International Conference on Quantum Optics

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Book of Abstracts

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

Contents

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Additional extended abstracts, including a full author list, images, references, etc. are to be found online. If such an extended abstract is available, this is indicated at the contribution and its ID for online retrieval is given.

We thank Wolfgang Niedenzu for providing us with this nice template for our book of abstracts.

Talks Monday, 26 February

Entanglement Made Scalable

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The concept of entanglement brings out the quantum superposition principle for correlations. It is a key pillar of quantum physics and has widely been studied for two qubits. However, its full potential will develop in multi-qubit quantum systems. The talk presents a new photonic technology that for the first time produces and controls in an efficient way a plethora of multi-qubit entangled states. This opens up realistic pathways towards measurement-based quantum computation and loss-tolerant quantum communication in quantum networks.

Quantum chemistry on a programmable quantum simulator

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Simulations of quantum chemistry and quantum materials are believed to be among the most important potential applications of quantum information processors, but realizing practical quantum advantage for such problems is challenging. We introduce a simulation framework for strongly correlated quantum systems that can be represented by model spin Hamiltonians which leverages reconfigurable qubit architectures and algorithms for extracting chemically relevant spectral properties via classical co- processing of quantum measurement results.

Harnessing quantum emitter rings for efficient energy transport and trapping

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Extended Abstract Online (ID 14)

Efficient transport and harvesting of excitation energy under low light conditions is an important process in nature and quantum technologies alike. Here we formulate a quantum optics perspective to excitation energy transport in configurations of two-level quantum emitters with a particular emphasis on efficiency and robustness

against disorder. We study a periodic geometry of emitter rings with subwavelength spacing, where collective electronic states emerge due to near-field dipole-dipole interactions. The system gives rise to collective subradiant states that are particularly suited to excitation transport and are protected from energy disorder and radiative decoherence. Comparing ring geometries with other configurations shows that that the former are more efficient in absorbing, transporting, and trapping incident light. Because our findings are agnostic as to the specific choice of quantum emitters, they indicate general design principles for quantum technologies with superior photon transport properties and may elucidate potential mechanisms resulting in the highly efficient energy transport efficiencies in natural light-harvesting systems.

Towards explainable AI in quantum science

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Preparing tensor network states on quantum devices

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Quantum simulation requires preparing appropriate states in quantum devices, such as thermal states at a given temperature or ground states. Such states are typically well described through tensor networks, which motivates the question how to move from a given tensor network description to an algorithm to prepare said state. I'll present some of our recent work that showed that MPS can be prepared in log-depth quantum circuits and that certain two-dimensional tensor network states can be prepared sequentially, which may have applications also for photonic state preparation. Hopefully I'll be able to also include some current work where we generalize some of these ideas.

References

[1] Preparation of matrix product states with log-depth quantum circuits, D Malz, G Styliaris, ZY Wei, JI Cirac, arXiv preprint arXiv:2307.01696

[2] Efficient adiabatic preparation of tensor network states, ZY Wei, D Malz, JI Cirac, Physical Review Research 5 (2), L022037 (2023)

[3] Generation of photonic tensor network states with Circuit QED, ZY Wei, JI Cirac, D Malz, Physical Review A 105 (2), 022611 (2022)

[4] Sequential generation of projected entangled-pair states, ZY Wei, D Malz, JI Cirac, Physical Review Letters 128 (1), 010607 (2022)

Observation of false vacuum decay in a ferromagnetic superfluid

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Extended Abstract Online (ID 9)

In quantum field theory, the decay of an extended metastable state into the real ground state is known as "false vacuum decay" and it takes place via the nucleation of spatially localized bubbles. Despite the large theoretical effort to estimate the nucleation rate and intriguing speculations over the fate of our universe, experimental observations were still missing. In our experiment, we observe bubble nucleation in isolated and highly controllable superfluid atomic systems, and we find good agreement between our results, numerical simulations and instanton theory opening the way to the emulation of out-of-equilibrium field phenomena in atomic systems.

Quantum Correlated Light - Routinely used in Gravitational Wave Detectors

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Light with squeezed quantum uncertainty allows for the sensitivity improvement of laser interferometers. Since 2010, the gravitational-wave (GW) detector GEO600 has been using squeezed light in all of its searches for GWs [1]. The successful sensitivity improvement triggered the implementation of squeezed light sources also in Advanced LIGO and Advanced Virgo. On April 1st, 2019 these observatories started their third observational run. Since then they have been detecting more than one GW event per week. An increased event rate of up to 50% is due to the exploitation of squeezed states of light [2,3]. Squeezed light is fully described by quantum theory, however, observations on squeezed light represent physics that is not self-evident. I present a description of why a squeezed photon counting statistic

is rather remarkable [4].

References

[1] LIGO Scientific Collaboration, Nature Physics 7, 962 (2011);

[2] M. Tse et al., Phys. Rev. Lett. 123, 231107 (2019);

[3] L. Acernese et al., Phys. Rev. Lett. 123, 231108 (2019);

[4] R. Schnabel, Annalen der Physik 532, 1900508 (2020).

Routing of Photonic Qubits for Quantum RAM with a Single Atom

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We present a scheme and experimental realization of a photonic quantum routing node for quantum randomize-access memory (QRAM), using the photon-atom quantum SWAP gate. In our scheme (developed in collaboration with Prof. Liang Jiang from the university of Chicago) the atom is initialized in one of two ground states and a dual-rail control photonic qubit either interacts with it and toggles it to the other ground state, or not. Subsequently, an incident target photonic time-bin qubit is either transmitted or reflected from the atom, depending on the state of the control qubit. In preliminary results we achieve fidelities of 83% for the control routing qubit, 76% for the Target qubit routing, and 95% for the Target qubit coherence.

