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Book of Abstracts

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Contents

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Talks Monday, 21 February

Quantum state engineering with macroscopic objects

Eugene Polzik
Niels Bohr Institite, Copenhagen University
polzik@nbi.dk

Recent experiments on generation of entangled and Fock states of macroscopic objects will be presented.

Continuous Bose-Einstein condensation and superradiant clocks

Florian Schreck
Univesity of Amsterdam
schreck@uva.nl

Extended Abstract Online (ID 127)

Ultracold quantum gases are excellent platforms for quantum simulation and sensing. So far these gases have been produced using time-sequential cooling stages and after creation they unfortunately decay through unavoidable loss processes. This limits what can be done with them. For example it becomes impossible to extract a continuous-wave atom laser, which has promising applications for precision measurement through atom interferometry [1]. I will present how we achieved continuous Bose-Einstein condensation, creating BECs that persist in a steady-state for as long as we desire. Atom loss is compensated by feeding fresh atoms from a continuously replenished thermal source into the BEC by Bose-stimulated gain [2]. The only step missing to create the long-sought continuous-wave atom laser is the addition of a coherent atom utcoupling mechanism. In addition this BEC may give us access to interesting driven-dissipative quantum phenomena over unprecedented timescales. The techniques we developed to create the continuous source of thermal atoms are also nicely suited to tackle another challenge: the creation of a continuously operating superradiant clock [3]. These clocks promise to become more rugged and/or more short-term stable than traditional optical clocks, thereby opening new application areas. I will present how we are eveloping two types of superradiant clocks within the European Quantum Flagship consortium iqClock, the first operating on a kHz-wide transition of Sr [4] and the second on the mHz-narrow Sr clock transition.

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Strong and controllable dipole-dipole interaction between optically levitated nanoparticles

Uros Delic
University of Vienna
uros.delic@univie.ac.at
Extended Abstract Online (ID 44)

Arrays of coupled mechanical oscillators have been proposed for exploring collective optomechanical effects, quantum many-body dynamics, topological phonon transport, (quantum) synchronization etc. So far, the experimental strategy has been to mediate interaction between two clamped oscillators via an optical cavity, thus limiting the scalability of such systems and confining the interaction toolbox to available cavity interaction techniques. Engineering a direct interaction between an array of oscillators would allow us to create macroscopic entangled states and explore weak forces between two nanoscale objects even in absence of an optical cavity. We realize a trap array of levitated particles and engineer direct interactions between their motional degrees of freedom. I will present our results on strong and tunable dipole-dipole ("optical binding") and Coulomb interaction between particles in parallel optical tweezers, which paves the way for studying quantum many-body physics with massive solid-state objects.

Atomic quantum simulation with large spins and qudits

Torsten Zache
Innsbruck University and IQOQI
torsten.zache@uibk.ac.at

A variety of atomic systems, including, e.g., ultracold atomic gases, trapped ions and Rydberg tweezer arrays, provide natural platforms for studying quantum many-body physics. In this talk I will discuss how Rydberg atoms in an external electric field realise long-range interacting Heisenberg-type spin models with large spin length S

» 1/2. We propose to employ arrays of such atoms for the quantum simulation of quantum field theories, in particular the paradigmatic Sine-Gordon model and its massive extension which is known to be dual to quantum electrodynamics in one spatial dimension. In this context, we propose to apply Hamiltonian learning in a field theory setting, which can provide a verification of such quantum simulations. I will conclude with an outlook on using Rydberg atoms for holonomic quantum computation based on qudits. This includes an entangling operation among qudits that is well suited for the realisation of so-called plaquette terms, thus enabling the simulation of lattice gauge theories in higher spatial dimensions.

Emergent Kardar-Parisi-Zhang phase in quadratically driven condensates

Oriana Diessel
Max Planck Institute of Quantum Optics
oriana.diessel@mpq.mpg.de
Extended Abstract Online (ID 53)

In bosonic gases at thermal equilibrium, an external quadratic drive can induce a Bose-Einstein condensation described by the Ising transition, as a consequence of the explicitly broken U(1) phase rotation symmetry down to $\mathbb{Z}2$. However, in physical realizations such as exciton-polaritons and nonlinear photonic lattices, thermal equilibrium is lost and the state is rather determined by a balance between losses and external drive. A fundamental question is then how nonequilibrium fluctuations affect this transition. Here, we show that in a two-dimensional driven-dissipative Bose system the Ising phase is suppressed and replaced by a nonequilibrium phase featuring Kardar-Parisi-Zhang (KPZ) physics. Its emergence is rooted in a U(1)-symmetry restoration mechanism enabled by the strong fluctuations in reduced dimensionality. Moreover, we show that the presence of the quadratic drive term enhances the visibility of the KPZ scaling, compared to two-dimensional U(1)-symmetric gases, where it has remained so far elusive.

Quantum computing nodes with rare earth ions

David Hunger
Karlsruhe Institute of Technology (KIT)
david.hunger@kit.edu

Rare earth ions doped in solids are a promising material platform for quantum technologies, given their remarkable optical and spin coherence, and their potential for high-density integration. Recent progress on detecting and controlling individual ions in optical microcavities has indicated the possibility to use them as multi-qubit registers for quantum networking and computing. I will summarize ideas on realizing rare-earth-ion-based quantum computing nodes [1], report on experimental progress on dynamical switching of Purcell enhancement with tunable microcavities [2], and present recent developments on molecular rare earth ion complexes [3] with promising coherence properties.

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Multi-qubit-enhanced phase estimation in one- and two-dimensional ion crystals with up to 91 particles

Matthias Bock

IQOQI Innsbruck

matthias.bock@uibk.ac.at

Extended Abstract Online (ID 68)

Correlation spectroscopy of multi-qubit systems is a technique to probe phase differences between qubits in the presence of correlated phase noise even if the probe times are longer than the qubit coherence time. The quantification of these phase differences is essential if the multi-qubit system is utilized for applications such as quantum computers, simulators or atomic clocks. Here we show specific applications of correlation spectroscopy for linear chains with 51 ions and 2D planar crystals with up to 91 ions. Among these applications are measurements of ion–ion distances, transition frequency differences due to quadrupole shifts or the sensing of magnetic field gradients. Furthermore, we quantify fluctuations of the laser-ion detuning via single-shot Ramsey measurements by analyzing multi-particle correlations. Employing the planar 91-ions crystals, we demonstrate that the information contained in the 91-particle correlations reduces the measurement uncertainty of the phase estimation as compared to the case where only two-particle correlations are analyzed.

Talks Tuesday, 22 February

Emergence of many body physics, atom by atom

Selim Jochim
Heidelberg University
jochim@uni-heidelberg.de
Extended Abstract Online (ID 129)

We prepare samples of up to 20 fermionic atoms with ultralow entropies in a two-dimensional configuration. We developed a single atom and spin sensitive imaging technique that allows us to detect all atoms of a sample either in real, or in momentum space. From such measurements we can infer correlations in the system. In our fermionic system, these are present already in a noninteracting sample and give rise to so-called Pauli Crystals. More interesting correlations arise as soon as interactions in the system are turned on. Now, Cooper pairs and a BCS-like system can be observed to form with p,-p-correlations emerging at the Fermi surface. In our trapped finite system, pairing occurs only at a finite attraction strength, which results in the precursor of a quantum phase transition. To further understand the emergence of many body physics from the few-body limit we are currently exploring a single impurity in a finite Fermi sea to observe the transition from a molecular to a polaronic state.

Quantum Photonics using Structured Photons

Robert Fickler
Tampere University
robert.fickler@tuni.fi
Extended Abstract Online (ID 96)

Spatially structured photons have found many fruitful applications in quantum photonics due the possibility of encoding high-dimensional quantum states. In one study, we use this enlarged Hilbert space to encode up to four qubits on a single photon and implement a quantum version of a finite automaton (FA), i.e. a fundamental computational device making binary decisions using finite states. We demonstrate its advantage over a classical FA in terms of resource efficiency, by solving the prime number promise problem with less states than clas-sically possible [1]. We further study more complex quantum state operations by implementing gen-eral unitary mode transformations for structured photons using multi-plane light-conversion techniques. Using this high-dimensional multiport scheme, we observe two-photon interferences between multiple spatial modes along a single beamline [2]. Interestingly, this two-photon bunching leads to novel spatial-mode N00N-states, for which the known phase super-sensitivity of N00N-states translates to a super-resolution in angular and longitudinal displacement [3]. Finally, we investigate the propagation of photons that are confined to a cylindrical geometry using ring-core fibers and study the effect of interferometric self-imaging known as the Talbot effect. We show that ring-core fibers act as controllable high-order optical beamsplitters for single photons and demonstrate two-photon interference within this complex self-imaging effect [4]. The presented schemes show novel approaches to complex quantum information tasks using structured photons and new ways to implement linear optical networks for applications in quantum photonics.

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Stochastic Simulation of Dissipative Spin Systems

Peter Rabl
TU Wien
peter.rabl@tuwien.ac.at

I will discuss an efficient numerical method for simulating the dynamics of interacting spin ensembles in the presence of dephasing and decay. The method builds on the discrete truncated Wigner approximation for isolated systems, but is generalized for dissipative spin systems by replacing the deterministic mean-field evolution by a stochastic process that preserves the length of each spin. This technique can be applied for simulating nonclassical spin-squeezing effects or the dynamics and steady states of cavity QED models with hundred thousand interacting two-level systems and without relying on any symmetries. This opens up the possibility to perform accurate real-scale simulations of a diverse range of experiments in quantum optics or with solid-state spin ensembles under realistic laboratory conditions.

Coupling electrons and light in electron microscopy

Claus Ropers
Max Planck Institute for Multidisciplinary Sciences, University of Göttingen
claus.ropers@mpinat.mpg.de

Providing the most detailed views of atomic-scale structure and composition, Transmission Electron Microscopy (TEM) serves as an indispensable tool for structural biology and materials science. Optical excitations in electron microscopy are accessible through spontaneous inelastic scattering of electrons, analysed in electron-energy loss and cathodoluminescence spectroscopy. The stimulated variants of the underlying scattering processes become accessible through optical illumination of the sample. In this talk, I will introduce basic principles and selected applications of inelastic electron-light scattering in electron microscopy. These include the nanoscale imaging of optical fields [1], the coherent control of the free-electron quantum state for spatial [2] and temporal [3,4] electron beam manipulation, such as the preparation of attosecond electron bunches [5]. Moreover, recent progress in the coupling of electron beams to whispering gallery modes [6] and integrated photonic resonators [7] will be discussed, including the preparation and characterization of electron-photon pair states [8].

