Quantum Simulation with Engineered Dissipation

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BOOK OF ABSTRACTS

Obergurgl

16-22 February 2025

INVITED SPEAKERS

Probing quantum many-body dynamics using subsystem Loschmidt echo

Monika Aidelsburger

The Loschmidt echo - the probability of a quantum many-body system to return to its initial state following a dynamical evolution - generally contains key information about a quantum system, relevant across various scientific fields including quantum chaos, quantum many-body physics, or high-energy physics. However, it is typically exponentially small in system size, posing an outstanding challenge for experiments. Here, we experimentally investigate the subsystem Loschmidt echo, a quasi-local observable that captures key features of the Loschmidt echo while being readily accessible experimentally. Utilizing quantum gas microscopy, we study its short- and long-time dynamics. In the short-time regime, we observe a dynamical quantum phase transition arising from genuine higher-order correlations. In the long-time regime, the subsystem Loschmidt echo allows us to quantitatively determine the effective dimension and structure of the accessible Hilbert space in the thermodynamic limit. Performing these measurements in the ergodic regime and in the presence of emergent kinetic constraints, we provide direct experimental evidence for ergodicity breaking due to fragmentation of the Hilbert space. Our results establish the subsystem Loschmidt echo as a novel and powerful tool that allows paradigmatic studies of both non-equilibrium dynamics and equilibrium thermodynamics of quantum many-body systems.

Exploring self-ordered phases of Fermions in high-finesse cavities

Jean-Philippe Brantut

I will present our investigations of self-ordering in a Fermi gas with simultaneous and independent control over light-matter and atom-atom interactions. First, I will show that the interplay of the two leads to a strong coupling between Fermion pairs and photons at photo-association transition, such that the ordered phase acquires a pair-density wave character. Second, I will describe direct, in-situ imaging of density-waves in the Fermi gas, allowing us to observe the correlations between atomic and photonic degrees of freedom.

Universal Phenomena in Time Crystals

Sebastian Diehl

Time crystals are states of matter with spontaneously broken time-translation symmetry, a phenomenon impossible at thermodynamic equilibrium but enabled when detailed balance is violated. They appear in diverse systems, from many-body quantum optics to active matter. We show that at the critical point for time crystalline order, even infinitesimal deviations from equilibrium drive the system to a novel non-equilibrium fixed point, defining a new universality class with a universally divergent effective temperature. In the time crystalline phase, the collective Goldstone mode of broken time translations universally leads to robust realizations of Kardar-Parisi-Zhang physics in any dimension. These insights open pathways to activating quantum matter in platforms such as exciton-polaritons, magnon condensates, and solid-state ferrimagnets, where weak non-equilibrium drives induce strong macroscopic effects absent in equilibrium.

Collective radiation of laser-driven atoms in a high-finesse cavity

Peter Domokos

By considering linear scattering of cold atoms inside an undriven high-finesse optical resonator, we experimentally demonstrate effects unique to a strongly coupled vacuum field. Arranging the atoms in an incommensurate lattice, with respect to the resonator mode, the scattering can be suppressed by destructive interference: resulting in a subradiant atomic array. We show however, that strong collective coupling leads to a drastic modification of the excitation spectrum, as evidenced by well-resolved vacuum Rabi splitting in the intensity of the fluctuations. Furthermore, we demonstrate a significant polarization rotation in the linear scattering off the subradiant array via Raman scattering induced by the strongly coupled vacuum field.

Cavity control of phase transition in complex quantum materials

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The physical properties of many complex Quantum Materials (QM), such as transition metal oxides, stem from intricate electron, phonon, and magnon interactions. These materials are highly responsive to external factors like pressure, doping, magnetic fields, and temperature, resulting in complex phase diagrams. These allow for switching between different macroscopic functionalities through fine-tuned control parameters. QM's responsiveness also makes them ideal for experiments where tailored electromagnetic fields lead to novel, sometimes exotic, physical properties. Time-domain studies have shown that ultrashort mid-IR pulses can induce quantum coherent states.

In this presentation, I will explore controlling macroscopic properties of quantum materials by integrating them into resonant optical cavities. This involves examining the effects of vacuum fluctuations and how cavity embedding alters energy exchange with the thermal electromagnetic environment. I will discuss the impact of strong and weak coupling to cavity modes in 1T-TaS2, a material for Charge Density Wave systems and present our recent discovery of cavity thermal control over the metal-insulator transition and the sensitivity of vibrational coupling to the cavity mode structure. Finally, I will discuss the potential of cavity electrodynamics to sustain non-equilibrium stationary states in complex matter.

Waveguide QED with Unconventional Band Structures and Autonomous Stabilization of Floquet States in Superconducting Circuits

Alicia J. Kollár

January 13, 2025

Abstract

The field of superconducting circuits has emerged as a rich platform for both quan-tum computation and quantum simulation. Due to the native strong qubit-photon interactions, these systems can be used to study dynamical phase transitions, many-body phenomena, and spin models in driven-dissipative systems. Temporal control can be used to implement synthetic dimensions and lattices of coplanar waveguide (CPW) resonators realize artificial photonic materials in the tight-binding limit. I will present data from two new experiments, one featuring qubits in an unconventional flat-band lattice, and a second showing that static dissipation can be used to stabilize quasienergy states of a time-periodic Floquet Hamiltonian.

Non-equilibrium as a resource: Non-thermal steady-states of cavity-quantum-materials

Francesco Piazza

Coupling a system to two different baths can lead to novel phenomena escaping the constraints of thermal equilibrium. In quantum materials inside optical cavities, this feature can be exploited as electrons and cavity-photons are easily pulled away from their mutual equilibrium, even in the steady state. This offers new routes for a non-invasive control of material properties and functionalities. Motivated by recent experimental puzzles arising with transition-metal-dichalcogenides inside Fabry-Perot cavities, we show how the absence of thermal equilibrium between electrons and photons leads to qualitative modifications of the material's properties in two different ways: 1) the electron distribution shows enhanced fluctuations near the Fermi surface due to the breaking of detailed balance; 2) the scattering between electrons in the steady state acquires a genuinely non-thermal component which can for instance enhance the tendency to pair and become superconducting.

Highly-Entangled Stationary States from Strong Symmetries

Frank Pollmann

We find that the presence of strong non-Abelian conserved quantities can lead to highly entangled stationary states even for unital quantum channels. We derive exact expressions for the bipartite logarithmic negativity, Rényi negativities, and operator space entanglement for stationary states restricted to one symmetric subspace, with focus on the trivial subspace. We prove that these apply to open quantum evolutions whose commutants, characterizing all strongly conserved quantities, correspond to either the universal enveloping algebra of a Lie algebra or to the Read-Saleur commutants. The latter provides an example of quantum fragmentation, whose dimension is exponentially large in system size. We find a general upper bound for all these quantities given by the logarithm of the dimension of the commutant on the smaller bipartition of the chain. As Abelian examples, we show that strong U(1) symmetries and classical fragmentation lead to separable stationary states in any symmetric subspace. In contrast, for non-Abelian SU(N) symmetries, both logarithmic and Rényi negativities scale logarithmically with system size. Finally, we prove that while Rényi negativities with $n>2$ scale logarithmically with system size, the logarithmic negativity (as well as generalized Rényi negativities with $n<2$) exhibits a volume law scaling for the Read-Saleur commutants. Our derivations rely on the commutant possessing a Hopf algebra structure in the limit of infinitely large systems, and hence also apply to finite groups and quantum groups.

Entanglement generation in driven-dissipative cavities via strong symmetries

Ana Maria Rey Ayala

Probing non-equilibrium critical phenomena in clean and pristine situations can help us shed light on novel emergent behaviors. I will discuss the use of long-live dipoles in an optical cavity as an ideal system to study a prototype driven-dissipative model explored theoretically since the 1970s under the name of cooperative resonance fluorescence, describing an ensemble of coherently driven dipoles, all collectively emitting light by coupling to common radiation mode. I will discuss the experimental observation of its non-equilibrium phase diagram as a first step towards finer control of driven-dissipative systems featuring long-lived coherences such as boundary time crystals and robust entangled states for quantum sensing . By transferring population to an additional level I will also discuss a way to dynamically generate metrologically useful spin-squeezed states. In contrast to other dissipative approaches, in this case we do not rely on complex engineered dissipation or input states, or on tuning the system to a critical point. Instead, we utilize a strong symmetry, a special type of symmetry that can occur in open quantum systems and emerges naturally in systems with collective dissipation, such as superradiance.

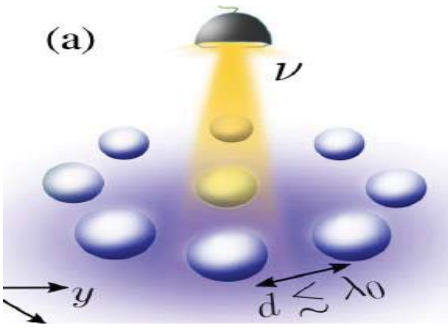
Engineered quantum dynamics in dipole coupled nano arrays of quantum emitters

Helmut Ritsch

Theoretical Physics, University of Innsbruck

An array of closely spaced, dipole coupled quantum emitters exhibits collective energy shifts as well as super- and sub-radiance with characteristic tailorable spatial radiation patterns. As a striking example we identify a sub-wavelength sized ring of exactly 9 identical dipoles with an extra identical emitter with a extra loss channel at the center as the most efficient configuration to deposit incoming photon energy to center without reemission. For very tiny structures below a tenth of a wavelength a full quantum description exhibits an even larger enhancement than predicted from a classical dipole approximation. Adding gain to such systems allows to design minimalistic classical as well as non-classical light sources.

On the one hand this could be the basis of a new generation of highly efficient and selective nano antennas for single photon detectors for microwaves, infrared and optical frequencies, while on the other hand it could be an important piece towards understanding the surprising efficiency of natural light harvesting molecules.



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Making and Probing Quantum Fluids of Light: Mott Insulators, Superfluids, and Cats

Jonathan Simon

In this talk I will describe work in the Simon/Schuster collaboration exploring strongly correlated fluids of states of light. Beginning with an introduction to the analogy between photons in a lattice of cavities and electrons in the ionic lattice comprising a solid, I will focus in on our explorations of such physics in a superconducting quantum circuit, where we have demonstrated the ability to build crystals of light using reservoir engineering, and more recently, adiabatic preparation of fluids. I will then extend the adiabatic preparation protocol to an qubit-controlled protocol, where we entangle the state of the fluid with the state of a qubit. By subsequently undoing this entanglement and sandwiching this entanglement/disentanglement sequence within a Ramsey protocol commonly employed in atomic clocks, we are able to learn about the manybody system through the auxiliary qubit. We use this new tool as a thermodynamic probe of the manybody system, and even enhance its coherence through manybody spin-echo. This work will lead us to the question: can small quantum computers fundamentally change how we probe materials?

Quantum Simulation and Sensing with Matter wave Interferometers and Clocks

James Thompson

Laser-cooled atoms in a high-finesse optical cavity are a powerful tool for quantum simulation and quantum sensing. The optical-cavity enhances the light-matter interaction, mediating effective atom-atom interactions and probing of the quantum state below the mean-field level. In this talk, I will provide an overview of my group's recent experimental work in this area. We perform cavity-enhanced quantum non-demolition measurements to create highly-entangled states [1], with the first realization of a squeezed matter wave interferometer for inertial sensing [2] and a squeezing-enhanced differential strontium optical lattice clock comparison [3]. We have also realized cavity-mediated momentum-exchange interactions that give rise to a collective recoil mechanism with analogies to Mössbauer spectroscopy for suppressing Doppler dephasing in matter wave interferometers [4] and on optical transitions [5]. We have realized 3 and 4-body interactions [6] as well as arbitrary XYZ Hamiltonian engineering in a matter wave interferometer, including realizing two-axis counter twisting for the first time since its proposal more than 30 years ago [7]. We have utilized spin-exchange interactions [8] to explore several dynamical phase transitions [9] including an emulation of long-predicted dynamical phases of a BCS superconductor [10, 11]. If time permits, I will lastly briefly touch on the observation of a dissipative superradiant phase transition [12] and truly continuous lasing between momentum states [13].

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Quenching dynamics of ultracold interacting Fermi gases

Haibin Wu[*1], **Shujin Deng** [1]

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Understanding the non-equilibrium dynamics of complex quantum systems with strong interactions is one of the most challenging problems in modern manybody physics, which is crucial for solving many fundamental problems in physics, such as establishing important connections with the early evolution of quark gluon plasma, neutron stars, and the Big Bang. In this talk we will present our recent experimental progress of quenching dynamics of ultracold Fermi gases, including two sets of experiments of quenching a cavity-mediated long-range interaction over a quantum phase transitions and quenching an s-wave interaction to unitarity [1,2].

References

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Quantum simulation and quantum optics with atom arrays

Johannes Zeiher

Neutral atoms trapped in optical lattices and optical tweezers are a versatile platform for quantum simulation of many-body systems and for realizing quantum optical interfaces. In this talk, I will report on our recent progress on realizing large-scale neutral-atom arrays with microscopic single-atom control. In particular, I will present our efforts on loading, cooling, and imaging individual strontium atoms in a new experimental setup that combines optical lattices with local control achieved through optical tweezers. Using optical lattices as pinning potentials, we obtain high-fidelity and low-loss imaging performance under repulsive Sisyphus-cooling. Leveraging the unique combination of lattice and tweezers and the high-fidelity imaging in our setup, we demonstrate a novel scheme to iteratively assemble and continuously maintain large-scale atom arrays. This approach paves the way to scale tweezer-based quantum simulators to larger system sizes and provides an alternative preparation route of Hubbard systems in optical lattices without the need for evaporation.