Temperature-enhanced critical metrology

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We show that the performance of critical quantum metrology protocols can be enhanced by considering systems at finite temperature. To this end, we consider a toy-model squeezing Hamiltonian and the paradigmatic Ising model. We show that the enhancement can be achieved by adiabatic preparation of the critical state and by preparing the thermal state directly in the proximity of the critical point. Therefore, we argue that finite temperature can be considered as a resource in quantum metrology.

Optical Electrons and Light - Imaging and Information

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Electron-induced damage is one of the major challenges in imaging biological matter with electron beams. We will discuss two techniques that open possibilities for dose-effective measurements:

First, we will discuss ponderomotive electron beam shaping [1]. An electron beam interacts with a shaped high-intensity laser pulse, which induces a phase shift proportional to the local light intensity. Since the light intensity distribution can be shaped arbitrarily, we can use this to arbitrarily shape the wavefront of an electron beam. We demonstrate concave and convex electron lensing and the ability to program complex electron deflection patterns. This beam-shaping technique is lossless and doesn't induce inelastic scattering. It can be used for the realization of a phase plate, an aberration correction plate, or adaptive measurement schemes. The latter we will discuss from an information-theoretical perspective [2].

Second, we will discuss optical near-field electron microscopy (ONEM) which has been proposed as a way to circumvent electron-induced damage [3]: In ONEM, a sample is probed non-invasively using light, and the resulting near-field interference patterns are converted into an electron current using a photocathode. The emitted electrons are then imaged with nanometric resolution using an aberration-corrected Low Energy Electron Microscope (LEEM). For sample-photocathode distances much smaller than the optical wavelength ($z \ll \lambda$) this allows for label-free superresolution microscopy of interfaces. After introducing the basics of this new imaging concept, we will discuss first images obtained with this new microscopy technique.

References

[1] Marius Constantin Chirita Mihaila, Philipp Weber, Matthias Schneller, Lucas Grandits, Stefan Nimmrichter, Thomas Juffmann, Transverse Electron Beam Shaping with Light. Phys. Rev. X 12, 031043 (2022)

[2] D. Bouchet, J. Dong, D. Maestre, and T. Juffmann, Fundamental Bounds on the Precision of Classical Phase Microscopes, Phys. Rev. Appl., 15(2), 024047 (2021)

[3] Marchand, R., Šachl, R., Kalbac, M., Hof, M., Tromp, R., Amaro, M., van der Molen, S. J. & Juffmann, T., Optical Near-Field Electron Microscopy. Physical Review Applied 16, 014008 (2021)

Talks Tuesday, 27 February

Quantum solitons in frustrated Wigner crystals

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We analyse the ground state emerging from the competition between a periodic potential and a Wigner crystal in one dimension, consisting of a selforganized chain of particles with the same charge. This system is a paradigmatic realization of the Frenkel-Kontorova model with Coulomb interactions. We derive the action of a Coulomb soliton in the continuum limit and demonstrate the mapping to a massive (1+1) Thirring model with long-range interactions. Here, the solitons are charged fermionic excitations over an effective Dirac sea. The mismatch between the periodicities of potential and chain, giving rise to frustration, is a chemical potential whose amplitude is majorly determined by the Coulomb self-energy. The mean-field limit is a long-range antiferromagnetic spin chain with uniform magnetic field and predicts that the commensurate, periodic structures form a complete devil's staircase as a function of the charge density. Each step of the staircase correspond to the interval of stability of a stable commensurate phase and scales with the number N of charges as 1/lnN. This implies that there is no commensurate-incommensurate phase transition in the thermodynamic limit. For finite systems, however, the ground state has a fractal structure that could be measured in experiments with laser-cooled ions in traps.

Ultracold atoms in optical cavities

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The realization and control of non-trivial quantum phases by the coupling of quantum light and matter is currently of great interest. We investigate the coupling of atoms confined to optical lattices to a cavity field which leads to an effective long-range interaction between the atoms. We determine the coupled state of the cavity and the atoms beyond the typically employed mean field approach using two different approaches, a numerical approach based on the matrix product state and a analytical perturbative approach.

How to administer an antidote to Schrödinger's cat

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Extended Abstract Online (ID 50)

In his famous Gedankenexperiment, Schrödinger imagined a box with a cat and a poisonous substance that is released based on the 50% probable decay of a radioactive atom. The survival of the cat and the state of the poison become entangled, and the fate of the cat is determined upon opening the box. We present an experimental technique that keeps the cat alive on any account. Our approach relies on the time-resolved Hong–Ou–Mandel effect: two long, identical photons impinging on a beam splitter always bunch in either of the outputs. Interpreting the first photon detection as the state of the poison, the second photon is identified as the state of the cat. Once the first photon's state has been determined, the second normally follows suite. However, we here demonstrate that a sudden phase change between the inputs, administered conditionally on the outcome of the first detection, allows us to steer the second photon to a pre-defined output and thus ensures that the cat is always observed alive.

Engineering of many-body states in a driven-dissipative cavity QED system

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Exposing a many-body system to external drives and losses can fundamentally transform the nature of its phases, and opens perspectives for engineering new properties of matter. How such characteristics are related to the underlying microscopic processes is a central question for our understanding of materials. A versatile platform to address it are quantum gases coupled to the dynamic light fields inside optical resonators. This setting allows to create synthetic many-body systems with tunable, well-controlled dissipation channels, and at the same time to induce cavity-mediated long-range atom-atom interactions. If these are sufficiently strong, the system can undergo self-organization to a crystalline state.

By engineering the involved light field modes, we study in real-time the dynamics of a phase transition between two such crystals. When the dissipation via cavity losses and the coherent timescales are comparable, we find a regime of limit cycle oscillations leading to a topological pumping of the atoms [Dreon et al., Nature, 608, 494 (2022)].

