Quantum Simulations with Atoms and Light

Joint CQOM/ITAMP workshop

Aarhus Institute of Advanced Studies, Aarhus University
August 13 to August 17, 2018

Center for Quantum Optics & Quantum Matter

ITAMP

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Danmarks Grundforskningsfond
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Venue:

Aarhus Institute of Advanced Studies (AIAS), Aarhus University, Buildings 1630-1632, Høegh-Guldbergs Gade 6B, 8000 Aarhus C, Denmark.

Contact:

Grete Flarup
Email: cqom@phys.au.dk
Phone: +45 87 15 56 69
Dept. of Physics and Astronomy
Aarhus University

Thomas Pohl
Email: pohl@phys.au.dk
Phone: +45 29 40 88 46
Dept. of Physics and Astronomy
Aarhus University

Organizers:

Thomas Pohl (Aarhus University)
Georg Bruun (Aarhus University)
Jan Arlt (Aarhus University)
Alexander Szameit (Rostock University)
Hossein Sadeghpour (ITAMP)

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	Mo, 08/13	Tue, 08/14	Wed, 08/15	Thu, 08/16	Fri, 08/17
		chair: Antoine Browaeys	chair: Richard Schmidt	chair: Rudi Grimm	chair: Hossein Sadeghpour
9:15 – 9:50		**Stefanie Barz**	**Rudi Grimm**	**Eugene Demler**	**Darrick Chang**
9:50 – 10:25		**Anders Sørensen**	**Pietro Massignan**	**Michael Drewsen**	**Wolfram Pernice**
10:25 – 10:50		coffee break	coffee break	coffee break	coffee break
10:50 – 11:25		**Johannes Zeiher**	**Tilman Esslinger**	**Giovanna Morigi**	**Joseph Thywissen**
11:25 – 12:00		**Benoit Vermersch**	**Ronen Kroeze**	**Mikael Rechtsman**	**Michael Fleischhauer**
12:00 – 13:45	registration & lunch 12:30-13:30	lunch	lunch	lunch	lunch
	chair: Jan Arlt	chair: Luis Santos	chair: Georg Bruun	chair: Michael Fleischhauer	lab tours
13:45 – 14:20	**Antoine Browaeys**	**Klaus Sengstock**	**Georgy Shlyapnikov**	**Alexander Keesling**	
14:20 – 14:55	**Luis Santos**	**Richard Schmidt**	**Julian Leonard**	**Alexey Gorshkov**	
14:55 – 15:20	**Matteo Zaccanti**	**Alejandro Saenz**	Ole Rømer Colloquium: **Tilman Esslinger**	**David Petrosyan**	
15:20 – 15:45	**Nils Byg Jørgensen**	**Sebastian Hofferberth**		**Lucas Teuber**	
15:45 – 16:15	coffee break	coffee break		coffee break	
	chair: Stefanie Barz	chair: Darrick Chang	Guided tour and dinner at the ARoS art museam	chair: Hrvoje Buljan	
16:15 – 16:50	**Gregor Weihs**	**Robert Nyman**		**Florian Mintert**	
16:50 – 17:25	**Hrvoje Buljan**	**Francesco Piazza**		**Jan Klaers**	
17:25 – 18:00	**Juergen Volz**	**Jaewook Ahn**		**Dimitris Angelakis**	
		dinner & poster session		lab tours	

TALKS

Monday, August 13 2018

13:30 – 13:45	Welcome
13:45 – 14:20	**Antoine Browaeys** *Institut d'Optique, Paris, France* The Su-Schrieffer Heeger model with hard-core bosons in arrays of Rydberg atoms
14:20 – 14:55	**Luis Santos** *Leibniz University of Hannover, Germany* Disordered lattice models with power-law hopping
14:55 – 15:20	**Matteo Zaccanti** *INO-CNR & LENS, Sesto Fiorentino, Italy* Growth and coexistence of spin and pairing correlations in quenched repulsive Fermi gases
15:20 – 15:45	**Nils Byg Jørgensen** *Department of Physics and Astronomy, Aarhus University, Denmark* Quantum simulations with Bose polarons
15:45 – 16:15	coffee break
16:15 – 16:50	**Gregor Weihs** *University of Innbruck, Austria* Creation and Interference of Multiphoton States
16:50 – 17:25	**Hrvoje Buljan** *University of Zagreb, Croatia* Engineering Weyl fermions and anyons
17:25 – 18:00	**Juergen Volz** *TU Vienna, Austria* Multimode strong coupling of cold atoms close to a nanofiber ring resonator

13:45 – 14:20 **Mo, August 13**

Antoine Browaeys, Sylvain de Léséleuc, Pascal Scholl, D. Barredo, V. Lienhard, T. Lahaye
Laboratoire Charles Fabry, Institut d'Optique, CNRS, France

The Su-Schrieffer Heeger model with hard-core bosons in arrays of Rydberg atoms

This talk will present our recent experimental implementation of the Su-Schrieffer-Heeger model originally introduced to explain the conductivity of poly-acetylen. It is now considered as one of the simplest example of topological system. We implement this model in arrays of individual Rydberg atoms, each considered as a two-level system. The coupling between the sites results from the resonant dipole-dipole interaction between atoms. The spin excitations are equivalent to hard-core bosons. We demonstrate that the hard-core constraint allows the preparation of a symmetry protected topological phase.

Luis Santos

Leibniz University of Hannover, Germany

Disordered lattice models with power-law hopping

I will review some of our recent works on disordered lattice models with power-law hops. I will start with a brief discussion on polar molecules pinned in an optical lattice. For imperfect lattice fillings, dipole-induced exchange of rotational states results in an effective disorder model for spin-like excitations, characterized by the presence of dominant multifractal states in three dimensional lattices [1]. I will then discuss one-dimensional systems with general power law hops, 1/r^a, showing that algebraic localization occurs both for short-range (a>1) and, more remarkably, for long-range (a<1) hops [2]. Moreover, there is a surprising duality between the localization properties of long- and short-range models. In the final part I will comment about quasi-disordered, Aubry-Andre (AA), models with power-law hops [3]. Whereas in the standard AA model (infinite a) the whole eigenstate spectrum transitions from extended to localized at a critical quasi-disorder strength, at finite power a the spectrum may present a mobility edge. Moreover, a hierarchy of phases appears characterized by a transition of whole sections of the spectrum from extended to either localized (for a>1) or, more remarkably, multifractal (for a<1). I will discuss in detail the corresponding phase diagram and how ergodic-to-multifractal transitions may be revealed by monitoring the dynamics in the lattice.

[1] X. Deng, B. L. Altshuler, G. V. Shlyapnikov, and L. Santos, Phys. Rev. Lett. **117**, 020401 (2016)
[2] X. Deng, V. E. Kravtsov, G. V. Shlyapnikov, and L. Santos, Phys. Rev. Lett. **120**, 110602 (2018)
[3] X. Deng, S. Ray, S. Sinha, G. V. Shlyapnikov, and L. Santos, in preparation

14:55 – 15:20 **Mo, August 13**

Matteo Zaccanti
INO-CNR & LENS, Sesto Fiorentino, Italy

Growth and coexistence of spin and pairing correlations in quenched repulsive Fermi gases

In this talk I will discuss recent experimental investigation on the out-of-equilibrium dynamics of a two-component Fermi gas of ultracold lithium atoms, following a quench to strong repulsive interactions.

By means of time-resolved pump-probe spectroscopy, we study the evolution of the system under the competing action of the ferromagnetic and pairing instabilities. At short timescales and for critical interactions, we find the growth of spin anti-correlations to be faster than the pairing ones. At longer times, while pairing processes prevent spin de-mixing over large length scales, in spite of a slow but uninterrupted atom-to-molecule conversion our data point to the microscopic coexistence of these two concurrent mechanisms, which persist in a slowly-evolving atom-pair admixture over very long times. Our results clarify the fate of the repulsive Fermi gas, reconciling seemingly discordant conclusions from previous studies within a unified framework.

15:20 – 15:45 **Mo, August 13**

Nils Byg Jørgensen

Aarhus University, Denmark

Quantum simulations with Bose polarons

The concept of a single particle interacting with its surroundings is found throughout physics. A key example is the polaron quasiparticle composed of an impurity and its excitations of a surrounding medium. This generic scenario can be studied in new detail by utilizing ultracold quantum gases, which offer a versatile and unique test bench. The polaron was recently observed in a Bose-Einstein condensate for the first time, opening up for multiple intriguing research pathways. We currently explore several of these. Interferometric techniques are employed to study the formation dynamics of the Bose polaron. Additionally, the Bose polaron is predicted to contain compelling features, which are analogue to hot quark-gluon plasmas. Our recent experimental results on these topics show promising developments towards a deeper understanding of impurity physics.

16:15 – 16:50 **Mo, August 13**

Gregor Weihs
University of Innbruck, Austria

Creation and Interference of Multiphoton States

Quantum states of multiple photons are conjectured to enable all-optical quantum repeaters and quantum computers. While photon loss is ubiquitous and source and detection efficiencies are from perfect, there are models that can deal with these errors with reasonable overhead.

In my talk, I will present our work on efficient sources of multiphoton states, for example from multiexciton cascades in nanowire quantum dot molecules. The quantum dots are grown in nanowires which act as antennas that improve the outcoupling. As a result, our source surpasses earlier reported sources by orders of magnitude in brightness.

Applying multiphoton states in any linear optical network involves multiparticle interference. I will present theoretical results on the complete generalization of the Hong-Ou-Mandel interference of two photons on a beamsplitter. In this work, we cover all possible scenarios of an arbitrary number of bosons or fermions in an arbitrary multiport beamsplitter with a surprisingly simple criterion.

In a slightly different setting, we experimentally investigated the interference of a time-correlated three-photon state through Franson interferometry. I will show how we achieved genuine three-photon interference with high visibility, which enables tests of the foundations of quantum mechanics.

16:50 – 17:25 **Mo, August 13**

Hrvoje Buljan

Department of Physics, Faculty of Science, University of Zagreb, Croatia

Engineering Weyl fermions and anyons

I will present two topics of research in our group related to synthetic topological quantum matter [1]: (i) topological phases in 3D optical lattices, more specifically a proposal for experimental realization of Weyl semimetals in ultracold atomic gases [2], and (ii) anyons [3,4]. I will present one possible route to engineer anyons in a 2D electron gas in a strong magnetic field sandwiched between materials with high magnetic permeability, which induce electron-electron vector interactions to engineer charged flux-tube composites [3]. I will also discuss intriguing concepts related to extracting observables from anyonic wavefunctions [4]: one can show that the momentum distribution is not a proper observable for a system of anyons [4], even though this observable was crucial for the experimental demonstration of Bose-Einsten condensation or ultracold fermions in time of flight measurements. I will show how time of flight measurements can be used to extract anyonic statistics [4].

[1] N. Goldman, G. Juzeliunas, P. Ohberg, I. B. Spielman, Rep. Prog. Phys. **77**, 126401 (2014).

[2] Tena Dubček, Colin J. Kennedy, Ling Lu, Wolfgang Ketterle, Marin Soljačić, Hrvoje Buljan, *Weyl points in three-dimensional optical lattices: Synthetic magnetic monopoles in momentum space*, Phys. Rev. Lett. **114**, 225301 (2015).

[3] M. Todorić, D. Jukić, D. Radić, M. Soljačić, and H. Buljan, *The Quantum Hall Effect with Wilczek's charged magnetic flux tubes instead of electrons*, Phys. Rev. Lett. **120**, 267201 (2018).

[4] Tena Dubček, Bruno Klajn, Robert Pezer, Hrvoje Buljan, Dario Jukić, *Quasimomentum distribution and expansion of an anyonic gas*, Phys. Rev. A **97**, 011601(R) (2018).

17:25 – 18:00 **Mo, August 13**

Juergen Volz
TU Vienna, Austria

Multimode strong coupling of cold atoms close to a nanofiber ring resonator

I will report on the experimental implementation of a new cold-atom based platform that realizes the multimode strong coupling regime of cavity quantum electrodynamics. In this regime, the light-matter coupling rates become larger than the free spectral range of the cavity. As a consequence, the atoms simultaneously strongly interact with several different longitudinal resonator modes. This type of atom-light coupling is qualitatively different from conventional cavity quantum electrodynamics and enables, e.g., the strong interaction between photons in different cavity modes.

Our experimental setup is based on a 30 m long fiber ring resonator containing an optical nanofiber with a waist diameter of 400 nm. Overlapping the nanofiber waist with a magneto-optical trap, we interface the resonator with an ensemble of cold cesium atoms. Due to the strong transverse confinement of the light, we achieve a significant coupling strength between a single atom and the evanescent part of the guided field. Consequently, the collective coupling of a few tens of atoms is sufficient to reach a coupling strength in excess of the resonator's free spectral range of 7 MHz and thus enter the regime of multimode strong coupling [1].