In the second part of the talk, I will report on our progress on realizing a novel experimental platform aimed at coupling an atom array to a high-finesse optical resonator, with the goal to perform fast, non-destructive state readout of individual atoms through the cavity. This platform opens new perspectives on remote entanglement generation in optical tweezer arrays, or quantum simulation of open system dynamics.

Topological classification of driven-dissipative nonlinear systems

Oded Zilberberg

Topological classification of matter has become crucial for understanding the linear response of (meta-)materials, with associated quantized bulk phenomena and robust topological boundary effects. nonlinear systems, topological phenomena recently garnered significant interest. In particular, weak nonlinearities can result in parametric gain, leading to "non-Hermitian" metamaterials and the associated topological classification of open systems. Here, we venture into this expanding frontier using an moves away from quasilinear approximations around the closed system classification. To this end, we the topology of structurally stable vector flows, and thus propose a new topological graph invariant to characterize nonlinear out-of-equilibrium dynamical systems via their equations of motion. We exemplify approach on the ubiquitous model of a dissipative bosonic Kerr cavity, subject both to one- and two-drives. Using our classification, we can identify the topological origin of phase transitions in the system, as explain the robustness of a multicritical point in the phase diagram. We, furthermore, identify that the invariant distinguishes population inversion transitions in the system in similitude to a Z2 index. Our spans across the classical-to-quantum regimes, and extensions to coupled nonlinear cavities are postulated.

HOT TOPIC SPEAKERS

Nonreciprocal phase transitions in active quantum spins

Matteo Brunelli

Nonreciprocal interactions, in which an agent A attracts another agent B while B repels A, lead to exciting phenomena in classical systems, such as novel phase transitions and time-crystal behavior. Whether such phenomena can emerge in quantum many-body systems remains an open question. In this talk, I will present a model of two species of driven quantum spins featuring attraction-repulsion type interactions, analogous to predator-prey dynamics [1]. The model can be realized with two atomic ensembles coupled via chiral waveguides. In the thermodynamic limit, nonreciprocal interactions result in a nonreciprocal phase transition into time-crystalline states [2], associated with spontaneous breaking of parity-time symmetry. For a finite number of spins, signatures of the time-crystal phase can still be observed by examining equal-time or two-time correlation functions. Continuous monitoring of the waveguide's output field also induces a time-crystal state in finite-size systems, where parity-time symmetry is spontaneously broken, and the corresponding quantum trajectories reveal quantum traveling-wave states.

[1] T Nadolny, C Bruder, M Brunelli, Nonreciprocal synchronization of active quantum spins, arXiv:2406.03357 (accepted in PRX)

[2] M Fruchart, R Hanai, PB Littlewood, V Vitelli, Non-reciprocal phase transitions, Nature 592, 7854 (2021)

In situ observation of density-wave ordering in strongly interacting Fermi gases

Tabea Bühler

We study quantum many-body phenomena in strongly correlated Fermions. A hybrid setup of ^{6}Li atoms, cooled to the degenerate regime, and a high-finesse optical cavity makes it possible to implement fundamentally different types of interactions and control their strength. This gives rise to phase transitions such as the transition to a density-wave ordered state [1]. The poster focuses on the recent advances on the in situ observation of density-wave ordering, by means of resonant high-intensity absorption imaging. We show the extraction of spatial and local information about the density modulation of the gas, enabled by an optical microscopy setup with a numerical aperture of 0.39. By quantifying the density modulation contrast, we obtain direct information about the order parameter of the studied phase transition. Furthermore we investigate the correlation between atomic and photonic signatures of the density-wave ordering phase transition, where we record amplitude and phase of the photonic signal by means of a heterodyne detection setup. Lastly, the poster provides an outlook on future studies enabled by the imaging optics setup, as for example the study of spatial arrangement in the density-wave ordered state in strongly interacting, spin-imbalanced gases.

[1]: Helson, V., Zwettler, T., Mivehvar, F. et al. Density-wave ordering in a unitary Fermi gas with photon-mediated interactions. Nature 618, 716–720 (2023). https://doi.org/10.1038/s41586-023-06018-3

Observation of universal dissipative dynamics in strongly correlated quantum gases

Wenlan Chen

Dissipation is unavoidable in quantum systems. It usually induces decoherence and changes quantum correlations. To access the information of strongly correlated quantum matters, one has to overcome or suppress dissipation to extract the underlying quantum phenomena. However, here we find an opposite effect: dissipation can be utilized as a powerful tool to probe the intrinsic correlations of quantum many-body systems. Applying highly-controllable dissipation in ultracold atomic systems, we observe universal dissipative dynamics in strongly correlated one-dimensional quantum gases. The total particle number of this system follows a universal stretched-exponential decay, and the stretched exponent measures the anomalous dimension of the spectral function, a critical parameter that characterizes strong quantum fluctuations and imposes great experimental challenges in measurements. This method could have broad applications in detecting strongly correlated features, including spin-charge separations and Fermi arcs in quantum materials.

Optical response and superradiance in driven excitonic condensates

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Bilayer materials hosting interlayer excitons—comprising of electrons in one layer and holes in the other—are a promising experimental platform for realising high-temperature condensate and studying their dynamical properties. Imposing a chemical potential bias, either through optical pumping or electrical contacts, drives exciton condensates into distinct dynamical regimes. We investigate how these regimes manifest in emitted light and how they are influenced by placing the material within an optical cavity.

We show that in a bilayer system where charge can tunnel between the layers, the chemical potential bias means that an exciton condensate is in the dynamical regime of the Josephson effect. By increasing the bias voltage, the system undergoes a transition from the phase-trapped to phase-delocalized dynamical condensation. Optical spectroscopy can identify these phases, with a strong response to weak fields near the transition due to the instability in the order parameter dynamics [1].

If such a system is placed in an optical cavity within the phase-trapped regime, coupling to photons favours a superradiant state. The phenomenon allows the device to convert DC current into coherent photons at tunable frequencies determined by the bias and material thickness. These findings highlight mechanisms to control and harness excitonic condensates for optoelectronic applications [2].

[1] Alexander Osterkorn, Yuta Murakami, Tatsuya Kaneko, Zhiyuan Sun, Andrew J Millis, Denis Golež, arXiv:2410.22116.

[2] Zhiyuan Sun, Yuta Murakami, Fengyuan Xuan, Tatsuya Kaneko, Denis Golež and Andrew J. Millis PRL 133, 217002 (2024).

Controlling the dynamics of atomic correlations via the coupling to a dissipative cavity

Catalin-Mihali Halati

We analyze the non-equilibrium dynamics in an open system composed by a quantum gas of bosons in a lattice interacting via both contact and global interactions. We discuss several dynamical features stemming from to the quantum nature of the cavity field and the fluctuations in the atoms-cavity coupling, using numerically exact simulations based on novel matrix product states implementations. Firstly, we report the onset of periodic oscillations of the atomic coherences exhibiting hallmarks of synchronization after a quantum quench. The dynamical behavior exhibits the many-body collapse and revival of atomic coherences and emerges from the interplay of the quantum dissipative nature of the cavity field and the presence of a (approximate) strong symmetry in the dissipative system. We further show that the approximate symmetry can dynamically self-organize. We argue that the approximate symmetry can be tailored to obtain long-lived coherences. These insights provide a general recipe to engineer the dynamics of globally-interacting systems. Furthermore, we investigate the spreading of the atomic density-density correlations and we show how the instantaneous propagation of correlations via the cavity field contributes to the melting of the light-cone behavior as one increases the atoms-cavity coupling strength.

Injection locking of a continuous time crystal

H. Keßler[*1], **P. Kongkhambut** [1], **A. Bölian**[1] **J. Skulte** [1,2], **L. Mathey** [1,2], **J. G. Cosme** [3], **A. Hemmerich** [1,2],

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Discrete (DTCs) and continuous time crystals (CTCs) are novel dynamical many-body states, that are characterized by robust self-sustained oscillations, emerging via spontaneous breaking of discrete or continuous time translation symmetry. DTCs are periodically driven systems that oscillate with a subharmonic of the drive, while CTCs are driven continuously and oscillate with a system inherent frequency. Here, we explore a phase transition from a continuous time crystal to a discrete time crystal. A CTC with a characteristic oscillation frequency ω_{CTC} is prepared in a continuously pumped atom-cavity system [1]. Modulating the pump intensity of the CTC with a frequency ω_{dr} close to 2 ω_{CTC} leads to robust locking of ω_{CTC} to $\omega_{\mathrm{dr}}/2$, and hence a DTC arises [2]. This phase transition in a quantum many-body system is related to subharmonic injection locking of non-linear mechanical and electronic oscillators, lasers or entrainment in biological systems.

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Cavity-induced phenomena: from quantum phase transitions and cat states to cavity-enhanced superconductivity

Valerii Kozin

We begin by discussing the behavior of two double quantum dots coupled to a cavity mode, focusing on the emergence of cavity-induced quantum phase transitions, which manifest in both continuous and discontinuous forms due to the interplay between cavity-mediated and Coulomb interactions. This interplay leads to the formation of cat states, which are potential candidates for quantum computing. In the second part, we delve into the enhancement of superconductivity in a two-dimensional electron gas coupled with a quantized cavity mode, where increased coupling strength linearly raises the superconducting gap, potentially observable via scanning tunneling microscopy.

Superradiance of strongly interacting dipolar excitons in moiré quantum materials

Jan Kumlin

Moiré lattices created in two-dimensional heterostructures exhibit rich many-body physics of interacting electrons and excitons and, at the same time, suggest promising optoelectronic applications. Here, we study the cooperative radiance of moiré excitons that is demonstrated to emerge from the deep subwavelength nature of the moiré lattice and the strong excitonic onsite interaction. In particular, we show that the static dipole-dipole interaction between interlayer excitons can strongly affect their cooperative optical properties, suppressing superradiance of disordered states while enhancing superradiance of ordered phases of moiré excitons. Moreover, we show that doping permits direct control of optical cooperativity, e.g., by generating supperradiant dynamics of otherwise subradiant states of excitons. Our results show that interlayer moiré excitons offer a unique platform for exploring cooperative optical phenomena in strongly interacting many-body systems, thus, holding promise for applications in quantum nonlinear optics.

Emergence of unidirectionality and phase separation in optically dense emitter ensembles

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We examine emergent dissipative non-equilibrium phenomena arising from the interaction between light and an optically dense ensemble of two-level emitters in a one-dimensional geometry. Our study investigates the transition between two emblematic models of Quantum Optics – the driven-dissipative Dicke model and the Maxwell-Bloch equations – through the framework of a parent spin model describing bidirectional waveguide quantum electrodynamics (QED). By varying system parameters such as spatial disorder, optical depth, and external driving strength, we identify distinct phases and phase separations in the emitters' inversion and dipole correlations as well as in the properties of transmitted and reflected light [1]. Employing higher-order cumulant expansion, beyond mean-field theory, allow us to infer squeezing spectra and photon anti-bunching in regimes of strong driving, which are inaccessible through exact few-photon wave-function calculations [2].

References

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Exploring the dynamical and ground state properties of 1D anyons

J. Kwan, P. Segura, Y. Li, S. Kim, B. Bakkali-Hassani,
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Low-dimensional quantum systems can host anyons, particles with exchange statistics that are neither bosonic nor fermionic. Despite indications of a wealth of exotic phenomena, the physics of anyons in one dimension (1D) remains largely unexplored. In this work, we realize Abelian anyons in 1D using ultracold atoms in an optical lattice, where we implement the statistical parameter via a density-dependent Peierls phase [1]. Our scheme, based on Floquet engineering, allows for arbitrary exchange statistics and tunable interactions, which we leverage to explore the dynamical behavior of two anyons undergoing quantum walks. We observe the anyonic Hanbury Brown-Twiss effect and the formation of bound states without effective on-site interactions. Then, once interactions are introduced, we observe spatially asymmetric transport in contrast to the symmetric dynamics of bosons and fermions.

Next, we explore the ground state behavior of 1D anyons via adiabatic state preparation, ramping Hubbard parameters to connect an initial Fock state to a target ground state of two anyons. As we tune the statistical phase from 0 to π, we observe fermionization manifesting as the gradual buildup of Friedel oscillations in the density profiles [2]. These ground states also host chiral bound states, which we probe by manipulating the expansion dynamics. Our work expands the toolset for Hamiltonian engineering, and enables the experimental exploration of the many-body phenomena of 1D anyons, such as the statistically-induced Mott insulator to superfluid phase transition [3] and a novel two-component superfluid [4].

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Dynamics in 1D quantum wires, Anyonization of bosons and many-body dynamical localization

Manuele Landini

I will present our latest results on strongly interacting one-dimensional systems. In particular, I will report on the observation of an asymmetric momentum distribution, hallmark of anyonic correlations, resulting from the acceleration of a spin impurity in the system. A hard-core interacting anyonic model describes the charge degrees of freedom of the system at finite momentum and the momentum distribution of the impurity mirrors the one of the charge system. This mapping provides a powerful tool for the observation of the properties of anyonic systems in and out of equilibrium. In the second part of the talk, I will present results related to the observation of dynamical localization in an interacting kicked Lieb Liniger model. Localization in this system has been the subject of debate both on the theory and experimental side. Our observations show clearly that the one dimensional system localizes for any value of interaction we are able to reach. I will briefly report on the prospects regarding the interfacing between Yb tweezer arrays and multimode cavities under development in our group.