In a second set of experiments, we make use of the cavity-mediated interaction to induce the formation of pairs of correlated atoms. We demonstrate that this process is based on the amplification of vacuum fluctuations [Finger et al., arXiv:2303.11326 (2023)].

Probing quantum dynamics with strongly driven ultracold atoms

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Degenerate gases in modulated optical lattices are a flexible testbed for quantum simulation of matter driven far from equilibrium. I will present results from a sequence of recent experiments in this area, on topics ranging from interacting quantum kicked rotors to localization in driven quasicrystals. Time permitting, I will also discuss a new tweezer-based degenerate gas platform under construction at UC Santa Barbara which aims at the study of quantum interactive dynamics.

Rydberg polaritons at the boundary of weak and strong coupling

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Advancing the field of quantum optics hinges on achieving precise control over single- and few-photon interactions. This requires a dual approach: the hybridization of light and matter to form polaritons, and the creation of strong interactions within the matter degrees of freedom. In this presentation, we will explore two complementary platforms to address these objectives.

In the first part, we delve into the world of Rydberg excitons, highly excited bound states of electrons and holes in semiconductors, showcasing their ability to induce significant optical nonlinearities in crystals. Ongoing efforts to push these nonlinearities to the ultimate quantum limit of single photons will also be discussed.

The second part provides an overview of recent progress on giant diatomic molecules composed of two Rydberg atoms (Rydberg macrodimers), excited from an optical lattice. These molecules feature an intriguing binding mechanism mediated by van der Waals forces. We will explore how Rydberg macrodimers can be optically coupled to a continuum of free motional states, leading to the formation of multi-atom molecules bound by light.

Fisher Information in Electromagnetic Scattering

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I will present a recent body of work on the concept of Fisher Information in electromagnetic scattering problems. Specifically, I will show how to extract from any complex system the maximum amount of Fisher Information about a specific parameter (like the position of a specific target), that will then allow one to estimate the value of this parameter with the highest possible precision [1,2]. As we recently demonstrated, the Fisher Information satisfies quite fundamental invariance and conservation laws [3,4] in analogy to the seminal Poynting theorem. I will discuss the interesting consequences of these insights on metrology, micro-manipulation and levitated opto-mechanics.

References

[1] Bouchet, Rotter & Mosk, Nature Physics 17, 564 (2021)

[2] Bouchet, Rachbauer, Rotter, Mosk & Bossy, PRL 127, 253902 (2021)

[3] Horodynski, Bouchet, Kühmayer & Rotter, PRL 127, 233201 (2021)

[4] Hüpfl, Russo, Rachbauer, Bouchet, Lu, Kuhl & Rotter, arXiv:2309.00010

Lasing regimes for self-organization in a driven thermal atomic gas

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Cavity QED in the regime of short cavity memory and long atomic coherence times allows us to see physics where large atom numbers are necessary to produce strong coupling as a collective effect [1]. This so-called bad-cavity regime shows both sub- and superradaint behavior when the atoms are pumped resonantly [2], and can produce continuous superradiant lasing under incoherent repumping [3]. But this system can also be used to study the optomechanical interactions that lead to self-organization of the atoms in lattice structures.

We will present our investigation of an interesting regime where quasi-continuous emission is observed from an ensemble of cold 88Sr atoms while being pumped near-resonantly from a direction perpendicular to the cavity axis. We map out how the emitted light frequency depends on both the pump and cavity detunings, and use a numerical model that illustrates the effect of light forces in the system, which can lead to self-organisation.

References

[1] S A Schäffer, M Tang, M R Henriksen, A A Jørgensen, B TR Christensen, J W Thomsen. Lasing on a narrow transition in a cold thermal strontium ensemble, Phys. Rev. A, 101, 1, 013819 (2020)

[2] E Bohr, S L Kristensen, C Hotter, S A Schäffer, J Robinson-Tait, J W Thomsen, T Zelevinsky, H Ritsch, J H Müller. Collectively enhanced Ramsey readout by cavity sub-to superradiant transition, arXiv preprint arXiv:2306.12544 (2023)

[3] S L Kristensen, E Bohr, J Robinson-Tait, T Zelevinsky, J W. Thomsen, and J H Müller. Subnatural Linewidth Superradiant Lasing with Cold 88Sr Atoms. Phys. Rev. Lett. 130, 223402 (2023)

Color centers in diamond as optically addressable spin qubits

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Extended Abstract Online (ID 121)

Optically addressable spins in the solid state are promising candidates for realizations of quantum networks and quantum computing nodes. We study NV centers in diamond coupled to an optical microcavity to enhance the optical emission and get efficient access to the spin degree of freedom. Studying small ensembles, we observe collectively enhanced emission and non-trivial photon statistics, despite the presence of inhomogeneities and spatial separation between emitters. As an alternative color center, we study SnV centers in diamond, which can possess superior optical coherence properties. We observe hour-long spectral stability and Fourier-limited emission linewidths of individual emitters. Due to its strong spin-orbit splitting, SnV centers also possesses long electron spin lifetimes at temperatures around 1K. To control the electron spin with high fidelity, the use of microwave fields is required. However, the magnetic transitions are heavily suppressed in unstrained emitters. This limitation can be overcome by inducing strain and precisely aligning the DC magnetic field orientation. To avoid Ohmic losses in the microwave line, which restricts coherence through heat induction, we fabricate a superconducting coplanar waveguide on a diamond membrane. We induce strain in the diamond by using a polymer with a high coefficient of thermal expansion for fixation. We demonstrate coherent manipulation of the electron spin and evaluate the decoherence properties for different magnetic field orientations at mK temperature. Prospects for integration into a microcavity for efficient spin-photon interfacing are discussed.