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Photon emission from a segmented ion-trap – cavity system: simulation and implementation

Stephan Kucera
Universität des Saarlandes
stephan.kucera@mx.uni-saarland.de

Atom-photon interfaces [1] [2] are basic requirements for quantum networks with single trapped ions. The efficiency of such interfaces has been shown to increase significantly by the use of resonators [3]. Following this direction, we are developing a new segmented ion trap for 40Ca+ ions with an integrated fiber cavity [4] [5] envisaging the implementation of a 'quantum repeater cell' (QR-cell) according to [6] on the basis of single-photon emission. The segmented electrode structure of the trap is directly built on top of ceramic ferrules using laser micromachining and physical vapor deposition coating. Two of these ferrules opposing each other form the ion trap and the bores hold the optical fibers forming the resonator. This has been shown to be a highly passively stable design [7]. In addition, the bore protects the ion from charge accumulation on the fibers. We present finite element method simulations of the trap to estimate the potentials and the micromotion of the trap as a result of the geometric properties, such as the bore and the electrode size. The status of the implementation is also presented. Besides the technical realization of the trap-cavity system we show numerical simulations of the Hong-Ou-Mandel visibility [8] as a function of various cavity parameters similar to calculations in [3]. The high interference capability is a key ingredient for generating high-quality repeater operations with more than a single QR-cell via photonic bell-state projection. We study ways to engineer the indistinguishability via different initial level populations of the ion, exploiting the different decay channels from the excited state.

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Spin-dependent sub-wavelength lattices for ultracold atoms

Gediminas Juzeliunas

Institute of Theoretical Physics and Astronomy, Vilnius University

gediminas.juzeliunas@gmail.com

We analyze a tripod atom light coupling scheme characterized by two dark states playing the role of quasi-spin states [1]. It is demonstrated that by properly configuring the coupling laser fields, one can create a lattice with spin-dependent sub-wavelength barriers. This allows to flexibly alter the atomic motion ranging from atomic dynamics in the effective brick-wall type lattice to free motion of atoms in one dark state and a tight binding lattice with a twice smaller periodicity for atoms in the other dark state. Between the two regimes, the spectrum undergoes significant changes controlled by the laser fields. The tripod lattice can be produced using current experimental techniques. The use of the tripod scheme to create a lattice of degenerate dark states opens new possibilities for spin ordering and symmetry breaking.

References

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Quantum nonlinear optics based on 2D Rydberg atom arrays

Daniel Goncalves Romeu
Institut of Photonic Sciences (ICFO)
daniel.goncalves@icfo.es
Extended Abstract Online (ID 2)

We explore the combination of sub-wavelength, two-dimensional atomic arrays and Rydberg interactions as a powerful platform to realize strong, coherent interactions between individual photons with high fidelity. In particular, the spatial ordering of the atoms guarantees efficient atom-light interactions without the possibility of scattering light into unwanted directions, for example, allowing the array to act as a perfect mirror for individual photons. In turn, Rydberg interactions enable single photons to alter the optical response of the array within a potentially large blockade radius R_b, which can effectively punch a large "hole" for subsequent photons. We show that such a system enables a coherent photon-photon gate or switch, with an error scaling $\sim R_b^{-4}$ that is significantly better than the best known scaling in a disordered ensemble. We also investigate the optical properties of the system in the limit of strong input intensities.

Talks Wednesday, 23 February

Cavity quantum-electrodynamics with a strongly interacting Fermi gas

Jean-Philippe Brantut
EPFL
jean-philippe.brantut@epfl.ch

I will report on the investigation of strongly correlated Fermi gases by dispersive coupling to photons in a high-finesse cavity. In a first experiment, we observe Kerr non-linearity in the transmission spectrum of the cavity in the presence of the gas. Tracking the non-linearity in the BEC-BCS crossover, we measure the density-density response function, allowing for ab-initio comparison with theory. In a second experiment, we use a transverse pump and observe the emergence of a superradiant, self-organized phase for strong pump. I will discuss the interpretation of these observations and the perspectives open by the combination of cavity QED and strongly correlated Fermions for the quantum simulation of complex condensed-matter problems.

Preparing fractional quantum Hall states in an optical lattice

Julian Leonard
TU Wien
julian.leonard@tuwien.ac.at

The interplay between magnetic fields and strongly interacting particles can lead to exotic phases of matter that exhibit topological order, such as fractional quantum Hall states. These phases were discovered in a solid-state setting, yet, many of their properties remain unresolved. It has been proposed that topological matter may be created with neutral atoms by engineering synthetic magnetic fields. However, so far these experiments have mostly explored the weakly interacting regime, which precludes access to correlated many-body states. We report on the generation of strongly correlated states of bosons in a synthetic magnetic field. We use a bottom-up strategy based on quantum state engineering in the interacting Harper-Hofstadter model: starting from an unentangled state with two particles, we ramp the system's parameters to adiabatically connect the initial state with the target state. This allows us to reach and characterize quantum states at different filling factors, and to observe the transition from topologically trivial states to Laughlin-type fractional quantum Hall states. Our results mark the starting point for the exploration of strongly correlated topological matter with ultracold atoms.

Fluctuations and symmetry effects in many-body self-organization in a dissipative cavity

Catalin-Mihai Halati
University of Geneva
catalin.halati@unige.ch

We investigate the full quantum evolution of ultracold interacting bosonic atoms on a chain and coupled to an optical cavity. Extending the time-dependent matrix product state techniques and the many-body adiabatic elimination techniques to capture the global coupling to the cavity mode and the open nature of the cavity, we examine the long time behavior of the system beyond the mean-field elimination of the cavity field. We show that the fluctuations beyond the mean-field state give a mixed state character to the dissipative phase transition and self-organized steady states. In the case of ideal bosons coupled to the cavity, the open system exhibits a strong symmetry which leads to the existence of conservation laws and multiple steady states. We find that the introduction of a weak breaking of the strong symmetry by a small interaction term leads to a direct transition from multiple steady states to a unique steady state.

Quantum controlling levitated solids

Markus Aspelmeyer
University of Vienna
markus.aspelmeyer@univie.ac.at

I will discuss recent experimental advances in quantum controlling levitated solids, including demonstrations of the motional quantum ground state of optically trapped nanoparticles in a room temperature environment. I will also discuss the perspective for such experiments to create extreme quantum superposition states involving both large mass and macroscopically distinct separation in the center of mass states. This is related to the long-standing question whether gravitational phenomena require a quantum description.

Observation of a limit cycles phase in a recoil resolved atom-cavity system

Hans Keßler
Institut für Laser-Physik, Universität Hamburg
hkessler@physnet.uni-hamburg.de

Extended Abstract Online (ID 104)

We observe a limit cycle phase in our recoil resolved atom-cavity system using pump light blue-detuned with respect to the atomic resonance. Since the pump protocol is time-independent, the emergence of a limit cycle phase heralds the breaking of continuous time-translation symmetry and can be interpreted as a continuous time crystal. Our experiments are the first demonstration of a continuos time translation symmetry breaking.

Superglass formation in an atomic BEC with competing long-range interactions

Stefan Ostermann
Harvard University
stefanostermann@g.harvard.edu
Extended Abstract Online (ID 60)

The complex dynamical phases of quantum systems are dictated by atomic interactions that usually evoke an emergent periodic order. Here, we study a quantum many-body system with two competing and substantially different long-range interaction potentials where the dynamical instability towards density order can give way to a superglass phase, i.e. a superfluid disordered amorphous solid, which exhibits local density modulations but no long-range periodic order. We consider a two-dimensional BEC in the Rydberg-dressing regime coupled to an optical standing wave resonator. The dynamic pattern formation in this system is governed by the competition between the two involved interaction potentials repulsive soft-core interactions arising due to Rydberg dressing and infinite-range sign changing interactions induced by the cavity photons. The superglass phase is found when the two interaction potentials introduce incommensurate length scales. The dynamic formation of this peculiar phase without any externally added disorder is driven by quantum fluctuations and can be attributed to frustration induced by the two competing interaction energies and length scales.

Emerging long-range magnetic phenomena in a quantum gas coupled to a cavity

Fabian Finger
Institute for Quantum Electronics, ETH Zürich
ffinger@ethz.ch
Extended Abstract Online (ID 98)

Dissipative and coherent processes are at the core of the evolution of many-body systems. Their interplay can lead to new phases of matter and complex non-equilibrium dynamics. However, probing these phenomena microscopically in a setting of controllable coherent and dissipative couplings proves challenging. We realize such a system using a 87Rb spinor Bose-Einstein condensate (BEC) strongly coupled to a single optical mode of a lossy cavity. Two transverse laser fields incident on the BEC allow for cavity-assisted Raman transitions between different motional states of two neighboring spin levels. Adjusting the drive imbalance controls coherent dynamics and dissipation, with the appearance of a dissipation-stabilized phase and bistability [1]. By characterizing the properties of the underlying polariton modes, we give a microscopic interpretation of our observations. Moreover, we realize dynamical superradiant currents in a spin-textured lattice in momentum space [2]. Real-time, frequency-resolved measurements of the leaking cavity field allow us to locally resolve individual tunneling events and cascaded dynamics. Together, our results open new avenues for investigating spin-orbit coupling in dissipative settings and dynamical gauge fields in driven-dissipative settings.

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Talks Thursday, 24 February

Exploring new scientific frontiers with programmable atom arrays

Mikhail Lukin
Harvard University
lukin@physics.harvard.edu

We will discuss the recent advances involving programmable, coherent manipulation of quantum many-body systems using neutral atom arrays excited into Rydberg states, allowing the control over 200 qubits in two-dimensional arrays. Recent results involving the realization of exotic phases of matter, study of quantum phase transitions and exploration of their non-equilibrium dynamics will be presented. In particular, we will report realization and probing of quantum spin liquid states - the exotic states of matter have thus far evaded direct experimental detection. Finally, recent progress involving testing quantum optimization algorithms and realization of novel architecture based on dynamically reconfigurable entanglement will be described. Prospects for scaling up these techniques, including realization of large-scale quantum processors and quantum simulators will be discussed.

Dense arrays: A novel quantum tool

Susanne Yelin
Harvard University
syelin@g.harvard.edu

The physics of cooperative atoms/radiators in regular 2D arrays is dominated by two properties: first, a strongly frequency-selective reflectivity and second, the ability to confine polariton modes cleanly on the surface. This makes such a system highly sensitive to and controllable by light fields. Applications of these systems include beam steering, quantum information processing, metrology, and nonlinear single-photon techniques.

A Quantum Klystron–Controlling Quantum Systems with Modulated Electron Beams

Philipp Haslinger
Technische Universität Wien- Atominstitut
philipp.haslinger@tuwien.ac.at

Coherent manipulation of quantum systems with precisely controlled electromagnetic fields is one of the key elements of quantum optics and quantum technologies. In this talk I will give an overview of our recent work [1], which theoretically demonstrates that the non-radiative electromagnetic near-field of a temporally modulated free-space electron beam can be utilized for coherent control (even on the nanoscale e.g. in an electron microscope) of quantum systems. Such manipulation can be performed with only classical control over the electron beam itself. Potential challenges like shot noise and decoherence through back action on the electrons are insignificant for most of the parameter ranges. I will conclude with a possible experimental realization using laser cooled, state-selected potassium atoms and point out applications such as painted potentials, which could be realized using a spatially modulated electron beam.