Mesoscopic fluctuations in entanglement dynamics

Lih-King Lim

Central to the new frontiers of many-particle quantum physics is the time evolution of entanglement. Stemming from various dynamical processes of information, fluctuations in entanglement evolution differ conceptually from out-of-equilibrium fluctuations of traditional physical quantities. We report a counterintuitive fundamental result in the dynamics of quantum entanglement that connects two seemingly unrelated fields, mesoscopic fluctuations in electronic systems and entanglement dynamics. The underpinning of such phenomenon is an emergent random structure in the evolution of the many-body wavefunction in two classes of integrable --- either free fermions or interacting spins --- lattice models. For each class, it leads to a universal scaling law for the variance in the long-time statistics of entanglement evolution, and the full distribution displays a sub-Gaussian upper and a sub-Gamma lower tail. These statistics are independent of both the system's microscopic details and the choice of entanglement probes. Our results have practical implications for controlling entanglement in mesoscopic devices and lay a theoretical foundation for understanding fluctuations observed in experiments using various quantum simulation platforms.

Ref: Lih-King Lim, Cunzhong Lou, Chushun Tian, Nat. Commun. 15, 1775 (2024).

Bragg spectroscopy of a dissipation-induced instability in an atom-cavity system

Gabriele Natale

In recent years, ultra-cold atom research has driven significant advancements in quantum optics, condensed matter physics, and quantum information processing, leading to the discovery of novel states of matter and new quantum simulation platforms. While many studies have focused on weakly interacting, short-range systems, there is a growing interest in systems with long-range interactions, especially those involving dissipation, which leads to complex dynamics. Understanding these systems can reveal new quantum phenomena and advance both quantum technology and fundamental physics.

Our experiment investigates the collective phenomena of a Bose-Einstein Condensate (BEC) of rubidium atoms trapped in two crossed high-finesse cavities. The coupling between the BEC and the cavity produces long-range interactions, resulting in two roton-like excitation modes corresponding to exotic superradiant phases [1,2]. The tunability of our system allows us to examine a parameter regime where the energy of these two modes would cross in a closed system. However, the inherent dissipation makes the fate of these two modes less trivial. To reveal the evolution of these modes, we performed Bragg spectroscopy measurements. We observed the coalescence of the two modes when their energies are close, leading to a dissipation-induced instability. Moreover, we studied the individual softening of the modes as they approach their respective phases, along with a diverging susceptibility.

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Photon BECs in dye-filled microcavities and VCSELs

A. Pelster[*1]
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The talk provides an overview of current theoretical challenges for describing a photon Bose-Einstein condensate (BEC), which represents a modern prime example for an open dissipative quantum many-body system. In the original experimental platform of dye-filled microcavities [1] the technique of direct laser writing [2] allows to microstructure potentials with different geometries on the mirror surfaces. In this way soon lattices of coupled photon condensates containing hundreds of individual sites are realizable, which are expected to have spiral vortices [3]. We show that their shape can be approximately determined analytically with a projection optimization method, which extends the variational optimization method for BECs of closed systems to open-dissipative condensates [4]. Furthermore, quite recently photon BECs have also been observed in vertical cavity surface-emitting lasers (VCSELs) [5–7]. Here frequent photon absorption and emission processes occur due to the creation and annihiliation of excitons in the semiconductor device, yielding a thermalization of photons. But it was found experimentally that the extracted spectral temperatures are significantly lower than those of the device, which warrants a theoretical explanation.

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Fate of the Fermi surface in a non-homogeneous cavity field

Michele Pini

The experimental realization of driven ultracold Fermi gases in optical resonators provides interesting new platforms to study unconventional quantum phases of matter induced by long-range cavity-mediated interactions. So far, mostly superradiant instabilities accompanied by a density wave of the fermions have been studied in these systems. Here, we report instead on pairing and exchange instabilities, solving the competition problem within a controlled perturbative approach by exploiting the long-range nature of the cavity-mediated interaction. For a spin-polarized Fermi gas, we show that its Fermi surface gets reshaped and the system undergoes a phase transition to a Cooper/pair density wave superfluid, independently of the sign of the interaction coupling. This allows to observe the pairing instability for repulsive interactions, where the superradiant instability is absent. Therefore, the system paves the way to interesting experimental implementations.

Quantum-limited measurements for open quantum simulators with tunnel-coupled superfluids

Maximilian Prüfer

Quantum measurements are usually realized by coupling an isolated quantum system to an auxiliary meter system. Thus, weak, repeated measurements present an intriguing pathway toward controlled open quantum simulators. We present a quantum-limited generalized measurement scheme for tunnel-coupled superfluids. Our results reveal the capability to detect quantum properties and dynamical evolution [1]. Finally, we will discuss progress toward achieving repeated or continuous measurements with local control, aiming to create controllable open quantum simulators in the future.

[1] Prüfer, M., Minoguchi, Y., et al., arXiv 2408.07002 (2024)

Towards cavity-mediated entanglement within an atomic array

Johannes Schabbauer

Creating multi-particle entangled states deterministically is one of the big challenges for quantum information processing. While this was achieved locally in several systems, for instance with arrays of optical tweezers using Rydberg interactions between atoms, we set up an experiment to engineer non-local interactions between single atoms in optical tweezers by strong coupling to an optical cavity. In our experiment we reach the single-atom strong-coupling regime using a fiber cavity (C=80). Our cavity setup also enables good optical access for high-resolution microscopes, which are used for trapping, site-resolved imaging and addressing of single atoms in optical tweezers. Our experiment enables us to study multi-particle entangled states and many-body systems with programmable interactions. The dispersive shift of the cavity resonance can be used to perform non-destructive measurements and to implement protocols for dissipative state preparation.

Generalized Zeno effect and entanglement dynamics induced by fermion counting

Lukas Sieberer

Repeated projective measurements induce the quantum Zeno effect, the freezing of the evolution of a quantum system in an eigenstate of the measured observable. For local observables in a many-body system, these eigenstates exhibit area-law scaling of the entanglement entropy. The quantum Zeno effect, thus, stabilizes area-law entanglement in many-body systems that would unitarily evolve towards volume-law entanglement in the absence of measurements. But while the freezing of dynamics provides an intuitive explanation for area-law entanglement through repeated measurements, is it also a requirement? We address this question by considering a one-dimensional system of free fermions subjected to a generalized measurement process: The system exchanges particles with its environment, but each fermion leaving or entering the system is counted. In contrast to the freezing of dynamics due to frequent projective measurements, a high rate of fermion counts induces fast fluctuations in the state of the system. Still, instantaneous correlations and entanglement properties of free fermions subjected to local projective measurements and fermion counting are strikingly similar. We explain this similarity through a generalized Zeno effect induced by fermion counting. Furthermore, we find a unifying long-wavelength description of both systems in terms of a nonlinear sigma model, derived in the framework of replica Keldysh field theory. Our analytical predictions are in good agreement with numerical results, showing that both systems exhibit area-law entanglement for any nonzero measurement rate. However, we identify a finite critical range of length scales on which entanglement grows logarithmically and signatures of conformal invariance are observable.

Dissipative realization of Kondo models

Martino Stefanini

The Kondo effect [1] is one of the most iconic phenomena in condensed matter physics, showing how strongly correlated behavior emerges out of simple ingredients: a localized, interacting impurity level coupled to extended reservoirs of free, spinful fermions. Despite being well-known in solid state [1] and with quantum dots [2], its realization in analog quantum simulators with ultracold atoms is not well explored [3]. In this talk, I will present the results of our recent work [4] in which we show how one can harness two-body losses to provide a dissipation-only realization of the Kondo effect. This setup is suitable to transport experiments with ultracold atoms [5], which provide a direct way of revealing the Kondo effect through conductance measurements. We find that if a strong loss is concentrated on one impurity site, the dynamics of the system can be effectively described by an Anderson impurity model with infinite repulsion, perturbed by a small residual dissipation. While the Anderson model gives rise to the Kondo effect, this residual dissipation competes with it, offering an instance of a nonlinear dissipative impurity where the interplay between coherent and incoherent dynamics emerges from the same underlying physical process. We observe this competition in various signatures of the Kondo effect in transport across the impurity. If the losses are concentrated on more than one site and tuned opportunely, our setup is able to reproduce higher-spin versions of the Kondo model. Since the number of fermionic reservoirs can be increased beyond two, our results pave the way to the simulation of exotic phases of higher-spin, multi-channel Kondo models with ultracold atoms.

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Critical dynamics in light-matter coupled systems

Iris Ulčakar[1,2], Gianluca Lagnese[1], Lorenzo Rossi[3], Alexander Poshakinskiy[3], Darrick Chang[3,4], Zala Lenarčič[1]

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Recent advances in quantum simulation are focused on combining matter and light to engineer new types of interactions, typically characterized by long-range effects, requiring the development of advanced numerical simulation techniques. For instance, ordered arrays of atoms placed at distances smaller than the wavelength of light display photo-mediated long-range interactions and a peculiar correlated emission. The main features observed when starting from a highly excited initial state are a superradiant burst at short times, followed by a non-trivial subradiant critical regime with a slow power-law relaxation. By integrating out the photonic degrees of freedom, the dynamics are effectively described by a Lindblad equation with long-range interactions and dissipation. To simulate these dynamics, we employ a recently proposed numerical approach that combines a positive operator-valued measure (POVM) description of the density matrix—approximated by a neural network—with a time-dependent variational principle (TDVP) to project the evolution of the state onto the neural network manifold. From a more physical perspective, by applying a time-dependent Generalized Gibbs Ensemble Ansatz (GGE), we uncover the role of (approximate) integrability at long times, which leads to the observed polynomial decay.

Stabilizing Rényi entropy and entanglement distributions in complex random networks

Angelo Valli

Although it may still be somewhat elusive, quantum complexity is a central theme in quantum computing. Within the framework of quantum resource theory, entanglement and nonstabilizerness (or "magic") play a prominent role in characterizing quantum complexity. Entanglement is regarded as the discriminant for quantumness but it is not exhaustive, as highly-entangled states produced by Clifford circuits can be efficiently simulated classically. The lack of complexity of these states is encoded in the spectral property of the corresponding Clifford circuits [1]. On the other hand, magic — as measured by stabilizer Rényi entropy, quantifies non-Clifford resources required to prepare a quantum state and is pivotal for quantum advantage. We obtain the magic and entanglement distributions by numerically sampling Haar-random circuits. Both distributions are highly concentrated with exponentially suppressed, asymptotically Gaussian fluctuations. Typical Haar states are resourceful in both magic and entanglement [2]. Furthermore, while the two resources are related (e.g., entanglement is instrumental to generating high-magic states) little is known about their relationship. We find that magic- and entanglement- fluctuations are asymptotically independent, as the covariance of the joint distribution is exponentially suppressed, and vanishing in the thermodynamic limit [2]. Our work shed light on the interplay and statistical properties of key quantum resources.

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Entanglement phase transitions in boundary-driven open quantum systems

Darvin Wanish

We present a numerical framework based on tree tensor operators that enables large-scale simulation of out-of-equilibrium open quantum many-body systems and direct access to entanglement monotones. To showcase its utility, we study a paradigmatic open-system problem, the boundary-driven XXZ spin-chain. Our results demonstrate the framework's ability to probe entanglement in open systems and distinguish it from other correlations. Moreover, we uncover entanglement phase transitions driven by both the coupling to the environment and the anisotropy parameter. These transitions reveal an immediate connection between entanglement and spin current, and connect the known transport regimes of the model to distinct entanglement phases, i.e., separable, area-law and volume-law. Our work paves the way toward exploring entanglement in open systems out-of-equilibrium, a necessary step for developing scalable quantum technologies.

Robustness of dissipative quantum algorithms against noise-induced barren plateaus

Elias Zapusek,[1] Ivan Rojkov,[1] and Florentin Reiter[1]

[1] *Institute for Quantum Electronics, ETH Zürich, 8093 Zürich, Switzerland*

Noise is a major hurdle towards practical applications of quantum computing. In parameterized quantum and circuits quantum machine learning, it can lead to noise induced barren plateaus, which limits the depth and therefore system size that can be considered. Specifically, the expectation value of the cost function becomes exponentially concentrated at a noise-induced fixed point and the gradients are exponentially suppressed in the depth of the algorithm [1]. Dissipative algorithms that cool towards many body ground states offer a potential solution [2]. These algorithms leverage nonunitary dynamics to achieve desirable properties, such as stabilizing these states for times beyond a system's coherence time [3]. By parameterizing these algorithms, we unlock a multitude of applications that go beyond quantum simulation. We derive an exact expression for their steady state and demonstrate that there are problems where a unitary learner suffers from noise-induced barren plateaus, while a dissipative learner can avoid them. We verify this analytic result with simulations (see Fig. 1), providing empirical support for our theoretical findings. Dissipative evolution can reduce the entropy of a quantum system, a crucial property in the present pre-fault-tolerant era where errors increase entropy. We demonstrate how this property can be harnessed algorithmically.

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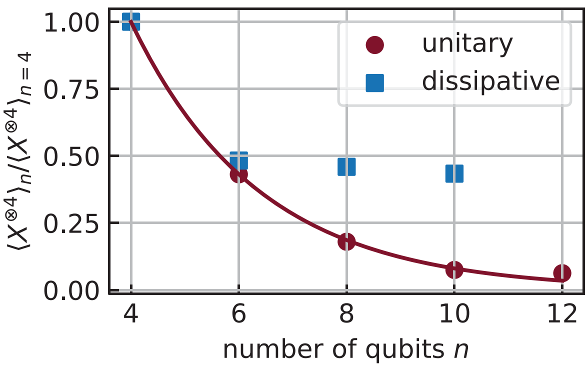

FIG. 1: **Absence of noise induced barren plateaus in dissipative learners** We plot the expectation value of one pauli string after training against the number of qubits. The problem we consider the preparation of Toric code ground states. A unitary circuit requires a depth that scales with $\sqrt{n}$ while depth of individual jumps of the dissipative algorithm is constant. Consequently, the expectation value of the unitary learner exponentially approaches the noise induced fixed point in the number of qubits while the expectation value of the dissipative learner is constant.