Error-correction in Long Ion Chains

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Extended Abstract Online (ID 119)

We implement one round of fault-tolerant Steane-type Z-stabilizer readout of the Bacon-Shor [[9,1,3]] quantum error-correcting code in a chain of 23 $^{171}Yb^{+}$ ions. We demonstrate twofold suppression of the error in the logical data and in the Z-syndrome compared to a fault-tolerant Shor-style protocol. To counter the dominant errors, caused by axial motion of the ions, demonstrate deterministic sorting of $^{171}Yb^{+}$-$^{172}Yb^{+}$ chains. Sympathetic cooling using $^{172}Yb^{+}$ opens the door to partial readout and qubit reuse in long circuits and the study of controlled dissipation in individually-addressed long ion chains.

Talks Wednesday, 28 February

Quantum magnetic induction tomography

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Measurements of conductivity are ubiquitous in science and technology. Magnetic induction tomography (MIT) used for non-invasive conductivity measurements is based on response of a conducting object to ac magnetic fields. We have developed a method of Quantum MIT where entangled atomic spins are used as ultrasensitive meters for detection of weakly conducting objects. Applications to bio-medical sensing will be presented.

The maximum refractive index of optical materials: from quantum optics to quantum chemistry

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It is interesting to observe that all known optical materials have a refractive index that is of order unity at visible/telecom wavelengths. However, it is not easy to reconcile this with the fact that the individual atoms making up the material are well-known to have a huge optical response near resonance, when isolated, as characterized by a scattering cross section that is much larger than the physical size of the atom. Here, we develop minimal but unifying models to understand the index of a collection of atoms as a function of density, ranging from the "quantum optics" regime of well-isolated atoms, to the "quantum chemistry" regime relevant for real-life solids. Importantly, our models simultaneously account for non-perturbative multiple light scattering, which is a key factor in what makes the problem surprisingly rich and complex. Our work suggests that an ultrahigh index material (n 30) with low losses is in principle allowed by the laws of nature. If realizable, such a material would have profound implications for optical technologies, due to the extreme reduction of optical wavelength and the associated potential for miniaturization of optical devices and enhancement of optical resolution.

Anomalous photon bunching

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Extended Abstract Online (ID 126)

It is commonly admitted that bunching is maximum for fully indistinguishable photons and gradually declines if photons are made distinguishable. Here, we disprove this alleged simple link between indistinguishability and bunching by exploiting a recent finding in the theory of matrix permanents. We exhibit a family of optical circuits such that the bunching probability of photons into two modes can be substantially boosted by making them partially distinguishable. This unexpected behavior questions our understanding of multiparticle interference in the grey zone between ideal bosons and classical particles.

Certification of many-body systems

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A ubiquitous problem in physics is to understand the ground-state properties of classical and quantum many-body systems. It is also one of the main applications of first-generation of quantum computing devices, such as quantum optimisers or simulators. Classically, since an exact solution soon becomes too costly when increasing the system size, variational approaches are often employed as a scalable alternative: energy is minimised over a subset of all possible states and then different physical quantities are computed over the solution state. However, strictly speaking, all what these methods provide are provable upper bounds on ground-state energy. Relaxations to the ground-state problem based on semi-definite programming represent a complementary approach, providing lower bounds to the ground-state energy but, again, no provable bound on any other relevant quantity. We first discuss how these relaxations can be useful to benchmark the performance of quantum optimisers. After that, we show how relaxations, when assisted with an energy upper bound, can be used to derive certifiable bounds on the value of any physical parameter, such as correlation functions of arbitrary degree or structure factors, at the ground state. We illustrate the approach in paradigmatic examples of 1D and 2D spin-one-half systems.

Strongly-interacting bosons at dimensional crossover: single-particle correlation and anomalous cooling

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Extended Abstract Online (ID 37)

Dimensionality plays an essential role in determining the nature and properties of quantum gases. Fruitful physics may appear at the crossover between dimensions. In the current generation of cold atom experiments, the dimensionality of the system can be controlled by optical lattices. In this talk, I will firstly present our recent study of strongly-interacting bosons at 2D-1D dimensional crossover [1]. We find, using Cesium atoms in optical lattices, that the single-particle correlation function of the system evolves from a Berezinskii-Kosterlitz-Thouless (BKT) form to a Tomonaga-Luttinger liquid (TLL) type. The behavior of the correlation with distance, reflects the fact that the particles see their dimensionality as being one or two depending on whether they are probed on short or long distances, respectively. These results are consistent with our theoretical prediction [2] obtained via ab-initio quantum Monte Carlo (QMC) calculations. In addition, the comparison of the experimentally measured correlation function with the QMC calculation, allows us to perform thermometry on the low dimensional bosons with 1 nK sensitivity [3]. Strikingly, during the dimensional reduction process, we find that the temperature for the 1D case can be much lower than the initial temperature in 3D. Our findings show that this decrease results from the interplay of dimensional reduction and strong interactions.

References

[1] Y. Guo, H. Yao, S. Ramanjanappa, S. Dhar, M. Horvath, L. Pizzino, T. Giamarchi, M. Landini and H.-C. Nägerl, arXiv: 2308.00411 (2023)

[2] H. Yao, L. Pizzino, T. Giamarchi, SciPost Phys. 15, 050 (2023)

[3] Y. Guo, H. Yao, S. Dhar, L. Pizzino, M. Horvath, T. Giamarchi, M. Landini, H.-C. Nägerl, arXiv:2308.04144 (2023)

Spin squeezing and entanglement generation in two-dimensional ion crystals with up to 105 ions

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Recent developments in ion trap design enabled stable trapping and cooling of two-dimensional (planar) ion crystals with more than 100 particles. Such crystals have promising applications in quantum simulation of 2D spin models as well as quantum metrology. In this talk, I will present our ion trap apparatus and describe some tools and techniques to cool and control 2D crystal with up to 105 ions. By means of coupling the spin state – encoded in a Zeeman ground-state qubit – to the out-of-plane motional modes we realize the long-range transverse-field Ising model in our system. To assess the performance of our quantum simulator and to prove multi-partite entanglement, we implement a recently developed protocol to create spin-squeezed states, a valuable tool in quantum-enhanced metrology. Despite not having infinite-range interactions at hand, we show that operating the simulator in the power-law XY regime gives an evolution being well-approximated by the one-axis twisting model. This enables the creation of highly-squeezed states with Wineland parameters of more than 9dB for up to 105 particles and unambiguously verifies multi-partite entanglement in planar ion crystals.