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Two-fluid interfaces

Silke Weinfurtner
The University of Nottingham
silke.weinfurtner@nottingham.ac.uk

TBA

Entanglement-Optimal Trajectories of Many-Body Quantum Markov Processes

Hannes Pichler
IQOQI & UIBK
hannes.pichler@uibk.ac.at

Extended Abstract Online (ID 105)

In this talk I present a method to solve the equations of motion of open quantum many-body systems. It is based on a combination of generalized wave function trajectories and matrix product states. More specifically, we developed an adaptive quantum stochastic propagator, which minimizes the expected entanglement in the many-body quantum state, thus minimizing the computational cost of the matrix product state representation of quantum trajectories. I illustrate this approach on the example of one-dimensional open Brownian circuit: First, I show that this model dis- plays an entanglement phase transition between area and volume law when changing between different propagators and then I show that our method autonomously finds an efficiently representable area law unravelling.

References

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Talks Friday, 25 February

Landauer vs. Nernst: What is the True Cost of Cooling a Quantum System?

Marcus Huber
TU Wien and IQOQI Vienna
marcus.huber@tuwien.ac.at

Thermodynamics connects our knowledge of the world to our capability to manipulate and thus to control it. This crucial role of control is exemplified by the third law of thermodynamics, Nernst's unattainability principle, stating that infinite resources are required to cool a system to absolute zero temperature. But what are these resources? And how does this relate to Landauer's principle that famously connects information and thermodynamics? We answer these questions by providing a framework for identifying the resources that enable the creation of pure quantum states. We show that perfect cooling is possible with Landauer energy cost given infinite time or control complexity. Within the context of resource theories of quantum thermodynamics, we derive a Carnot-Landauer limit, along with protocols for its saturation. This generalises Landauer's principle to a fully thermodynamic setting, leading to a unification with the third law and emphasising the importance of control in quantum thermodynamics.

A fast and bright source of coherent single-photons using a quantum dot in an open microcavity

Richard Warburton
Department of Physics, University of Basel
richard.warburton@unibas.ch
Extended Abstract Online (ID 121)

A fast and bright source of coherent single-photons is realised using a quantum dot in an open microcavity.

Relaxation of single-mode excitations in a quasi-condensate

Frederik Møller
Atominstitut, TU Wien
frederik.moller@tuwien.ac.at
Extended Abstract Online (ID 42)

The dynamics and relaxation of interacting quantum many-body systems are highly complicated. Ultracold gases in reduced dimensions offer a powerful experimental platform for studying these phenomena, however, the complexity of such systems makes it challenging to distinguish competing mechanisms of relaxation. Here we present the realization of a one-dimensional quasi-condensate in a box-potential with an adjustable trap bottom. By switching the trap bottom shape from an eigenmode of the box to a flat potential we can accurately excite a single mode of the condensate. The very controlled manner in which the quench is conducted allows for excellent comparison to theory, thus facilitating an in-depth study of the many-body dynamics. We find simple Luttinger-Liquid descriptions unable to capture the observed relaxation, indicating the presence of phonon-phonon interactions. Instead, the dynamics accurately follow predictions of Generalized Hydrodynamics (GHD), which describes the relaxation as caused by individual constituents of the mode dephasing with respect to one another. Further, our setup is an ideal platform for observing diffusive dynamics, which constitutes higher-order corrections to GHD.

Experimental quantum photonic memristor

Michele Spagnolo
University of Vienna
michele.spagnolo@univie.ac.at
Extended Abstract Online (ID 40)

Memristive devices are a class of physical systems with history-dependent dynamics characterised by signature hysteresis loops in their input-output relations. In the past few decades, memristive systems have attracted enormous interest in electronics. This is because memristive dynamics is very pervasive in nanoscale devices, and has potentially groundbreaking applications, ranging from energy-efficient memories to physical neural networks and neuromorphic computing platforms. Recently, the concept of a quantum memristor was introduced by a few proposals, all of which face limited technological practicality. Here we propose and experimentally demonstrate a novel quantum-optical memristor that is based on integrated photonics and acts on single photon states. We fully characterise the memristive dynamics of our device and tomographically reconstruct its quantum output state. Finally, we propose a possible application of our device in the framework of quantum machine learning through a scheme of quantum reservoir computing, which we apply to classical and quantum learning tasks. Our simulations show promising results, and may break new ground towards the use of quantum memristors in quantum neuromorphic architectures.

A Nanoscale Coherent Light Source

Laurin Ostermann
University of Innsbruck
`laurin.ostermann@uibk.ac.at`

A laser is composed of an optical resonator and a gain medium. When stimulated emission dominates mirror losses, the emitted light becomes coherent. We propose a new class of coherent light sources based on wavelength sized regular structures of quantum emitters whose eigenmodes form high-Q resonators. Incoherent pumping of few atoms induces light emission with spatial and temporal coherence. We show that an atomic nanoring with a single gain atom at the center behaves like a thresholdless laser, featuring a narrow linewidth. Symmetric subradiant excitations provide optimal operating conditions.

Variational quantum circuits for reinforcement learning

Sofiene Jerbi
University of Innsbruck
`sofiene.jerbi@uibk.ac.at`
Extended Abstract Online (ID 43)

We propose two hybrid quantum-classical reinforcement learning models, which we show can be effectively trained to solve several standard benchmarking environments. Moreover, we demonstrate and formally prove the ability of variational quantum circuits to solve certain learning tasks that are intractable to classical models, under widely-believed complexity theoretic assumptions.

Posters

Phase-space inequalities: certification of nonclassicality beyond negativities

Elizabeth Agudelo
TU Wien
elizabeth.agudelo@tuwien.ac.at

Extended Abstract Online (ID 123)

The identification and characterization of nonclassical states of light is a central task in quantum optics and photonic quantum information. Nonclassicality as a resource is of major importance for quantum technologies such as quantum metrology, communication, or entanglement generation. Therefore, it is crucial to develop efficient and experimentally accessible tools for the characterization of nonclassical light. One possibility of identifying genuine nonclassical features is using the framework of quasiprobability distributions. Alternatively, inequality conditions based on moments of observables can be used. We introduce a framework that unifies the certification of quantum correlations through quasiprobability distributions and inequality conditions. In this way, we demonstrate a deep connection between correlation measurements and phase-space distributions and device nonclassicality conditions which exploit the advantages of both approaches. Our method correlates arbitrary phase-space functions at arbitrary points in phase space, including multimode scenarios and higher-order correlations.

Deterministic entanglement between two distant qubits using two-mode squeezed states of light

Joan Agustí Bruzón
TU Wien
joan.agusti@tuwien.ac.at

We explore the possibility of entangling two distant qubits using two-mode squeezed states of light. The two-mode squeezed states are generated using a non-degenerate parametric amplifier. The output is then coupled in a cascaded way to a pair of spatially separated qubits. The entanglement of the light fields is then transferred to the qubits, allowing us to create a pair of maximally entangled state in the qubits. We analytically derive an effective master equation for the qubits using effective filtered modes to account for the finite bandwidth of the qubits. This scheme coincides well with a full numerical treatment with the master equation. The effective mode description shows that in the finite bandwidth regime there is

an optimal pump strength and surpassing this -while increasing the squeezing- the maximum amount of attainable entanglement will be lowered by a proliferation of impurity in the output of the parametric amplifier.

Causal Process Tomography of a Fiber-Based Quantum SWITCH

Michael Antesberger
University of Vienna
michael.antesberger@univie.ac.at
Extended Abstract Online (ID 41)

The field of indefinite causal order in quantum mechanics has seen more and more interest in the past years, both theoretically and experimentally. In such processes, different parties act in a superposition of different orders. Since the first experimental realization of a process with an indefinite causal order, the quantum SWITCH, several protocols taking advantage of this new resource have emerged. In previous experiments, the causal non-separability of two parties has been verified by measuring a so-called ‘causal witness’. Nevertheless, the corresponding process matrix has only been evaluated theoretically. Here, we experimentally reconstruct the process matrix of a new passively-stable fiber-based architecture for the quantum SWITCH based on time-bin encoded qubits, which can readily be scaled to more parties. We perform a full characterization of this new type of quantum SWITCH by implementing causal process tomography for the first time. We then compare the tomography results to those obtained by directly measuring several different causal witnesses. Finally, we present the first measurement of the fidelity of our experimental quantum SWITCH to the ideal quantum SWITCH.

Cooperative effects in dense cold atomic gases including magnetic dipole interactions

Nico Baßler
Friedrich Alexander Universität/Max-Planck Institut für die Physik des Lichts
nico.bassler@mpl.mpg.de

We theoretically investigate cooperative effects in cold atomic gases exhibiting both electric and magnetic dipole-dipole interactions, such as occurring in Dysprosium gases. In the quantum non-degenerate case, a quantum optics path is taken to show the emergence of tailorable spin models in the high excitation limit. In the opposite case of low excitation limit, we provide analytical and numerical results

detailing the effect of magnetic interactions on the directionality of scattered light and characterize sub- and superradiant effects. In the quantum degenerate case, a many body physics approach is taken, showing the interplay between sub- and superradiance and the fermionic or bosonic quantum statistics nature of the gas.

High-dimensional entanglement from an array of non-interacting photon emitters

Tom Bell
University of Bristol
tj.bell@bristol.ac.uk

Encoding high-dimensional quantum information into single photons can provide a variety of benefits for quantum technologies, such as improved noise resilience. However, the efficient generation of on-demand, high-dimensional entanglement was thought to be out of reach for current and near-future photonic quantum technologies. We present a protocol for the near-deterministic generation of N-photon, d-dimensional photonic GHZ states using an array of d non-interacting single-photon emitters. We analyse the impact on performance of common sources of error for quantum emitters, such as photon spectral distinguishability and temporal mismatch, and find they are readily correctable with time-resolved detection to yield high fidelity GHZ states of multiple qudits. Using time-resolved detection to herald successful outcomes, we show that inconsistencies in the single photon emission spectra can be compensated for to yield high fidelity qudit GHZ states, even with distinguishable photons. We provide analytic and numerical results on the performance of our scheme. When applied to a quantum key distribution scenario, our protocol exhibits improved loss tolerance and key rates when increasing the dimensionality beyond binary encodings.

Entanglement multiplexing through a multicore fiber

Martin Bohmann
IQOQI Vienna
martin.bohmann@oeaw.ac.at
Extended Abstract Online (ID 126)

In our work, we explore a new paradigm and experimentally demonstrate multiplexing of quantum signals by space-division multiplexing of quantum signals over a multicore fiber. To this end, we generate polarization-entanglement photon pairs at telecommunication wavelengths and distribute several pairs simultaneously and independently through a 19-path multicore fiber. Exploiting quantum correlations ind different degrees of freedom of the generated photon pairs, we are able to deterministically couple and transmit entangled photons pairs through dedicated cores of the multicore fiber. Furthermore, we show the long-term stability of our experiment over 24 hours, demonstrating its technological readiness. Our results provide a major contribution to the field of quantum communication by introducing quantum space-division multiplexing. This new paradigm allows to overcome rate limits in quantum communication, and will therefore play an essential roll in advancing quantum communication links. Furthermore, the presented scheme opens the door for many extensions, including multi-user communication networks, multiplexing in multiple degrees of freedom, and high-dimensional quantum communication.