DK-ALM

HOT TOPICS

Thursday 20 February 2025

Jessica Hartmann, group Martin Beyer

Reactivity of Sea Salt Aerosols with Atmospherically Relevant Acids in the Gas Phase

J. C. Hartmann, Y. Sheng, S. J. Madlener, C. van der Linde, M. Ončák, C. K. Siu, M. K. Beyer,

As one of the most impactful aerosols in Earth's atmosphere, sea salt aerosols play a significant role in climate processes. Sodium chloride, their main component, is involved in numerous atmospheric processes, including chemical reactions with atmospherically relevant trace gases. These reactions are simulated in our experiments.

We use electrospray ionization (ESI) to produce gas-phase sodium chloride cluster ions. Atmospherically relevant acids, e.g. formic and pyruvic acid, are introduced as reaction gas into the cell of a Fourier transform ion cyclotron resonance mass spectrometer (FT-ICR MS) and reaction kinetics are recorded. We observe a sequential acid uptake by both anions and cations, accompanied by HCl release (Figure 1). These results coincide with the observed reactions of sea salt aerosols with sulfuric or nitric acid in both atmospheric conditions [1] and laboratory studies [2]. Reactivity depends on the gas-phase acidity of the neutral reactant. Furthermore, magic cluster sizes identified in prior studies [3] show a reduced reactivity for each acid used in our experiments.

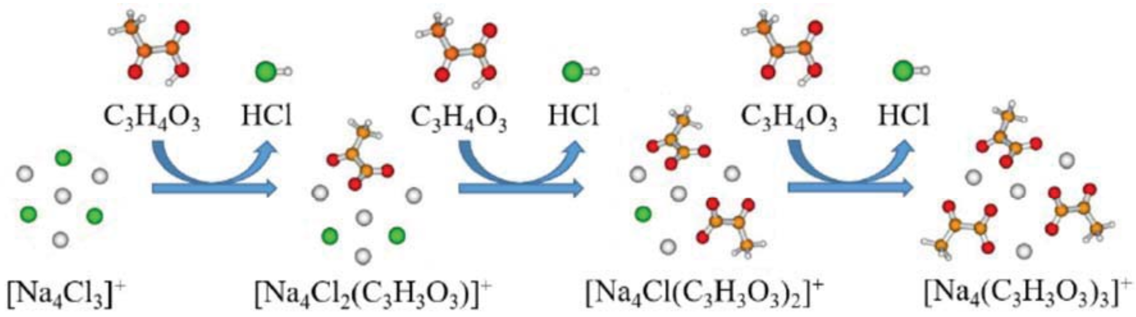

Figure 1: Sequential uptake of pyruvic acid by $[Na_4Cl_3]^+$ with release of HCl.

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Desislava Atanasova, group Gerhard Kirchmair

Novel 3D circuit QED architecture for quantum information processing

Desislava G. Atanasova, Ian Yang, Teresa Hönigl-Decrinis, Daria Gusenkova, Ioan Pop, Gerhard Kirchmair

Superconducting circuits based on 3D architectures offer a way for hardware-efficient quantum information processing. Combined with nonlinearity, a single bosonic mode can replace a multi-qubit register, thus significantly reducing the required control electronics. Compared to their purely planar counterpart, 3D circuits possess longer lifetimes and a straightforward design that eases engineering the interactions in composite systems.

In this work, a superconducting coaxial cavity[1] is coupled to a fluxonium qubit[2] via a readout resonator. The tunability of the qubit, provided by a magnetic flux hose[3], is used to adjust the cavity-qubit interaction in situ. Combined with an element for two-photon dissipation, this setup could be utilized as an improved building block for a fully protected logical qubit.

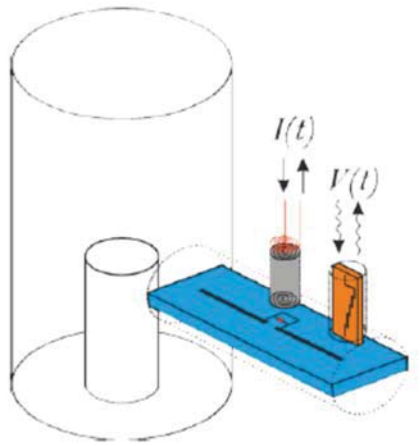

Figure 1: Setup schematic. The system consists of a coaxial cavity (white), fluxonium chip (blue), magnetic flux hose[4] (grey) and a Purcell filter[5] (orange).

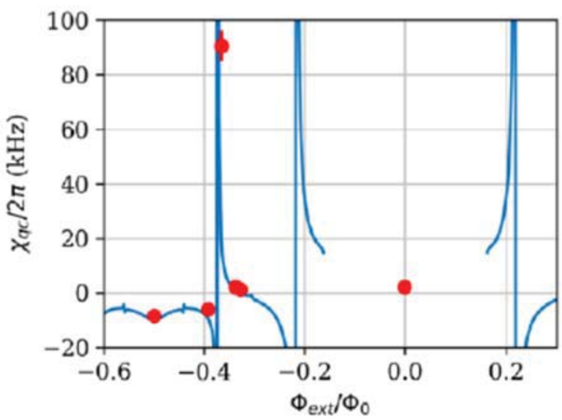

Figure 2: Simulated[4] dispersive shift between the cavity and the qubit as a function of the normalised trapped flux (blue) together with the measured datapoints (red).

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Arfor Houwman & Louis Lafforgue, group Francesca Ferlaino

Control and scattering properties in dipolar spin mixtures

Louis Lafforgue, J.J. Arfor Houwman, Manfred J. Mark, Francesca Ferlaino

Lanthanides, such as erbium and dysprosium, are emerging as valuable resources in quantum-gas science [1]. Among interesting properties, they are known for their large spin manifold in the ground state. To utilize these characteristics, precise control of the spin population and a thorough understanding of collision processes are needed. Here, we demonstrate a novel method for manipulating the spin population by means of a laser tuned to a clock-like transition present in erbium at 1299nm [2]. By applying a sequence of Rabi-pulse pairs we can climb the ladder of Zeeman sublevels and prepare arbitrary superpositions of spin states. This allows us to record Feshbach resonance spectra of various spin mixtures to investigate spin-dependent on- and off-resonant scattering processes. Our results can be used to benchmark quantum scattering calculations, and to identify regions allowing to tune inter- and intraspecies contact interaction. Furthermore, the use of interference between inelastic and elastic loss channels - characterized by a Fano profile in the Feshbach spectra - enables us to create long-lived spin mixtures of bosonic erbium.

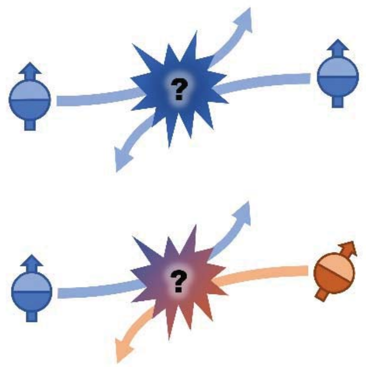

Figure 1: Collisional properties between particles at ultralow temperatures can depend on their internal spin

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Martin Fasser, group Helmut Ritsch

Subradiance and superradiant long-range excitation transport among quantum emitter ensembles in a waveguide

Martin Fasser, Laurin Ostermann, Helmut Ritsch, Christoph Hotter

In contrast to free space, in waveguides the dispersive and dissipative dipole–dipole interactions among quantum emitters exhibit a periodic behavior over remarkably long distances. We propose a novel setup, to our knowledge, exploiting this long-range periodicity in order to create highly excited subradiant states and facilitate fast controlled collective energy transport among far-apart ensembles coupled to a waveguide. For sufficiently large ensembles, collective superradiant emission into the fiber modes dominates over its free space counterpart. We show that, for a large number of emitters, a fast transverse coherent pulse can create almost perfect subradiant states with up to 50% excitation. On the other hand, for a coherent excitation of one sub-ensemble above an overall excitation fraction of 50% we find a nearly lossless and fast energy transfer to the ground state sub-ensemble. This transport can be enhanced or suppressed by controlling the positions of the ensembles relative to each other, while it can also be realized with a random position distribution. In the optimally enhanced case this fast transfer appears as superradiant emission with subsequent superabsorption, yet, without a superradiant decay after the absorption. The highly excited subradiant states, as well as the superradiant excitation transfer, appear as suitable building blocks in applications such as active atomic clocks, quantum batteries, quantum information protocols, and quantum metrology procedures such as fiber-based Ramsey schemes.

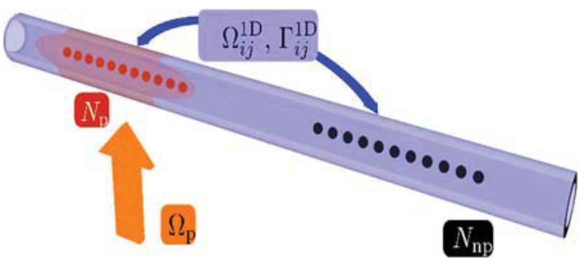

Figure 1: Model of two ensembles of atoms coupled to a waveguide mode.

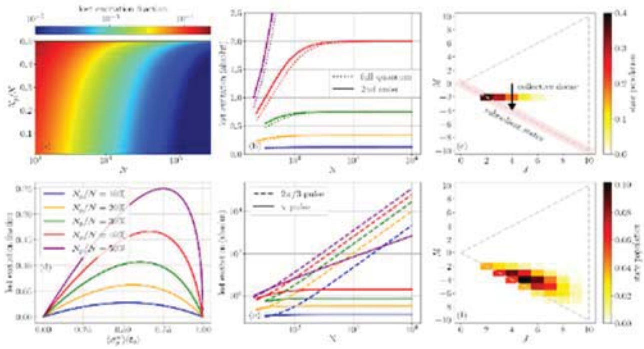

Figure 2: Subradiant states.

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Tommaso Faleo, group Gregor Weihs

Optimised spectral purity from parametric down-conversion via engineered phase matching and pump spectral shaping

Tommaso Faleo, Christopher L. Morrison, Rom´eo Beignon, Francesco Graffitti, Vikas Remesh, Stefan Frick, Alessandro Fedrizzi, Gregor Weihs, Robert Keil

Photonic quantum technologies rely on highly indistinguishable single-photon sources. The primary limitation to achieving near-perfect photon indistinguishability in spontaneous parametric down-conversion (SPDC) sources are spectral correlations between down-converted photons, which typically necessitates spectral filtering. Recent advancements in engineering the effective nonlinearity have significantly reduced these correlations, resulting in spectral purities of 98.6% with bulk KTP crystals using loose spectral filtering [1], where the main limitation for higher purities is associated with a non-Gaussian pump spectrum. Here, we demonstrate an SPDC source that employs both effective nonlinear engineering and spectral shaping of the pump laser pulses to achieve a Gaussian phase matching function (PMF) and a Gaussian pump envelope function (PEF), which theoretically results in the generation of pure down-converted photons [2]. We designed the poling of a group-velocity matched KTP crystal at telecom wavelength to optimise the Gaussian profile of the effective nonlinearity and implemented the Gaussian spectral shaping of a broadband femtosecond-pulsed laser via a 4f pulse shaper and a transmissive spatial light modulator (SLM) to match the spectral width of the PEF to the spectral width of the PMF (see Fig. 1(a)). This configuration theoretically leads to a spectral purity P>99.9% (Fig. 1(b)). Experimentally, we reconstructed the joint spectral amplitude (JSA) using dispersive fibre time-of-flight (TOF) spectroscopy [3] and obtained the purity via Schmidt decomposition. Assuming a flat spectral phase, we measured a spectral purity P>99.8%, without spectral filtering, mainly limited by the residual mismatch of the widths of the PMF and the PEF (see Fig. 1(c)). These results represent a significant advance in the development of high-purity single-photon sources and demonstrate the potential of combined nonlinearity engineering and spectral shaping techniques, providing a way to achieve near-perfect photon indistinguishability.

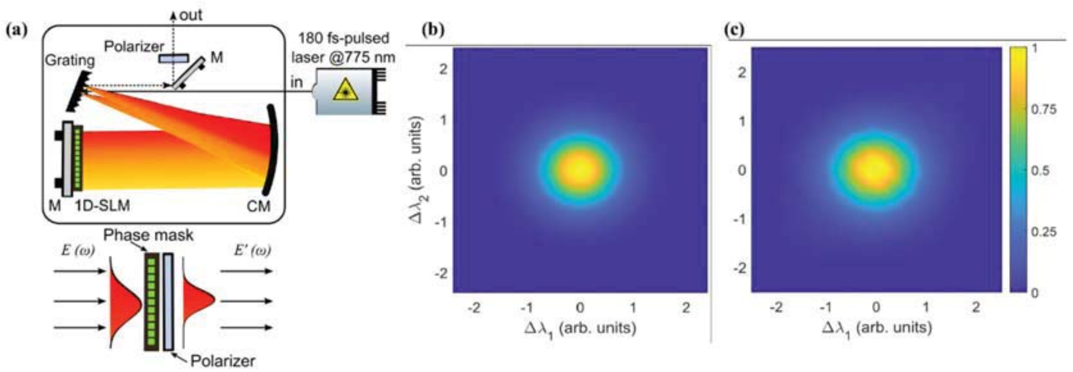

Figure 1: (a) Gaussian spectral shaping of the PEF is achieved through a 4f-pulse shaper based on an intensity-only modulation SLM to match the spectral width of the crystal's PMF. (b) Simulation of the JSA when combining both engineering of the crystal domains and spectral shaping of the pump laser results in near-perfect spectral purity P>99.9%. (c) Experimental TOF reconstruction of the JSA (flat spectral phase) with a measured purity P=99.8%.