A scalable quantum switch for a genuine indefinite causal order

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Extended Abstract Online (ID 138)

The quantum switch applies gates in a superposition of orders, having potential applications that go beyond standard fixed-order quantum circuits. It also touches foundational questions regarding causal relationships at the quantum level. Experiments have realized the quantum switch for two gates, but scaling these approaches up requires a combinatorial explosion of physical resources. Moreover, experiments have been criticized for having loopholes regarding how many times each gate is used. We present a proposal for a better implementation of the quantum switch, circumventing the practical scaling problems and the foundational criticisms. Our proposal requires single-photon level nonlinearities to coherently route a photon through gates. The number of nonlinear interactions is quadratic in the gate number. Moreover, each gate only has a single mode traversing it, solving the gate-use loophole. We believe that an experimental implementation of our proposal is within reach.

Talks Thursday, 29 February

Exploring quantum error correction frontier with programmable atom arrays

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A broad effort is currently underway to develop quantum computers that can outperform classical counterparts for certain computational or simulation tasks. Suppressing errors is one of the central challenges for useful quantum computing, requiring quantum error correction for large-scale processing. However, the overhead in the realization of error-corrected "logical" qubits, where information is encoded across many physical qubits for redundancy, poses significant challenges to large-scale logical quantum computing. In this talk, we will discuss the recent advances involving programmable, coherent manipulation of quantum systems based on neutral atom arrays excited into Rydberg states, allowing the control over several hundred qubits in two dimensions. In particular, we use this platform to explore quantum algorithms with encoded logical qubits and quantum error correction techniques. Using this logical processor with various types of error-correcting codes, we demonstrate that we can improve logical two-qubit gates by increasing code size, outperform physical qubit fidelities, create logical GHZ states, and perform computationally complex scrambling circuits using 48 logical qubits and hundreds of logical gates. These results herald the advent of early error-corrected quantum computation, enabling new applications and inspiring a shift in addressing both the challenges and opportunities that lay ahead.

On-chip hybrid potentials for levitation experiments

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Nowadays, most levitation platforms are complex and bulky, limiting their integration into confined settings like cryostats. Miniaturized levitation setups on the other hand offer enhanced control over the particle's motion by enabling precise engineering of optical and electric fields due to proximity effects. Furthermore on-chip systems combine flexibility and complexity in one platform, similar to the development of integrated ion traps or solid state systems. Here we demonstrate optical levitation and motion control in vacuum of silica nanoparticles on hybrid optical / electrostatic chips. Specifically, by combining lensless optical trapping and position detection by means of a set of optical fibers combined with planar electrodes, we cool the particle motion to few hundred phonons without the use of high NA optics.

Machine-learning the phase diagram of the BEC/BCS crossover

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We determine the phase diagram of strongly correlated fermions in the crossover from Bose-Einstein condensates of molecules (BEC) to Cooper pairs of fermions (BCS) utilizing an artificial neural network. By applying advanced image recognition techniques to the momentum distribution of the fermions, a quantity which has been widely considered as featureless for providing information about the condensed state, we measure the critical temperature and show that it exhibits a maximum on the bosonic side of the crossover. Additionally, we backanalyze the trained neural network and demonstrate that it interprets physically relevant quantities.

The limits of Generalized Hydrodynamics

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I will describe our experiments to test and test the limits of generalized hydrodynamics as a theory of nearly integrable 1D Bose gases.

Universal Self-Organization Dynamics in a Strongly Interacting Fermi Gas

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Extended Abstract Online (ID 33)

Cavity-coupled many-body systems constitute a new emergent field in condensed matter systems, where complex quantum materials are combined with cavity quantum electrodynamics (cQED) to substantially modify material properties by strong light-matter coupling. One particularly fascinating perspective is the modification of superconductivity with light. However, due to the complexity of condensed matter systems, numerous fundamental questions remain unanswered. By combining cQED with a strongly interacting Fermi gas, we bridge the gap between ultracold bosonic gases and condensed matter systems, providing an ideal, microscopically controllable platform for the study of collective light-matter coupling in strongly correlated matter. Our most recent research explores the interplay of strong, short-range collisional interactions in the Bose-Einstein condensate to Bardeen-Cooper-Schrieffer (BEC-BCS) crossover and engineered, long-range cavity-mediated interactions. In our latest experiments, we advance our understanding of density-wave ordering by investigating the out-of-equilibrium dynamics of quenches across the quantum phase transition in the BEC-BCS Crossover. By observing the photons leaking from the optical cavity following a quench in atom-light coupling, we reveal the universal behaviour of the critical slow-down in this driven-dissipative system. Additionally, in a separate series of experiments, we introduce a new type of cQED many-body system, where long-range interactions between pairs and atoms are engineered by performing self-organization close to a photoassociation transition.

Replica symmetry breaking in a quantum-optical vector spin glass

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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.