In my talk, I will show our first experimental results on the transition from single-mode to multimode strong coupling by varying the number of atoms interacting with the cavity field. Then, we plan to study the nonlinear properties of the atom-resonator system as well as its non-Markovian dynamics [2] and the possibility of implementing protocols for quantum simulation or quantum information processing [3].

[1] P. Schneeweiss, S. Zeiger, T. Hoinkes, A. Rauschenbeutel & J. Volz, Opt. Lett. **42**, 85 (2017).
[2] D. O. Krimer, M. Liertzer & S. Rotter, Phys. Rev. A **89**, 033820 (2014).
[3] V. Torggler, S. Krämer & H. Ritsch, Phys. Rev. A **95**, 32310 (2016).

Tuesday, August 14 2018

9:15 – 9:50	**Stefanie Barz** *University of Stuttgart, Germany* Three photons can be different in four ways
9:50 – 10:25	**Anders Sørensen** *Niels Bohr Institute, Denmark* Strongly correlated photon transport with weakly coupled emitters
10:25 – 10:50	coffee break
10:50 – 11:25	**Johannes Zeiher** *Max Planck Institute for Quantum Optics, Garching, Germany* Probing off-resonantly driven Rydberg gases at the single-atom level
11:25 – 12:00	**Benoit Vermersch** *IQOQI Innsbruck, Austria* Measuring scrambling and entanglement via randomized measurements
12:00 – 13:45	lunch
13:45 – 14:20	**Klaus Sengstock** *University of Hamburg, Germany* Topology in Floquet engineered optical lattices
14:20 – 14:55	**Richard Schmidt** *Max Planck Institute for Quantum Optics, Garching, Germany* Atomtronics with a spin
14:55 – 15:20	**Alejandro Saenz** *Humboldt-Universität zu Berlin, Germany* A Cold-Atom Quantum Simulator for Attosecond Science
15:20 – 15:45	**Sebastian Hofferberth** *University of Southern Denmark,* Odense, Denmark Free-space QED with a single Rydberg superatom
15:45 – 16:15	coffee break
16:15 – 16:50	**Robert Nyman** *Imperial College London, UK* Non-equilibrium condensation of just a few photons
16:50 – 17:25	**Francesco Piazza** *Max Planck Institute for the Physics of Complex Systems, Dresden, Germany* Interaction-induced transparency for strong-coupling polaritons
17:25 – 18:00	**Jaewook Ahn** *Department of Physics, KAIST, South Korea* Quantum simulation with Rydberg atom assemblages

9:15 – 9:50 **Tue, August 14**

Stefanie Barz
University of Stuttgart, Germany

Three photons can be different in four ways

Quantum interference of two independent particles in pure quantum states is fully described by the particles' distinguishability: the closer the particles are to being identical, the higher the degree of quantum interference. In this talk, I will show that the distinguishability between pairs of photons is not sufficient to fully describe the photons' behaviour in a scattering process when more than two particles are involved. Here, a collective phase, the triad phase, plays a role. I will further show that partial distinguishability plays a role in the characterisation of quantum devices and that it can also be the basis for generating entangled states.

9:50 – 10:25 **Tue, August 14**

Anders Sørensen

Niels Bohr Institute, Copenhagen, Denmark

Strongly correlated photon transport with weakly coupled emitters

Photons in a waveguide strongly coupled to two-level emitters realize a strongly interacting photon fluid with effective photon-photon interaction. The combination of this with external driving and dissipation realizes a strongly correlated out-of equilibrium quantum system. As a first step towards studying such systems, we show that strongly correlated photon transport can be observed in waveguides containing optically dense ensembles of chirally coupled emitters. Remarkably, this occurs even for weak coupling efficiencies.

Specifically, we compute the photon transport properties through a chirally coupled system of N two-level systems driven by a weak coherent field, where each emitter can also scatter photons out of the waveguide. The photon correlations arise due to an interplay of nonlinearity and coupling to a loss reservoir, which creates a strong effective interaction between transmitted photons. The highly correlated photon states are less susceptible to losses than uncorrelated photons and have a power-law decay with N. This is described using a simple universal asymptotic solution governed by a single scaling parameter which describes photon bunching and power transmission. We show numerically that, for randomly placed emitters, these results hold even in systems without chirality. The effect can be observed in existing tapered fiber setups with trapped atoms.

[1] *Chiral waveguide QED: Strongly correlated photon transport with weakly coupled emitters*, Sahand Mahmoodian, Mantas Čepulkovskis, Sumanta Das, Peter Lodahl, Klemens Hammerer, and Anders S. Sørensen, arXiv:1803.02428

10:50 – 11:25 **Tue, August 14**

Johannes Zeiher

Max Planck Institute for Quantum Optics, Garching, Germany

Probing off-resonantly driven Rydberg gases at the single-atom level

Utilizing the strong interactions between highly excited Rydberg states in an ultracold atomic gas offers a unique playground to study few and many-body physics. In particular, the off-resonant optical admixture of Rydberg interactions to an atomic ground state, so-called "Rydberg dressing", has been proposed as a source of novel interactions.

I will present our experimental approach of realizing Rydberg-dressed Ising spin interactions in an atomic Mott insulator of Rubidium-87 by off-resonant single-photon coupling to Rydberg p-states. First interferometric measurements on a two-dimensional sample demonstrated versatile control of these interactions, however the coherence of the observed dynamics was limited. In contrast, coherence times are substantially increased in a one-dimensional spin chain, allowing for the detection of interaction-driven coherent collapse and revival dynamics of the magnetization in the chain.

Furthermore, I will present our progress on exploring exotic Rydberg interaction potentials. In particular, we were able to observe "Rydberg macrodimers", molecular bound states between two Rydberg atoms hosted by local minima in the interaction potential landscape. Combining the spectroscopic measurements with microscopic readout of the atom loss allows for developing a consistent understanding of relative line strengths, opening the path to controlling molecular photo-association at the ultimate level. Furthermore, the high spectral resolution of our measurements enables a precise characterization of the binding potential, challenging state-of-the-art calculations of such interactions.

In future experiments, the loss of atoms at the molecular resonances might provide a way to engineer interesting many-body phases stabilized by dissipation.

11:25 – 12:00 **Tue, August 14**

Benoit Vermersch
IQOQI Innsbruck, Austria

Measuring scrambling and entanglement via randomized measurements

The spreading of entanglement and the "scrambling" of quantum information play a key role in our understanding of the emergence (or not) of thermal equilibrium in closed quantum systems. While entanglement can be quantified in terms of Rényi entropies, the concept of scrambling is related to out-of-time-ordered correlations (OTOCs), which can be measured based on backward time evolution and/or ancillas.

In the first part of my talk, I will present our latest work showing how to measure OTOCs and diagnose scrambling in many-body systems [1]. Our key result is the mapping between OTOCs and statistical correlations between measurements performed after time-evolution from a random distribution of initial states. This provides us with a protocol to measure OTOCs in state-of-the-art experiments.

In the second part of my talk, I will briefly discuss recent theoretical [2,3] and experimental [4] results related to the measurement of Rényi entropies with randomized measurements.

[1] BV, A. Elben, L. Sieberer, N.Y. Yao, P. Zoller (in preparation)
[2] A. Elben, BV, M. Dalmonte, I Cirac, P. Zoller, PRL **120**, 050406 (2018)
[3] BV, A. Elben, M. Dalmonte, I Cirac, P. Zoller, PRA **97**, 023604 (2018)
[4] T. Brydges, A. Elben, P. Jurcevic , BV, C. Maier, B. Lanyon, P. Zoller, R. Blatt, C. Roos arxiv: 1806.05747

13:45 – 14:20 **Tue, August 14**

Klaus Sengstock

University of Hamburg, Germany

Topology in Floquet engineered optical lattices

Topological properties lie at the heart of many fascinating phenomena in solid-state systems such as quantum Hall systems or Chern insulators. The topology of the bands can be captured by the distribution of Berry curvature, which describes the geometry of the eigenstates across the Brillouin zone. Using fermionic ultracold atoms in a hexagonal optical lattice, we engineered the Berry curvature of the Bloch bands using resonant driving and show a full momentum-resolved state tomography from which we obtain the Berry curvature and Chern number (Science 352, 1091 (2016)).

Furthermore, we study the time-evolution of the many-body wavefunction after a sudden quench of the lattice parameters and observe the appearance, movement, and annihilation of vortices in reciprocal space. We identify their number as a dynamical topological order parameter, which suddenly changes its value at critical times. Our measurements constitute the first observation of a so called ‚dynamical topological phase transition, which we show to be a fruitful concept for the understanding of quantum dynamics far from equilibrium (arXiv 1608.05616).

The talk will discuss general concepts of topology and dynamics of ultracold quantum gases in optical lattices.

Richard Schmidt

Max Planck Institute for Quantum Optics, Garching, Germany

Atomtronics with a spin

We propose an experiment to investigate the full counting statistics of nonequilibrium spin transport with an ultracold quantum gases. Our setup uses the ability of exquisite spin control available in atomic systems to generate spin transport that is induced by an impurity atom immersed in a spin-imbalanced two-component Fermi gas. In contrast to conventional solid state realizations, in ultracold atoms spin relaxation and the decoherence from external sources can be largely suppressed. As a consequence, one can directly count the number of spins in each reservoir to investigate the quantum and thermal noise in spin transport - a notorious challenge in solid state devices. Moreover, using Ramsey interferometry, the dephasing of the impurity spin can be measured. This makes it possible to realize the non-equilibrium orthogonality catastrophe which goes beyond Anderson's paradigm by having a fermionic system that is initially in a highly excited state. The Ramsey response of the non-equilibrium orthogonality catastrophe exhibits an exponential decay even when the system is prepared in a zero temperature state, in contrast to the conventional power-law decay of Anderson’s orthogonality catastrophe. Using the theory of Toeplitz determinants we derive analytical expressions for the impurity response at late times. An analytical mapping on a single-Fermi sea problem reveals a remarkable connection of the decay rate of the Ramsey contrast and the probability to observe spin flips in the fermionic system.

Alejandro Saenz
Humboldt-Universität zu Berlin, Germany

A Cold-Atom Quantum Simulator for Attosecond Science

The full ab initio treatment of atoms and, especially, of molecules exposed to ultrashort intense laser fields remains a paramount challenge. Solutions of the time dependent Schrödinger equation for atoms or molecules in intense laser fields are presently basically restricted to two-electron systems like helium atoms or hydrogen molecules. In fact, it is evident that the complete exact theoretical treatment of atoms or molecules with more than a very small number of electrons and nuclei will remain an unsolvable task for any classical computer, since the corresponding Hilbert space increases exponentially and the interaction with an intense laser field quickly spreads the electronic wavefunctions over a very large volume both in position and momentum space. In such a situation, a quantum simulator may provide an alternative approach to the problem. Such a quantum simulator for strong-field physics, based on optically trapped ultracold neutral atoms was recently introduced [1]. It allows for the exploration of the features of strong field-physics on a much slower time scale. In fact, the sub-femtosecond processes known from the famous three-step model that explained, e.g., high-harmonic generation are slowed down by 13 orders of magnitude, resulting in processes on the millisecond time scale. This should provide a detailed glance into tunneling processes. More importantly, the extreme flexibility of the quantum-simulator system allows for systematic studies of the influence of the trapping potential (including multi-well structures simulating molecular potentials) and, especially, of the many-particle interactions on the strong-field response of atomic and molecular systems. Even with regards to the driving external field a much higher flexibility is available, including an extreme variability with respect to the frequency-range as well as to the pulse shape like true half-cycle pulses. It was demonstrated that the characteristic features of strong-field physics are well reproduced using realistic experimental parameters. It should be noted that this quantum simulator is somewhat unusual in the sense that it is not designed to simulate experiments that seem or are even impossible to be performed, but to support the theoretical interpretation of experiments by providing in-depth tests for theoretical models, for example the so-called strong-field approximation that so far lacks a clear extension beyond the single-active-electron response.

[1] S. Sala, J. Förster, A. Saenz, Phys. Rev. A **95**, 011403(R) (2017).

15:20 – 15:45 **Tue, August 14**

Sebastian Hofferberth

University of Southern Denmark, Odense, Denmark

Free-space QED with a single Rydberg superatom

Photons, for all practical purposes, do not interact. Engineering reliable interactions between individual photons enables both practical applications and is of great fundamental interest. Mapping the strong interaction between Rydberg excitations in ultracold atomic ensembles onto single photons enables the realization of optical nonlinearities which can modify light on the level of individual photons.

