quantum electrodynamics (QED) is the remarkably successful theory of the interaction of light and matter. It shows unprecedented levels of agreement with experiment, with the most famous example being the anomalous magnetic moment of the electron, where theory and experiment have found consistency up to one part in 10 trillion. In order to design the next generation of precision tests of QED, the effect the extended material objects have on the fundamental properties of atoms and electrons in their vicinity must be quantified to ever-increasing precision. The main part of the presentation will be an outline of new developments in one of these effects, namely the surface-dependent shift in the anomalous magnetic moment of an electron [1]. Following this there will be a brief presentation of some experimentally-focused work concerning motional atomic level shifts and decay rates near complex nanostructures [2], as well as an account of a recently-developed unified approach to Casimir forces for fields carrying arbitrary spin [3] in which the well-known electromagnetic Casimir force emerges as a special case.

[1] R. Bennett & C. Eberlein New J. Phys. **14** 123035 (2012) [2] R. Bennett: Phys. Rev. A **92**, 022503 (2015) [3] A. Stokes & R. Bennett New J. Phys. **17**, 073012 (2014)

Q 71.2 Fri 15:00 f442

Casimir–Polder interaction and symmetry breaking — ●STEFAN YOSHI BUHMANN¹, VALERY N. MARACHEVSKY², and STEFAN SCHEEL³ — ¹Freiburg University, Freiburg, Germany — ²St. Petersburg University, St. Petersburg, Russia — ³Rostock University, Rostock, German

Casimir–Polder interactions between atoms and surfaces are due to correlated quantum fluctuations of the atomic charge density and the electromagnetic field. Using second-order perturbation theory within the framework of macroscopic quantum electrodynamics, they can be expressed in terms of the electromagnetic response of the atoms on the one hand and the surface on the other [1].

We show that the Casimir–Polder potential can be used to probe unusual properties of both interacting objects, such as the violation of fundamental symmetries. To that end, we consider CP-violating atoms interacting with a perfect T-violating mirror or a plane surface with Chern–Simons interaction [2].

[1] S. Y. Buhmann, *Dispersion Forces I* (Springer, Heidelberg, 2012).

[2] S. Y. Buhmann, V. N. Marachevsky, S. Scheel, *CP-violating CP interactions*, in preparation (2015).

Q 71.3 Fri 15:15 f442

Medium-assisted Casimir–Polder interaction between chiral molecules — ●PABLO BARCELONA and STEFAN YOSHI BUHMANN — Institute of Physics, Freiburg University, Germany

Using second-order perturbation theory with an effective Hamiltonian, we calculate the Casimir–Polder force between two ground-state chiral molecules at zero temperature in the presence of magnetodielectric bodies. In free space, the Casimir–Polder force has a small chiral component depending on both electric and magnetic transitions. With

The effects of curvature in deformed optical lattices — ●NIKODEM SZPAK — Fakultät für Physik, Universität Duisburg-Essen

Special designs of optical lattices, involving complex or unitary matrix-valued tunneling amplitudes, enable for various realizations of effective gauge fields on the lattice. Analogously, local deformations of the optical lattices influencing the real part of the tunneling amplitudes can be interpreted in terms of an effective metric of a curved space. We review some setups, including finite-width laser beams or traps, giving rise to such artificial curvature and discuss interesting phenomena associated with it, like ground state (de)localization or focusing of traveling waves.

the presence of a material environment we find some highly symmetric configurations where the electric and magnetic contributions of the Casimir–Polder force cancel, making the chiral component the dominant contribution. This is achieved via magnetoelectric plates which exhibit chiral properties. The dominant chiral Casimir–Polder force is discriminatory with respect to enantiomers of different handedness.