Quantum Ötzi: piecing together the past of quantum systems

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One of the most famous tidbits of received wisdom about quantum mechanics is that one "cannot ask" how a particle got to where it was finally observed, e.g., which path of an interferometer a photon took before it reached the screen. What, then, do present observations tell us about the state of the world in the past? I will describe two experiments looking into aspects of this “quantum retrodiction." The first experiment I will describe addresses a century-old controversy: that of the tunneling time. Since the 1930s, and more heatedly since the 1980s, the question of how long a particle spends in a classically forbidden region before being transmitted has been a subject of debate. Using Bose-condensed Rubidium atoms cooled down to a nanoKelvin, we have now measured just how long they spend inside an optical beam which acts as a “tunnel barrier” for them. I will describe these ongoing experiments, as well as proposals we are refining to study exactly what happens during the time it takes to “collapse” an atom to be in the barrier. I will also introduce some of our more recent experiments, which revisit the common picture that when light slows down in glass, or a cloud of atoms, it is because the photons “get virtually absorbed” before being sent back along their way. We have carried out an experiment that lets us distinguish between the time spent by transmitted photons and by photons which are eventually absorbed, asking the question “how much time are atoms caused to spend in the excited state by photons which are not absorbed?”

Neutral Atoms in Tweezer Arrays for Hybrid Rydberg Quantum Computing

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Extended Abstract Online (ID 92)

The KAT-1 project in Eindhoven is developing a full-stack quantum computer, accessible online via QuantumDelta NL’s Quantum Inspire platform. Our quantum processor unit (QPU) is made of strontium atoms in a 2D optical tweezer array generated by a spatial light modulator. High-fidelity single-qubit control is achieved by laser coupling of the clock transition, and two-qubit gates by using Rydberg excitations to control the interaction of atoms between different tweezer sites. The

QPU will be used to solve problems in quantum chemistry with pulsed-based quantum optimization algorithms. This poster reports on the progress of our new strontium machine, including cooling and loading atoms into tweezers and the control software for the experimental setup. We explore the possibility of introducing a fiber array for single qubit driving into our platform to extend its addressability and parallelizability. Furthermore, we are investigating a method to enhance the connectivity of the two-qubit gate by adjusting the tweezer position outside the plane of the atomic array.

Route to chaos in an atom-cavity system

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Extended Abstract Online (ID 15)

In driven non-linear systems various kinds bifurcations can be observed on their route to chaos. From the evolution of Floquet multipliers one can extract information which serves as precursors of phase transitions and dynamical instabilities. This method is applied in classical non-linear physics for example as early warning signals. Using our very well controlled atom-cavity platform, we are able to prepare our system in these different regimes and study the bifurcation theory experimentally in a quantum gas. Therefore, we pump our setup perpendicular to the cavity axis with a standing wave light field. Crossing a critical pump strength, we observe a pitchfork phase transition from a normal to a steady state self-organized phase [1]. Employing an open three level Dicke model, this transition can be understood as by a transi- tion between two fix points. If the pump strength is increased further, the system over-goes a Hopf-bifurcation and limit cycles, which have time crystalline proper- ties, emerge [2]. In our model we cannot find fix points in that parameter regime but stable attractive orbits. For strong pumping, we observe a second bifurcations, in our case a Neimark-Sacker bifurcation. The main characteristics is an oscilla- tion with two incommensurate frequencies, which can me dubbed a continuous time quasicrystal [3]. Finally, we observe chaotic dynamics with many contributing fre- quencies.

Dissipative Dicke time crystals: an atoms' point of view

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We develop and study an atom-only description of the Dicke model with time-periodic couplings between atoms and a dissipative cavity mode. The cavity mode is eliminated giving rise to effective atom-atom interactions and dissipation. We use this effective description to analyze the dynamics of the atoms that undergo a transition to a dynamical superradiant phase with macroscopic coherences in the atomic medium and the light field. Using Floquet theory in combination with the atom-only description we provide a precise determination of the phase boundaries and of the dynamical response of the atoms. From this we can predict the existence of dissipative time crystals that show a subharmonic response with respect to the driving frequency. We show that the atom-only theory can describe the relaxation into such a dissipative time crystal and that the damping rate can be understood in terms of a cooling mechanism.

Talks Friday, 1 March

Entanglement of trapped-ion qubits separated by 230 m

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Entanglement-based quantum networks hold out the promise of new capabilities for secure communication, distributed quantum computing, and interconnected quantum sensors. However, only a handful of elementary quantum networks have been realized to date. I will present results from our prototype network, in which two calcium ions are entangled with one another over a distance of 230 m, via a 520 m optical fiber channel linking two buildings. At each of two network nodes, the electronic state of an ion is entangled with the polarization state of a single cavity photon; subsequent to interference of the photons at a beam splitter, photon detection heralds entanglement between the two ions. Fidelities of up to 88% are achieved with respect to a maximally entangled Bell state. We will consider possible routes to improve both fidelity end efficiency, paving the way for long-distance networks of entangled quantum processors.

Making and exploring Bose-Einstein condensates of dipolar molecules

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Extended Abstract Online (ID 156)

We have recently created the first Bose-Einstein condensates of dipolar molecules. Building on our demonstration of microwave shielding of NaCs molecules, we now efficiently cool gases of NaCs from 700 nK to less than 10 nK, deep into the quantum degenerate regime. The lifetime of the molecular BEC is almost 2 seconds, reaching a level of stability similar to ultracold atomic gases. This becomes possible with a new collisional shielding method that dramatically suppresses inelastic losses by four orders of magnitude compared to unshielded molecules.

In this talk, I will discuss our experimental approach and share our latest insights. BECs of NaCs offer exciting prospects for the exploration of dipolar quantum matter in regimes that have been inaccessible so far.

Modular computation architecture based on locally controlled logical systems

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Extended Abstract Online (ID 12)

We consider quantum computer architectures based on logically encoded systems consisting of multiple qubits that interact via some always-on, long-ranged coupling, and utilize solely single qubit control. We show that one can remotely mediate entanglement between different subsystems without any quantum control using one logical system. Using multiple logical systems allows one to selectively mediate interactions between systems, and obtain a programmable quantum simulator or processor. Furthermore, the encoding can serve to make the effective interaction between logical systems resilient against position fluctuations of the components, thereby providing a novel way to deal with imperfections, e.g. in cooling or heating of systems due to moving atoms or ions around. We demonstrate a significant improvement of achievable gate fidelities in several scenarios, including collective and individual position fluctuations , and classical and quantum treatment thereof. We show how to use such a setup to obtain a modular computational architecture that utilizes multipartite entanglement generated between modules to implement sets of gates or non-local parts of whole circuits between modules.