Here, we discuss our recent experiments coupling an optical medium smaller than a single Rydberg blockade volume to a few-photon probe field. Due to the large number of atoms in the blockaded volume and the efficient coupling to the probe light mode, we achieve coherent coupling between the probe field and the effective Rydberg "superatom" even if the probe pulse contains only a few photons. We observe the effective interaction between two and three photons, mediated by the single emitter, in the two- and three-body correlations imprinted onto the transmitted probe light. Our system enables us to study the dynamics of a single two-level system strongly coupled to a quantized propagating light field in free space and opens the way to controlled manipulation of few-photon pulses via Rydberg superatoms.

16:15 – 16:50 **Tue, August 14**

Robert Nyman

Imperial College London, UK

Non-equilibrium condensation of just a few photons

Photons in a dye-filled optical microcavity come to thermal equilibrium through multiple emission and re-absorption events from a fluorescent dye. The photon populations are described by the ideal-gas grand-canonical distribution. With sufficient population, Bose-Einstein condensation (BEC) occurs, leading to macroscopic occupation of the lowest-energy cavity mode.

I will explore how thermal equilibrium breaks down, when the photon re-absorption rate becomes low compared to cavity loss. We observe multi-mode condensation. The system shows a rich non-equilibrium phase diagram which demonstrates how photon BEC crosses over to more mundane laser operation. Decondensation, where a mode's population dramatically decreases with increasing pump rate, is predicted [1]. We have recently demonstrated BEC of just 7 photons [2]. Non-equilibrium phase transitions with so few particles inspire us to re-think how we define the concept of condensation threshold.

[1] HJ Hesten, RA Nyman, and F Mintert, Phys. Rev. Lett. **120**, 040601 (2018).
[2] BT Walker ... RA Nyman, arXiv:1711.11087.

16:50 – 17:25 **Tue, August 14**

Francesco Piazza

Max Planck Institute for the Physics of Complex Systems, Germany

Interaction-induced transparency for strong-coupling polaritons

We investigate the properties of the electromagnetically induced transparency (EIT) window in presence of strong and partially dissipative interactions between the polaritons. Upon increasing the photon-pump strength, we find a first-order transition between an opaque phase with strongly broadened polaritons and a transparent phase where a long-lived polariton branch with highly tunable occupation emerges. In the transparent phase the window is reconstructed via nonlinear interference effects induced by the polariton interactions. Based on a systematic diagrammatic expansion for the non-equilibrium Dyson equations we are able to make quantitatively valid predictions for response and correlation functions. We identify photonic crystal waveguides as an ideal setup, where the tuneability of interactions allows in particular to make energy shifts dominate over scattering processes, favouring the interaction-induced transparency (IIT) transition even at low polariton densities.

17:25 – 18:00 **Tue, August 14**

Jaewook Ahn

Department of Physics, KAIST, South Korea

Quantum simulation with Rydberg atom assemblages

Recent experiments have shown that capturing single atoms at an optically resolvable distance and then rearranging them in an arbitrary lattice structure can be rapidly achievable [1-3]. Once these atoms are entangled through time-dependent Rydberg state excitation, the trap geometry and external fields bring about numerous ways to coherently manipulate these Rydberg atom assemblages. As an example, we have observed quenched dynamics of quantum Ising-like model using our N=10-30 Rydberg atom assemblages in linear and zig-zag chain structures and the result agrees well with the detailed balance principle of the occupation probabilities of prequench states in a thermalization dynamics [4]. This Rydberg-atom quantum simulation platform can be easily extendable to lattice configurations in two and even three dimensions. So, soon-to-be scaling of the number of qubits to N=100 will hopefully bring us to an uncharted computational domain with full of classically intractable problems.

[1] H. Kim et al., *In situ single-atom array synthesis using dynamic holographic optical tweezers*, Nature Comm. **7**, 13317 (2016).
[2] M. Endres et al., *Atom-by-atom assembly of defect-free one-dimensional cold atom arrays*, Science **354**, 1024 (2016).
[3] D. Barredo et al., *An atom-by-atom assembler of defect-free arbitrary two-dimensional atomic arrays*, Science **354**, 1021-1023 (2016).
[4] H. Kim et al., *Detailed balance of thermalization dynamics in Rydberg atom quantum simulators*, Phys. Rev. Lett. **120**, 180502 (2018).

Wed, August 15

9:15 – 9:50	**Rudi Grimm** *University of Innsbruck and IQOQI, Austria* Mass-imbalanced fermion mixtures
9:50 – 10:25	**Pietro Massignan** *UPC, Spain* Bose Polarons at Finite Temperature and Strong Coupling
10:25 – 10:50	coffee break
10:50 – 11:25	**Tilman Esslinger** *ETH Zurich, Switzerland* From Terminal to Terminal with heat and atoms
11:25 – 12:00	**Ronen Kroeze** Stanford University, USA Tunable-Range, Photon-Mediated Atomic Interactions in Multimode Cavity QED
12:00 – 13:30	lunch break
13:30 – 14:05	**Georgy Shlyapnikov**, *CNRS, Universite Paris Sud, France and Russian Quantum Center, Moscow, Russia* Superfluidity of Supersolids
14:05 – 14:30	**Julian Leonard** *Harvard University, Cambridge, USA* Microscopy of many-body localization in one dimension

Department of Physics and Astronomy — Phys. Aud.

15:00 – 16:00	**Ole Rømer Colloquium:** **Tilman Esslinger** *ETH Zurich, Switzerland* Supersolid Higgs and Goldstone Modes

9:15 – 9:50 **Wed, August 15**

Rudi Grimm

University of Innsbruck and IQOQI, Austria

Mass-imbalanced fermion mixtures

Mass imbalance in two-component fermion systems favors exotic regimes of superfluidity, such as Sarma and FFLO phases. While the exciting prospects have been pointed out in theoretical work, there has not been any experimental realization so far. The reason for this surprising fact is the shortage of available species combinations suited for this purpose. We now introduce a new system, a mixture of Dy-161 and K-40, the mass ratio of which (about 4) is sufficient to change substantially the phase diagrams as compared to the case of mass-balanced spin mixtures. The Dy-K mixture offers a combination of very interesting properties, which make it very attractive for experiments. We will report on progress in the preparation of a doubly degenerate mixture and in our search for Feshbach resonances.

9:50 – 10:25 **Wed, August 15**

Pietro Massignan
UPC, Barcelona, Spain

Bose Polarons at Finite Temperature and Strong Coupling

Dilute impurities in a quantum bath constitute a paradigmatic realization of quasiparticles. While impurities in a Fermi gas are rather well understood by now, both theoretically and experimentally, we show here that impurities in a Bose gas hold an unexpected surprise. Indeed, we find that the quasiparticle formed around a single impurity at negative energies at zero temperature fragments into two quasiparticles as soon as the gas is heated up.

This is a purely nonperturbative effect due to the coupling of the quasiparticle to a gapless bosonic mode, and it bears strong similarities with a feature predicted more than 30 years ago (and not yet observed), i.e., the emergence of plasminos in hot quark-gluon plasmas, and in Yukawa and QED theories.

10:50 – 11:25 **Wed, August 15**

Tilman Esslinger
ETH Zurich, Switzerland

From Terminal to Terminal with heat and atoms

We study fundamental concepts of particle and heat transport in a model system using ultracold atoms. It consists of a narrow channel connecting two macroscopic reservoirs of fermionic lithium atoms. For non-interacting atoms, we observe quantized conductance and the system finds an ideal description in the Landauer-Büttiker formalism, which views conduction as the transport of carriers from one terminal to another. For increasing attractive interactions, the particle conductance is unexpectedly enhanced even before the gas is expected to turn into a superfluid, showing plateau-like features at non-universal values. Inspired by the fountain effect in superfluid helium, we studied heat and particle transport in a unitary Fermi gas. After heating one of the reservoirs, we observed a particle current flowing from cold to hot and found the system, after an initial response, in a non-equilibrium steady state with finite temperature and chemical potential differences across the channel.

11:25 – 12:00 **Wed, August 15**

Ronen Kroeze
Stanford University, USA

Tunable-Range, Photon-Mediated Atomic Interactions in Multimode Cavity QED

Optical cavity QED provides a platform with which to explore quantum many-body physics in driven-dissipative systems. Single-mode cavities provide strong, infinite-range photon-mediated interactions among intracavity atoms. However, these global all-to-all couplings are limiting from the perspective of exploring quantum many-body physics beyond the mean-field approximation. The present work demonstrates that local couplings can be created using multimode cavity QED. This is established through measurements of the threshold of a superradiant, self-organization phase transition versus atomic position. Specifically, we experimentally show that the interference of near-degenerate cavity modes leads to both a strong and tunable-range interaction between Bose-Einstein condensates (BECs) trapped within the cavity. We exploit the symmetry of a confocal cavity to measure the interaction between real BECs and their virtual images without unwanted contributions arising from the merger of real BECs. Atom-atom coupling may be tuned from short range to long range. This capability paves the way toward future explorations of exotic, strongly correlated systems such as quantum liquid crystals and driven-dissipative spin glasses.

13:30 – 14:05 **Wed, August 15**

Georgy Shlyapnikov,

LPTMS, CNRS, Universite Paris Sud, France and Russian Quantum Center, Moscow, Russia

Superfluidity of Supersolids

I will give an overview of the studies of supersolid states of bosons, which were predicted several tens of years ago and found experimentally only in 2017. These peculiar states are characterized by a simultaneous presence of superfluidity and crystalline order. In the dilute limit for bosons in free space, supersolidity appears as a Bose-Einstein condensate with the wavefunction that has the form of a crystal lattice on top of a uniform background. The supersolidity has been observed in a spin-orbit-coupled two-component Bose-Einstein condensate as a stripe phase, which is featuring density modulations in the direction of spin-orbit coupling. The superfluid behavior of the stripe phase will be characterized by calculating the drag force acting on a moving impurity. Because of the gapless band structure of the excitation spectrum, the Landau critical velocity vanishes if the motion is not strictly parallel to the stripes, and energy dissipation takes place at any speed. By estimating the time over which the energy dissipation occurs, I will show that for slow impurities the effects of friction can be very small on a time scale up to several seconds, which is comparable with the duration of a typical experiment.

I will eventually raise the question of the effects of the drag force on the moving striped Bose-Einstein condensate. The issue is that in contrast to ordinary uniform superfluids, where it can only reduce the velocity of the flow, in the stripe phase the friction may act in the direction of weakening or eliminating the density modulations.

14:05 – 14:30 **Wed, August 15**

Julian Leonard
Harvard University, Cambridge, USA

Microscopy of many-body localization in one dimension

An interacting quantum system that is subject to disorder may cease to thermalize due to localization of its constituents, thereby marking the breakdown of thermodynamics. The key to our understanding of this phenomenon lies in the system's entanglement, which is experimentally challenging to measure.

We realize such a many-body-localized system in a disordered Bose-Hubbard chain and characterize its entanglement properties. We observe that the particles become localized, thereby suppressing transport and preventing the thermalization of subsystems. Notably, we measure the development of non-local correlations, whose evolution is consistent with a logarithmic growth of entanglement entropy.

15:00 – 16:00	Phys. Aud.	Wed, August 15

Ole Rømer Colloquium:

Tilman Esslinger
ETH Zurich, Switzerland

Supersolid Higgs and Goldstone Modes
The concept of a supersolid state is paradoxical. It combines the crystallization of a many-body system with dissipationless flow of the atoms it is built of. This phase requires the breaking of two symmetries, the phase invariance of a superfluid and the translational invariance to form the crystal. I will report on a quantum simulation experiment in which we realized a supersolid phase breaking a continuous translational symmetry along one direction. It emerges from two discrete spatial symmetries by symmetrically coupling a Bose-Einstein condensation to the modes of two optical cavities. The collective excitations of the system have the nature of Higgs and Goldstone modes. The amplitudes of the field of the two optical cavities form real and imaginary part of a U(1)-symmetric order parameter. Monitoring the cavity fields in real-time allows us to observe the dynamics of the associated Higgs and Goldstone modes and reveal their amplitude and phase nature. We use a spectroscopic method to measure their frequencies and give a tunable mass to the Goldstone mode at the crossover between continuous and discrete symmetry. Our experiments provide a link between previous spectroscopic measurements and the theoretical concept of Higgs and Goldstone modes.