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The Boundary for Quantum Advantage in GaussianBoson Sampling

Jacob Bulmer
University of Bristol
jacob.bulmer@bristol.ac.uk
Extended Abstract Online (ID 75)

Gaussian Boson Sampling (GBS), in which photons are measured from a highly entangled Gaussian state, is a leading approach in pursuing quantum advantage. State-of-the-art quantum photonics experiments that, once programmed, run in minutes, would require 600 million years to simulate using the best pre-existing classical algorithms. We find substantially faster classical GBS simulation methods, including speed and accuracy improvements to the calculation of loop hafnians, the matrix function at the heart of GBS. These results reduce the run-time of classically simulating state-of-the-art GBS experiments to several months - a nine orders of magnitude improvement over previous estimates

Superradiant lasing in inhomogeneously broadened ensembles

Anna Bychek
Institute for Theoretical Physics, University of Innsbruck
Anna.Bychek@uibk.ac.at
Extended Abstract Online (ID 6)

Theoretical studies of superradiant lasing on optical clock transitions predict a superb frequency accuracy and precision closely tied to the bare atomic linewidth. Such a superradiant laser is also robust against cavity fluctuations when operated in a bad-cavity regime. Recent predictions suggest that this unique feature persists even for a hot and thus strongly broadened ensemble, provided the effective atom number is large enough. Here we use a second-order cumulant expansion approach to study the power, linewidth and lineshifts of such a superradiant laser as a function of the inhomogeneous width of the ensemble. We show how sufficiently large numbers of atoms subject to strong optical pumping can induce synchronization of the atomic dipoles over a large bandwidth. This generates collective stimulated emission of light into the cavity mode leading to narrow-band laser emission at the average of the atomic frequency distribution. The linewidth is orders of magnitudes smaller than that of the cavity as well as the inhomogeneous gain broadening and exhibits reduced sensitivity to cavity frequency noise.

Symmetry-resolved entanglement detection using partial transpose moments

Jose Carrasco
University of Innsbruck
jose.carrasco@uibk.ac.at

TBA

Atomic waveguide QED with atomic dimers

David Castells Graells
Max Planck Institute of Quantum Optics
david.castells@mpq.mpg.de

Quantum emitters coupled to a waveguide is a paradigm of quantum optics, whose essential properties are described by waveguide quantum electrodynamics (QED). We study the possibility of observing the typical features of the conventional waveguide QED scenario in a system where the role of the waveguide is played by a one-dimensional subwavelength atomic array. For the role of emitters, we propose to use anti-symmetric states of atomic dimers – a pair of closely spaced atoms – as effective two-level systems, which significantly reduces the effect of free-space spontaneous emission. We solve the dynamics of the system both when the dimer frequency lies inside and when it lies outside the band of modes of the array. Along with well-known phenomena of collective emission into the guided modes and waveguide mediated long-range dimer–dimer interactions, we uncover significant non-Markovian corrections which arise from both the finiteness of the array and through retardation effects.

Quantum optics and optomechanics with a hemispherical mirror

Giovanni Cerchiari
University of Innsbruck
giovanni.cerchiari@uibk.ac.at

Current endeavors in quantum physics aim to analyze dipolar scatterer's quantum states of motion with solely optical setups. To achieve this goal, it is mandatory to access the positional and structural information of the object of interest to observe its motional states. We recently developed a technique to measure the motion of dipolar scatterers based on altering their spontaneous emission of radiation. With theoretical models and experimental data at hand, I will explain how our method achieves higher sensitivity than state-of-the-art setups adopted in the field of levitated optomechanics. Our results lay the groundwork for attaining full and purely optical SE-based control of motional states and can find application in atomic physics, optomechanics and microscopy.

Enhancing the performance of optomechanical sensors by continuous photon-counting

Lewis Clark
Centre of New Technologies, University of Warsaw
l.clark@cent.uw.edu.pl

Optomechanical systems are rapidly becoming one of the most promising platforms for observing quantum behaviour, even approaching macroscopic systems. These systems are well understood at both a theoretical and experimental level. The potential for using such devices for applications such as quantum sensing is thus high, and some work has already been carried out to understand how such devices can be used. Motivated by the recent interest in using continuous measurements and Bayesian inference as a tool for quantum sensing, we apply these techniques to an optomechanical system in this work. We

find that even with a single quantum trajectory of photon-click events, we are capable of accurately inferring optomechanical parameters being sensed, such as the internal frequency of the mechanical oscillator or its light-coupling strength, with average precision that can surpass the bound set by the quantum Fisher information for a single-shot measurement in reasonable amounts of time. Our work thus presents a novel approach to quantum sensing in optomechanical systems, having potential to guide the design of future devices.

Multi-qubit gates for Rydberg atoms and their application in entanglement measurements

Denise Cocchiarella
Universität Innsbruck
Denise.Cocchiarella@student.uibk.ac.at
Extended Abstract Online (ID 26)

Arrays of trapped neutral atoms excited to Rydberg states are a promising component for large-scale quantum information systems. Due to their strong state-dependent interactions, Rydberg atoms are naturally suited to implement quantum gates. Recently two-qubit entangling gates based on the Rydberg blockade mechanism have been implemented in optical tweezers [Levine et al 2019]. I will review this work and discuss possible extension thereof to multi-qubit settings. Then I will discuss applications of these multi-qubit gates for measuring entanglement in quantum simulators, and experimentally estimate the central charge of conformal field theories realized in Rydberg atom arrays.

Ultrastrong Coupling in an Optomechanical System

Kahan Dare
Universität Wien
kahan.mcaffer.dare@univie.ac.at
Extended Abstract Online (ID 86)

The ultrastrong coupling regime, where the coherent coupling rate approaches the transition energy of the system, is a rarely studied area of physics despite its vast array of novel physics such as two-mode squeezing, the dynamical Casimir effect and non-gaussian ground states. Only a handful of experiments have been recently developed to probe this regime due to the large technologically challenges associated with engineering such a system.

Here, we implement a simple scheme for reaching the ultrastrong coupling regime in an optomechanical system which can be dynamically tuned to implement a wide range of quantum control protocols. We achieve this by coupling a levitated nanoparticle to an optical cavity through coherent scattering. Together with the ability to cool the system to its motional ground state, this result opens up quantum experiments in the USC regime to simple table-top systems. Lastly, we outline how to extend this to the deep strong coupling regime and its potential for future applications.

Experimental Single-Copy Entanglement Distillation

Sebastian Ecker
IQOQI Vienna
sebastian.ecker@oeaw.ac.at

Overcoming noise in long-distance entanglement distribution is a key challenge for many quantum technological applications. A promising candidate for this purpose is entanglement distillation. Here the communicating parties receive at least two mixed entangled photon pairs and distill a single photon pair with a higher degree of entanglement. While these protocols are well-studied in theory, they lack the required efficiency in photonic implementations. In our experimental work, we turn around the multi-copy paradigm and utilize entanglement in multiple degrees of freedom of a single photon pair. Specifically, we make use of the polarization and the energy-time domain of photons, both of which are extensively field tested. We experimentally chart the domain of distillable states and achieve fidelity gains up to 13.8%. Our approach enables distillation rates which are orders of magnitude higher than in conventional entanglement distillation protocols and therefore pave the way towards high-capacity and noise-resilient quantum networks.

1) Quantum simulators for fundamental physics / 2) Dynamics of rapidly crossing a phase transition

Sebastian Erne
Atominstitut TU Wien
erne@atomchip.org

Extended Abstract Online (ID 78)

1) Ultracold atoms and their non-equilibrium evolution present an ideal platform to study fundamental processes of quantum field theory and the relaxation dynamics of quantum many-body systems. Here, we present recent results and future prospects for analogue quantum simulators based on effective field theory descriptions. In particular, we discuss the relaxation in an inhomogeneous extended bosonic Josephson junction and its connection to the sine-Gordon model [1], superradiant instabilities and recurrences in multiquantum vortex decay [2], common soundrings during the relaxation of vortex clusters [3], and measurement of the analogue

circular Unruh effect via local interferometric two-frequency detectors [4][5]. The continuous non-destructive measurements of cold atom systems paves the way to study this fundamental and yet still untested prediction of quantum field theory, that a linearly accelerated observer in the vacuum observes a thermal state at the Unruh-temperature.

2) Universality near continuous phase transitions has led to a tremendous increase in our understanding of the fundamental aspects governing the large scale structure formation of seemingly different systems. This insensitivity to microscopic details culminated in the renormalization group (RG) program of quantum field theory, enabling a comprehensive classification of systems based on their universal properties near fixed points of the RG flow. We discuss implications of universal aspects on the real time evolution during and after rapidly driving a system through a phase transition. In particular, we present results on (i) defect nucleation and its connection to the Kibble-Zurek mechanism for rapidly cooling quenched one-dimensional Bose gases [1] and coupled quantum wires [2] and (ii) universal self-similar scaling dynamics, e.g. associated with the approach of a non-thermal fixed point, during the relaxation of isolated [3] or open [4] systems driven far from equilibrium.

Bayesian optimization of photonic quantum circuits with crosstalk noise

Fulvio Flamini
University of Innsbruck
fulvio.flamini@uibk.ac.at
Extended Abstract Online (ID 55)

We numerically investigate the impact of thermal crosstalk in unitary transformations implemented via universal photonic architectures. We present a strategy to refine its characterization and to optimize the voltage-to-phase map necessary to achieve a target transformation. This strategy is based on a simple and efficient Bayesian optimization.

Heralded storage of single photons from a cavity enhanced source based on spontaneous parametric down conversion.

Sonali Gera
Stony Brook University

sonali.gera@stonybrook.edu

Extended Abstract Online (ID 63)

We will be reporting on the heralded storage of narrowband single photons from a cavity enhanced single photon source in a room temperature quantum memory based on electromagnetically induced transparency. Our source is based on spontaneous parametric down conversion in a type I PPKTP crystal that is placed inside a narrow linewidth cavity, making the down-converted photons compatible with atomic ensembles. The cavity is pumped with blue light at 397.5nm and the down-converted photon pairs at 795nm are split on a beam splitter. After filtering through two temperature-tuned Fabry-Perot etalons, one photon from the pair heralds the presence of another and triggers the memory preparation. We report a spectral brightness of $\sim$ 2000 photons per mW per MHz, an improvement from production rates of similar setups.