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SPECIAL SESSION

Wednesday 19 February 2025

A think-tank for many-body quantum optics

Jamir Marino

An interactive discussion session exploring the future directions and emerging challenges in Atomic, Molecular, and Optical (AMO) physics, with a particular focus on quantum simulation and strongly correlated physics. The session will delve into the impact of drive and dissipation in these systems, addressing theoretical advancements, experimental breakthroughs, and potential applications in quantum technologies. Participants will have the opportunity to engage in thought-provoking discussions, exchange ideas on novel research approaches, and explore interdisciplinary connections that could shape the next generation of discoveries in these fields.

POSTER SESSION

Tuesday 18 February 2025

Floquet engineering counting pump photons

Orjan Ameye

Non-equilibrium many-body systems manifest across multiple physics disciplines. Typically, the problem touches on describing the stationary behaviour of complex models of coupled nonlinear oscillators. In my talk, I will discuss our recently developed framework for describing many-body out-of-equilibrium stationary states, in both the quantum and classical limits. In our approach, we address the shortcomings of the rotating-wave approximation (RWA) for periodically driven oscillators. Specifically, combining the canonical quantum description with the RWA yields incorrect results for finite detuning. Consequently, the standard RWA description is incompatibele with the classical limit [1]. To address this, we introduce an alternative operator basis that reconciles the RWA with off-resonant driving. In doing this, we reconcile the quantum and classical high-frequency expansions.

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Accuracy of time-dependent GGE

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Unitary integrable models typically relax to a stationary Generalized Gibbs Ensemble (GGE), but in experimental realizations dissipation often breaks integrability. These dynamical effects can be modeled in the Markovian limit with the famous Lindblad equation for the density matrix $\hat{\rho}$ In this work, we used the recently introduced time-dependent GGE (t-GGE) approach [1] [2] to describe the open Markovian dynamics of a gas of bosons subject to various diffusion effects. We employed Tensor Network (TN) methods to provide numerical evidence of the exactness of the t-GGE in the limit of adiabatic dissipation, and of its accuracy in the regime of weak but finite dissipation. That accuracy is tested for two-point functions via the rapidity distribution, see Fig 1(left) for an example with simultaneous gain and loss and through a non-Gaussianity measure for more complicated correlations. We combine this description with Generalized Hydrodynamics, showing that it correctly captures transport at the Euler scale, see Fig 1(right). Our results demonstrate that the t-GGE approach is robust in both homogeneous and inhomogeneous settings.

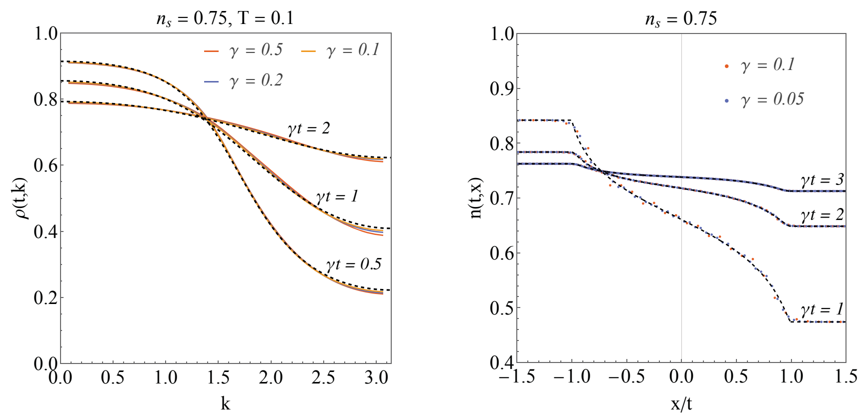

Fig. 1: (left) Comparison of the rapidity distribution for the exact TN evolution (full-color lines) and the analytical prediction obtained with the t-GGE approximation (dashed black lines) at fixed $\gamma t \in \{0.5, 1, 2\}$ for decreasing rate $\gamma = (\gamma_{Loss} + \gamma_{Gain})$, and value of the stationary density $n_s = 0.75$. (right) Comparison of the density profile evolution $n(t,x)$ (dashed black lines) with $n(0,x) = \theta(L/2 - x)$ and simulation results, for $n_s = 0.75$. Dots represent the exact TN data for two different γ and system sizes.

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The postselection problem in lattice bosons undergoing continuous measurements

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We study the postselection problem in a solvable model of bosons hopping on a lattice subjected to continuous local measurements of quadrature observables [Fig. 1(a)]. We find that the postselection overhead for local observables can be reduced by post-processing the entire measurement record into a few numbers per trajectory and then postselecting based only on these numbers. We then provide a step-by-step protocol designed to recover conditional connected two-point functions, which display an exponentially decaying profile that is not observable in the unconditional, trajectory averaged, state. We test the protocol numerically in a way that mimics real experiments, showing that various conditional observables can be recovered using a single ensemble of quantum trajectories [Fig. 1(b)]. We then illustrate how to design this post-processing stage using only information present in the unconditional dynamics. These models can be implemented in cavity-QED and circuit-QED.

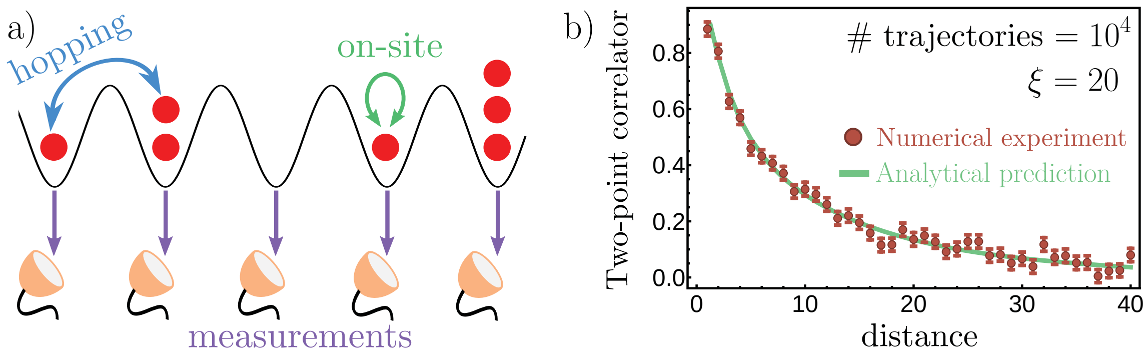

Fig. 1: (a) Bosons hopping on a lattice undergoing local continuous measurements. (b) Conditional two point correlator between quadrature observables as a function of distance, hidden behind the postselection barrier. Our protocol recovers this profile.

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Spin squeezing generation for quantum metrology

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We theoretically analyze spin squeezing generation in N cavity-coupled atoms, by performing continuous homodyne measurement of the transmitted cavity field, with the goal of improving the precision of optical clocks [1][2]. Our study, when conducted under the adiabatic cavity removal approximation, reveals an asymptotic scaling $N^{-2/3}$ for spin squeezing in case of conditional evolution. This result can be obtained only by accurately considering the curvature of the Bloch sphere. Furthermore, employing fully microscopic QuTiP simulations [3] of conditional open quantum system dynamics, we investigate the dependence of spin-squeezing generation on cavity and atomic parameters and elucidate the crossover from the bad cavity to a cavity-filling regime, where quantum advantage is lost. This can be also investigated by going beyond the leading order in the coupling and adopting a quantum cumulants approach [4].

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Engineering non-reciprocity in interacting bosonic systems

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While generic interaction with an external environment are detrimental for quantum simulators, the use of engineered dissipation has emerged as a powerful tool to generate exciting novel phenomena in quantum many-body systems [1][2][3]. In particular, reservoir engineering has been used to investigate non-reciprocal quantum systems, where the action-reaction principle is broken [4][5][6]. In this poster, I will give a retrospective on reservoir engineering techniques in the particular case of non-reciprocal couplings of non-interacting bosons. Generalizing these results to the interacting case is non-trivial due to the absence of clear non-reciprocity in the equations of motion and to the large Fock space dimension. In our work [7], we use tensor network techniques to simulate the dynamics of a Bose-Hubbard system coupled to engineered dissipation. We first show how the non-recipocal couplings of the non-interacting chain are inherited at the interacting level in a certain parameter range. In the second part of the poster, I will present a scheme that allows to engineer dissipation and non-reciprocity specifically at the interacting level. Finally, I will conclude showing the interplay of non-reciprocity in the two cases and how it can realize fascinating dynamical phenomena.

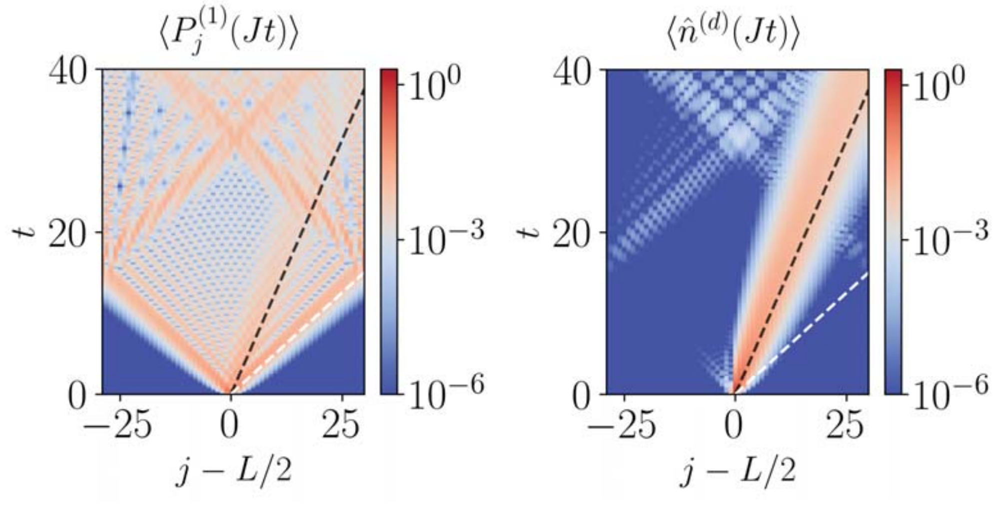

Fig. 1: Dynamics of the single particle population $P_j^{(1)}(Jt)$ (left) and of the doublon density $\hat{n}_j^{(d)}(Jt)$ (right) show extremely different behaviors due to the engineered dissipation targeting repulsively bound pairs only (doublons). Hence, single particles are not affected by non-reciprocity and travel in both directions equally. On the contrary, interaction-induced doublons are strongly affected by the dissipation and move only towards the right. Single-particle and doublon lightcones are shown as white and black dashed lines, respectively.

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Continuous sensing and parameter estimation with the boundary time-crystal

Albert Cabot

A boundary time-crystal is a quantum many-body system whose dynamics is governed by the competition between coherent driving and collective dissipation. It is composed of N two-level systems and features a transition between a stationary phase and an oscillatory one. The fact that the system is open allows to continuously monitor its quantum trajectories and to analyze their dependence on parameter changes. This enables the realization of a sensing device whose performance we investigate as a function of the monitoring time T and of the system size N. We find that the best achievable sensitivity is proportional to $sqrt{T} N$, i.e., it follows the standard quantum limit in time and Heisenberg scaling in the particle number. This theoretical scaling can be achieved in the oscillatory time-crystal phase and it is rooted in emergent quantum correlations. The main challenge is, however, to tap this capability in a measurement protocol that is experimentally feasible. We demonstrate that the standard quantum limit can be surpassed by cascading two time-crystals, where the quantum trajectories of one time-crystal are used as input for the other one. Beyond this optimal protocol, we also consider simpler protocols making use of only one system, and based on one-time and two-time correlations of the emitted light. We find that that by measuring the appropriate two-time correlations, one can retrieve a significant amount of the total QFI in the time-crystal phase. Finally, we address the effect of imperfections, as finite detection efficiency or unwanted decay channels.

Reduced Basis for Open Quantum Systems

Hans Christiansen

The accurate and reliable simulation of open many body quantum systems pose a formidable challenge for modern theoretical condensed matter physics, with the potential to describe many important questions related to the interplay between interactions, driving, and dissipation effects. In many cases, a reduced description in terms of a Lindblad master equation can be used. However, for increasing system size, even this reduced description quickly becomes intractable. In this work, we consider effective descriptions of the Lindblad master equation in terms of a 'reduced basis' approach, mapping the equation to a subspace of much smaller dimension while retaining the essential long-time dynamics. Using this method, we demonstrate fast and efficient computations of dynamical effects in Lindblad systems like dissipative phase transition and incoherent quantum tunnelling.

Quantum Thermalization Dynamics of Fermi Gases Quenched to the BEC-BCS Crossover

Licheng Yi , Shuxian Yu , Meimei Wu , Shujin Deng , and Haibin Wu

Understanding nonequilibrium dynamics of strongly interacting quantum systems represents one of the most challenging problems in many-body physics. Here we explore quantum thermalization dynamics in real-time in an ultracold Fermi gas suddenly quenched to the BEC-BCS crossover. When quenched to unitarity, we observe that the cloud size remains unchanged in the early evolution while the momentum distribution emerges two prethermal states with a lifetime difference of two orders of magnitude in the early and intermediate stage before very slowly evolving to the final stationary state. We reveal that a crossover momentum, at which the momentum distribution keeps unchanged, is determined by the thermal wavelength at high temperatures and the Fermi momentum while at low temperatures. We identify the universal prethermal dynamics scaling where momentum distributions with different temperatures collapse onto one curve. When quenched to the BEC side, the thermalization rapidly relaxes into a prethermal state and exhibits the low energy oscillation related to the molecular bound states. Our work provides benchmarks for the study of quantum thermalization in strongly interacting fermionic many-body systems.