Thursday, August 16

9:15 – 9:50	**Eugene Demler** *Harvard University, USA* New theoretical approaches to quantum impurity problems
9:50 – 10:25	**Michael Drewsen** *Department of Physics and Astronomy, Aarhus University, Denmark* Direct frequency comb driven Raman transitions in the terahertz range: From high resolution atomic ion spectroscopy to search for physics beyond the Standard Model
10:25 – 10:50	coffee break
10:50 – 11:25	**Giovanna Morigi** *Saarland University, Germany* Quenches across critical photonic systems
11:25 – 12:00	**Mikael Rechtsman** *Pennsylvania State University, USA* Topological photonics: Weyl points and protected defect modes
12:00 – 13:45	lunch break
13:45 – 14:20	**Alexander Keesling** *Harvard University, USA* Probing critical dynamics across quantum phase transitions on a Rydberg simulator
14:20 – 14:55	**Alexey Gorshkov** *JQI and QuICS, NIST/University of Maryland, USA* Few-body and many-body physics with photons
14:55 – 15:20	**David Petrosyan** *IESL & FORTH, Heraklion Greece* Bound magnons in a Rydberg lattice gas
15:20 – 15:45	**Lucas Teuber** *University Rostock, Germany* Optimal design strategy for non-Abelian Abelian gauge fields based on quantum metric
15:45 – 16:15	coffee break
16:15 – 16:50	**Florian Mintert** *Imperial College London, UK* Quantum simulations with polychromatically driven optical lattices
16:50 – 17:25	**Jan Klaers** *University of Twente, The Netherlands* Variable potentials for thermalized photons
17:25 – 18:00	**Dimitris Angelakis** *Technical University of Crete, Greece* Quantum simulations with interacting photons: Spectral signatures of many-body localization in quantum superconducting chips

9:15 – 9:50 **Thu, August 16**

Eugene Demler
Harvard University, Cambridge, USA

New theoretical approaches to quantum impurity problems

New variational approach to the analysis of dynamics of quantum impurities will be discussed. This method is based on a generalized canonical transformation that decouples the impurity from the bath degrees of freedom. This transformation introduces long-range multi-particle interactions between the bath degrees of freedom, which can be analyzed using Gaussian variational states. I will discuss applications of this method to a broad class of problems, including Anderson impurity and Kondo models.

9:50 – 10:25 **Thu, August 16**

Michael Drewsen
Department of Physics and Astronomy, Aarhus University, Denmark

Direct frequency comb driven Raman transitions in the terahertz range: From high resolution atomic ion spectroscopy to search for physics beyond the Standard Model

By the direct application of a fs laser frequency comb, we have recently been able to coherently drive Raman transitions between the metastable 3d $^2D_{3/2}$ and 3d $^2D_{5/2}$ levels in the $^{40}Ca^+$ ion separated by 1.8 THz with ~10 Hz absolute resolution [1]. Besides improving the accuracy of this fine structure splitting by a factor of 5, we have measured the isotope shift of this splitting for $^{42,44,46,48}Ca^+$ ions with the same precision. Combined with ~1KHz resolved isotope shift measurements of the 4s $^2S_{1/2}$ -3d $^2D_{5/2}$ transition, we have been able to produce a so-called King plot, showing an unprecedented high degree of linearity. Combined with theoretical models for coupling of ordinary baryonic matter with potential Dark Matter particles, our result represent the best bounds of the strength of such coupling at present at the low mass limit.

[1] C. Solaro, S. Meyer, K. Fisher, M. V. DePalatis, M. Drewsen, "Direct frequency-comb-driven Raman transitions in the terahertz range", accepted for publication in Phys. Rev. Lett. **120**, 253601 (2018).

10:50 – 11:25 **Thu, August 16**

Giovanna Morigi
Saarland University, Saarbrücken, Germany

Quenches across critical photonic systems

We review recent work on the relaxation dynamics of ultracold atoms interacting via long-range optomechanical interactions. The interactions are mediated by cavity photons and their range is such that the energy is non-additive. We identify observables which allow us to draw a connection with the out-of-equilibrium statistical mechanics of long-range interacting systems. We further discuss novel features due to the driven-dissipative nature.

11:25 – 12:00 **Thu, August 16**

Mikael Rechtsman

Pennsylvania State University, USA

Topological photonics: Weyl points and protected defect modes

In this talk, I will present initial background on topological photonics in propagating (i.e., waveguide array / multi-core fiber) geometries. I will then demonstrate how we have used these platforms to make the first observation of Weyl points in optics. We observe Weyl points via their real-space observables, namely the direct observation of surface "Fermi arc" states and bulk conical diffraction associated with the linear dispersion in all directions. Finally, I will present our experiments on the topological protection of zero-dimensional defect modes in a higher-order topological crystalline insulator structure. The protection of these modes is fundamentally different than that of chiral edge states (for example) because they are two dimensions lower than the host lattice. We expect that these will find use in robust and thus inexpensive fabrication of photonic crystal fiber devices.

13:45 – 14:20 **Thu, August 16**

Alexander Keesling
Harvard University, Cambridge, USA

Probing critical dynamics across quantum phase transitions on a Rydberg simulator

Controllable, coherent many-body quantum systems can provide insights into fundamental properties of quantum matter, enable the realization of exotic quantum phases, and ultimately offer a platform for computation that may surpass classical computing. Recently, reconfigurable arrays of neutral atoms with programmable interactions have become promising systems to study such quantum many-body phenomena, due to their isolation from the environment, and high degree of control.

In this talk, I will describe how, using such a platform, we observe critical dynamics across quantum phase transitions into ordered phases breaking a discrete Z_N symmetry. Varying the rate at which the phase transition is crossed allows us to observe the power-law scaling of the correlation length, as predicted by the Kibble-Zurek mechanism. The scaling exponent observed experimentally is consistent with theoretical predictions for the Ising universality class when sweeping into a Z_2-ordered phase, and with the 3-state Chiral Clock Model for the transition into the Z_3-ordered phase. Finally, I will discuss possible applications for generation of high-fidelity entangled states and quantum optimization.

14:20 – 14:55 **Thu, August 16**

Alexey Gorshkov
JQI and QuICS, NIST/University of Maryland, USA

Few-body and many-body physics with photons

First, we will report on the demonstration of interacting qubit-photon bound states with superconducting circuits. Second, we will show how the concept of single-excitation bound states can be used to understand the propagation of photons through atomic ensembles. Third, we will discuss the use of Rydberg-mediated photon-photon interactions for the realization of single-photon sources, single-photon switches, single-photon subtractors, and few-photon bound states.

14:55 – 15:20 **Thu, August 16**

David Petrosyan

Institute of Electronic Structure & Laser (IESL), Foundation for Research and Technology - Hellas (FORTH), Greece

Bound magnons in a Rydberg lattice gas

Realizing tunable spin lattices in the quantum regime is challenging. We show that a spin lattice with strong nearest-neighbor interactions and tunable long-range hopping of excitations can be realized by a regular array of laser driven atoms, with an excited Rydberg state representing the spin-up state and a Rydberg-dressed ground state corresponding to the spin-down state. We find exotic interaction-bound states of Rydberg excitations - magnons - that propagate in the lattice via the combination of resonant two-site hopping and non-resonant second-order hopping processes. Arrays of trapped Rydberg-dressed atoms can thus serve as a flexible platform to simulate and study fundamental few-body physics in a lattice.

Lucas Teuber

University Rostock, Germany

Optimal design strategy for non-Abelian gauge fields based on quantum metric

Channeling photons, and thereby Abelian gauge bosons, through a system of four coupled waveguides we experimentally simulated a non-Abelian gauge field.

The waveguide system is governed by a tight-binding Hamiltonian which is parameterized by real coupling coefficents and describes a generalized STIRAP (STImulated Raman Adiabatic Passage) process [1] with two bright and two dark states. In the dark subspace, the adiabatic evolution for a closed curve in the parameter manifold is characterized by the non-Abelian gauge field as introduced by Wilczek and Zee [2]. However, the adiabaticity is constrained by the propagation length and the coupling strength in the waveguide system. Therefore, prior to the experiment, we designed optimally adiabatic processes using the quantum metric tensor.

[1] U. Gaubatz, P. Rudecki, S. Schiemann, and K. Bergmann, J. Chem. Phys. **92**, 5363 (1990)
[2] F. Wilczek and A. Zee, Phys. Rev. Lett. **52**, 2111 (1984)

16:15 – 16:50 **Thu, August 16**

Florian Mintert

Imperial College London, UK

Quantum simulations with polychromatically driven optical lattices

Polychromatic driving offers the possibility to tune effective processes in the setting of Floquet theory. We analyse to what extent suitable choice of driving permits to realise desired processes for atoms in shaken optical lattices. Within fundamental restrictions imposed by the geometry of the underlying lattices, it is possible to explore topologically non-trivial phases by varying the driving profile. The effective tunnelling and interaction processes permit to realise correlated many-body phases and we explore what phases can be obtained in a given lattice geometry.

16:50 – 17:25 **Thu, August 16**

Jan Klaers

University of Twente, The Netherlands

Variable potentials for thermalized photons

Controlling the flow of light is a fundamental requirement for quantum simulations with light. We have recently introduced a novel reversible microstructuring technique, which allows to control the transverse flow of light in a high finesse optical microresonator [1]. This technique is based on the direct laser writing of a thermo-sensitive polymer enclosed in an optical microresonator. At temperatures slightly above room temperature this polymer shows an extremely large thermo-optical coefficient: small temperature changes lead to large changes in the index of refraction of the medium. This property can be used to spatially modulate the index of refraction of the optical medium in the resonator plane with micrometer resolution, which effectively introduces a fully tuneable trapping potential for light in a microresonator. In particular, it is possible to capture photons onto periodic lattices sites. Furthermore, a controllable tunnel coupling between adjacent lattice sites can be achieved by either a fine-tuning of the lattice constant or by manipulating the potential landscape between the sites. A unique feature of this technique is the fact that it is fully reversible. If the temperature of the polymer drops to room temperature, the polymer recovers to its original state. This property allows to successively implement an arbitrary number of different tunnel coupling configurations in the same system, which would not be possible with standard semiconductor microstructuring techniques. This provides an ideal platform to perform photonic simulations of condensed matter physics.

[1] D. Dung, C. Kurtscheid, T. Damm, J. Schmitt, F. Vewinger, M. Weitz, and J. Klaers, “Variable potentials for thermalized light and coupled condensates”, Nature Photonics **11**, 565 (2017)

17:25 – 18:00 **Thu, August 16**

Dimitris Angelakis

Technical University of Crete, Greece

Quantum simulations with interacting photons: Spectral signatures of many-body localization in quantum superconducting chips

Working examples of quantum simulators today include cold atoms trapped with lasers and magnetic fields and ions in electromagnetic traps. Interacting photons in light-matter systems, in the optical but also in the microwave regime, have also recently emerged as a promising avenue especially for simulating out of equilibrium many-body phenomena in a natural driven-dissipative setting.

I will initially give a brief review in non-specialist terms the early proposals on quantum simulations of Mott insulators, Fractional Hall states and the quantum field theory models with interacting photons in closed systems [1,2]. Some results in simulating exotic phases in the driven dissipative setting will also be mentioned [3], including a recent idea for topological pumping of Fock states [4].

In the main part, I will present in more detail a recent experiment probing aspects of the many-body localization transition using interacting photons in the latest superconducting quantum chip of Google [5]. Most experimental techniques only indirectly probe the many-body energy spectrum. Here, using a chain of nine superconducting qubits, we implement a novel technique for directly resolving the energy levels of interacting photons. We benchmark this method by capturing the intricate energy spectrum predicted for 2D electrons in a magnetic field, the Hofstadter butterfly. By increasing disorder, the spatial extent of energy eigenstates at the edge of the energy band shrink, suggesting the formation of a mobility edge. At strong disorder, the energy levels cease to repel one another and their statistics approaches a Poisson distribution -the hallmark of transition from the thermal to the many-body localized phase. Our work introduces a new many-body spectroscopy technique to study quantum phases of matter.