Quantum optics with spin waves

Carlos Gonzalez-Ballestero

University of Innsbruck

carlos.gonzalez-ballestero@uibk.ac.at

Extended Abstract Online (ID 77)

Spin waves – magnetization waves propagating in saturated ferromagnets – are promising information carries in future technologies due to their useful properties, such as tunable dispersion relations and nonlinearities, nonreciprocity, and much lower losses than electronic currents. Recently spin wave quanta – magnons – have been proposed as promising components for hybrid quantum technology [1]. The demonstration of single magnon states [2] has opened the door to applications such as sensing or transduction. Exploring all these applications requires to develop and extend common quantum optics protocols to the realm of magnonics. Bridging the gap between magnonics and quantum optics could enable the design of novel hybrid quantum devices benefitting from the rich phenomenology of magnons, as well as from the extensive existing research on classical spin-wave technologies, including sensors, information processing devices, and alternative architectures such as neuromorphic computing [3]. In our work [4], we develop the theoretical formalism describing the interaction between spin waves and quantum emitters. We focus on solid-state paramagnetic spins such as nitrogen-vacancy centers, as they have excellent properties for quantum technologies and have already been coherently coupled to spin waves in the classical regime [5]. First, we derive the back-action of a dense spin ensemble on spin waves propagating on a ferromagnetic slab, and show how their propagation properties can be strongly and tunably modified in analogy to the phenomenon of slow light. Second, we derive the frequency shifts, the modification of the decoherence rates, and the mechanical force induced by spin waves on a spin ensemble. These modifications allow to optically or mechanically detect magnonic fields with sensitivity below the magnonic ground-state fluctuations using current techniques. Finally, we show how the natural anisotropy of the magnonic dispersion relation generates a nonreciprocal magnon-mediated coupling between different spins in the ensemble. Our work sets the theoretical basis for future hybrid quantum technologies based spin waves.

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Rotor Jackiw-Rebbi Model: A Cold-Atom Approach to Chiral Symmetry Restoration and Charge Confinement

Daniel González-Cuadra
University of Innsbruck, IQOQI
daniel.gonzalez-cuadra@uibk.ac.at

Understanding the nature of confinement, as well as its relation with the spontaneous breaking of chiral symmetry, remains one of the long-standing questions in high-energy physics. The difficulty of this task stems from the limitations of current analytical and numerical techniques to address nonperturbative phenomena in non-Abelian gauge theories. In this talk, I will show how similar phenomena emerge in simpler models, and how these can be further investigated using state-of-the-art cold-atom quantum simulators [1]. More specifically, I will introduce the rotor Jackiw-Rebbi model, a (1+1)-dimensional quantum field theory where interactions between Dirac fermions are mediated by quantum rotors. Starting from a mixture of ultracold atoms in an optical lattice, I will show how this quantum field theory emerges in the longwavelength limit. For a wide and experimentally relevant parameter regime, the Dirac fermions acquire a dynamical mass via the spontaneous breakdown of chiral symmetry. I will consider the effect of both quantum and thermal fluctuations, and show how they lead to the phenomenon of chiral symmetry restoration. Moreover, I will uncover a confinement-deconfinement quantum phase transition, where mesonlike fermions fractionalize into quarklike quasiparticles bound to topological solitons of the rotor field. The proliferation of these solitons at finite chemical potentials again serves to restore the chiral symmetry, yielding a clear analogy with the quark-gluon plasma in quantum chromodynamics, where the restored symmetry coexists with the deconfined fractional charges. These results indicate how the interplay between these phenomena could be analyzed in more detail in realistic atomic experiments.

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Towards Quantum Advantage via Topological Data Analysis

Casper Gyurik

Leiden Institute for Advanced Computer Science, Leiden University

cgyurik@gmail.com

Extended Abstract Online (ID 88)

Even after decades of quantum computing development, examples of generally useful quantum algorithms with exponential speedups over classical counterparts are scarce. Recent progress in quantum algorithms for linear-algebra positioned quantum machine learning (QML) as a potential source of such useful exponential improvements. Yet, in an unexpected development, a recent series of “dequantization” results has equally rapidly removed the promise of exponential speedups for several QML algorithms. This raises the critical question whether exponential speedups of other linear-algebraic QML algorithms persist. In this paper, we study the quantum-algorithmic methods behind the algorithm for topological data analysis of Lloyd, Garnerone and Zanardi through this lens. We provide evidence that the problem solved by this algorithm is classically intractable by showing that its natural generalization is as hard as simulating the one clean qubit model – which is widely believed to require superpolynomial time on a classical computer – and is thus very likely immune to dequantizations. Based on this result, we provide a number of new quantum algorithms for problems such as rank estimation and complex network analysis, along with complexity-theoretic evidence for their classical intractability. Furthermore, we analyze the suitability of the proposed quantum algorithms for near-term implementations. Our results provide a number of useful applications for full-blown, and restricted quantum computers with a guaranteed exponential speedup over classical methods, recovering some of the potential for linear-algebraic QML to become one of quantum computing's killer applications.

Cavity QED with Strongly Interacting Fermions

Victor Helson
Laboratory for Quantum Gases - EPFL
victor.helson@epfl.ch
Extended Abstract Online (ID 48)

I will report on our most recent results regarding the study of strongly interacting Fermions coupled to light in a high-finesse optical cavity.

Emergent atom pump in a non-hermitian system

Simon Hertlein
Institute for Quantum Electronics, Eidgenössische Technische Hochschule Zürich
hersimon@phys.ethz.ch
Extended Abstract Online (ID 97)

We study a Bose-Einstein Condensate dispersively coupled to a high finesse resonator. When the dissipation and the coherent timescales are comparable, we find a regime of persistent oscillations where the cavity field does not reach a steady state. In this regime the atoms experience an optical lattice that periodically deforms itself, even without providing an external time dependent drive. Eventually, the dynamic lattice triggers a pumping mechanism.

Super-resolution using transverse-spatial N00N states

Markus Hiekkamäki
Tampere University
markus.hiekkamaki@tuni.fi
Extended Abstract Online (ID 100)

Photonic N00N states, i.e. states of light where N photons are in an extremal superposition between two orthogonal states, have an increased phase-sensitivity in comparison to their classical counterparts. Using the increased phase sensitivity offered by N00N states, in conjunction with the intrinsic properties of transverse-spatial modes, enables various types of measurements with sensitivities beyond the classically allowed limits. In the present work, we harness the angular sensitivity of orbital angular momentum (OAM) modes and create two-photon twisted N00N states for arbitrary OAM values through photon bunching. We then use these twisted N00N states to demonstrate angular super resolution, in a single beam. To demonstrate the systems capabilities, we measured rotation sensitivities of heralded single photons and two-photon N00N states with OAM values up to 100. The flexibility of the system also allows the generation of N00N states between radial modes which we have further used to demonstrate super-resolution in the longitudinal direction. Finally, these radial-mode N00N states have allowed us to examine the Gouy phase of two-photon Fock states.

Collective Effects in Dipole-Coupled Quantum Emitters

Raphael Holzinger
Institute for Theoretical Physics Innsbruck
`raphael.holzinger@uibk.ac.at`
Extended Abstract Online (ID 5)

Recent studies have shown that sub-wavelength sized rings of quantum emitters pos- sess subradiant eigenmodes which mimic high-Q optical resonators. We add a con- tinuously pumped atom as a gain medium in the ring's center creating a minimalistic coherent light source.

Cavity Sub- and Superradiance Enhanced Ramsey Spectroscopy

Christoph Hotter
University of Innsbruck
`christoph.hotter@uibk.ac.at`
Extended Abstract Online (ID 37)

Ramsey spectroscopy in large, dense ensembles of ultra-cold atoms trapped in optical lattices suffers from dipole-dipole interaction induced shifts and collective superradiance limiting its precision and accuracy. We propose a novel geometry implementing fast signal readout with minimal heating for large atom numbers at lower densities via an optical cavity operated in the weak single atom but strong collective coupling regime. The key idea is controlled collective transverse $\pi/2$-excitation of the atoms to prepare a macroscopic collective spin protected from cavity superradiance [1, 2]. This requires that the two halves of the atomic ensemble are coupled to the cavity mode with opposite phase, which is naturally realized for a homogeneously filled volume covering odd and even sites of the cavity mode along the cavity axis. The origin of the superior precision can be traced back to destructive interference among sub-ensembles in the complex non-linear collective atom field dynamics. In the same configuration we find surprising regular self-pulsing of the cavity output for suitable continuous illumination. Our simulations for large atom numbers employing a cumulant expansion [3] are qualitatively confirmed by a full quantum treatment of smaller ensembles.

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Giant enhancement of third-harmonic generation in graphene–metal heterostructures

Philipp Jenke

Vienna Center for Quantum Science and Technology (VCQ), Faculty of Physics, University of Vienna

philipp.jenke@univie.ac.at

Extended Abstract Online (ID 16)

Nano-optical plasmonic structures have the potential to amplify nonlinear processes by efficiently focusing far-field light into small sub-wavelength volumes. Two dimensional materials such as graphene are promising candidates for nonlinear optoelectronic applications due to their strong intrinsic and electrically tunable optical nonlinear response, while supporting plasmonic excitations. Here, enhance the third-order optical nonlinear response of graphene–insulator–metal heterostructures by three orders of magnitude with respect to bare graphene. We achieve this using metallic nanoribbons to simultaneously launch acoustic graphene plasmons and enhance the far field pump light in the graphene layer. Furthermore, by manipulating the electrical environment we can modulate the nonlinear optical signal. This work shows the potential of nonlinear processes driven by graphene plasmons in graphene–insulator–metal heterostructures for optically controlled and electrically tunable nano-optoelectronic components, compatible with established nanofabrication techniques.

Room-temperature, cavity-less, ponderomotive squeezing of light by a levitated nanoparticle

Aisling Johnson
University of Vienna, Faculty of Physics and IQOQI Vienna
aisling.johnson@univie.ac.at

Ponderomotive squeezing, or mechanical squeezing of light, arises due to the correlation between the amplitude and the phase of a light field induced by its interaction with a mechanical resonator. Here, using a simple room-temperature optomechanical experiment based on the levitation of a nanosphere in a tightly focussed optical trap, we measure a reduction fluctuations below the vacuum level in the light back-scattered by the levitated particle. Our detection relies on a heterodyne scheme and the simultaneous numerical demodulation of two orthogonal quadratures of motion, allowing us to perform state tomography. This powerful measurement method is applied to the search for optomechanical entanglement and I will also discuss the recent developments towards this goal.

Sensitivity limits of phase microscopy

Thomas Juffmann
Univ. of Vienna
thomas.juffmann@univie.ac.at

Cryogenic electron microscopy and tomography have led to a revolution in structural biology, enabling the reconstruction of proteins, and sub-cellular structure, respectively. Optical phase contrast microscopy is widely used as a label-free technique for live cell microscopy. In all these techniques, a specimen imparts a phase shift on the probe (photons or electrons), which can be measured using interferometric techniques. The measurement sensitivity is limited by the finite number of probe particles that can be detected due to sample, source, or detector constraints.

I will briefly discuss a Fisher information treatment of phase microscopy, and will show ways how to improve on current techniques using wave-front shaping, cavity or quantum enhanced measurements. I will demonstrate how wave-front shaping can optimize phase contrast (1,2), and how multi-passing the probe particles through a sample can be used for high sensitivity / low damage imaging (3). The latter could potentially allow for cryo-electron microscopy with unprecedented resolution (4). Finally, I will introduce the hybrid imaging technique 'Optical Near-field Electron Microscopy', which extracts information non-invasively from optical near fields using electron optics with nanometric resolution (5).