Enhanced many-body quantum scars from the non-Hermitian Fock skin effect

Jean-Yves Desaules

In contrast to extended Bloch waves, single particles can become spatially localized due to the so-called skin effect originating from non-Hermitian pumping. Here we show that in kinetically constrained many-body systems, the skin effect can instead manifest as dynamical amplification within the Fock space, beyond the intuitively expected and previously studied particle localization and clustering. We exemplify this non-Hermitian Fock skin effect in an asymmetric version of the PXP model and show that it gives rise to ergodicity-breaking eigenstates—the non-Hermitian analogs of quantum many-body scars. A distinguishing feature of these non-Hermitian scars is their enhanced robustness against external disorders. We propose an experimental realization of the non-Hermitian scar enhancement in a tilted Bose-Hubbard optical lattice with laser-induced loss. Additionally, we implement digital simulations of such scar enhancement on the IBM quantum processor. Our results show that the Fock skin effect provides a powerful tool for creating robust non-ergodic states in generic open quantum systems.

Entangled Absorbing States in SU(2)-Symmetric Monitored Quantum Circuits

Tobias Dörstel

Monitored quantum circuits, representing open quantum systems where unitary evolution is interspersed with measurements, provide a platform for exploring novel non-equilibrium phenomena and are relevant to topics such as dissipative state engineering. While symmetries are known to be important for closed quantum systems, their role in monitored circuits is currently a topic of intense investigation. In this work, we investigate a one-dimensional monitored quantum circuit of spin-1/2 particles with SU(2) symmetry, a fundamental non-Abelian symmetry relevant to many condensed matter systems. We identify a subspace of entangled dark states, invariant under measurements. By introducing measurement-dependent feedback, we demonstrate that these dark states become absorbing. We find that these absorbing states can be reached efficiently, independent of the form of the feedback operators. The timescale to reach these absorbing states scales algebraically with system size, a result we confirm numerically. Finally, we generalize these results to different feedback protocols and geometries, including systems with long-range interactions. Our results highlight the significant role of symmetry in the dynamics of monitored quantum circuits and demonstrate the potential of feedback mechanisms for efficient state preparation.

A cavity-microscope for micrometer-scale control of atom-photon interactions [1].

Ekaterina Fedotova[*1], **Francesca Orsi** [1], **Rohit Prasad Bhatt** [1], **Michael Alexander Eichenberger** [1], **Nick Sauerwein** [1], **Nathan Honoré** [1], **and Jean-Philippe Brantut** [1]

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Cavity quantum electrodynamics studies the strong interaction between matter and the electromagnetic field of an optical cavity: the enhanced interaction is useful both for reading the properties of the atoms with a fast, sensitive and weakly destructive measurement and for quantum simulation where atoms interact by exchanging photons with each other at a distance. One of the drawbacks of these systems is the loss of spatial information that cavity-based measurement implies: the result of these measurements is an average of the properties of the atoms over the entire cavity field volume.

I will explain how we built and operated a cavity-microscope device that overcomes this problem: it realizes both a cavity and a pair of high numerical-aperture lenses in a single device and can be used to couple a microscopic part of the atomic cloud to the cavity field. We produce a cavity-based image of the atomic density by scanning the position of the microscope focus. This technology opens the doors to analog quantum simulations of programmable, all-to-all interacting systems. This includes the possibility of exploring models of holographic quantum matter such as the Sachdev-Ye-Kitaev model [2]. I will report on our progress toward an experimental implementation of the SYK model using cold fermionic atoms in a high-finesse cavity. This includes the study of self-organization in the presence of tight confinement and the development of optical techniques to randomize cavity-mediated interactions

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Quantum metrology in the ultra-strong coupling limit of light-matter interactions: Leveraging virtual excitations without extracting them

Karol Gietka

Virtual excitations, inherent to ultra-strongly coupled light-matter systems, induce measurable modifications in system properties, offering a novel resource for quantum technologies. In this work, we demonstrate how these virtual excitations and their correlations can enhance precision measurements, without extracting them. By leveraging the paradigmatic Dicke model, which describes the interaction between an ensemble of two-level atoms and a single radiation mode, we propose a method to harness hybridized light-matter modes for quantum metrology. Our findings not only reveal the potential of virtual excitations in surpassing classical precision limits but also generalize to a wide array of ultra-strongly coupled systems. This approach paves the way for experimentally accessible advancements in sensing and quantum technology.

Non-thermal cavity control of order in electronic systems

Md Mursalin Islam

Cavity-quantum-materials have emerged as a platform to study non-thermal many-body physics with applications to the control of collective electron behavior. In an electronic system coupled to cavity photons, the superconducting gap has been predicted previously to be enhanced, due to a 'Eliashberg effect' taking place due to electromagnetic fluctuations as instead of a coherent laser source [1,2]. We extend this idea for the case of charge-density-wave order and systematically derive a generalized gap equation for the non-thermal situation using field theoretical methods. This allows us to compare the modified gap equations for superconductors and charge-density-waves: we find that while the two equations are exactly equivalent only in thermal equilibrium, they assume different forms in non-thermal settings. Our formalism also allows us to systematically investigate the role of disorder in the non-thermal enhancement of the gap in both the cases.

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Eliashberg theory for non-thermal steady-state superconductivity

Christian Johansen

In recent years, innovative mechanisms have been proposed to induce superconductivity in non-equilibrium conditions, either through cavity-mediated interactions or by driving the boson that mediates electron pairing. In such scenarios, the electron-boson interaction responsible for pairing resembles that of conventional electron-phonon interactions, suggesting that the super-conducting phase transition can be effectively described using Eliashberg theory approximations, as is standard in phonon-mediated superconductivity. While these approximations are valid, it is necessary to go beyond a thermal equilibrium description to account for the non-thermal nature of the system. To achieve this we use the real-time Keldysh path-integral formalism to extend the theory to non-thermal steady states. A key consequence of the non-thermal conditions is the emergence of a new equation governing non-thermal pair correlations, which couples to the gap equation. To explore these correlations, we apply the theory to a model system characterized by perfect forward-scattering electron-boson interactions, driven out of thermal equilibrium by coupling to two distinct environments. Our results demonstrate that, in non-thermal settings, these additional correlations are essential for accurately capturing the system's behavior at the phase transition.

Positive Operator Valued Measures Neural Networks for simulation of light-matter coupled systems.

Gianluca Lagnese[1], **Darrik Chang**[2,3], **Markus Schmitt**[4], **Zala Lenarčič**[1]

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We employ a recently proposed numerical approach [1] to model open systems dynamics. This methodology is based on the positive operator valued measure (POVM) description of the quantum state: such representation is naturally interpreted as a probability distribution over a complete set of measurements, which can be approximated by a neural network. Then we exploit a time-dependent variational principle (TDVP) to project the dynamics of the evolved state over the neural network manifold. As an example, we target systems made of arrays of atoms trapped in an optical or tweezer lattice with photo-mediated dipole-dipole long-range interaction and correlated dissipation between them. When atoms are placed at distances smaller then the wavelength of light and are prepared in a all-excited state, such a system exhibits a superradiant burst, followed by a non-trivial "subradiant" critical regime with slow power-law relaxation. We explore whether the considered numerical technique has the capacity to described such long-range interacting open systems up to very long times, where the interesting correlated regime appears. A crucial question that we address is the upscaling to larger system sizes, as a potential complementary tool to more standard tensor network techniques, which are not efficient for long-range interacting and two dimensional setups.

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Highly-entangled stationary states from strong symmetries

Yahui Li

We find that the presence of strong non-Abelian conserved quantities can lead to highly entangled stationary states even for unital quantum channels. We derive exact expressions for the bipartite logarithmic negativity, Rényi negativities, and operator space entanglement for stationary states restricted to one symmetric subspace, with focus on the trivial subspace. We prove that these apply to open quantum evolutions whose commutants, characterizing all strongly conserved quantities, correspond to either the universal enveloping algebra of a Lie algebra or to the Read-Saleur commutants. The latter provides an example of quantum fragmentation, whose dimension is exponentially large in system size. We find a general upper bound for all these quantities given by the logarithm of the dimension of the commutant on the smaller bipartition of the chain. As Abelian examples, we show that strong U(1) symmetries and classical fragmentation lead to separable stationary states in any symmetric subspace. In contrast, for non-Abelian SU(N) symmetries, both logarithmic and Rényi negativities scale logarithmically with system size. Finally, we prove that while Rényi negativities with $n>2$ scale logarithmically with system size, the logarithmic negativity (as well as generalized Rényi negativities with $n<2$) exhibits a volume law scaling for the Read-Saleur commutants. Our derivations rely on the commutant possessing a Hopf algebra structure in the limit of infinitely large systems, and hence also apply to finite groups and quantum groups.

SU(3) Fermi-Hubbard model with three-body losses

Alice Marché

Two and three-body losses are one of the most investigated mechanisms that can induce a many-body correlated open quantum dynamics in a fermionic degenerate gas. Particular attention in experimental and theoretical analyses has been devoted to the steady properties of the setup. In the case of two-body losses, the dissipative dynamics is known to generate many-body entangled steady-states due to total spin conservation. My poster presents the case of a SU(3) invariant fermionic gas on a lattice subject to local three-body losses. In this case, we show that steady-state properties, such as the total number of fermions remaining on the lattice, are ruled by the conservation of the expectation values of the two independent Casimir operators of SU(3). A basis of the Hilbert space which takes care of the symmetries of the system can be written in terms of semi-standard Young tableaux. We demonstrate what is the effect of a loss process on a state belonging to this relevant basis. We also derive a mean-field equation for the dynamics of the density of fermions on the lattice, using the formalism of time-dependent generalized Gibbs ensemble.

Robust Prethermalization in Open Systems

Arkadeep Mitra

Driven quantum systems out of equilibrium is a fascinating field in quantum mechanics that has resulted in the realization of novel phases of matter, for example prethemalization. Although much has been explored in prethermalization in closed quantum systems, such realizations in open quantum systems remain largely unaddressed precisely because a system-bath interaction would be deterrent to the stability of such a phase. Interestingly it has been recently shown by Saha et al.* and Chakrabarti et al.** that prethermal steady states can be obtained in dipolar spin-1/2 systems coupled to a heat bath in the presence of a strong resonant drive. The drive plays a crucial role in the stability of such a prethermal phase. We study the robustness of prethermalization in such a system against characteristics of the drive and temperature of the bath and show that the prethermal phase is fairly robust over a range of relevant parameters.

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Exceptional stationary state in a dephasing many-body open quantum system

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The eigenstate thermalization hypothesis (ETH) [1] is a cornerstone of condensed matter physics, offering a simple and physical framework to explain the emergence of thermal features in the late-time dynamics of closed quantum systems. However, recent studies have revealed the existence of rare eigenstates, quantum many-body scar states, that escape thermalization and violate ETH.

In this work [2], we study an open many-body system that hosts, together with the infinite temperature state, a single additional stationary state. This exceptional state, the pure state fully polarized along the z-direction, plays the role of a many-body scar. We show that this state is progressively erose when put in contact with a bath: physically, it means that the scar is thermodynamically unstable, and it will gradually dissolve onto the infinite temperature state when perturbed.

In particular, we focus on the limit of a large decoherence rate, and we study the system using an effective classical stochastic model. We prove that the erosion process is described by a *membrane picture*, where the interface between the infinite temperature state and the scar evolves in time following a driven Brownian motion with a finite velocity. We present numerical data and we show that the universal properties of this mechanism remain unchanged even beyond the regimes of exact solvability of the protocol.

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Towards Yb Many-Atom Interaction Using Tweezer Arrays in a Cavity QED Setup

Reza Mosala Nejad

We present progress towards building a new platform interfacing a multimode high-finesse cavity and quantum gases. The multimode cavity will enable us to realize tunable-range interactions between the The use of Yb is motivated by its versatile transitions and having both fermionic and bosonic isotopes. tweezer array, we will control the position and hence the interaction of the atoms. Currently, the vacuum assembled, and we are optimizing the 556nm narrow-line MOT. Next step will be to load the atoms out MOT into a dipole trap to realize Yb BEC.

Genuine quantum effects in Dicke-type models

Kai Müller

We theoretically investigate the occurrence of genuine quantum effects and beyond mean-field physics in the balanced and unbalanced open Dicke model with a large number of atoms N. These models of driven-dissipative quantum many-body systems have recently been realized in experiments involving ultracold gases inside optical cavities and are known to exactly obey mean-field predictions in the thermodynamic limit $N\rightarrow \infty$. Here we show which quantum effects survive for large but finite N by employing a novel open-systems method that allows us to obtain an exact numerical solution up to a mesoscopic number of atoms ($N\cong 1000$). While we find that beyond-mean-field effects vanish quickly with increasing N in the balanced Dicke model, we are able to identify parameter regimes in the unbalanced Dicke model that allow genuine quantum effects to persist even for mesoscopic N. They manifest themselves in an entangled steady state and a modification of the phase diagram that can't be computed from mean-field theory.

Liouville Fock state lattices

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To gain new insights into open system dynamics and propose novel lattice simulators, in this work we put forward an extension of the Fock state lattices [1] framework to include Lindblad master equations. This is done utilizing the vectorization of the Lindblad equation, where we represent the density operator as a vector in a doubled Hilbert space [2]. We provide a set of simple rules to determine the emerging lattice structure and its geometrical properties, relating it to symmetries and conserved quantities while also providing some examples such as the one in the figure below. As potential paths to simulate classical stochastic equations and more general lattice dynamics, we further address other representations such as the one given by Symmetric Informationally Complete measurements [3].