Q 71.4 Fri 15:30 f442

Casimir–Polder interaction of neutrons with surfaces — ●VALENTIN GEBHART, JULIANE KLATT, and STEFAN YOSHI BUHMANN — Albert-Ludwigs-University, Freiburg, Deutschland

Searching for an example of the elusive repulsive dispersion force we study the Casimir–Polder interaction of a neutron with a metal or dielectric plate. By using macroscopic quantum electrodynamics and perturbation theory we examine the position-dependent potential of the magnetizable neutron in front of a plate with arbitrary dielectric properties. We indeed find a purely repulsive dispersion interaction whose amplitude is very sensitive to the model used for the plate permittivity. Finally, we discuss the relevance of the proposed interaction in neutron-interferometry experiments [1].

[1] H. Rauch, H. Lemmel, M. Baron, R. Loidl, *Measurement of a confinement induced neutron phase*, Nature **417**, 630 (2002).

Q 71.5 Fri 15:45 f442

From Casimir-Polder Force to Dicke Physics: Interaction between Atoms and a Topological Insulator — ●SEBASTIAN FUCHS¹, STEFAN YOSHI BUHMANN¹, and JOHN ALEXANDER CROSSE² — ¹Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Straße 3, 79104 Freiburg, Germany — ²Department of Electrical and Computer Engineering, National University of Singapore, 4 Engineering Drive 3, Singapore 117583

We apply the theory of macroscopic quantum electrodynamics in dispersing and absorbing media to study the Casimir–Polder force between an atom and a topological insulator [1]. The electromagnetic response of a topological insulator surface leads to a mixing of electric and magnetic fields, breaking time-reversal symmetry [2, 3]. The coupling of these fields to an atom causes shifts of the atom’s eigenenergies and modified decay rates near the surface of the topological insulator. Energy shifts and modified decay rates cannot only be triggered by the presence of a material, but can be caused by other atoms in close proximity as well. The collective dynamics of atoms (Dicke Physics) leads to a superradiant burst [4]. Combining macroscopic QED and Dicke physics opens the door to the investigation of cooperative atom-surface interactions. [1] S. Y. Buhmann, *Dispersion Forces II*, Springer-Verlag Berlin Heidelberg (2012). [2] S. Y. Buhmann, D. T. Butcher, and S. Scheel, *New Journal of Physics* **14**, 083034 (2012). [3] J. A. Crosse, S. Fuchs, and S. Y. Buhmann, *Physical Review A*, in print, arXiv: 1509.03012 (2015). [4] S. Fuchs, J. Ankerhold, M. Blencowe, and B. Kubala, arXiv: 1501.07841 (2015).

Q 71.6 Fri 16:00 f442

Paraxial Theory of Direct Electro-Optic Sampling of the Quantum Vacuum — ●ANDREY S. MOSKALENKO, CLAUDIUS RIEK, DENIS V. SELETSKIY, GUIDO BURKARD, and ALFRED LEITENSTORFER — Department of Physics and Center for Applied Photonics, University of Konstanz, Germany

The quantum vacuum is one of the most fundamental states of light and matter fields. Quantum mechanics teaches us that the vacuum is

not just empty space: E.g., in the vacuum state, even in the absence of any photons, the electromagnetic field is not strictly zero but fluctuates. A fundamental question is whether and how one can access these fluctuations directly. Despite many indirect measurements, this question has remained open until very recently [1].

We theoretically show that vacuum fluctuations of the electric field in free space can be directly detected using the linear electro-optic effect [2]. We demonstrate that the fluctuations in the ground state lead to an increase of the measured signal variance on top of the shot noise and can be directly resolved, as experimentally confirmed [1]. Furthermore, applying the theory to a squeezed vacuum state, we predict that temporal oscillations of the electric field noise, significantly beating the pure vacuum level, can be traced with sub-cycle resolution [2]. We believe that our findings pave the way for an approach to quantum optics operating in an extreme time-domain limit, providing access to quantum statistics of light on a sub-cycle time scale.

[1] C. Riek et al., *Science* **350**, 420 (2015).

[2] A.S. Moskalev et al., arXiv:1508.06953, accepted in PRL.