1. D.G. Angelakis and C. Noh "Many-body physics and quantum simulations with light", Report of Progress in Physics, **80** 016401 (2016).
2. D. G. Angelakis, M. F. Santos, S. Bose, "Photon blockade induced Mott transitions and XY spin models in coupled cavity arrays", Phys. Rev. A **76**, 031805 (2007); J. Cho, D. G. Angelakis, S. Bose, "Fractional Quantum Hall state in coupled cavities". Phys. Rev. Lett. **101**, 246809 (2008); D. G. Angelakis, M. Huo, D. Chang, L. C. Kwek, V. Korepin "Mimicking interacting relativistic theories with stationary light", Phys. Rev. Lett. **110**, 100502 (2013).
3. J. J. Mendoza-Arenas, S. R. Clark, S. Felicetti, G. Romero, E. Solano, D. G. Angelakis, and D. Jaksch "Beyond mean-field bistability in driven-dissipative lattices: Bunching-antibunching transition and quantum simulation", Phys. Rev. A **93**, 023821 (2016);
4. J. Tangpatinanon, V. M. Bastidas, P. Roushan, S. Assam, D. Jaksch, D. G. Angelakis, "Topological pumping with photons in nonlinear resonator arrays", Physical Review Letters, **117**, 213603 (2016).
5. P. Roushan, C. Neill, J. Tangpanitanon, V.M. Bastidas, A. Megrant, R. Barends, Y. Chen, Z. Chen, B. Chiaro, A. Dunsworth, A. Fowler, B. Foxen, M. Giustina, E. Jeffrey, J. Kelly, E. Lucero, J. Mutus, M. Neeley, C. Quintana, D. Sank, A. Vainsencher, J. Wenner, T. White, H. Neven, D. G. Angelakis, J. Martinis, "Spectral signatures of many-body localization with interacting photons", Science **358**, 6367 (2017).

Friday, August 17

9:15 – 9:50	**Darrick Chang** *ICFO, Spain* Open critical dynamics in a one-dimensional optical lattice clock
9:50 – 10:25	**Wolfram Pernice** *University of Muenster, Germany* Waveguide integrated single photon detectors
10:25 – 10:50	coffee break
10:50 – 11:25	**Joseph Thywissen** *University of Toronto, Canada* Dynamical Phase Transition in a Quantum Simulation of the Heisenberg Model
11:25 – 12:00	**Michael Fleischhauer** *University of Kaiserslautern, Germany* Topology of non-equilibrium and finite-temperature states in interacting systems
12:00 – 12:10	Closing

9:15 – 9:50 **Fri, August 17**

Darrick Chang
ICFO, Barcelona, Spain

Open critical dynamics in a one-dimensional optical lattice clock

There have been concerted efforts in recent years to realize the next generation of clocks using alkaline earth atoms in an optical lattice. Assuming that the atoms are independent, such a clock would benefit from a sqrt(N) enhancement in its stability, associated with the improved signal-to-noise ratio of a large atom number. Any kind of atomic interactions, however, could result in a clock inaccuracy. Here, we investigate the effect of one type of interaction, dipole-dipole, in which atoms excited during the clock protocol emit and re-absorb photons. Taking a simple system consisting of a 1D atomic array, we find that dipole-dipole interactions in fact result in open critical dynamics, as a set of collective excitations acquire a decay rate approaching zero in the thermodynamic limit due to subradiance. As one particular consequence, the decay of atomic excited population at long times exhibits power-law behavior, instead of the exponential expected for non-interacting atoms. The population distribution also exhibits fermionic spatial correlations at long times, due to the microscopic properties of the subradiant states. These results suggest that lattice clocks and collectively emitting atomic ensembles in general constitute rich many-body open systems.

9:50 – 10:25 **Fri, August 17**

Wolfram Pernice
University of Münster, Germany

Waveguide integrated single photon detectors

Nanophotonic circuits employ waveguiding devices to route light across quasi-planar integrated optical chips in analogy to electrical wires in integrated electrical circuits. Using materials with high refractive index allows for confining light into sub-wavelength optical wires. Interaction with the environment is possible through near-field coupling to the evanescent tail of propagating optical modes. This approach is particularly interesting for designing highly sensitive detectors which are able to register individual photons and constitute fundamental building blocks for emerging quantum photonics. I will present recent progress on realizing waveguide integrated single photon detectors, with a focus on superconducting nanowire single photon counters (SNSPDs). SNSPDs provide high efficiency and good timing performance, as well as broad optical detection bandwidth. To move towards applications in high bandwidth quantum communication, ultrafast detectors with high efficiency are needed. We realize compact SNSPDs with sub-micrometer effective length by embedding them in photonic crystal cavities to recover high absorption efficiency. These detectors possess sub-nanosecond recovery times and ultralow noise equivalent power. Being made by scalable fabrication techniques, waveguide SNSPDs hold promise for photonic integrated quantum technologies.

10:50 – 11:25 **Fri, August 17**

Joseph Thywissen
University of Toronto, Canada

Dynamical Phase Transition in a Quantum Simulation of the Heisenberg Model
We demonstrate a new kind of quantum simulator for the collective Heisenberg model. The simulator uses the two lowest hyperfine states of a degenerate gas of fermionic Potassium (40K) atoms, tuned to a weakly interacting regime where the motional states of atoms remain in their initial single-particle motional eigenstates for the duration of the simulation. There is no spatial lattice, but the motional modes form a lattice in mode space, where spin-spin interactions are long range. Spin dynamics driven by a competition between interactions and inhomogeneity: collective Heisenberg spin-exchange interactions tend to synchronize spins, while axial field inhomogeneities tend to demagnetize the ensemble.

We observe a dynamical phase transition (DPT) between a ferromagnetic gapped phase featuring long-lived magnetization and an ungapped phase in which magnetization decays quickly. Using transverse magnetization as the order parameter, we explore the (dynamical) phase diagram of the model by tuning the interaction strength (with a Feshbach resonance) and the inhomogeneity variance (with vector light shifts). We also test the validity of the spin-model mapping of the simulator, through the many-body echo strength after an effective time-reversal operation. Outside the weakly interacting regime, the spin-model description breaks down and mode-changing collisions demagnetize the gas. Our work delineates the regime in which a lattice spin model can be simulated simply with harmonically trapped alkali atoms, and thereby test the DPT paradigm in a system of more than 10^4 atoms.

11:25 – 12:00 **Fri, August 17**

Michael Fleischhauer

Dept. of Physics & research center OPTIMAS, University of Kaiserslautern, Germany

Topology of non-equilibrium and finite-temperature states in interacting systems

Topological states of matter have fascinated physicists since a long time due to the exotic properties of elementary excitations and the topological protection of edge states and currents. The notion of topology is ususally associated with ground states of (many-body)-Hamiltonians. I will discuss a classification for topological phases of matter applicable to finite-temperature states as well as non-equilibrium steady states of driven, dissipative systems based on the many-body polarization. In contrast to quantized charge transport and geometric phases, the polarization can be used to probe topological properties of non-interacting and interacting closed and open systems alike and remains a meaningful quantity at finite T. For non-interacting fermions it defines a topological invariant, the *ensemble topological phase* (ETP) [1], which can be extended to interacting systems. I discuss the physical significance of the ETP visible e.g. in the transfer of topological properties to auxilary degrees of freedom with zero effective temperature. For bosons it is shown that interactions are required for the existence of non-trivial topological properties of the many-body polarization. Specific examples of non-interacting and interacting systems will be discussed.

[1] C.E. Bardyn, L. Wawer, A. Altland, M. Fleischhauer, S.Diehl , PRX **8**, 011035 (2018)

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POSTERS

Luis A. Peña Ardila, *Aarhus University, Denmark* From polarons to bipolarons in Bose-Einstein condensates
Zhengyang Bai, *East China Normal University, Shanghai, China* Soliton-defect Interaction in Cold Rydberg Gases
Simon Ball, *University of Southern Denmark, Odense, Denmark* Rydberg quantum optics in an ultracold gas
Arturo Camacho-Guardian, *Aarhus University* Landau effective interaction between quasiparticles in a Bose-Einstein condensate
Mikkel Berg Christensen, *Aarhus University* Observation of Atom Number Fluctuations in a Bose-Einstein Condensate
Nishant Dogra, *ETH Zurich, Switzerland* Formation of a spin texture in a quantum gas coupled to a cavity
Tena Dubček, *University of Zagreb, Croatia* Topological matter via synthetic magnetism
Callum W. Duncan, *Heriot Watt University, Edinburgh, UK* Linked and knotted synthetic magnetic fields in ultracold gases
Kieran Fraser, *Max Planck Institute for the Physics of Complex Systems, Dresden, Germany* Self-localised topological defects in the steady-state of driven atoms coupled to optical waveguides
Jad Halimeh, *Max Planck Institute for the Physics of Complex Systems, Dresden, Germany* Aging dynamics in quenched noisy long-range quantum Ising models
Robert Heck, *Aarhus University, Denmark* Remote optimization of an ultra-cold atoms experiment by experts and citizen scientists
Samuel Häusler, *ETH Zurich, Switzerland* Beyond particle transport through a quantum point contact using ultracold atoms
Jesper Hasseriis Mohr Jensen, *Aarhus University, Denmark* GROUP: GRadient Optimization Using Parametrization
Nikolaj Jørgensen, *Aarhus University, Denmark* Moving polarons in ultracold condensed matter systems
Mark Kremer, *University Rostock, Germany* Demonstration of a non-quantized square-root topological insulator using photonic Aharonov-Bohm cages
Marian Philipp Kreyer, *University of Innsbruck and IQOQI, Academy of Science, Austria* Accurate Determination of the Dynamical Polarizability of Dysprosium
Ronen Kroeze, *Stanford University, USA* Tunable-Range, Photon-Mediated Atomic Interactions in Multimode Cavity QED
Vasiliy Makhalov, *Collège de France, Sorbonne University, France* Control and manipulation of internal states of Dysprosium
Giovanni Italo Martone, *University of Southern Paris, France* Drag force and superfluidity in the supersolid stripe phase of a spin-orbit-coupled BEC
Stuart J. Masson, *University of Auckland, New Zealand* Heralded entanglement in a spinor gas in an optical cavity
Callum R. Murray, *Aarhus University, Denmark* Photon Substraction by Many-body Decoherence
Kristian Knakkergaard Nielsen, *Aarhus University, Denmark* Dynamical formation of the Bose polaron through impurity-bath decoherence
Christopher Parmee, *University of Cambridge* Phases of driven dissipative atomic dipoles with nonlocal dissipation
Cornelis Ravensbergen, *University of Innsbruck and IQOQI, Academy of Science, Austria* Creation of a double degenerate Fermi-Fermi mixture of dysprosium and potassium atoms
Thomas Guldager Skov, *Aarhus University, Denmark* Investigation of the Properties of the Bose Polaron
Bugra Tüzemen, *Warsaw University of Technology, Poland* 3D Dynamics of Spin Imbalanced Unitary Fermi Gas
Valentin Walther, *Aarhus University, Denmark* Giant optical nonlinearities from Rydberg excitons in semiconductor microcavities
Niclas Westerberg, *Heriot Watt University, Edinburgh, UK* The dynamical Casimir effect in the presence of memory
Niclas Westerberg, *Heriot Watt University, Edinburgh, UK* A simple approach to quantum dispersive light through single-particle quantum mechanics
Yongchang Zhang, *Aarhus University, Denmark* Long-range interactions and symmetry-breaking in quantum gases through optical feedback

Luis A. Peña Ardila
Department of Physics and Astronomy, Aarhus University, Denmark

From polarons to bipolarons in Bose-Einstein condensates

Mobile impurities in a Bose-Einstein condensate can form quasi-particles termed Bose-Polarons. In this talk I show how these quasi-particles are originated when a single impurity is dressed by the excitations of the quantum bosonic bath. The most striking advantage of these polarons is the huge degree of controllability of the coupling strength between the impurity and the bosonic bath. Thus, one can realize polarons from weak all the way up to the strong interacting regime [1,2]. For strong interactions two polaron can bind together forming bound bipolarons states. They emerge due to the induced non-local interaction mediated by density oscillations of the bath [3,4]. Polarons and bipolarons in ultra-cold quantum gases could be used as a robust platform for quantum simulation in a condensed matter context.

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Zhengyang Bai and Guoxiang Huang
State Key Laboratory of Precision Spectroscopy, East China Normal University, Shanghai, China

Soliton-defect Interaction in Cold Rydberg Gases

We present a scheme to realize the interaction between defects and nonlocal optical solitons in a cold gas of atoms in electronically Rydberg states. By virtue of electro-magnetically induced transparency, strong long-range Rydberg-Rydberg interaction is mapped into a probe laser beam, resulting in a large, nonlocal optical Kerr nonlinearity and formation of stable, low-power nonlocal optical solitons. We show that, by storing a gate laser field that plays a role of a defect in the Rydberg gas, the nonlocal optical solitons display an enhanced reflection. We also show that the reflection, transmittance, and capture of the nonlocal optical solitons when colliding with defects can be actively manipulated via tuning the laser lights in the system. Our study opens a route for designing nonlinear switchers, and may have other promising applications in light information processing and transmission.

