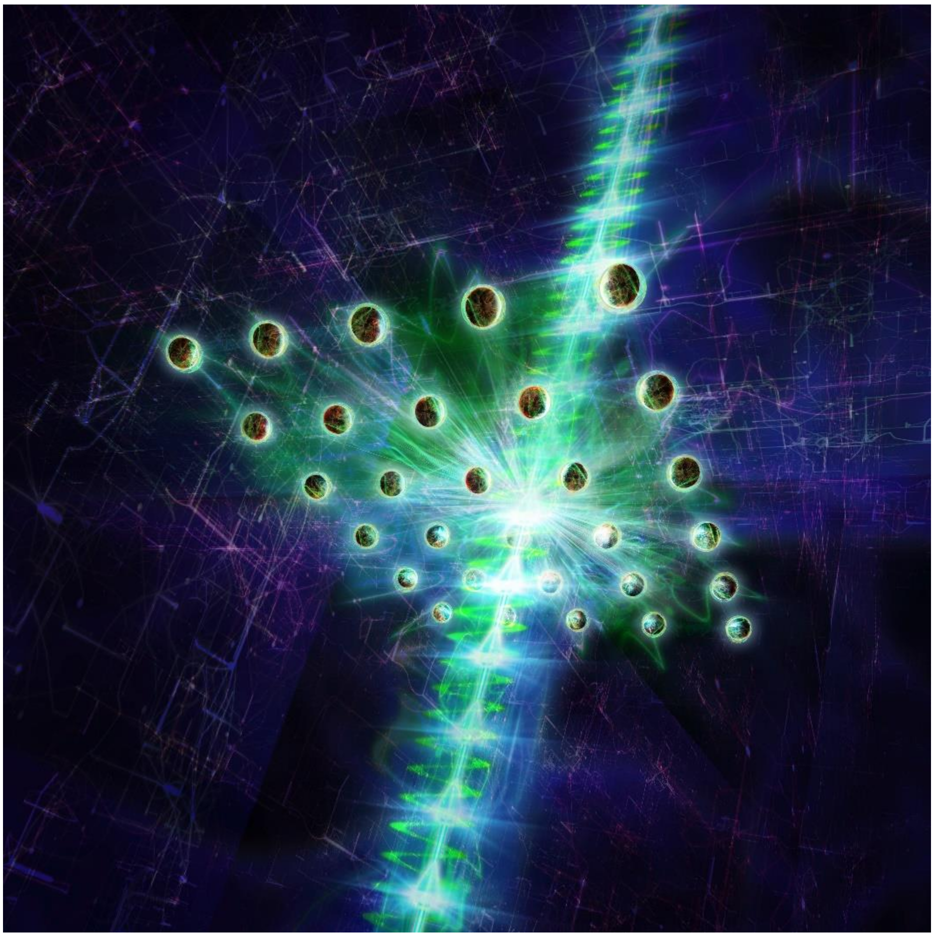

Quantum Simulation with Engineered Dissipation: "Next Generation" Symposium

March 25-26, 2024

ICFO

Organized by ICFO, Institut Jožef Stefan and the QuantERA Consortium QuSiED

QUANTERA ERA-NET Cofund in Quantum Technologies · ICFO · Jožef Stefan Institute

Program

Monday, March 25

9-9:10	Welcome
9:10-9:50	Johannes Zeiher (MPQ) *Continuous operation of large-scale atom arrays in a lattice-tweezer hybrid setup*
9:50-10:20	Iris Ulčakar (Institut Jozef Stefan) *Iterative construction of conserved quantities in dissipative nearly integrable systems*
10:20-10:50	Coffee break
10:50-11:30	Farokh Mivehvar (Innsbruck) *Rotational Superradiance in a Time-Reversal Symmetry-Broken Quantum Gas inside an Optical Cavity*
11:30-12:00	Charlie-Ray Mann (ICFO) *Quantum Spin Liquids in Rydberg Arrays Coupled to a Cavity*
12-14	Lunch/free discussions
14-14:40	Markus Schmitt (Regensburg) *Simulating non-equilibrium quantum matter with neural quantum states*
14:40-15:10	Phatthamon Kongkhambut (Hamburg) *Observation of a phase transition from a continuous to a discrete time crystal*
15:10-15:40	Coffee break
15:40-16:20	Rocío Sáez-Blázquez (TU Wien) *Nonperturbative vacuum shifts in cavity QED*
16:20-16:50	Reza Mosala Nejad (Innsbruck) *Towards Yb in Cavity*
16:50-20:00	Discussions/free time
20:00-	Symposium dinner – Rocxi Beach Restaurant (Castelldefels)