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Effect of an optical dipole trap on resonant atom-light interactions

Teresa Karanikolaou

ICFO, Institute of Photonic Sciences

teresa.karanikolaou@icfo.eu

Extended Abstract Online (ID 34)

The optical properties of a fixed atom are exquisitely well-known and investigated. For example, one important phenomenon is that the atom can have an extraordinarily strong response to a resonant photon, as characterized by a resonant elastic scattering cross section given by the wavelength of the transition itself, $\sigma_{sc} \sim \lambda^2$. The case of a tightly trapped ion, where the ground and excited states are equally trapped, is also well-known. Then, the elastic cross section is reduced by a fraction corresponding to the square of the "Lamb-Dicke parameter", while this same parameter also dictates the probability of inelastic scattering that gives rise to motional heating. In contrast, there are many emerging quantum optics setups involving neutral atoms in tight optical dipole traps, such as coupled to nanophotonic waveguides and cavities or in atomic arrays, where the goal is to utilize efficient atom-light interactions on resonance. Often, while the ground state is trapped, the excited state may in fact be untrapped or even anti-trapped. Here, we systematically analyze the consequences that this unequal trapping has on reducing the elastic scattering cross section, and increasing the motional heating rate. This analysis may be useful to optimize the performance of quantum optics platforms where equal trapping cannot be readily realized.

Quantum variational optimization of Ramsey interferometry and atomic clocks

Christoph Raphael Kaubrügger
LFU Innsrbruck
raphael.kaubruegger@uibk.ac.at

We discuss quantum variational optimization of Ramsey interferometry with ensembles of entangled atoms, and its application to atomic clocks. We identify best input states and generalized measurements within a variational approximation for the corresponding entangling and decoding quantum circuits. These circuits are built from basic quantum operations, such as one-axis twisting, or finite range interactions. Optimization is defined relative to a cost function, which in the present study is the Bayesian mean square error of the estimated phase for a given prior distribution, i.e. we optimize for a finite dynamic range of the interferometer. In analogous variational optimizations of optical atomic clocks, we use the Allan deviation for a given Ramsey interrogation time as the relevant cost function for the long-term instability. Remarkably, even low-depth quantum circuits yield excellent results that closely approach the fundamental quantum limits for optimal Ramsey interferometry and atomic clocks. We successfully implement experimentall a programmable quantum sensor operating close to the fundamental limits on a trapped ion quantum computer with up to 26 Ions.

Silicon quantum photonic device for multidimensional controlled unitaries

Konstantina Koteva
The University of Bristol
k.i.koteva@bristol.ac.uk
Extended Abstract Online (ID 124)

We present a fully reconfigurable silicon quantum photonic device capable of performing controlled four-dimensional unitary operations with 0.84 +/- 0.02 fidelity. We report its characterisation by process tomography and deploy it to successfully perform a quantum model learning protocol.

Quantum correlations with generative neural networks

Tamás Kriváchy
IQOQI Vienna/TU Wien
krivachy.tamas@gmail.com

In many cases, correlations are defined to be quantum by a negative definition. A state is entangled if it is not separable. Observed correlations in a Bell setup are nonlocal if there does not exist a local model. Such definitions make it difficult to analytically decide if something is classical (local, separable) or non-classical (nonlocal, entangled).

We approach this question numerically by using neural networks. We parametrize separable states (Bell-local strategies) by neural networks. Then, given a target state (Bell correlation), we ask the neural network to minimize the distance to the target. If the network succeeds, we have a certificate of classicality, as the nerual network was designed to only represent classical objects. On the contrary, if the neural network can not apporach the target distribution well, it is a strong hint of truly quantum behavior. This allows us to come up with, and test conjectures in analytically difficult to handle scenarios, such as network nonlocality, or to establish noise tolerance estimates for high-dimensional bipartite systems or for different types of multipartite entanglement.

Analog quantum simulation of the massive Sine-Gordon model

Andreas Kruckenhauser
IQOQI Innsbruck
andreas.kruckenhauser@uibk.ac.at

TBA

Highly pure single photon source on a tuneable ring resonator

Alexandre Mainos
University of Bristol
a.mainos@bristol.ac.uk

Extended Abstract Online (ID 72)

We present a technique for generating single photons with high spectral purity using a fully tuneable add-drop coupled ring structure. This tuneability allows for controlling the coupling to the cavities, and so their spectral linewidths. We show that increasing the pump resonance linewidth with respect to the photon generation linewidth enables purity enhancement, which can be further increased with a wider pump laser width.

Topological two-dimensional Floquet lattice on a single superconducting qubit

Daniel Malz
Max Planck Institute of Quantum Optics
daniel.malz@mpq.mpg.de
Extended Abstract Online (ID 74)

Current noisy intermediate-scale quantum (NISQ) devices are not only interesting as digital quantum processors, but also constitute powerful platforms for analog quantum simulation. While it is well known that the static Hamiltonian of a quantum computer offers opportunities for simulation, the possibility to implement arbitrary drives on each site of the lattice in fact promise an enormous freedom to engineer many-body models. In a first part, I will show experimental results from quasiperiodic driving of a single qubit, which allows us to observe a temporal version of the half-Bernevig-Hughes-Zhang Chern insulator (Malz & Smith, PRL 126, 163602 (2021)). Using simple error mitigation, we achieve consistently high fidelities of around 97%. I will then present promising preliminary results on the many-body case and give an outlook on promises and limitations of analogue simulation of driven many-body systems on quantum computers.

Resource Theory of Causal Connection

Simon Milz
IQOQI Vienna
simon.milz@oeaw.ac.at
Extended Abstract Online (ID 84)

The capacity of distant parties to send one another signals is a fundamental requirement in many information-processing tasks. Such ability is determined by the causal structure connecting the parties, and more generally, by the intermediate processes carrying signals from one laboratory to another. Here we build a fully fledged resource theory of causal connection for all multi-party communication scenarios, encompassing those where the parties operate in a definite causal order, and also where the order is indefinite. We define and characterize the set of free processes and three different sets of free transformations thereof, resulting in three distinct resource theories of causal connection. In the causally ordered setting, we identify the most resourceful processes for two- and three-party scenarios. In contrast, our results suggest that in the general setting there is no global most valuable resource. Finally, we provide a monotone of causal connection, the signalling robustness, and derive tight bounds thereof. Our results offer a flexible and comprehensive framework to quantify and transform general quantum processes, as well as insights into their multi-layered causal connection structure.

Quantum-enhanced interferometry with large heralded photon-number states

Monika Mycroft
Faculty of Physics, University of Warsaw
monika.mycroft@fuw.edu.pl
Extended Abstract Online (ID 19)

Optical phase measurements are inherently limited by quantum fluctuations in light known as the shot noise limit. Some quantum states, e.g. the N00N state, allow us to overcome that limit in principle, but they are found to be vulnerable to decoherence and their creation is challenging in practice. In my talk I will introduce novel probe states which require only resources readily available in the laboratory and which enable surpassing the shot noise limit even in the presence of substantial photonic losses.

Dipolar atoms in a one-dimensional optical lattice

Gabriele Natale
University of Innsbruck
gabriele.natale@uibk.ac.at
Extended Abstract Online (ID 109)

We here report on measurements of ultracold dipolar erbium atoms confined in a one-dimensional lattice. In the regime of small mean-field interactions, we observe that the dipole-dipole interactions play an important role in determining the number of occupied lattice sites. We additionally perform Bloch oscillation measurements varying the scattering length, from the contact dominated regime to the dipolar dominated one.

Observing quantum-speed-limit crossover with matter-wave interferometry

Gal Ness
Technion - Israel Institute of Technology
gn@technion.ac.il
Extended Abstract Online (ID 13)

Quantum mechanics sets fundamental limits on the speed at which quantum states can be transformed in time. Two well-known quantum speed limits are the Mandelstam– Tamm and the Margolus–Levitin bounds, which relate the maximum rate of evolu- tion to the system's energy uncertainty and mean energy, respectively. We perform fast matter-wave interferometry experiments and track the motion of a single atom in a spin-dependent lattice. This setup constitutes a multi-level quantum system in which we concurrently test both speed limits. Our data reveal two different regimes: one where the Mandelstam–Tamm limit constrains the evolution at all times, and a second where a crossover between the two limits occurs at longer times. We take a geometric approach to quantify the deviation from the speed limit, measuring how far the matter-wave's quantum evolution deviates from the geodesic trajectory in the Hilbert space of the multi-level system. Our results [1], establishing quantum speed limits beyond the simple two-level system, are crucial to understand the ul- timate performance of quantum computing devices and related advanced quantum technologies.

References

[1] G. Ness, M. R. Lam, W. Alt, D. Meschede, Y. Sagi, A. Alberti, Observing crossover between quantum speed limits, Sci. Adv. 7, abj9119 (2021).

Trapping and cooling of large two-dimensional ion crystals in a monolithic Paul trap

Tuomas Ollikainen
IQOQI Innsbruck
tuomas.ollikainen@uibk.ac.at
Extended Abstract Online (ID 76)

Over the last decade, linear strings of ions have proved remarkably successful platform for quantum simulations. Scaling the system up to two-dimensional (2D) ion crystals would allow a higher number of qubits in the system and inherently enable quantum simulations of more complicated 2D spin systems. Here, we experimentally realize stably-trapped 2D ion crystals with up to 91 particles in a monolithic Paul trap, and characterize the stability of the planar crystal configurations. We implement electromagnetically-induced-transparency (EIT) cooling and show that it can be used to ground-state cool the out-of-plane modes of the 2D ion crystal. Finally, we measure the mean phonon numbers and heating rates of the 2D ion crystal, and implement a novel method for multi-ion thermometry based on the initial dynamics of the motional sidebands.

Excitonic Tonks-Girardeau and charge-density wave phases in monolayer semiconductors

Rafał Ołdziejewski
Max Planck Institute of Quantum Optics
rafal.oldziejewski@mpq.mpg.de

Excitons in two-dimensional semiconductors provide a novel platform for fundamental studies of many-body interactions. In particular, dipolar interactions between spatially indirect excitons may give rise to strongly correlated phases of matter that so far have been out of reach of experiments in ultracold gases. Here, we show that excitonic few-body systems in atomically thin transition-metal dichalcogenides confined to a one-dimensional geometry undergo a crossover from a Tonks-Girardeau to a charge-density-wave regime. To this end, we take into account realistic system parameters and predict the effective exciton-exciton interaction potential. We find that the pair correlation function of excitons contains key signatures of the many-body crossover already at small exciton numbers and show that photoluminescence spectra provide readily accessible experimental fingerprints of these strongly correlated quantum many-body states. We then study the system within the Luttinger Liquid theory that agrees remarkably well with few-body exact calculations in predicting spatial correlation functions and blueshifting of the photoluminescence spectra for an increasing number of excitons. Finally, we predict the excitation spectrum of the system for all densities in the many-body limit and study the temporal-spatial pair-correlation functions of emitted photons. Our findings showcase TMDs as an alternative platform for many-body dipolar physics in low-dimensions that may outperform most alternative experimental settings in different tasks and that may complement studies using ultracold molecules that have yet to reach the required densities and control to realize their full potential.