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Simon Ball, Nina Stiesdal, Philipp Lunt, Christoph Tresp, and Sebastian Hofferberth
University of Southern Denmark, Odense, Denmark

Rydberg quantum optics in an ultracold gas

Mapping the strong interaction between Rydberg excitations in ultracold atomic ensembles onto single photons enables the realization of optical nonlinearities which can modify light on the level of individual photons. This approach forms the basis of a growing Rydberg quantum optics toolbox, which already contains photonic logic building-blocks such as single-photon sources, switches, transistors, and conditional pi-phase shifts [1].

We also present the recent demonstration of strong coherent interaction between an optical medium smaller than a single Rydberg blockade volume to a few-photon probe field [2]. Due to the large number of atoms in the blockaded volume and the efficient coupling to the probe light mode, we achieve coherent coupling between the probe field and the effective Rydberg "superatom" even if the probe pulse contains only a few photons. This enables us to study the dynamics of a single two-level system strongly coupled to a quantized propagating light field in free space. Furthermore, by controlling the dephasing between the internal degrees of freedom of the superatom, we realize a free-space single-photon absorber, which deterministically absorbs exactly one photon from an input pulse. We show that this system can be used for the subtraction of one photon from the input pulse over a wide range of input photon numbers [3]

We further present our investigation of intrinsic three photon correlations in this same superatom-system, and introduce our steps towards the formation of multiple interacting superatoms. Additionally, we discuss the development of a new experiment designed to study the interactions between a large number of Rydberg polaritons simultaneously propagating through a medium with extremely high atomic density [4]. It is proposed to overcome the atomic density limitations through the use of Ytterbium, an alkaline-earth-like element without a p-wave resonance between the Rydberg electron and surrounding ground state atoms [5].

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A. Camacho-Guardian and G. M. Bruun
Department of Physics and Astronomy, Aarhus University,

Landau effective interaction between quasiparticles in a Bose-Einstein condensate

Landau's description of the excitations in a macroscopic system in terms of quasiparticles stands out as one of the highlights in quantum physics. It provides an accurate description of otherwise prohibitively complex many-body systems, and has led to the development of several key technologies.

In this paper, we investigate theoretically the Landau effective interaction between quasiparticles, so-called Bose polarons, formed by impurity particles immersed in a Bose-Einstein condensate (BEC). In the limit of weak interactions between the impurities and the

BEC, we derive rigorous results for the effective interaction. They show that it can be strong even for weak impurity-boson interaction if the transferred momentum/energy between the quasiparticles is resonant with a sound mode in the BEC. We then develop a diagrammatic scheme to calculate the effective interaction for arbitrary coupling strengths, which recovers the correct weak coupling results. Using this, we show that the Landau effective interaction in general is significantly stronger than that between quasiparticles in a Fermi gas, mainly because a BEC is more compressible than a Fermi gas. The interaction is particularly large near the unitarity limit of the impurity-boson scattering, or when the quasiparticle momentum is close to the threshold for momentum relaxation in the BEC. Finally, we show how the Landau effective interaction leads to a sizeable shift of the quasiparticle energy with increasing impurity concentration, which should be detectable with present day experimental techniques.

Mikkel Berg Christensen
Department of Physics and Astronomy, Aarhus University,

Observation of Atom Number Fluctuations in a Bose-Einstein Condensate
Particle number fluctuations play a central role in our understanding of the statistical properties of bosonic systems. While the fluctuations are well understood for many quantum systems at zero temperature, the case of an interacting quantum system at finite temperature still poses numerous experimental and theoretical challenges. Despite the intense investigation of Bose-Einstein condensates (BECs), the fluctuations between the BEC and the thermal component have therefore not been investigated. Here we report the observation of these fluctuations. Our experiments are based on stabilization technique which allows for the preparation of ultracold thermal clouds at the shot noise limit, eliminating numerous technical noise sources. Moreover, we utilize the correlations established by the evaporative cooling process to determine the fluctuations and the sample temperature precisely. Thus, the telltale signature of these fluctuations, a sudden increase close to the critical temperature, was observed. We compare our result with theoretical predictions for the ideal gas and find good agreement.

N. Dogra, M. Landini, K. Kroeger, L. Hruby, T. Donner and T. Esslinger
Institute for Quantum Electronics, ETH Zurich, 8093 Zurich, Switzerland

Formation of a spin texture in a quantum gas coupled to a cavity
We report on the observation of strong opto-magnetical effects on the self-organization of a degenerate atomic system coupled to a single-mode high-finesse optical cavity and subjected to an off-resonant pump field, propagating transversely to the cavity axis. The opto-magnetical effects arise from the presence of multiple atomic transitions which gives rise to non-zero vectorial polarizability and hence spin dependent atom-cavity (vectorial) coupling. The relative strength of the vectorial coupling with respect to the scalar coupling can be tuned by changing the polarization of the pump field. We observe spin dependent threshold of the self-organization process and spin dependent phase of the scattered light in the organized phase as a function of the pump field polarization. The observed behaviour can be understood in the context of a modified Dicke model. By starting with a mixture of two spin states, we identify two different regimes. In the regime of strong scalar coupling, the

self-organization process generates density modulations in the atomic system. By increasing the ratio of vectorial over scalar component beyond a critical point, we observe the appearance of a new self-organization pattern consisting of magnetization modulations, a spin texture. We locate the transition point by analysing the phase of the light emitted by the atoms in the organized phase. Our findings pave the way to the exploitation of opto-magnetic effects for quantum simulation of long-range magnetic interactions.

Tena Dubček
Department of Physics, Faculty of Science, University of Zagreb, Croatia

Topological matter via synthetic magnetism

Topological phases are nowadays causing a lot of excitement, due to their fascinating emergent behavior, which opens the way for diverse technological applications. By taking advantage of tunable synthetic magnetic fields, we point out how topological phases that otherwise rely on complicated space groups and are thus hardly obtainable, can be realized in simple lattice geometries. Namely, we show that Weyl points, and all of the related phenomena, can be experimentally addressed in an experimentally viable ultracold atomic lattice with laser assisted tunneling [1]. We also consider the realization and detection of a state with fractional statistic in an ultracold atomic gas. We demonstrate how standard methods and understanding have to be taken with caution when studying topological matter via quantum simulation and synthetic magnetism. Specifically, we point out that the momentum distribution, one of the key signatures of quantum states of matter, is not a proper observable for a system of anyons [2]. As a substitute, we propose to use the asymptotic single-particle density after expansion of anyons in free space from the state.

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Callum W. Duncan, Calum Ross, Niclas Westerberg, Manuel Valiente, Bernd J. Schroers, and Patrik Öhberg
Heriot Watt University, Edinburgh, Scotland

Linked and knotted synthetic magnetic fields in ultracold gases

We show how synthetic magnetic fields which arise from light-matter coupling are naturally interpreted as the pullbacks of the area element of the sphere to Euclidean space via certain maps. These maps define topological magnetic fields which can be synthetically realised by equating the map to the ratio of Rabi frequencies for three coupled internal energy levels of an ultracold atom. We consider examples of maps which can be physically realised in terms of Rabi frequencies, which lead to linked and knotted synthetic magnetic fields acting on the neutral atoms. We show that the topological nature of the magnetic fields are transferred to the wavefunction of a Bose-Einstein condensate, with linked and knotted vortex rings in the ground states.

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Kieran Fraser
Max Planck Institute for the Physics of Complex Systems, Germany

Self-localised topological defects in the steady-state of driven atoms coupled to optical waveguides

We study a gas of fermionic laser-driven atoms coupled to the electromagnetic modes of an optical waveguide. The presence of the Fermi surface causes the translational invariance of the system to be spontaneously broken in the steady state and a self-organised lattice forms. There are two possible patterns of dimerisation. We find that metastable self-localised soliton states, composed of an atom trapped at the domain wall, exist. If the atom-filling of the emergent optical lattice is larger than one, an excess particle is self-trapped by an optical soliton (or kink) localised at the interface between two domains with different dimerisation. Each defect carries a Z2 topological quantum number and the excess particle is trapped in an edge state located at the soliton.

Jad Halimeh
Max Planck Institute for the Physics of Complex Systems, Dresden, Germany

Aging dynamics in quenched noisy long-range quantum Ising models

We consider the d-dimensional transverse-field Ising model with power-law interactions $J/r^{d+\sigma}$ in the presence of a noisy longitudinal field with zero average. We study the longitudinal-magnetization dynamics of an initial paramagnetic state after a sudden switch-on of both the interactions and the noisy field. While the system eventually relaxes to an infinite-temperature state with vanishing magnetization correlations, we find that two-time correlation functions show aging at intermediate times. Moreover, for times shorter than the inverse noise strength κ and distances longer than $a(J/\kappa)^{2/\sigma}$ with a being the lattice spacing, we find a critical scaling regime of correlation and response functions consistent with the model A dynamical universality class with an initial-slip exponent $\theta=1$ and dynamical critical exponent $z=\sigma/2$. We obtain our results analytically by deriving an effective action for the magnetization field including the noise in a non-perturbative way. The above scaling regime is governed by a non-equilibrium fixed point dominated by the noise fluctuations.

Robert Heck, Ottó Elíasson, Jens Schultz Laustsen, Carrie Weidner and Jacob Sherson
Department of Physics and Astronomy, Aarhus University, Denmark

Remote optimization of an ultra-cold atoms experiment by experts and citizen scientists

Quantum technology is stepping out of the lab, gradually becoming also accessible to outside users. An example is the IBM Quantum Experiment open to the public, which is also used by theoreticians in order to test and develop new algorithms directly under real experimental conditions [1]. In our group, we are working towards giving outside users access to our ultra-cold atom experiment which will act as a flexible remotely accessible quantum simulator. The flexibility is achieved with a quantum gas microscope with single-site imaging and addressing in optical lattices combined with arbitrary light field potentials

created by Digital Micromirror Devices (DMDs) and will be able to simulate complex quantum systems.

We take the first step on the way to opening the experiment up to outside users when strategies in creation of a Bose-Einstein condensate (BEC) are explored [2]. First four distinct strategies for creating BECs are investigated experimentally: hybrid and crossed dipole trap configurations in combination with either large volume or dimple loading from a magnetic trap. We find that although each conventional strategy appears locally optimal, “bridges” can be identified. Next two distinct implementations of a novel remote interface improve the solution for creation of a BEC. Firstly, a team of theoretical optimal control researchers employed a Remote version of their dCRAB optimization algorithm (RedCRAB). Secondly, 600 citizen scientists from around the world participated through a gamelike interface in the closed-loop optimization during the “Alice challenge”. The design of this study allows also for quantitative insight in the collective search behavior of the citizen scientists. This information is valuable for the development of new, domain general optimization algorithms and machine learning methods.

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Samuel Häusler, Dominik Husmann, Martin Lebrat, Philipp Fabritius, Jean-Philippe Brantut, Laura Corman, and Tilman Esslinger
Institute for Quantum Electronics, ETH Zurich, Switzerland and Institute of Physics, EPFL, Switzerland

Beyond particle transport through a quantum point contact using ultracold atoms
Transport measurements through a quantum system probes its excitations which, in the case of strongly correlated matter, are challenging to characterise. Particle transport, which has been an essential observable in solid state physics has been measured in our cold atom system consisting of two reservoirs of fermionic lithium atoms connected through a quantum point contact. Here, we go beyond pure particle transport by combining it either with heat or spin transport.

First, we study the coupling between particle and heat currents at unitarity close to the superfluid transition. After heating one reservoir we observe a violent initial particle current from cold to hot that brings the system to a non-equilibrium steady state where currents vanish. The steady state reveals a finite particle and suppressed thermal conductance, thus strongly violating the Wiedemann-Franz law. This violation signals a breakdown of Fermi liquid behaviour and remains for wider channel geometries, where the system relaxes back to equilibrium. These findings are related to the celebrated fountain effect in bosonic helium II.

Second, we recently implemented a "spin-sieve" using near-resonant light. It blocks particles of one spin species while the other can pass, realising a local strong effective Zeeman field on the order of the Fermi energy.

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Jesper Hasseriis Mohr Jensen, J. J. W. H. Sørensen and J. F. Sherson
Department of Physics and Astronomy, Aarhus University, Denmark

GROUP: GRadient Optimization Using Parametrization

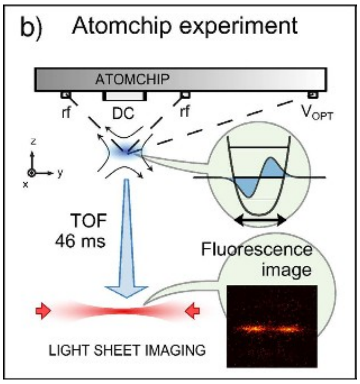

Fig.1: (Excerpt from [1]) Vienna atomchip experiment. Driving the BEC into the first excited state is an initialization step of a twin-atom beams source.