Q 71.7 Fri 16:15 f442

Lateral Casimir–Polder forces — ●RICARDO OUDE WEERNINK and STEFAN YOSHI BUHMANN — Albert-Ludwigs-Universität Freiburg, Freiburg, Germany

Lateral Casimir–Polder forces can occur when excited-state atoms undergo asymmetric downward circular dipole transitions [1]. Lateral in this regard means parallel to the surface of a metal or dielectric body. As recently observed for the case of a nanofiber, the atoms' decay leads to asymmetrically emitted fields [2], causing this force.

We study this effect for a simple model geometry: an excited two-state atom is positioned in a vacuum half space close to a half space filled with homogeneous dielectric. By use of macroscopic quantum electrodynamics, the lateral force can be described as a function of the system's Green's tensor and the atomic dipole moment. Also, a non-vanishing asymmetry term for photons being emitted into the two lateral half spaces can be established. This asymmetry explains the physical origin of the force by virtue of conservation of momentum. Both the force as well as the emission asymmetry show an oscillating behaviour in space, with the oscillations being related to the wave-length of the emitted photons.

[1] *Directional spontaneous emission and lateral Casimir-Polder force on an atom close to a nanofiber*, S. Scheel, S. Y. Buhmann, C. Clausen and P. Schneeweiss, *Phys. Rev. A* **92**, 043819 (2015).

[2] *Quantum state-controlled directional spontaneous emission of photons into a nanophotonic waveguide*, R. Mitsch et al., *Nature Comm.* **5**, 5713 (2014).

Q 72: Ultrashort Laser Pulses III

Time: Friday 15:30–16:30

Location: a310

Q 72.1 Fri 15:30 a310

Line-by-line amplitude and phase modulation of a 10 GHz frequency comb for pump-probe spectroscopy — ●ALI SEER, OLIVER KLIEBISCH, DIRK HEINECKE, and THOMAS DEKORSY — Department of Physics and Center for Applied Photonics, University of Konstanz, D-78457, Germany

The time-resolved investigation of optically excited nanostructures with tailored pulse sequences is an important technique to study nanomechanical systems [1]. However these techniques are at present limited to 1 GHz or lower due to the lack of high repetition rate femtosecond pulse sources. Here we present a method to generate pulse trains with high repetition rates in the order of fundamental resonance frequencies of nanomechanical systems. Using a 10 GHz Ti:sapphire laser the wide spacing of the frequency comb modes [2] allows us to spatially resolve them using dispersive optics. Independent modulation of phase and amplitude of individual modes is performed using a spatial light modulator to realize line-by-line pulse shaping. Increase of repetition rate is achieved by optimization of modulator phase masks by a genetic algorithm. A tapered semiconductor amplifier is used in a double pass configuration to amplify pulses by factors up to 30 dB [3]. In this way intensity cross correlation measurements are carried out in a pump probe setup employing asynchronous optical sampling (ASOPS) with a second 10 GHz Ti:sapphire laser [4]. [1] Bruchhausen et al., *PRL* **106**, 077401 (2011). [2] Bartels et al., *Opt. Lett.* **33**, 1905 (2008). [3] Bolpasi et al., *Rev. Sci. Instrum.* **81**, 113108 (2010). [4] Gebis et al., *Opt. Express* **18**, 5974-5983 (2010).

Q 72.2 Fri 15:45 a310

High-speed stimulated Raman scattering microscopy with an all-optical nonlinear modulator — ●TOBIAS STEINLE, MORITZ FLOESS, ANDY STEINMANN, and HARALD GIESSEN — 4th Physics Institute and Research Center SCOPE, University of Stuttgart, 70550 Stuttgart, Germany

We introduce a novel technique for high-frequency modulation of femtosecond pulses based on period doubling enabled by nonlinear feedback in an optical parametric oscillator (OPO). We demonstrate the applicability of this technique in a stimulated Raman scattering experiment, where the modulated Raman pump is directly derived from the OPO, while the Stokes is provided by the same Yb:KGW oscillator that pumps the OPO. It is shown that the technique works over a broad spectral range with sufficient modulation depth. With this scheme, the highest possible modulation frequency, namely half the repetition rate, is achieved. Further, the modulation is intrinsically synchronized with the reference pulse train. Hence, it provides optimum performance in any pump-probe scheme. Also, it is scalable to higher modulation frequencies by scaling the repetition rate of the system.