Transferring spin polarization in disordered long-range interacting spin chains

Nikolaos Palaiodimopoulos
Foundation of Research and Technology Hellas (FORTH)- Institute of Electronic structure and Laser (IESL)
nikpalaio@iesl.forth.gr

Extended Abstract Online (ID 59)

Regular arrays of interacting qubits or spins are paradigmatic systems for quantum simulations and computations. In any realistic system, the spins interact with each other via a finite range potential, and transferring quantum states or spin

polarization requires quantum communication channels that can withstand certain degree of disorder. The main goal of the current project is to transfer spin polarization in a finite, disordered, one-dimensional spin chain with long-range dipole-dipole interactions. The most common approach towards introducing static disorder on a system is to assign random values either on the onsite energies (diagonal disorder) or on the couplings (off-diagonal). For the case of diagonal disorder we impose gaussian noise on the onsite energies of each site of the chain, while for the case of off-diagonal disorder, we consider the spin chain's sites to be positioned on the x-y plane, thus our system becomes quasi one-dimensional. Therefore, imposing gaussian noise on the x and y coordinates of each site, we effectively induce off-diagonal disorder on our system. In general, it is known that diagonal or off-diagonal disorder induce the localization of the chain's eigenstates and therefore the transfer probability gets degraded. We investigate when, to which extent and how we can circumvent the aforementioned undesirable degradation. To this end, we employ numerical methods in order to track down the system's extended eigenstates and suitably exploit them. More specifically, we consider the following situation: We assume that we have complete control (onsite energies and couplings) over two sites which will be referred to as sender and receiver. Initially, the spin excitation is localized on the sender site which is disconnected from the spin chain. The receiver on the other hand, is connected to the last site of the chain. If the system has some eigenstates that remain extended in the presence of disorder, we can tune the onsite energies of the sender and receiver to be resonant with the extended state's energy. Then, if we slowly turn on the coupling between the sender and the first site of the spin chain, while at the same time turn off the coupling between the receiver and the last site, we want to examine whether we can efficiently transfer the polarized spin excitation from the sender to the receiver "through" the extended state. Our work addresses the following research questions, given a particular type and strength of disorder: What are the characteristics of the "good" extended eigenstates and in which cases they are not particularly useful for transfer? How does the transfer time scales as the system size is increased and how long is best to wait? What is the maximum length of the chain that we can use to achieve a given mean transfer probability?

Quantifying n-photon indistinguishability on-chip

Mathias Pont
C2N
mathias.pont@c2n.upsaclay.fr
Extended Abstract Online (ID 35)

Quantum states made of many indistinguishable photons are key resources in optical quantum technologies. However, experimentally quantifying the multi-photon indistinguishability of a state of many photons is non trivial. We propose a novel way to accomplish this task using an interferometer that has $N = 2n$ modes and includes a cyclic array of beam splitters, which gives rise to quantum interference when n photons are injected. We experimentally demonstrate this technique using 4 photons from a quantum dot single-photon source and an 8-mode interferometer that is fabricated using femtosecond laser-written waveguides. Single-photons from a QD-SPS are separated into four spatial modes using a frequency-modulated AOM. For our cavity-embedded bright QD-SPS, 4-photon coincidences at the output of the interferometer are detected at a rate of 2.7 Hz. The number of four-photon coincidences as a function of the internal phase of the interferometer exhibits clear interference fringes. The visibility of the interference fringes gives direct access to the four-photon indistinguishability, which is measured here to be $c1 = 0.67 \pm 0.02$ (0.81 ± 0.03) without (with) spectral filtering and with 540 ns maximum delay between photons.

Exploiting the Photonic Non-linearity of Free Space Subwavelength Arrays of Atoms

Cosimo Carlo Rusconi

Max Planck Institute for Quantum Optics

cosimo.rusconi@mpq.mpg.de

Extended Abstract Online (ID 56)

Ordered ensembles of atoms, such as atomic arrays, exhibit distinctive features from their disordered counterpart. In particular, while collective modes in disordered ensembles show a linear optical response, collective subradiant excitations of subwavelength arrays are endowed with an intrinsic non-linearity. Such non-linearity has both a coherent and a dissipative component: two excitations propagating in the array scatter off each other leading to formation of correlations and to emission into free space modes. We show how to take advantage of such non-linearity to coherently prepare a single excitation in a subradiant (dark) collective state of a one dimensional array as well as to perform an entangling operation on dark states of parallel arrays. We discuss the main source of errors represented by disorder introduced by atomic center-of-mass fluctuations, and we propose a practical way to mitigate its effects.

Cavity-Enhanced Microscope for Cold Atoms

Nick Sauerwein
EPFL
nick.sauerwein@epfl.ch

We are setting up an apparatus aimed at combining high-resolution microscopy with continuous readout via cavity quantum electrodynamics. The core of our experiment is a cold gas of Lithium atoms in an optical system realizing both a high-finesse cavity and a high-numerical-aperture lens (0.37) combined in a single optical element. The cavity can be used to dispersively measure the presence of atoms in the cavity mode. A second short-wavelength laser is focused tightly into the lithium atom cloud leading to a local enhancement of the coupling to the cavity and allowing for a non-destructive density measurement with a sub-micron spatial resolution [1]. With the control over the coupling, we will be able to modify the cavity-mediated interactions both temporally and spatially, a promising feature for quantum simulation. Currently, we have assembled the system and managed to control the coupling of the atoms to the cavity by light-shifting their resonance frequency. The poster presents the design, the current status of the setup and outlines possible future experiments.

References

[1] Yang, D., et al., PRL 120, 133601, (2018)

Photon interaction via one-dimensional arrays of atoms coupled to waveguides

Björn Schrinski
Niels Bohr Institute
schrinski@nbi.ku.dk

Extended Abstract Online (ID 64)

As the interaction between photons in free space is completely negligible any applications of photon-interaction rely on indirect interaction via non-linear coupling to matter. We present a concise analytical description of photons coupled to a one-dimensional array of two-level atoms in the two- or three-level configuration. The description incorporates input, scattering of the polaritons that emerge as a coupled state inside the medium, and the ejection of the photons from the array. We discuss the emergence of (in-)elastic scattering regulated by the level structure of the emitter, the degree of chirality of the coupling and the detuning of the photons. We show how the developed theory can be expanded to an effective field theory to study many-body dynamics. Finally, we demonstrate that certain setups can function as a passive phase gate for photons with success probabilities and fidelities above 99 percent for a single digit number of emitters.

Non-localities in many-body systems

Wonmin Son
Sogang University
sonwm71@gmail.com

We find non-localities, violation of local realism, in the many-body ground states of spin-1 XXZ chain with on-site anisotropy. In order to identify the non-localities in higher spin systems, we exploit the generalized version of multipartite Bell-type inequalities which characterize symmetric entangled states under the most general settings via combination of high-order correlations. We provide the extendible picture on the relationship between the impossibility of local realistic model and many-body quantum phases in higher-spin system as the observable identifies measurable quantities to detect the non-locality on a particular many-body quantum state.

Quantum Error Suppression Using a Biased GKPRepetition Code

Matthew Stafford
University of Bristol
matthew.stafford@bristol.ac.uk

Extended Abstract Online (ID 69)

If scaled, quantum computation has the potential to solve problems which are intractable on classical systems. However to achieve this noise, which is present in any physical realisation, must be suppressed using Quantum Error Correction (QEC). In Continuous Variable (CV) quantum computation, GKP states have emerged as a promising candidate for bosonic error correction. In this work we study the code capacity behaviour of a rectangular lattice, biased GKP mode concatenated with an n-qubit repetition code which benefits from simple encoding, decoding and stabiliser measurements compared to full QEC codes. Under the Gaussian Displacement Channel we find this code suppresses error rates compared to a bare GKP qubit for a channel standard deviation up to $\sigma = 0.595$. In a low noise regime ($\sigma < 0.4$) we also find error rates can be effectively suppressed using just three biased modes, potentially allowing for low overhead error suppression in future implementations.

Rewinding time with photons

Teodor Strömberg
University of Vienna
teodor.stroemberg@univie.ac.at

We present and experimentally implement a universal rewinding protocol for two-level quantum systems. The protocol takes an unknown quantum state, evolving under an unknown Hamiltonian, and brings it back to its initial state. Unlike previous known time-translation protocols, ours can achieve an arbitrarily high probability of success, and is furthermore asymptotically optimal in the sense that it only requires O(T) amount of time to rewind the system by T units of time. Our experimental demonstration applies the protocol to qubits encoded in the polarization degree of photons, where the time evolution under a Hamiltonian for time ΔT is mimicked by applying the corresponding unitary operator. We compare our results to a classical strategy and find that the quantum protocol achieves a dramatically higher fidelity that is independent of choice of initial state, Hamiltonian and length of time to be rewound.

Lamb-shift and vacuum forces in ultrastrong coupling cavity QED

Rocío Sáez Blázquez
TU Wien
rocio.saez.blazquez@tuwien.ac.at

Extended Abstract Online (ID 50)

Over the last years there has been an increasing interest in the physics emerging from the ultrastrong light-matter interaction. Special attention has received the modification of ground-state properties under these extreme coupling conditions. Here we study the vacuum effects in a reduced cavity QED setup composed of a polar molecule interacting with the quantized field of a single-mode LC resonator. Following a rigorous microscopic description, we have been able to study the combined role of the induced charges on the metallic boundaries and the operative ultrastrong-coupling effects. Compared to large quantum chemistry simulations, our approach has also allowed us to derive analytical predictions for some regimes of interest. In particular, we have computed (non-diverging, cutoff-free) analytical estimates of the Lamb-shift corrections from all the higher electromagnetic modes and determined the modification of the interaction between a pair of molecules due to the electrostatic effects.

On-chip time-bin entanglement using Bragg-reflection waveguides as photon-pair sources

Hannah Thiel
University of Innsbruck
hannah.thiel@uibk.ac.at
Extended Abstract Online (ID 25)

To prepare quantum communication for its large scale commercialization, sources for quantum states of light have to be made smaller and better integrable. A promising candidate are Bragg-reflection waveguides (BRWs) made from the AlGaAs platform. Their strong $\chi^{(2)}$ nonlinearity enables photon pair production in the telecom wavelength range via parametric down-conversion. We improved the fabrication recipe for BRWs and achieved a reduction in sidewall roughness by a factor of three leading to a decrease in optical loss coefficient of 0.14/mm compared to previous samples. The BRW is end-face coupled to a polymer chip which hosts passive optical components for pump suppression and separation of the photons in a pair. The photons are then relayed to time-bin analysis stations which correspond to Alice and Bob in a quantum key distribution scenario. There, the photons are sent through on-chip asymmetric Mach-Zehnder interferometers and detected by superconducting nanowire detectors. The impossibility to distinguish between photons created in the two time bins is evidenced by interference in the coincidence counts between the two photons detected at Alice's and Bob's site. The visibility of this interference fringe is measured by varying the phase in one of the interferometers.