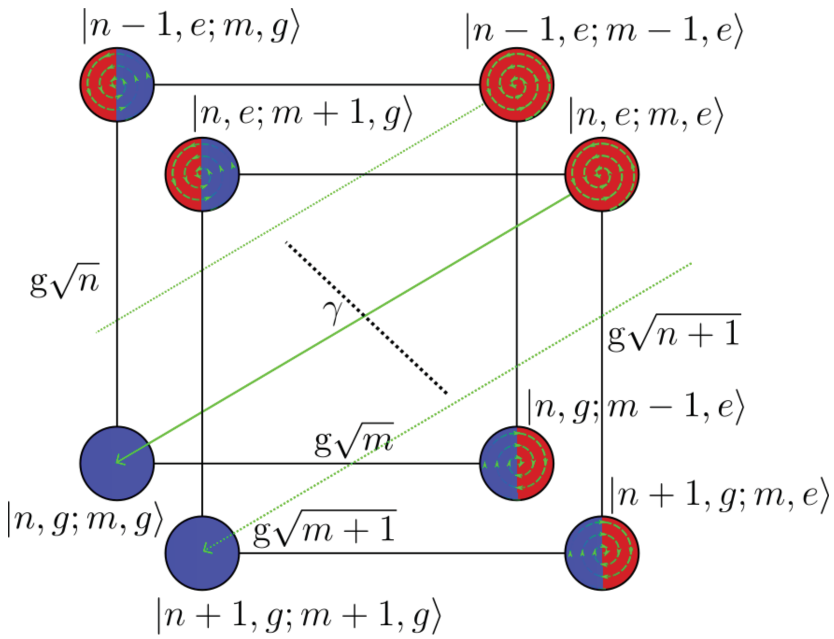

Fig. 1: Liouville-Fock state lattice of the Jaynes-Cummings model subjected to atom decay.

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POSTER SESSION

Thursday 20 February 2025

Emergence of Quantum Spin Liquids from Atom-Cavity Interactions

Mark Oehlgrien

Integrating Rydberg tweezer arrays into optical cavities presents an exciting new frontier in quantum optics, where one has the combination of short-range Rydberg interactions and long-range cavity mediated interactions. Here we propose that tweezer-cavity systems can serve as a novel paradigm to prepare and investigate quantum spin liquids (QSLs). Despite the anisotropic interactions, in the strong cavity limit the low-energy spectrum is in one-to-one correspondence with the singlet sector of the corresponding short-range Heisenberg model and hence, hosts a QSL if the corresponding Heisenberg model does. However, there is no such correspondence for other sectors, which means that the excitations of the QSL could in principle be strongly modified because of the presence of the long-range interactions. We also discuss several other intriguing aspects of the model which include the transition out of the "QSL" phase into the "squeezed Néel" phase and the presence of "partial" Lieb-Robinson bounds in the limit of dominating long-range interactions.

Bistable and oscillating phases in ordered atomic arrays

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We study the limit state phases of a driven-dissipative 2D array of either two- or three-level emitters. It is known that the former case shows bistable and oscillating phases in its long time dynamics for sufficiently small lattice spacing when considered in a mean field approximation [1,2]. We find that such phases can also in general be found for infinite arrays in the mean field when the collective energies of the system become sufficiently large at resonant lattice spacings. However, introducing either second order cumulants (going beyond mean field) or considering finite arrays, the situation becomes less clear. For small lattice spacings the emitters interact strongly and become highly correlated such that the mean field approximation is in general poor, and using either second order cumulants or exact calculations we find neither bistable nor oscillating phases. For resonant (non-small) lattice spacings, where the infinite case shows bistable and oscillating phases even beyond mean field, the finite systems suffers from the extremely slow convergence of the collective energies, such that very large systems are required to recover these phases.

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Simulating dissipation in chiral and topological materials using cold atoms

Jonah Peter

The role of dissipation in condensed matter systems is a current area of intense interest. Here we show that chiral atom arrays, for instance engineered with optical tweezers, can be used to simulate dissipative processes in chiral molecules and topological insulators alike. We first demonstrate a photonic analogue of the enigmatic chirality-induced spin selectivity (CISS) effect, in which electrons tunneling through chiral molecules become strongly spin polarized. Our quantum simulation approach reveals an analogous property of light, where photons of opposite circular polarization experience either superradiance or subradiance. We then show that certain chiral atom arrays exhibit an exact one-to-one mapping with an interacting, flat-band topological insulator. Our results provide an opportunity to study the interplay between dissipation, chirality, topology, and flat-band physics within a unified many-body platform.

Towards RbCs dipolar molecules in optical lattices

Karthick Ramanathan

Ultracold atoms in optical lattices offer extremely rich, versatile and controllable quantum engineering to explore interesting many-body physics. In particular, long-range interactions open up a lot more avenues of research in quantum simulation. Heteronuclear molecules with have a permanent dipole can be used to engineer electric dipole-dipole interactions which are strong, tunable and anisotropic. produced in their ground state in an optical lattice, these features of dipolar molecules can enable engineering of truly unique quantum systems. Building on the work done earlier in producing RbCs here, I talk about our experimental revamp and the sequence we use to achieve ground state RbCs also briefly talk about our recent efforts to understand the phenomenon of many-body dynamical (MBDL) that can be realised using the quantum kicked rotor model on a cesium BEC.

Many-body subradiant dynamics of light-matter interaction

Lorenzo Rossi

A form of correlated dissipation that leads to momentum-dependent loss naturally arises in many platforms where dynamics is governed by light-matter interactions. Examples include optical excitations in atomic arrays, quantum electrodynamics in superconducting circuits, and dipolar excitons in semiconductor double quantum wells. Given its momentum-selective nature, such correlated dissipation provides a powerful and universal route for dynamically generating correlated states of light in the long-lived many-body subradiant manifold. While a microscopic description becomes impractical in the thermodynamic limit, a separation of time scales between shorter relaxation times and longer decay times allows us to describe the dynamics within the subradiant manifold in terms of a time-dependent (Generalized) Gibbs ensemble ((G)GE). As a first example, we provide evidence that the subradiant dynamics of optical excitations in a one-dimensional array of atoms can be captured by a time-dependent GGE. We then argue how a low-temperature GE can emerge in higher-dimensional arrays.

Dissipative coupling induced phonon lasing and clock synchronization in cavity optomecanics

Jiteng Sheng

Similar to the long-range interactions observed in cold atomic ensembles mediated by cavity fields, the effective coupling between spatially separated macroscopic mechanical resonators can also be engineered through optomechanical interactions with a cavity field. Here we demonstrate that the dissipative coupling between mechanical resonators can be realized in a two-membrane cavity optomechanical system. Furthermore, the dissipative coupling induced phonon lasing and clock synchronization are implemented. These results highlight the potential of optomechanical interactions as a versatile and powerful tool for manipulating the collective states of macroscopic mechanical resonators.

Spectral Properties and Magic generation of T-doped Random Clifford Circuits

Dominik Szombathy

The Clifford group plays a fundamental role in modern quantum computation and quantum information, because it can be efficiently simulated on classical hardware, and can be augmented to a universal quantum computation gate set by just including the T-gate [1]. We investigate the spectral properties and magic generation of T-doped random Clifford circuits [2]. Applying Clifford gates to Pauli strings gives rise to periodic orbits. There is a direct relation between the structure of such orbits and the eigenvalue spectrum of the circuit. Operatively, we build N-qubit random brick-wall circuits and sample the closed trajectories (periodic orbits), and determine the distribution of the eigenvalues $\lambda=e^{i\theta}$ on the unit circle. The autocorrelation function of the phases of the eigenvalues displays peculiar properties: extreme degeneracies as well as some level-repulsion, and features reminiscent of a fractal pattern. To investigate the stability of orbits and head towards universal quantum computation, we introduce $\pi/4$ phase shift gates (T-gates). We find that even a single T-gate completely changes the properties of the circuit [3]. By increasing the number of T-gates (N_T), the correlation function rapidly approaches that of the random unitary circuits. Nevertheless, some statistically significant fraction of non-trivial orbits persists at low T-gate densities (N_T/N) [2]. We observe a similar phenomenology in the magic generation as a function of T-gate density. In particular, we find universal scaling of the maximum and mean magic as a function of N_T/N. We also highlight a remarkable structure of magic generated by these circuits. Injecting more and more T-gate the distribution becomes more continuous. Injecting a few T-gates the distribution is discrete but becomes continuous as N_T increases. At large densities N_T/N, most of the weight is found in a sharp peak well below the theoretical maximum.

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Numerical Simulations of Dissipation-Driven Coherent Ising Machines for Achieving Quantum Advantage

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The Ising machine, originally developed to model phase transitions in magnetic materials, has since demonstrated its versatility across a wide range of applications [1]. Its usefulness in solving NP-hard optimization problems has made it a valuable tool in fields such as Artificial Intelligence (AI) and Machine Learning (ML). This adaptability extends its potential impact beyond physics to industries like computer science, medicine, finance, telecommunications, and supply chain logistics, where it plays a crucial role in tackling complex challenges [2][3][4].

This study investigates an open quantum system, focusing on the development and implementation of theoretical models for a Coherent Ising Machine (CIM) with nonlinear dissipation. The CIM is composed of a network of Optical Parametric Oscillators (OPOs). We consider a low-loss coherent coupling to introduce a quantum regime that enhances the computational performance of the CIM. Due to the system's complexity, we employ extensive numerical simulations to explore the behaviour. Our approach examines various coupling strategies and the impact of quantum noise, with the goal of demonstrating quantum advantage in the CIM through improved simulation times (implying a quantum speed-up) and higher success rates.

We employ the Monte Carlo Wavefunction method, which scales better than any master equation approach [5]. Previous attempts utilized the positive-P method [6], which offers better scalability but poses challenges in sampling within the quantum regime. In this study, our quantum jump approach, which scales with the wavefunction, can simulate systems with Hilbert spaces exceeding 10^7 dimensions, and sample in both classical and quantum regimes.

We utilize quadrature mapping to evaluate success probabilities. Our preliminary investigation shows an improvement in the success rate and simulation time when quantum effects are introduced into our system. The main advantage of this approach is a balance between computer memory efficiency and computation time, providing valuable insights into the quantum dynamics and capabilities of the Coherent Ising Machines.

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Nonlinear response theory for lossy superconducting quantum circuits

Vasilii Vadimov

Quantum systems inherently interact with their environments, typically consisting of a macroscopic number of degrees of freedom [1]. These interactions give rise to a diverse range of phenomena, among which the most important are dissipation and decoherence [2]. In addition to the inevitable coupling to the natural environment, the study of open quantum systems is also motivated by the need to carry out measurements on real systems [3]. In such cases, the measurement apparatus itself acts as an environment, leading to decoherence. In our work we provide a formalism for calculation of electromagnetic field emitted by the superconducting circuits, which can be measured experimentally [4]. Starting from the Feynman–Vernon path integral formalism for the lossy circuits, we eliminate the influence functional by introducing auxiliary harmonic modes with complex-valued frequencies coupled to the non-linear degrees of freedom of the circuit. This results in a many-body Liouville equation for the state of the system. We propose a concept of time-averaged observables, inspired by experiment, and provide an explicit formula for producing their quasiprobability distribution. Finally, we demonstrate the applicability of our formalism through a study on the dispersive readout of a superconducting qubit [5].

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Challenging the traditional understanding of cavity QED with many atoms

Lukas Wangler

Harnessing the interaction between atoms and an optical cavity to generate long-range interactions is a well-established paradigm of quantum optics. An atom can emit a photon into a cavity mode, which is far detuned from atomic resonance, and subsequently the photon gets absorbed by another atom. This process gives rise to effective atom-atom interactions. The atoms also interact with the modes of the free-space electromagnetic field. Conventionally, interactions with free-space modes are modeled by introducing a spontaneous emission rate for each atom. However, a closer analysis reveals, that the free-space modes also mediate effective interactions between the atoms.

We demonstrate that for a large number of atoms, these free-space mediated interactions can dominate over the cavity-mediated interactions and thus challenge the traditional understanding of cavity QED. To explore this, we quantitively study the influence of free-space interactions on the example of cavity-based spin squeezing schemes.

Many body physics with ultracold atoms and molecules

Yi Zeng, Sudipta Dhar, Milena Horvath, Charly Beulenkamp, Krzysztof Zamarski, Yanliang Guo, Manuele Landini, Hanns-Christoph Nägerl

We present two recent findings from our CsIII experiment, which explores a broad spectrum of one-dimensional (1D) many-body physics. Additionally, we report on our progress toward constructing a new and ambitious KCs experiment. First, the CsIII experiment recently concluded the experiment of exploring emergent anyonic correlation in strongly interacting 1D hardcore bosons. Fractional statistics are observed by engineering spin-charge separation in the system, where the spin degrees of freedom is provided by a mobile impurity. Second, the CsIII experiment is finishing up the work with bethe strings, which are novel bound states appearing in 1D bosons with high attractive interactions. The dynamics of these bound states are also studied, with the application of generalized hydrodynamics.
For the new KCs molecule experiment, our goal is to develop a versatile quantum simulator featuring a unity-filling lattice of ultracold dipolar molecules, which will be probed under a quantum gas microscope. The dipolar molecules offer tunable long-range interactions, while quantum microscopy enables site-resolved detection and control. We are in the final stages of designing the apparatus and will soon commence its assembly. Simultaneously, we have made substantial progress in producing ultracold ground-state KCs molecules using our existing setup.

Loss-Induced Quantum Information Jet in an Infinite Temperature Hubbard Chain

Gergely Zarand

Information propagation in the one-dimensional infinite temperature Hubbard model with a dissipative particle sink at the end of a semi-infinite chain is studied. In the strongly interacting limit, the two-site mutual information and the operator entanglement entropy exhibit a rich structure with two propagating information fronts and superimposed interference fringes. A classical reversible cellular automaton model quantitatively captures the transport and the slow, classical part of the correlations but fails to describe the rapidly propagating information jet. The fast quantum jet resembles coherent free particle propagation, with the accompanying long-ranged interference fringes that are exponentially damped by short-ranged spin correlations in the many-body background.