Tuesday, March 26

9-9:40	Oriana Diessel (Harvard) *Emergent Kardar-Parisi-Zhang phase in quadratically driven condensates*
9:40-10:10	Hossein Hosseinabadi (JGU Mainz) *Far From Equilibrium Dynamics of Spin Glasses in Cavity Quantum Electrodynamics*
10:10-10:50	Marvin Holten (TU Wien) *Atom-Cavity Setup for Engineering Entanglement with Programmable Connectivity*
10:50-11:20	Coffee break
11:20-12:00	Ronen Kroeze (Ludwig-Maximilians-Universität) *Replica symmetry breaking in a quantum-optical vector spin glass*
12:00-12:30	Angelo Valli (Budapest Univ. of Technology and Economics) *Full counting statistics and cumulant evolution in infinite temperature quantum spin chains*
12:30-	Lunch/free discussions

Abstracts – Monday, March 25

Johannes Zeiher (MPQ)

Continuous operation of large-scale atom arrays in a lattice-tweezer hybrid setup

Neutral atoms trapped in optical lattices and optical tweezers are a versatile platform for quantum simulation of many-body systems and fulfil all requirements for digital quantum computing. 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 an 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.

Iris Ulčakar (Institut Jozef Stefan)

Iterative construction of conserved quantities in dissipative nearly integrable systems

Integrable systems offer rare examples of solvable many-body problems in the quantum world, but due to their fine-tuned structure, the effects of integrability in nature are observed only transiently. One way to overcome this limitation is to weakly couple nearly integrable systems to baths and driving: these will stabilize integrable effects up to arbitrary time and encode them in the stationary state approximated by a generalized Gibbs ensemble. However, the description of such driven dissipative nearly integrable models is challenging and no exact analytical methods have been proposed so far. In this talk, I will present an iterative scheme in which integrability breaking perturbations (baths) determine the conserved quantities that play the leading role in a truncated generalized Gibbs ensemble description. Following an example, I will show that our scheme can be used to construct unknown conserved quantities of integrable models, exhibiting a quasi-local nature. Finally, I will discuss a significant reduction of complexity in obtaining the GGE description for non-interacting many-body models.

Farokh Mivehvar (Univ. Innsbruck)

Rotational Superradiance in a Time-Reversal Symmetry-Broken Quantum Gas inside an Optical Cavity

Appearance of quantized vortices in a Bose-Einstein condensate (BEC) is the nontrivial response of the superfluid to the broken time-reversal symmetry caused by, for example, rotation or an external synthetic magnetic field. In this talk, I show that breaking of the time-reversal symmetry in a transversely-driven BEC coupled to a standing-wave cavity modifies drastically the superradiant phenomenon. In particular, it can amplify the superradiant scattering in the expense of the rotational motion of the BEC, leading to the so-called "rotational superradiance". In turn, cavity photons mediate long-range interactions among the vortices which compete with logarithmic pair-wise vortex interactions and deform the Abrikosov triangular vortex lattice.

Charlie-Ray Mann (ICFO)

Quantum spin liquids in Rydberg arrays coupled to a cavity

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 explore whether this constitutes an ideal platform for realizing quantum spin liquids (QSLs). Despite the anisotropic interactions, we show that 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. However, there is no such correspondence for other sectors, which means that these excitations (e.g. spinons in a topological Z_2 QSL) could in principle be strongly modified, and we will outline some of the steps we are taking to understand this.

Markus Schmitt (Regensburg)

Simulating non-equilibrium quantum matter with neural quantum states

The numerical simulation of many-body quantum dynamics constitutes a pivotal challenge of computational physics due to the typical growth of entanglement in the course of the evolution. I will discuss how combining the time-dependent variational principle with artificial neural networks as ansatz for the variational wave function allows us to overcome some of the current limitations. As an application I will address quantum phase transition dynamics in two spatial dimensions of a model that is experimentally realized in Rydberg quantum simulators.