The fundamental study and technological application of complex atomic systems such as Bose-Einstein condensates (BEC) and many-body systems necessitate precise manipulation of the system dynamics (e.g. Fig. 1 [1]). For instance, recent experiments have demonstrated that BEC prepared outside the ground state can probe novel many-body dynamics. However, the current preparation time scale is of the same order of magnitude as the decay of the excited states, which fundamentally limits the purity of all subsequent studies. The quest for experimental protocols realizing the dynamics necessary to transfer a prepared initial state into a desired target state within the shortest possible time can be solved within the mathematical framework of Quantum Optimal Control. However, despite enjoying success in many arenas the standard flavours of quantum control algorithms are not always capable of finding fast enough solutions to the required precision. It is the purpose of our current work to improve current quantum optimal control to search for faster methods of system preparation. In the search for new and robust algorithms, our recent group algorithm [2] combines gradient based optimization with a parametrization of the control in a reduced basis. This combination simultaneously addresses the individual disadvantages of the GRAPE and CRAB algorithms (briefly outlined below). Using GROUP we succesfully found better solutions to problems previously attacked by other control algorithms (compare Fig. 2 b)-c)).

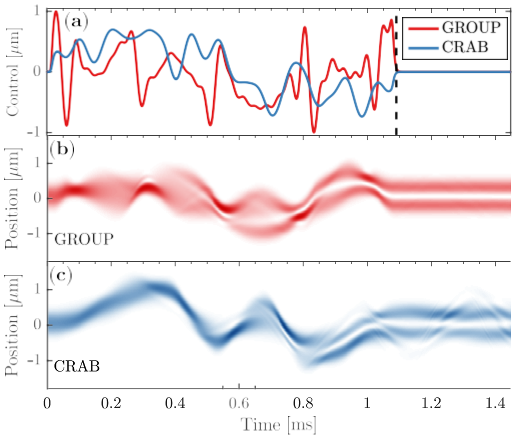

Fig.2: (a) Optimal controls found using GROUP (red) and CRAB (blue). The control is held constant after the vertical dashed line. (b) Condensate density $|\psi(x, t)|^2$ using group optimal solution with a transfer fidelity to the first excited state of F = 0.999. (c) Same as (b) using CRAB, showing residual oscillations due to a final fidelity of F = 0.92

In the GRAPE algorithm the dimensionality of the optimization problem is equal to the number of simulation time steps which can be on the order of thousands. The CRAB algorithm instead expands the control in a reduced function basis $\{f_n\}_{n=1}^{M}$ where the optimization is now performed on the space of basis coefficients $\{c_n\}_{n=1}^{M}$ which is typically in the order of tens. The drawback of the CRAB is that it uses a Nelder-Mead simplex method to perform the optimization. No gradient information is used to choose a descent direction.

GROUP addresses this issue by explicitly calculating the full gradient of the cost wrt. the coefficients. Fig. 2 [2] shows the optimized controls found by GROUP and CRAB to drive a 1D BEC obeying Gross- Pitaevskii mean field dynamics from the ground state into the first excited state of a slightly anharmonic potential [1, 2]. GROUP significantly improves the fidelity of the transfer and also display increased convergence rates.

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Nikolaj Jørgensen and Georg Bruun
Department of Physics and Astronomy, Aarhus University, Denmark

Moving polarons in ultracold condensed matter systems

The experimental capabilities to control collisional interactions in ultracold atomic gases, have enabled new explorations of the quantum impurity problem in recent years.

Here, we theoretically study the effects of finite impurity momenta on the properties of polarons formed from an impurity immersed in a Bose-Einstein Condensate (BEC) and in a BCS-superconductor. Using perturbation theory to second order in the impurity scattering length, one finds that an increasing momentum of the Bose polaron leads to an increase in the effective mass and decrease in its quasi-particle residue Z. For a BCS-superconductor one finds that the phonon contribution to the self-energy only becomes significant for a superconducting gap larger than 0.15 times the Fermi energy.

Mark Kremer
University Rostock, Germany

Demonstration of a non-quantized square-root topological insulator using photonic Aharonov-Bohm cages

Topological Insulators are a state of matter where spectral bands are characterized by quantized topological invariants. This quantization of topological indices lies at the foundation of the characteristic robustness of bulk responses and associated boundary-phenomena in TIs. Currently, there is no known setting that allows for Tis with bands possessing non-quantized topological indices to present such robust phenomena.

In our work, we theoretically devise and experimentally demonstrate a new type of topological insulator that exhibits non-quantized bulk topology alongside robust boundary states. Within our paradigm, the bands of the system do not admit quantized topological invariants, but the system holds a spectral symmetry such that by taking the square of its Hamiltonian quantized topological indices emerge.

Marian Philipp Kreyer, C. Ravensbergen, V. Corre, E. Soave, S. Tzanova, E. Kirilov, R. Grimm
Institute of Experimental Physics, University of Innsbruck and Institute of Quantum Optics and Quantum Information, Academy of Science, Austria

Accurate Determination of the Dynamical Polarizability of Dysprosium

We report a measurement of the dynamical polarizability of dysprosium atoms in their electronic ground state at the optical wavelength of 1064 nm, which is of particular interest for laser trapping experiments. Our method is based on collective oscillations in an optical dipole trap, and reaches unprecedented accuracy and precision by comparison with an alkali atom (potassium) as a reference species. We obtain values of 184.4(2.4) a.u. and 1.7(6) a.u. for the scalar and tensor polarizability, respectively. Our experiments have reached a level that permits meaningful tests of current theoretical descriptions and provides valuable information for future experiments utilizing the intriguing properties of heavy lanthanide atoms.

Ronen Kroeze
Stanford University, USA

Tunable-Range, Photon-Mediated Atomic Interactions in Multimode Cavity QED
Optical cavity QED provides a platform with which to explore quantum many-body physics in driven-dissipative systems. Single-mode cavities provide strong, infinite-range photon-mediated interactions among intracavity atoms. However, these global all-to-all couplings are limiting from the perspective of exploring quantum many-body physics beyond the mean-field approximation. The present work demonstrates that local couplings can be created using multimode cavity QED. This is established through measurements of the threshold of a superradiant, self-organization phase transition versus atomic position. Specifically, we experimentally show that the interference of near-degenerate cavity modes leads to both a strong and tunable-range interaction between BECs trapped within the cavity. We exploit the symmetry of a confocal cavity to measure the interaction between real BECs and their virtual images without unwanted contributions arising from the merger of real BECs. Atom-atom coupling may be tuned from short range to long range. This capability paves the way toward future explorations of exotic, strongly correlated systems such as quantum liquid crystals and driven-dissipative spin glasses.

Vasiliy Makhalov, T. Chalopin, C. Bouazza, A. Evrad, J. Dalibard, R. Lopes, S. Nascimbene
Laboratoire Kastler Brossel, Collège de France, Sorbonne University, France,

L. A. Sidorenkov
Department of Physics, ETH Zurich, Switzerland,

D. Dreon
Paris Observatory, Sorbonne University, France

A. Barker
Clarendon Laboratory, University of Oxford, United Kingdom

Control and manipulation of internal states of Dysprosium
For quantum simulations, one needs a quantum system easily accessible on one hand and non-trivial on the other. Ultracold gas of Dysprosium atoms is a promising candidate for this role. Due to specific properties of Dysprosium such as narrow transitions lines, the tensor polarizability of the ground state, or large magnetic dipole momentum it is possible to prepare and control quite a complex quantum state. For example, due to $J = 8$ for Dysprosium, a spin state of a single atom can be an equivalent of a state of 16 qubits. Artificial gauge fields and spin-orbit coupling in ultracold gases of Dysprosium atoms could be other examples. Moving towards realizations of a quantum simulator, we study properties of Dysprosium and ways to control its state. We exploit light-induced nonlinear spin coupling for preparation of the highly non-classical spin states in an ultracold gas of ^{164}Dy. We reconstruct the density matrix of the prepared states, monitor decoherence and demonstrate noticeable enhancement over the standard quantum limit.
Also, we report on a measurement of excited state polarizability of ^{164}Dy 626 nm narrow-line transition $|J = 8, m_J = -8\rangle \rightarrow |J' = 9, m'_J = -9\rangle$ for a cold gas trapped in a far-detuned 1070 nm optical trap. We've found that a tensorial component is larger than one of the ground state. Thus, one can cancel differential light-shift between the excited and the ground states by tuning the relative angle between the laser polarization and an external magnetic field, realizing so-called "magic-polarization".

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Giovanni Italo Martone,
Laboratory of Theoretical Physics and Statistical Models, University of Southern Paris, France

Drag force and superfluidity in the supersolid stripe phase of a spin-orbit-coupled BEC

The phase diagram of a Bose gas with equal Rashba and Dresselhaus spin-orbit coupling includes a supersolid stripe phase, which is featuring density modulations along the direction of the spin-orbit coupling. This phase has been recently found experimentally [1]. We characterize the superfluid behavior of the stripe phase by calculating the drag force acting on a moving impurity. Because of the gapless band structure of the excitation spectrum, the Landau critical velocity vanishes if the motion is not strictly parallel to the stripes, and energy dissipation takes place at any speed. Moreover, due to the spin-orbit coupling, the drag force can develop a component perpendicular to the velocity of the impurity. Finally, by estimating the time over which the energy dissipation occurs, we find that for slow impurities the effects of friction are negligible on a time scale up to several seconds, which is comparable with the duration of a typical experiment.

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Stuart J. Masson and A. S. Parkins
Department of Physics, University of Auckland, New Zealand

Heralded entanglement in a spinor gas in an optical cavity

Collisional dynamics in spinor Bose-Einstein condensates (BECs) - where an entire hyperfine level of a species is condensed - offer an avenue to investigation of many-body quantum dynamics [1]. In such systems, the interplay of spin collisional dynamics and magnetic field shifts governs the time evolution. This has led to the generation of quantum spin squeezing and many-body entanglement, and the study of quantum phase transitions and other quantum many-body phenomena. We proposed a method to 'manufacture' spinor physics using cavity-assisted Raman transitions instead of spin collisions [2].

Our scheme borrows from earlier engineered effective Dicke models for ensembles of two-level systems strongly coupled to a quantised cavity mode [3], but generalises it to integer spins. This model still allows for the study of the Dicke model, with such an approach having been demonstrated [4].

Here, we discuss how such an integer-spin system (e.g. s = 1) with all N atoms initiated in the m = 0 state can be projected by cavity output measurement into an entangled state. Considering an effective Tavis-Cummings model (TCM), each spin length present in the initial state should produce a distinct photon number in the cavity output field. Therefore, an ideal photon detector will perfectly project out a spin state of the form $|S,-S\rangle$. We show that in this case then the average run can be shown to have Heisenberg scaling of the metrological sensitivity. A non-ideal detector still produces entanglement with metrological sensitivity better than the standard quantum limit. By imlementing a sequence of TCM and anti-TCM interactions and measuring the consequent output pulses, it is also possible to regain the ideal case.

One particular example of this scheme would be the state with zero spin length: the macroscopic spin singlet. Our scheme prepares that state with efficiency equal to the initial population in that state, which is $1/(N+1)$ for the initial state above. We can enhance that efficiency by lifting a technique from BEC experiments. The singlet is a ground state of the

collisional Hamiltonian, so an adiabatic parameter sweep can be used to prepare it. However, due to the time scales involved, this is not practical experimentally [5]. Alternately, a 'quasi-adiabatic' parameter change can greatly enhance the overlap of the atomic state with the spin singlet [6]. We show that performing such a sweep is also possible with our methods. If the result of such a sweep is used as the input to the projective TCM scheme, then the probability of preparing the spin singlet can be raised to much more manageable numbers.

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Callum Robert Murray
Department of Physics and Astronomy, Aarhus University, Denmark

Photon subtraction by many-body decoherence

We present an experimental and theoretical investigation of the scattering-induced decoherence of multiple photons stored in a strongly interacting atomic ensemble. We derive an exact solution to this many-body problem, allowing for a rigorous understanding of the underlying dissipative quantum dynamics. Combined with our experiments, this analysis demonstrates a correlated coherence-protection process, in which the induced decoherence of one photon can preserve the spatial coherence of all others. We discuss how this effect can be used to manipulate light at the quantum level, providing a robust mechanism for single-photon subtraction, and experimentally demonstrate this capability.