New approaches to atom interferometry

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Interferometry with matter waves that are held in optical lattices has enabled observation of interference fringes after hold times of as long as 70 seconds, and has demonstrated the ability to precisely measure the gravity of a small source mass. We will discuss the limitations to the coherence and future prospects of this method.

Experimental superposition of time directions

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Extended Abstract Online (ID 23)

Differently from our day-to-day experience, the laws of Nature suggest that time is not an asymmetric quantity, which always flows from past to future. Indeed, the description of the evolution of quantum systems remains valid also when flipping the sign of the time coordinate. This leads to the conclusion that quantum systems could offer the possibility to study and implement processes displaying a superposition of time directions. It is noteworthy that this type of process, due to its generality, would not be describable through the process matrix formalism, introduced to represent indefinite causal order operations. An example of operation that remains valid both in the "forward" and "backward" time direction are unitary evolutions, whose "backward version" amounts to their transpose.

In our experiment, using the theoretical tools introduced in [1], we implement a quantum supermap (the so-called "quantum time flip") transforming a given channel, acting on a target system, into the superposition of its forward and backward forms. In detail, we encode the quantum state undergoing a time evolution in the polarization of a single photon, while the time direction is encoded in its path degree of freedom (control system). We show that polarization operations with waveplates naturally implement different time directions for forwards and backwards propagation directions, given the correct Stokes-parameter convention. Hence, we realize the quantum time flip deterministically by sending single photons through the waveplates in a superpositon of the two propagation directions.

We then witness the indefinitess in the time direction of our implemented process through a computational game, in which the use of the quantum time flip is demonstrated to guarantee an advantage over any other strategy, even those that exploit indefinite causal order. For this game, the highest winning probability for fixed-time direction strategies amounts to 0.92. In our case, the experimental success rate was 0.9945, which certifies that our apparatus is implementing a process indefinite in the time directions.

This result paves the way for future studies of processes with an indefinite time order, which promise to expand both the theoretical and experimental toolkit and open up new avenues for quantum information processing.

References

References

[1] G. Chiribella, Z. Liu, Communications Physics 5, 190 (2022).

Electron – Photon Pairs in Transmission Electron Microscopy

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Extended Abstract Online (ID 90)

Electron microscopy is a highly developed technology that employs the wave properties of electrons to resolve structures at an atomic level. In this work we investigate coherent cathodulmenescene (CL) photons and their corresponding electrons in a time-resolved coincidence measurement on the single particle level. Within a transmission electron microscope, a thin silicon membrane is illuminated by a collimated electron beam. The emitted CL photons are (wavelength sensitive) detected using single photon counting modules and time-stamped. The coincident electrons are detected in image and momentum space (using a Timepix3 detector). Such measurement scheme allows us to study momentum-position correlation.

Deterministic preparation of ultracold RbCs molecules in magic-wavelength optical tweezers

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Extended Abstract Online (ID 137)

We report the assembly of individual ultracold ground-state RbCs molecules in optical tweezers. Starting from individual Rb and Cs atoms cooled to the motional ground state of separate tweezers, we combine the atoms into a single tweezer and then use a combination of magnetoassociation and stimulated Raman adiabatic passage to create a molecule. The conversion efficiency from atom pairs to ground state molecules is around 50 %. However, we demonstrate a protocol to rearrange the molecules based upon high-field detection of the Rb atom in cases where the association is unsuccessful. We will discuss on-going experiments to transfer the molecules into magic-wavelength tweezers, where for bulk gases we have demonstrated rotational coherence times exceeding a second. This will enable the observation of spin-exchange interactions between molecules, leading to the prospect of entangling pairs of molecules and performing small-scale quantum simulations. Finally, we report a new hybrid platform that combines single ultracold molecules with single Rydberg atoms, opening a myriad of possibilities.

Experiments with subradiant atomic ensembles in a high-finesse optical cavity

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Extended Abstract Online (ID 56)

We report on our recent experiments performed with cold atoms strongly coupled to a single mode of a high-finesse optical cavity. We demonstrate an optical bistability between two hyperfine ground states of the atoms. While the atomic saturation is kept low, the source of nonlinearity is a cavity-assisted pumping between ground states of the atoms and the stability depends on the intensity of two driving lasers. We interpret the phenomenon in terms of the recent paradigm of driven-dissipative phase transitions, where the transmitted and driving fields are understood as the order and control parameters, respectively. Furthermore, we explore the radiation properties of light scattered by atoms into the cavity when they are in a subradiant configuration.

Adiabatic protocols in Lindbladian systems

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Extended Abstract Online (ID 54)

We develop a theory for adiabatic evolution of Lindbladian systems. While adiabatic theory of closed (Hamiltonian) systems is well established, real systems are open and can be described by non-Hermitian (Lindbladian) operators. Such operators have a complex gap that may close at exceptional points (EPs) – branch points in the eigenvalue spectrum. EPs are important for adiabatic theory for several reasons: (a) Instead of following individual eigenstates, adiabatic evolution can take place inside a multi-dimensional subspace spanned by Jordan chains, (b) Cyclic processes that involve encircling EPs may lead to mode swapping and chiral behavior, (c) EPs determine diabatic errors in the asymtotic limit. We classify the geometry and topology of EP surfaces in Lindbladians. We propose utilizing Lindbladian EPs for robust coherent control. Furthermore, we develop an optimal control method which finds pulses that optimally adhere to adiabatic eigenstates. Finally, we present a formula for asymptotic scaling of diabatic errors in Lindbladians.