Phatthamon Kongkhambut (Univ. Hamburg)

Observation of a phase transition from a continuous to a discrete time crystal

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 [1]. A CTC with a characteristic oscillation frequency ω_{CTC} is prepared in a continuously pumped atom-cavity system. Modulating the pump intensity of the CTC with a frequency ω_{dr} close to $2\omega_{CTC}$ leads to robust locking of ω_{CTC} to $\omega_{dr}/2$, and hence a DTC arises. This phase transition in a quantum many-body system is related to subharmonic injection locking of non-linear mechanical and electronic oscillators or lasers.

[1] P. Kongkhambut, et al., arxiv.org/abs/2402.12378v1

Rocío Sáez-Blázquez (TU Wien)

Nonperturbative vacuum shifts in cavity QED

In recent years, vacuum-induced modifications of molecular properties have regained considerable attention in the context of cavity QED, where the coupling of matter to individual electromagnetic modes is strongly enhanced by a tight confinement of the field. It has been speculated that under such ultrastrong coupling conditions, the electromagnetic vacuum could change the rate of chemical reactions or modify work functions, phase transitions and (super-)conductivity, even without externally driving the cavity mode.

Here we investigate the ground state energy shift of a single dipole due to its coupling to the electromagnetic vacuum in a confined geometry and address the fundamental question of whether or not it is possible to achieve conditions under which the light-matter coupling can result in nonperturbative corrections to the dipole's ground state. To do so we consider two simplified, but otherwise rather generic cavity QED setups, which allow us to derive analytic expressions for the total ground state energy and to distinguish explicitly between purely electrostatic and genuine vacuum-induced contributions. Importantly, this derivation takes the full electromagnetic spectrum into account while avoiding any ambiguities arising from an ad-hoc mode truncation.

Our findings show that while the effect of confinement per se is not enough to result in substantial vacuum-induced corrections, the presence of high-impedance modes, such as plasmons or engineered LC resonances, can drastically increase these effects.

Reza Mosala Nejad (Innsbruck)

Towards Yb in Cavity

In this project, the few-body (∼10) and many-body (∼100) physics of interacting Yb atoms will be investigated. The ultra-cold Yb atoms will be placed in an optical cavity which mediates the interaction between the atoms. The use of optical tweezer arrays will give us more control over the atom positioning within the cavity. In this talk, the current status of the project will be reported. This will include the experimental realization of the vacuum setup, a permanent magnet Zeeman slower, and $^1S_0 \rightarrow {}^1P_1$ and $^1S_0 \rightarrow {}^3P_1$ magneto-optical traps for different Yb isotopes. The design of the cavity will also be presented. In the end, the future plans envisaged as of now will be presented.

Abstracts – Tuesday, March 26

Oriana Diessel (Harvard)

Emergent Kardar-Parisi-Zhang phase in quadratically driven condensates

In bosonic gases at thermal equilibrium, an external quadratic drive can induce a Bose-Einstein condensation described by the Ising transition, as a consequence of the explicitly broken U(1) phase rotation symmetry down to $\mathbb{Z}_2$. However, in physical realizations such as exciton-polaritons and nonlinear photonic lattices, thermal equilibrium is lost and the state is rather determined by a balance between losses and external drive. A fundamental question is then how nonequilibrium fluctuations affect this transition. In my talk, I'll show that in a two-dimensional driven-dissipative Bose system the Ising phase is suppressed and replaced by a nonequilibrium phase featuring Kardar-Parisi-Zhang (KPZ) physics. Its emergence is rooted in a U(1)-symmetry restoration mechanism enabled by the strong fluctuations in reduced dimensionality. Moreover, I'll show that the presence of the quadratic drive term enhances the visibility of the KPZ scaling, compared to two-dimensional U(1)-symmetric gases, where it has remained so far elusive.

Hossein Hosseinabadi (JGU Mainz)

Far From Equilibrium Dynamics of Spin Glasses in Cavity Quantum Electrodynamics

The theory of spin glasses is one of the pillars of modern statistical physics, offering insights that extend beyond its own domain to illuminate the behavior of various complex systems. Despite the experimental discovery of spin glasses in solid-state platforms, the disordered nature of these systems has hindered a comprehensive exploration of their theoretical foundations. Recent advancements in cavity quantum electrodynamics (c-QED) have provided the opportunity to investigate this curious phase of matter with unprecedented precision and control. In this talk I discuss our recent work, which provides the understanding of real-time dynamics in the formation of spin glasses within a setup closely connected c-QED experiments. Employing non-equilibrium quantum field theory methods, we explore the emergence of spin glass order in real time following a quench. We address dynamics across a diverse range of parameters for long times, while treating quantum and classical fluctuations on the same footing. Our theoretical approach offers the potential to tackle numerous other systems of interest in the field of many-body quantum optics.