Kristian Knakkergaard Nielsen
Department of Physics and Astronomy, Aarhus University, Denmark

Dynamical formation of the Bose polaron through impurity-bath decoherence

We study the quantum dynamics of a single impurity following its sudden immersion into a Bose-Einstein condensate. The formation of the Bose polaron after such a quench stems from decoherence of the impurity, driven by collisions with the condensate. Using a master equation approach, we derive rigorous analytical results for the decoherence dynamics of the impurity, which reveals different stages of its evolution from a universal non-exponential initial relaxation to the final approach of the equilibrium state of the Bose polaron. The associated polaron formation time exhibit a strong dependence of the impurity momentum and is found to undergo a critical slowdown around the Landau critical velocity of the condensate. The rich non-equilibrium behavior of quantum impurities in a Bose gas revealed in this work is of direct relevance to recent cold-atom experiments, in which Bose polarons are created by a sudden quench of the impurity-bath interaction.

Christopher Parmee
University of Cambridge

Phases of driven dissipative atomic dipoles with nonlocal dissipation

We study an open quantum system of cold atoms illuminated by an external plane wave, which drives the dipolar transition between two energy levels. In this set up, the cold atoms map to a two-level spin system with long range interactions and nonlocal dissipation. We determine at the mean-field level the long-time phase diagram of the system as a function of external drive and detuning. We find a multitude of phases including antiferromagnetism, spin density waves, oscillations and phase bistabilities. We investigate some of these phases in more detail and explain how nonlocal dissipation plays a role in the long-time dynamics. Furthermore, we discuss what features would survive in the full quantum regime.

Cornelis Ravensbergen, V. Corre, E. Soave, M. Kreyer, E. Kirilov and R. Grimm
Institute of Experimental Physics, University of Innsbruck, and Institute of Quantum Optics and Quantum Information, Academy of Science, Austria

Creation of a double degenerate Fermi-Fermi mixture of dysprosium and potassium atoms

We report on the realization of a double degenerate mixture of fermionic ^{161}Dy and fermionic ^{40}K. Both samples are polarized in their absolute ground state. We perform evaporative cooling of dysprosium atoms, where thermalization at low temperatures occurs through dipolar scattering, and we sympathetically cool potassium atoms. The final temperature of both species in the mixture is about 0.35 T_F, while we reach below 0.1 T_F for Dy alone. We describe the trapping and cooling methods, in particular the evaporation sequence, for both species together and dysprosium alone. By analyzing the cross-thermalization of the two species we are able to provide an estimate of the inter-species s-wave scattering length. The properties of the Dy-K mixture make it a very promising candidate to explore the physics of strongly interacting mass-imbalanced Fermi-Fermi mixtures.

Thomas Guldager Skov, M. G. Skou, N. B. Jørgensen, J. J. Thuesen, G. M. Bruun and J. J. Arlt
Department of Physics and Astronomy, Aarhus University, Denmark

Investigation of the Properties of the Bose Polaron

The interaction of a mobile impurity with a medium plays a fundamental role in many fields ranging from solid state physics to the Standard Model. In particular, the interaction between impurity and medium leads to the formation of the polaron quasiparticle, which in 2016 was observed in a Bose- Einstein condensate [1, 2]. In the Aarhus experiment, polarons are formed using two different spin states of 39K and the interaction dependent energy of the polaron state is recorded using RF spectroscopy. By tuning the magnetic field across a Feshbach resonance, the interstate interaction strength can be varied allowing the formation of both attractive and repulsive polarons.

We present our recent efforts to observe the predicted temperature dependence of the attractive polaron energy [3], the polaron formation time [4], as well as a new evaluation of the results from 2016 showing good agreement with quantum Monte Carlo calculations.

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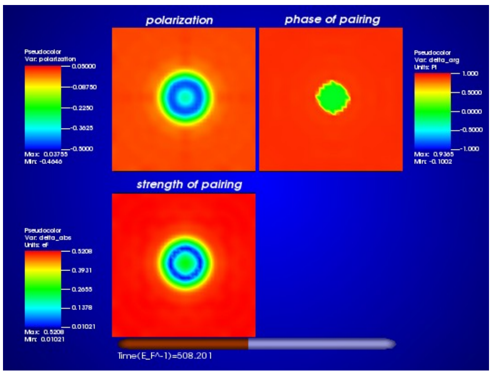
Bugra Tüzemen, P. Magierski, and G. Wlazlowski,
Warsaw University of Technology, Poland

3D Dynamics of Spin Imbalanced Unitary Fermi Gas

Non-equilibrium quantum many-body dynamics in superfluid Fermi systems are more demanding than their bosonic equivalents. The main tool to inspect such systems is the *Density Functional Theory* (DFT). However while extending the theory into Fermi superfluids, a great deal of difficulty arises from pairing correlations $\Delta(r, r')$, which are in principle non-local and give rise to a set of integro-differential equations. One way to overcome this problem is to introduce instead a local pairing field, $\Delta(r)$. This method is known as *Superfluid Local Density Approximation* (SLDA) [1] and it is particularly well suited for leadership class computers of hybrid (CPU + GPU) architecture. Using the most powerful supercomputers we are currently able to study a real-time 3D dynamics without any symmetry restrictions evolving up to hundred of thousands of superfluid fermions. It represents a true qualitative leap in quantum simulations of non-equilibrium systems, and allowed to describe for the first time a variety of phenomena, including the generation, real-time evolution, and interaction of quantized vortices, as well as their crossing and reconnection [2].

It is also allowed to describe pairing dynamics during nuclear reactions [3] and to reproduce all stages of a solitonic cascade observed in experiment in ultra-cold atomic cloud [4]. The recent extension of SLDA (so-called ASLDA) allows to simulate the spin-imbalanced systems as well.



I will present preliminary results on dynamically created polarized impurities in the *Unitary Fermi Gas* (UFG) - see figure. I will discuss conditions for enhanced stability of these impurities and in particular I will discuss the structure of the pairing field in the vicinity of the impurity which resembles the behavior of the pairing field in superconductor - ferromagnet junctions.

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Valentin Walther
Department of Physics and Astronomy, Aarhus University, Denmark

Giant optical nonlinearities from Rydberg excitons in semiconductor microcavities

The realization of exciton polaritons -- hybrid excitations of semiconductor quantum well excitons and cavity photons -- has been of great technological and scientific significance. In particular, the short-range collisional interaction between excitons has enabled explorations into a wealth of nonequilibrium and hydrodynamical effects that arise in weakly nonlinear polariton condensates. Yet, the ability to enhance optical nonlinearities would enable quantum photonics applications and open up a new realm of photonic many-body physics in a scalable and engineerable solid-state environment. Here we outline a route to such capabilities in cavity-coupled semiconductors by exploiting the giant interactions between excitons in Rydberg states. We demonstrate that optical nonlinearities in such systems can be vastly enhanced by several orders of magnitude and induce nonlinear processes at the level of single photons.

Niclas Westerberg
Institute of Photonics and Quantum Sciences, Heriot Watt University, Scotland

The dynamical Casimir effect in the presence of memory

Often in quantum simulation using optical models, such as the analogue gravity scenarios of cosmological particle creation or Hawking and Unruh radiation, one assumes that the medium is dispersion-less, i.e., that it has no memory of past events. The analogy is then achieved by making the refractive index space- and time-dependent. But what actually happens when the optical properties of the medium changes with time? This would be a system with two distinct types of temporal dynamics: The model parameters change with time, but it also possess a memory. We will show that this changes the vacuum emission properties drastically: Frequencies mix, something typically associated with nonlinear processes, despite the system being completely linear.

To discuss this, it is appropriate to use macroscopic quantum electrodynamics, the study of light-matter systems at a scale where the microscopic details of the matter system is irrelevant. This has been used to study a wide range of topics: Examples include Casimir-Polder forces, sonoluminescence and photon production in epsilon-near-zero materials. In general however, taking dispersion into account drastically complicates calculations. In this work, we quantise electromagnetism coupled to a dielectric medium, represented as a continuum of oscillators, which after a field transformation is reduced to a set of harmonic oscillators.

Niclas Westerberg, **A. Prain**, **D. Faccio and P. Öhberg**
Institute of Photonics and Quantum Sciences, Heriot Watt University, Scotland

A simple approach to quantum dispersive light through single-particle quantum mechanics

Often in quantum simulation using optical models, such as the analogue gravity scenarios of cosmological particle creation or Hawking and Unruh radiation [1], one assumes that the medium is dispersionless, i.e., that it has no memory of past events. The analogy is then achieved by making the refractive index space- and time-dependent. But what actually happens when the optical properties of the medium changes with time? This would be a system with two distinct types temporal dynamics: The model parameters change with time, but it also possess a memory. We will show that this changes the vacuum emission properties drastically: Frequencies mix, something typically associated with nonlinear processes, despite the system being completely linear.

To discuss this, it is appropriate to use macroscopic quantum electrodynamics, the study of light- matter systems at a scale where the microscopic details of the matter system is irrelevant. This has been used to study a wide range of topics: Examples include Casimir-Polder forces [2], sonoluminescence [3] and photon production in ε-near-zero materials [4]. In general however, taking dispersion into account makes calculations prohibitively complex. In this work [7], we quantise electromagnetism coupled to a dielectric medium, represented as a continuum of oscillators, which after a field transformation is reduced to a set of complex harmonic oscillators.

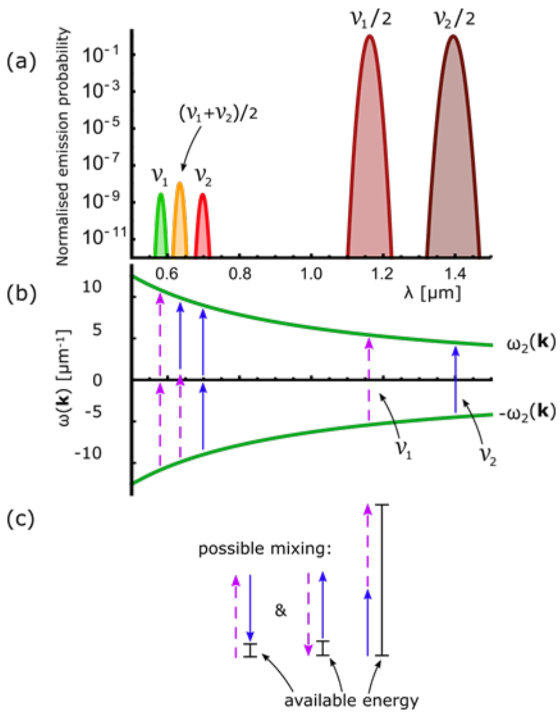

Fig.1: (a) The probability of exciting two polaritons back-to-back from the vacuum when modulating fused silica. Here we used $\delta n 10^{-4}$ by modulating the Ω_2-resonance (near-visible-ultaviolet) at frequencies $\nu_1 = \Omega_2/5$ and $\nu_2 = \Omega_2/6$ for N = 50 periods (100-250fs depending on wavelength). We also normalised to the maximum probability of ~ 10^{-8}: The absolute numbers are not important for this study. The peaks are labelled identifying each process, and we have ignored peaks that are outside the optical/infrared window. The spectrum is in vacuum wavelengths. Note in particular the $(\nu_1+\nu_2)/2$ peak: This would be absent in a dispersionless medium. (b) The polariton branch of interest as a function of vacuum wavelength. The excitation processes always involve a polariton-antipolariton pair, the latter living at negative frequency: The time-modulation provides the energy that couples the pair, here denoted as coloured arrows. Importantly, the total energy of the polariton-antipolariton pair ($2\omega_\alpha$) must be matched by the energy supplied by the time-modulation. (c) Illustration of the possible mixing processes at second order in perturbation theory.

Summarised, we consider a quasimicroscopic action describing electromagnetism coupled to a set of oscillators. Each of the natural oscillation frequencies $\Omega_j^2(\mathbf{x}, t)$ is in general space- and time-dependent. This action is inspired by the Hopfield model employed in Refs. [5, 6]. We then quantise this action in a path integral formalism, and by transforming into polariton field-coordinates we reduce the problem to that of complex harmonic oscillators in two-time potentials. From this, we calculate the probability to excite two back-to-back polaritons for a realistic scenario, when modulating the medium with two frequencies. This is illustrated in Fig. 1

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Yongchang Zhang
Department of Physics and Astronomy, Aarhus University, Denmark

Long-range interactions and symmetry-breaking in quantum gases through optical feedback

A lot of recent attention has been focused on long-range interaction in dipolar atoms and in cavity-assisted systems. Yet, it is an open challenge to engineer long-range interaction between atoms without large dipole moment in free space. Here, we propose to generate an exotic type of long-range interaction between ultracold atoms using a simple single-mirror optical feedback setup. We show that this effective interaction gives rise to a rich spectrum of ground states. In particular, we find that it can cause the spontaneous contraction of the quasi-two-dimensional condensate to form a self-bound one-dimensional chain of mesoscopic quantum droplets.