Spin squeezing and entanglement quantification in atomic gases

Giuseppe Vitagliano
Institute for Quantum Optics and Quantum Information - Vienna
poissongdb@gmail.com
Extended Abstract Online (ID 15)

I will present some recent results on entanglement detection and quantification with collective spin measurements in many-body ensembles. After a brief review of the idea of "Spin Squeezing" and its relation with multipartite entanglement, I will focus on the quantification of entanglement by means of entanglement monotones with spin squeezing methods. I will consider broad families of entangle- ment criteria that are based on variances of arbitrary operators and analytically derive the lower bounds these criteria provide for two relevant entanglement measures: the best separable approximation (BSA) and the generalized robustness (GR).

As a con- crete application, I will show the results of applying this method with experimental data of a spin-squeezed Bose-Einstein condensates of ~ 500 atoms

Nonlinear properties of quantum trajectories of many-body systems

Tatiana Vovk
University of Innsbruck
tatiana.vovk@uibk.ac.at
Extended Abstract Online (ID 67)

Quantum trajectory (QT) methods have proven useful for the numerical simulations of the dissipative dynamics of a system, described by the Lindblad master equation for its density matrix. The wide scope of problems solvable by QTs includes the dynamics of many-body quantum systems. Efforts were aimed to expand the QT methods by adapting the trajectory noise, optimizing the conditional algorithmic information, related to the von Neumann entropy, generalizing the jump operator, and so on. In the present work we consider the chains of M qubits as 1D many-body systems and focus on the properties of trajectories of such systems. We utilize photon number and homodyne measurements to construct the trajectories. We are specifically interested in the entanglement properties of the associated trajectories, which play a crucial role in advanced methods of many-body state propagation. We illustrate our approach on the paradigmatic example of the time evolution of a GHZ state of a many-body system under a Markovian dephasing channel.

Sequential generation of tensor network states

Zhi-Yuan Wei
Max Planck Institute for Quantum Optics
zhiyuan.wei@mpq.mpg.de
Extended Abstract Online (ID 70)

The sequential generation of tensor network states provides a way to deterministically prepare entangled states on both matter-based and photon-based quantum devices. In this talk, first, we discuss two implementations to sequentially generate photonic matrix product states, one based on a Rydberg atomic array, and another based on a microwave cavity dispersively coupled to a transmon. We show both implementations can generate a large number of entangled photons. Then, we introduce plaquette projected entangled-pair states (p-PEPS), a class of states in a lattice that can be generated by applying sequential unitaries acting on plaquettes of overlapping regions. We identify a subclass that can be more efficiently prepared in a radial fashion and that contains the family of isometric tensor network states. We also show how such subclass can be efficiently prepared using an array of photon sources, and devise a physical realization by extending the above cavity-transmon setup.

Simplified Quantum Optical Stokes observables and Bell's Theorem

Bianka Woloncewicz
International Center of Theory for Quantum Technologies (ICTQT), University of Gdansk (UG)
bibivolo@gmail.com
Extended Abstract Online (ID 113)

We introduce a simplified form of Stokes operators for quantum optical fields that involve the known concept of binning. Behind polarization analyzer photon numbers (more generally intensities) are measured. If the value obtained in one of the outputs, say H, is greater than in the other one, V, then the value of the simplified Stokes operator is, say, 1, otherwise it is -1. For equal photon numbers we put 0. Such observables do not have all properties of the Stokes operators, but surprisingly can be employed in Bell type measurements, involving polarization analyzers. They are especially handy for states of undefined number of photons, e.g. squeezed vacuum. We show that surprisingly they can lead to quite robust violations of associated Bell inequalities. For more information please have a llok on our arXiv:2112.00084.

Functional renormalization group approach to strongly-coupled Bose-Fermi mixtures in two dimensions

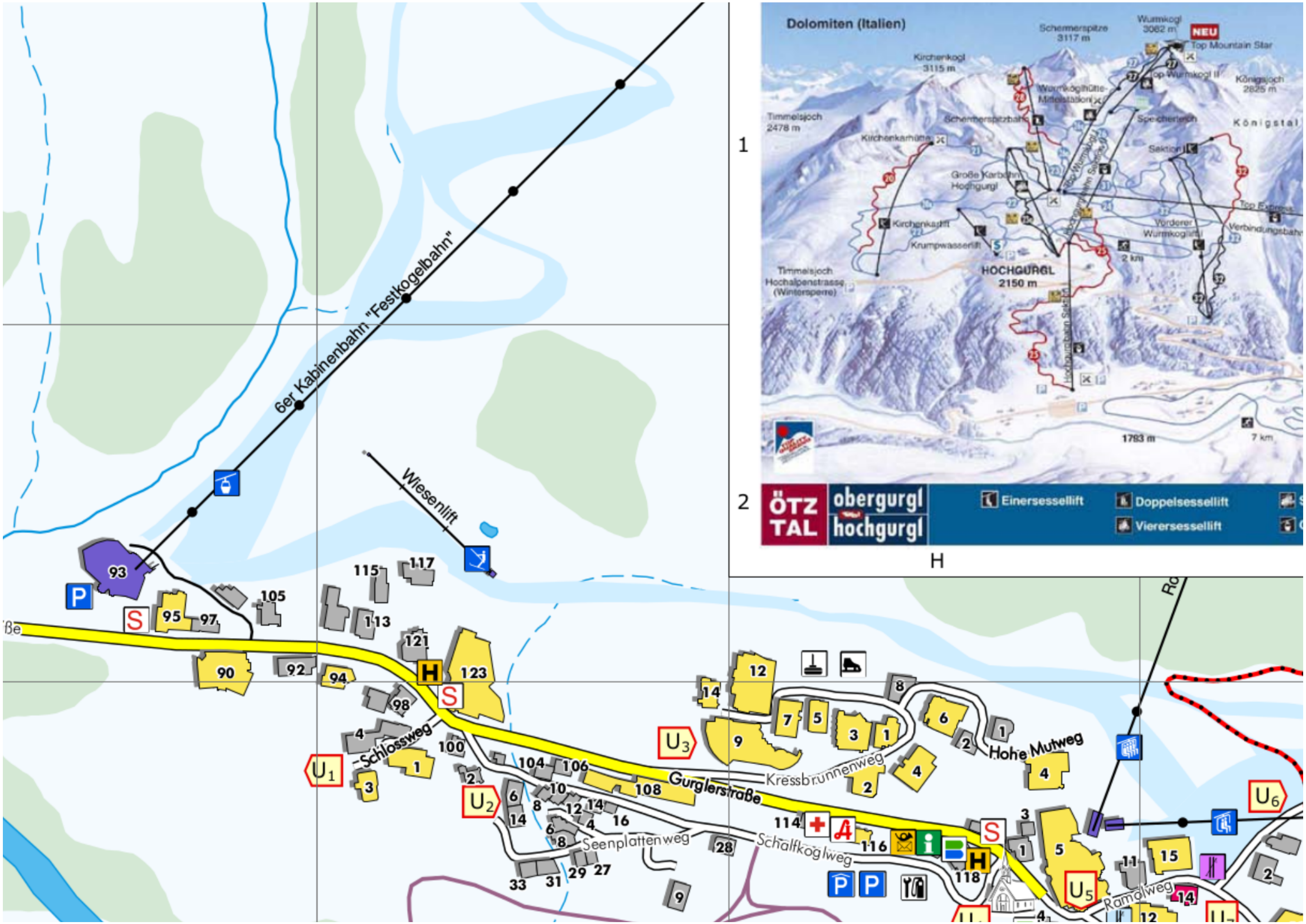
Jonas von Milczewski
Max Planck Institute of Quantum Optics
jvmilczewski@mpq.mpg.de

We study theoretically the phase diagram of strongly-coupled two-dimensional Bose-Fermi mixtures interacting with attractive short-range potentials as a function of the particle densities. We focus on the limit where the size of the bound state between a boson and a fermion is small compared to the average inter-boson separation and develop a functional renormalization group approach that accounts for the bound-state physics arising from the extended Fröhlich Hamiltonian. By

including three-body correlations we are able to reproduce the polaron-to-molecule transition in two-dimensional Fermi gases in the extreme limit of vanishing boson density. We predict frequency- and momentum-resolved spectral functions and study the impact of three-body correlations on quasiparticle properties. At finite boson density, we find that when the bound state energy exceeds the Fermi energy by a critical value, the fermions and bosons can form a fermionic composite with a well-defined Fermi surface. These composites constitute a Fermi sea of dressed Feshbach molecules in the case of ultracold atoms while in the case of atomically thin semiconductors a trion liquid emerges. As the boson density is increased further, the effective energy gap of the composites decreases, leading to a transition into a strongly-correlated phase where polarons are hybridized with molecular degrees of freedom. We highlight the universal connection between two-dimensional semiconductors and ultracold atoms and we discuss perspectives for further exploring the rich structure of strongly-coupled Bose-Fermi mixtures in these complementary systems.

Index

Back in 1989 Skiing lessons were mandatory for all conference participants.



6er Kabinenbahn "Festkogelbahn"
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Schlossweg
Gurglerstraße
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Schalfkoglweg
Ramolweg
Dolomiten (Italien)
Schermerspitze 3117 m
Wurmkogl 3082 m
NEU
Top Mountain Star
Kirchenkogl 3115 m
Königsjoch 2825 m
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			Ensembles	Quantum dynamics	Quantum Gases & Cavities	Quantum Simulation	Quantum Tech	
8.20			*Opening*					
8.30-9.00	Invited		Polzik	Jochim	Brantut	Lukin	Huber	return bus
9.00-9.30	Invited		Schreck	Fickler	Leonard	Yelin	Warburton	return bus
9.30-10:00	Hot topic		Delic	Rabl	Halati	Haslinger	Moeller	
10.00-10.45	Coffee							return bus
10.45-11.15	Invited		Zache	Ropers	Aspelmeyer	Weinfurtner		return bus
11.15-11.45	Hot topic		Diessel	Kucera	Keßler	Pichler	Spagnolo	
12:00-15.30	**lunch break**							
15.30-16.30	**Coffee + Cake**	BUS						
16.30-17.00	Hot topic	BUS	Hunger	Juzeliunas	Ostermann S.	Posters	Ostermann L.	
17:00-17.30	Hot topic	BUS	Bock	Romeu	Finger	Posters	Jerbi	
17.30-18.00	Hot topic	registration	Posters	Posters	Posters	Posters	Posters	
17.30-18.00	**Discussions**	registration	Posters	Posters	Posters	Posters	Posters	
18.00-18.30		registration	Dinner	Dinner	Dinner	Conference	Dinner	
18.30-19.00		Dinner	Dinner	Dinner	Dinner	Dinner	Dinner	
19.00-20.00		Dinner				? Hohe Mut ?		