Marvin Holten (TU Wien)

Atom-Cavity Setup for Engineering Entanglement with Programmable Connectivity

Entanglement is the fundamental resource for applications like quantum computation and communication beyond the possibilities of classical machines. Many current devices are limited to local connectivity when system size is increased. I report on the current status of our experiment, aimed at establishing an alternative platform for quantum simulation and information processing with full qubit connectivity. Our goal is to trap an array of individually addressable atoms inside an optical cavity, leveraging photon-mediated interactions to introduce non-local couplings and entangling operations between any two qubits in the system. This approach enables us to implement a non-destructive readout scheme relying on a few-photon field injected into the cavity. The unique combination of dissipation and non-destructive measurements opens up exciting possibilities for generating highly entangled many-body ensembles, such as large GHZ states. We aim to utilize this quantum processor to address longstanding questions about the thermalization of quantum systems and information scrambling. With its scalability and fully programmable connectivity, our architecture promises to unlock new pathways across a wide range of fields, including quantum optimization, communication, and simulation.

Ronen Kroeze (Ludwig-Maximilians-Universität)

Replica symmetry breaking in a quantum-optical vector spin glass

Multimode optical cavity QED provides a versatile platform with which to explore quantum many-body physics in driven-dissipative systems. Confocal cavities host all-to-all, sign-changing, photon-mediated spin interactions that enable study of spin glasses in a quantum optical setting. Using the density wave phases of multiple BECs located inside the cavity as pseudospin degrees of freedom, this system realizes an unusual type of transverse-field vector spin glass. Individual spin configurations are observed in cavity emission and reveal the emergence of replica symmetry breaking and nascent ultrametric structure as signatures of spin-glass order. The driven-dissipative nature of the system manifests as a nonthermal Parisi distribution, in qualitative correspondence with Monte Carlo simulations. These results enable further microscopic study of associative memories and spin glass physics, potentially down to the quantum-spin-level.

Angelo Valli (Budapest Univ. of Technology and Economics)

Full counting statistics and cumulant evolution in infinite temperature quantum spin chains

We investigate the spin-transfer statistics in one-dimensional anisotropic Heisenberg (XXZ) spin models. We introduce a novel tensor-network approach, with which we extract high-order cumulants directly from the generating function at unprecedented long times. We can validate our approach against quantum trajectory simulations – which give access to the full distribution but are limited to shorter times – allowing us to compare cumulant up to the sixth order for $S=1/2$ and $S=1$ spin chains [1]. $S=1/2$ spin chains are integrable, and at the isotropic point ($\Delta=1$) the variance of the spin transfer is characterized by an algebraic growth in time with a superdiffusive $z=3/2$ exponent as for a Kardar-Parisi-Zhang (KPZ) universal scaling. Fluctuations are weakly non-Gaussian (e.g., non-zero excess kurtosis) but incompatible with a Baik-Rains distribution, in agreement with recent experiments on quantum simulators [2] and with theoretical predictions for classical magnets [3]. In the easy-plane regime ($\Delta<1$) transport is ballistic with asymptotically Gaussian distribution. In the XX limit (i.e., $\Delta=0$), we can compare our simulations with exact results, obtained by fermionizing the spin chain. Remarkably, in the diffusive easy-axis regime ($\Delta>1$), we find distinctively non-Gaussian fluctuations, and cumulants consistent with those obtained from Mainardi-Wright family distributions [3]. For non-integrable $S=1$ spin chains, we find a distinctively different scenario. The spin transfer is the easy-plane regime displays a ballistic-to-diffusive crossover. Interestingly, a resilient scaling is observed, suggesting near-integrability. The dynamical exponent drifts away from the universal value $z=3/2$ logarithmically in time, possibly towards a $z=2$ diffusive regime – although we cannot numerically rule out a $z=5/3$ Fibonacci-ratio exponent [4]. In all regimes, we find fluctuations asymptotically consistent with Gaussianity.

[1] Valli et al., in preparation
[2] Google Quantum AI, arxiv:2306.09333 (2023)
[3] Krajnik et al. Phys. Rev. Lett. 132, 017101 (2024)
[4] Popkov et al. PNAS 112, 12645 (2015)