Lindblad or not to Lindblad? A pedagogical perspective

Aleksandra Ziolkowska

In many experimental contexts, the theories derived to explain isolated systems must be reconsidered in light of the environmental impact, which necessitates a new mathematical toolbox. A common framework to describe open quantum systems is the Lindblad equation. Although widely used, its parameters of validity are often misunderstood. Based on an extensive literature overview, we wrote a pedagogical review highlighting the exact mathematical nature of the assumptions underlying the Lindblad equation and the physical intuition behind them. We put an emphasis on the features of the system, environment, and their interaction that enable dynamics described well by the Lindblad master equation and underline which physical effects are omitted when casting a system into the Lindblad framework. The particular strength of our review lies in translating the mathematical constraints derived analytically in the 70s and 80s to physically intuitive requirements to be employed in an experimental setup or a model of interest.

Work with Martino Stefanini, Ulrich Poschinger, Dimitry Budker, Ferdinand Schmidt-Kaler, and Jamir Marino.

Poster session – 20.02.2025

Desislava ATANASOVA: hot topic talk on Novel 3D circuit QED architecture for quantum information processing

Roberts BERKIS: Improved quantum networks using fiber cavities and ion traps

Trapped ions coupled to an optical cavity have proven to be good candidates for atom–photon interface, which provide a basis for quantum network applications [1]. Increasing coupling strength between the cavity and ions remains a central focus for advancements of the ion-cavity systems. Promising approach involves the usage of microcavities fabricated on optical fibers,if specific technical challenges could be solved[2]. In this poster an existing experimental setup will be presented, that consists of linear Paul trap with an integrated fiber cavity along the trap axis [3]. Additionally, the design of new MEMS based microactuators and surface ion trap suitable for FFPC's will be presented[4].

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Alberto CANALI: Strongly Interacting Mixture of ^{161}Dy and ^{40}K: Hydrodynamic Crossover and Feschbach molecules

Ultracold, heteronuclear mass-imbalanced Fermi-Fermi mixtures provide a unique platform to explore exotic regimes of superfluidity [1]. We report on studies of hydrodynamic behavior of an ultracold strongly interacting fermionic mixture of ^{161}Dy and ^{40}K. Employing an interspecies Feshbach resonance at 7.3G [2], we investigated the dipole-mode spectrum of the mixture for different strengths of repulsive and attractive interactions. We characterized the oscillatory modes, observing a striking frequency locking in the unitarity regime. We extensively studied the damping rates of the oscillations across the resonance identifying three contributions, one related to the locked mode itself, one related to the spatial mixing of the two clouds, called ″slow damping mode″, and one related to the drag between the two species, called ″fast damping mode″. The fast damping is of particular interest as it allows for a characterization of the collisional properties on a time scale faster than all other relevant time scales, making it more robust against typical experimental limitations on resonance, such as heating and atom losses. From this fast mode we derive a microscopic friction coefficient, which is directly related to the universal description of friction in a resonant two-component Fermi gas [3]. We also report on the study of ultracold bosonic DyK Feshbach molecules, produced using the same Feshbach resonance through magneto association [4]. In particular we present the overcoming of trapping light induced losses and the observation of Pauli suppression of 2-body losses in the dimers lifetime [5].

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Lukas DEEG: Nonlinear Cooling in Magnetomechanics

For achieving groundstate cooling and quantum state preparation of macroscopic mechanical oscillators, microwave cavity optomechanics became a promising research field to test fundamental physics and quantum technologies. However, when increasing the size of mechanical objects, one inevitably enters the sideband unresolved regime, where cooling of the mechanical mode is limited. Recently, inductively coupled systems gained in interest within the community since they allow tuneable high coupling strengths between the mechanical and cavity mode. Here we show, that with our flux-mediated magnetomechanical system with coupling strength up to 50 kHz we achieve an increased cooling capability by harnessing the nonlinearity of our SQUID-cavity. Including the cavity nonlinearity in the theoretical description we can predict enhanced cooling and observe good agreement with our data. Furthermore, we verify predictions of the theory by experimentally observing backaction cooling of the mechanics beyond the bistable regime of the cavity mode. To operate in this regime, however, it is essential to ensure a good control of the cavity state, which we achieved by implementing a passive vibration isolation system to decrease mechanical noise in our experiment.

Alexander EBENBICHLER: The EDIBLES survey. X. The 6196 Å diffuse interstellar band: Identification of side DIBs as indication for a small carrier molecule

Numerous studies of diffuse interstellar band (DIB) profiles have detected substructures, implying large molecules as their carriers. However, some of the narrowest DIBs generally do not show such substructure, suggesting the possibility of very small carriers. Based on the previously found tight correlation of the three narrow DIBs at 6196, 6440 and 6623 Å and the present detection of weaker side DIBs to each of them in the extensive data set from the ESO Diffuse Interstellar Bands Large Exploration Survey, we investigate whether they may stem from small linear carrier molecules.

This approach can lead to concrete DIB carrier suggestions, which can be tested in laboratory measurements in future studies. We suggest that the DIBs we study here represent individual rotational transitions of a small molecule. We determined the molecular constants from observation and compared them with data from a large set of quantum-chemical calculations to confine possible carrier candidates. Furthermore, we determined rotational temperatures by fitting line ratios using the fitted molecular models. We determined molecular constants for three DIB systems and the corresponding transition types. The fitted rotational temperatures lie within the range of known interstellar diatomic molecules. We identified several DIB carrier candidates, almost all of them molecular ions. Some of them are metastable species, indicating the possibility of collision complexes as DIB carriers.

If our hypothesis holds, this would be a major step toward the identification of a carrier molecule of the 6196 Å DIB, the strongest among the narrow DIBs.

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Authors: A. Ebenbichler, M. Ončák, N. Przybilla, H.R. Hrodmarsson, J.V. Smoker, R. Lallement, A. Farhang, C. Bhatt, J. Cami, M. Cordiner, P. Ehrenfreund, N.L.J. Cox, J.Th. van Loon, B. Foing

Tommaso FALEO: hot topic talk on Optimised spectral purity from parametric down-conversion via engineered phase matching and pump spectral shaping

Martin FASSER: hot topic talk on Subradiance and superradiant long-range excitation transport among quantum emitter ensembles in a waveguide

Jessica HARTMANN: hot topic talk on Reactivity of Sea Salt Aerosols with Atmospherically Relevant Acids in the Gas Phase

Arfor HOUWMAN / Louis LAFFORGUE: hot topic talk by Arfor HOUWMAN on Control and scattering properties in dipolar spin mixtures; Poster will be presented by Louis LAFFORGUE

Lanthanides, such as erbium and dysprosium, are emerging as valuable resources in quantum-gas science [1]. Among interesting properties, they are known for their large spin manifold in the ground state. To utilize these characteristics, precise control of the spin population and a thorough understanding of collision processes are needed. Here, we demonstrate a novel method for manipulating the spin population by means of a laser tuned to a clock-like transition present in erbium at 1299nm [2]. By applying a sequence of Rabi-pulse pairs we can climb the ladder of Zeeman sublevels and prepare arbitrary superpositions of spin states. This allows us to record Feshbach resonance spectra of various spin mixtures to investigate spin-dependent on- and off-resonant scattering processes. Our results can be used to benchmark quantum scattering calculations, and to identify regions allowing to tune inter- and intraspecies contact interaction. Furthermore, the use of interference between inelastic and elastic loss channels - characterized by a Fano profile in the Feshbach spectra - enables us to create long-lived spin mixtures of bosonic erbium.

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Shan JIN: Symmetry reduction induced by argon tagging gives access to low-lying excited states of FeH+ in the overtone region of the Fe-H stretching mode

We explore the infrared spectroscopy of FeH^+, a molecule hypothesized to exist in interstellar environments. Despite its significance, FeH^+ has not yet been identified in the interstellar medium (ISM) through spectral observations due to a lack of laboratory data. The investigations of Argon-tagged FeH^+ employed infrared multiple-photon dissociation (IRMPD) spectroscopy to detect Fe–H stretching and its first overtone modes, including deuterated analogs [1,2]. Symmetry reduction due to argon tagging facilitates the observation of transitions otherwise forbidden in FeH^+. The experimental findings benchmark quantum chemical predictions, guiding future spectroscopic searches for FeH^+ in space. In the UV-Vis studies, we observed the electronic transition of FeH+ matched perfectly to the high-level quantum chemical calculations. In the collaboration with BESSY II, we successfully measured the tag-free X-ray spectra of FeH+ in the iron L2 and L3 regions [3]. Comparison with the interstellar absorption spectrum of Cygnus X-1 indicates that FeH+ cannot be ruled out as a component of the absorbing medium. Together, our studies provide critical laboratory data and computational insights into FeH^+, highlighting its astrophysical significance while advancing techniques for molecular ion spectroscopy. These efforts form the foundation for detecting FeH^+ in the interstellar medium and understanding its role in cosmic iron chemistry.

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Sarah M. MADLENER: The Influence of Chloride on the Photochemistry of Pyruvate in Salt Clusters

The Ocean covers around 70% of earth's surface and therefore marine aerosols are among the most important naturally occurring aerosols.[1] They influence earth's climate through direct and indirect interaction with solar radiation. Marine aerosols consist of inorganics salts, such as sodium chloride, as well as organic matter such as peptides, acids or saccharides. Pyruvic acid stands out as one of the most abundant alpha-keto carboxylic acids in the atmosphere. Upon irradiation, pyruvic acid undergoes C-C bond photolysis resulting in the release of neutral CO_2, observed in the actinic wavelength region with pyruvic acid vapor.[2,3]

This study now addresses the question whether the photochemistry changes if pyruvate is incorporated within a salt environment. The experiments were conducted on an APEX 9.4 T FTICR mass spectrometer that is equipped with an ESI source. Besides the action spectra and the laser kinetics, both measured using a UV/VIS OPO laser system, also sustained off-resonance irradiation CID spectra were recorded. We investigated two different systems, sodium pyruvate salt clusters $[Na_nPy_{(n-1)}]^+$ and pyruvate embedded in a sodium chloride cluster $[Na_nCl_{(n-1)}Py]^+$. Comparing now the spectra obtained for both systems shows that chloride has a significant influence on the photochemistry of pyruvate. We believe that the influence of the chloride ion is the reason for the occurrence of an absorption band towards 400 nm, visible only for the $[Na_nCl_{(n-1)}Py]^+$ clusters. In the literature, there is also no evidence for this absorption for either pure pyruvic acid or pure pyruvate. Quantum chemical calculations will be employed to identify the mechanisms behind this newly found absorption.

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Raamamurthy SATHYANARAYANAN: Creating high-Q systems for magnetomechanics

Superconducting circuits have shown great promise as a platform for the field of optomechanics [1]; in particular, they can be used to create quantum states in macroscopic mechanical oscillators [2], allowing for high precision sensing experiments and tests of fundamental physics. However, such protocols require that the mechanical oscillator first be cooled to the ground state [3]. This, in turn, requires that the optomechanical system be in the sideband-resolved regime, which requires a cavity of sufficiently high quality [4] [5]; unfortunately, the addition of a mechanical system and a coupling mechanism to our superconducting circuits invariably worsens the circuit, bringing us further from this regime. We present three strategies for mitigating these effects in our inductively coupled optomechanical setup. First, we fabricate magnetic-field resilient flux-tunable resonators through the use of niobium constriction junctions [6] [7]; these offer high quality factors but set challenging requirements on our lithography process. Second, we demonstrate that a flux transformer can be used to transmit a flux bias [8]; this allows us to separate the mechanical system from the circuit, suppressing losses due to the mechanics and the magnet. Third, we explore a more general approach of coupling a high-quality 3D cavity with a low-quality optomechanical system such that their modes are hybridized — creating an artificial sideband-resolved system in the high-Q mode [9] [10]. These latter strategies place new limits on the photon-enhanced optomechanical coupling, and we study these limits through experiment.

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Isaac Smith: Optimal computation (or simulation) using Pauli strings

Simulating a quantum system on quantum computer requires mapping the Hamiltonian describing the former to operations suited to the latter. In many cases, such as for simulations of fermionic systems, the set of resultant operations consists of rotations of Pauli strings. But how many Pauli strings are required? In this work, we (i) establish that for n qubits, at least 2n+1 Pauli strings are necessary for a universal gate set, (ii) provide an optimal compilation algorithm for gate sets of this type and (iii) compare compilation rates for different choices of gate set. As a consequence, we are able to investigate the optimality of gate sets arising from e.g., the Jordan-Wigner transformation of fermionic operators. These results may also find application in a number of other areas in which Pauli strings naturally arise, such as in trapped ion quantum computing and quantum optimisation.

Krzysztof Zamarski: Ultracold ground-state KCs molecules

Ultracold gases of alkali atoms have proven to be a versatile tool for the study of many-body quantum mechanics, thanks to the high degree of control that they offer. However, such atoms interact only via short-range, isotropic contact interactions, which limits their applicability as a simulator of real condensed matter systems. One of the most common methods of introducing long-range dipolar interactions into the system is associating pairs of atoms of different elements into molecules, which possess a permanent electric dipole moment. In our experiment, we have synthesized the first ultracold KCs molecules in their vibrational and rotational ground state reported so far. Using a novel simultaneous cooling scheme for potassium and caesium we are able to produce mixtures, which are cold enough for efficient magneto-association into weakly bound molecules to take place. We then apply the Stimulated Raman Adiabatic Passage (STIRAP) technique to transfer these molecules into their ground or second excited rotational state with efficiencies up to 75%. Once they are in either of these states, the interactions between them can be controlled using microwave radiation and high DC electric fields [1,2]. Such a system will provide an excellent platform for studying interacting spin models, exotic phases of matter, and new methods of quantum-enhanced sensing [3].

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