Q 72.3 Fri 16:00 a310

Broadband supercontinuum generation in high-confinement Si₃N₄ integrated optical waveguides — ●FLORIAN SCHEPERS¹, MARCO GARCIA PORCEL², JÖRN EPPING², TIM HELLOWIG¹, KLAUS-JOCHEN BOLLER², and CARSTEN FALLNICH^{1,2} — ¹Institute of Applied Physics, University of Münster, Germany — ²MESA+ Institute of Nanotechnology, University of Twente, The Netherlands

A novel approach for the fabrication of stoichiometric silicon nitride (Si₃N₄) waveguides allows the realization of Si₃N₄-waveguides with an increased thickness of up to 1.2 μm. This thickness enables anomalous dispersion in the near-infrared range. In addition the modal confinement for waveguides of such dimensions increases with the size of the waveguides. These two aspects make these waveguides highly desirable for the generation of ultra-broadband supercontinua. The waveguides can be designed such that the zero-dispersion wavelengths are favorable for pumping at multiple common laser wavelengths, importantly, around 1030 nm and 1550 nm where Yb- and Er-fiber lasers are available. Using ultrashort laser pulses at a wavelength of 1064 nm as a pump wave, a supercontinuum with a bandwidth of 495 THz has been obtained², spreading from 470 nm up to 2130 nm. This corresponds to the broadest supercontinuum ever generated on a chip. Similarly, using pump pulses in the telecommunication range near 1550 nm, a supercontinuum spanning from 560 nm to more than 2100 nm wavelength has been generated.

¹ Epping J., et al., *Opt. Express* **23**, 642 (2015).

² Epping J., et al., *Opt. Express* **23**, 19596 (2015).

Q 72.4 Fri 16:15 a310

Ultrakurzpuslaser-Mikrostrukturierung für die Anwendung in Dünnschichtphotovoltaik — ●JÜRGEN IMGRUNT¹, KAMBULAK-WAO CHAKANGA³, KARSTEN VON MAYDELL³ und ULRICH TEUBNER^{1,2} — ¹Institut für Laser und Optik, Hochschule Emden/Leer, University of Applied Sciences, 26723 Emden, Deutschland — ²Institut für Physik, Carl von Ossietzky Universität Oldenburg, 26111 Oldenburg, Deutschland — ³EWE Forschungszentrum NEXT ENERGY, 26129 Oldenburg, Deutschland

Lichtmanagement in Solarzellen spielt eine wichtige Rolle zur Verbesserung der Lichtabsorption und der Effizienz. Hierzu wurde eine Bearbeitungsstation auf der Basis eines Ultrakurzpuslaser aufgebaut (150 fs Pulsdauer bei 775 nm Zentralwellenlänge) und mehrere Glassubstrate erfolgreich strukturiert. Die Strukturgeometrie in Form von abgerundeten Ablationskratern mit ca. 3 μm Durchmesser konnte gut reproduziert werden. Die Substrate unterschieden sich allein im Strukturabstand, was Einfluss auf die Strukturqualität hatte. Für die Anwendung in der Dünnschichtphotovoltaik wurden die strukturierten Substrate auf die Streueigenschaften im sichtbaren und nahen infraroten Spektralbereich untersucht. Anschließend wurden Dünnschichtsolarezellen

auf den strukturierten Substraten hergestellt. Für die Dünnschichtso-
larzelle auf dem Substrat mit der höchsten Strukturdicke wurde eine

Erhöhung der Lichtabsorption und des externen Quantenwirkungsgrad
für den Spektralbereich $> 620nm$ gemessen.