Preparation, dynamics and extraction of entanglement in one-dimensional BECs

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Extended Abstract Online (ID 80)

The key ingredient for studying the dynamics of quantum many-body systems is the ability to prepare and manipulate quantum states and eventually perform an efficient readout of the available information. In this talk, I present our experimental studies using one-dimensional Bose-Einstein condensates on an atomchip combined with spatially resolved measurements.

We prepare quantum-correlated states of two tunnel-coupled superfluids and track the dynamical evolution of the relative atom number squeezing. The observed dynamics are governed by the interplay of on-site interactions and tunneling. Utilizing the control over the dynamics, we prepare optimized spin-squeezed states prolonging the phase coherence of the system.

We present our first experimental results concerning the implementation of weak probes for the simultaneous readout of number imbalance and phase to study mean-field dynamics and quantum correlations in this system with previously inaccessible observables.

Posters

Non-Hermitian dynamics and nonreciprocity of two optically coupled nanoparticles

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Extended Abstract Online (ID 47)

Optical levitation of dielectric objects in vacuum provides a unique optomechanical platform due to means of optical control of potentials and good isolation from the thermal environment. In recent years, different control techniques led to the demonstration of the motional quantum ground state cooling of single optically levitated dielectric nanoparticles in several experiments. Recently, tunable and nonreciprocal optical interactions have been measured between two nanoparticles levitated in two distinct optical tweezers, with single-site readout of particle motion. I will present our experimental platform for tweezer arrays of nanoparticles, and show our recent results on non-Hermitian collective dynamics of two nonreciprocally interacting nanoparticles. We also observe a mechanical lasing transition once a threshold coupling rate is achieved, supported by our nonlinear theory model. This work paves the way towards upscaling this platform to multiparticle arrays, in view of studying their nonequilibrium and collective mechanical behavior in the quantum regime.

Single-pair measurement of the Bell parameter

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Extended Abstract Online (ID 96)

We present the first single-pair Bell inequality test, able to estimate a Bell parameter value from each entangled pair. This is achieved by exploiting two weak measurements in sequence on each of the two photons constituting the pair, allowing to measure incompatible observables on the same quantum state without collapsing it. Such an approach, on the one hand, provides new insights into understanding the foundations of quantum mechanics. On the other hand, it grants unprecedented measurement capability because, after the Bell parameter measurement certifying the entanglement within the state, such entanglement remains almost unaltered and therefore exploitable for other practical purposes like, e.g., quantum technology protocols.

Metasurface-based hybrid optical cavities for chiral sensing

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Extended Abstract Online (ID 72)

Quantum metasurfaces, i.e., two-dimensional subwavelength arrays of quantum emitters, can be employed as mirrors towards the design of hybrid cavities, where the optical response is given by the interplay of a cavity-confined field and the surface modes supported by the arrays. We show that, under external magnetic field control, stacked layers of quantum metasurfaces can serve as helicity-preserving cavities. These structures exhibit ultranarrow resonances and can enhance the intensity of the incoming field by orders of magnitude, while simultaneously preserving the handedness of the field circulating inside the resonator, as opposed to conventional cavities. The rapid phase shift in the cavity transmission around the resonance can be exploited for the sensitive detection of chiral scatterers passing through the cavity. We discuss possible applications of these resonators as sensors for the discrimination of chiral molecules.

Non-Hermitian Anharmonicity Induces Single-Photon Emission

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Extended Abstract Online (ID 124)

Single-photon sources are in high demand for quantum information applications [Nature Photonics 3, 687 (2009)]. In this work, we theoretically propose a novel mechanism for generating single-photon emission, incorporating cavity modes with different losses. In contrast to the well-known photon blockade mechanism [Nature 436, 87 (2005)], which operates in the strong coupling regime of cavity QED systems and relies on anharmonicity in the energy levels, our proposed mechanism [Phys. Rev. Lett. 130, 243601 (2023)] does not require strong coupling. Instead, it relies on nonlinearity in loss, linked to the anharmonicity of non-Hermitian energies, that can be engineered within the weak coupling regime. We theoretically demonstrate this mechanism in the feasible setup of hybrid metallodielectric cavity weakly coupled to a two-level emitter, showcasing its potential for achieving high-purity single-photon emission at high repetition rates [Phys. Rev. Lett. 130, 243601 (2023)].

A cavity-microscope for micrometer-scale control of atom-photon interactions

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Extended Abstract Online (ID 70)

Cavity quantum-electrodynamics enables measurements of atoms with sensitivity limited by quantum backaction. Over the last decade, the possibility to observe and control the motion of few or individual atoms using cavity-enhanced light-matter coupling has been exploited to realize various quantum technological tasks, from quantum-enhanced metrology to quantum simulation of strongly-correlated matter. A principle limitation of these experiments lies in the mode structure of the cavity, which is hard-coded in the distance and geometry of the mirrors, effectively trading spatial resolution for enhanced sensitivity.

In this poster, I will present our cavity-microscope device allowing for spatio-temporal programming of the light-matter coupling of atoms in a high finesse cavity, which provides a spatial resolution an order-of-magnitude lower than the mode waist [1]. This is achieved through local Floquet engineering of the atomic structure, imprinting a corresponding light-matter coupling. We illustrate this capability by engineering micrometer-scale coupling, using cavity-assisted atomic measurements and optimization. Our system forms a single optical system with a single optical axis and has the same footprint and complexity as a standard Fabry-Perot cavities or confocal lens pairs, and can be used for any atomic species. This technique opens a wide range of perspectives from ultra-fast, cavity-enhanced mid-circuit readout to the quantum simulation of fully connected models of quantum matter such as the Sachdev-Ye-Kitaev model [2].

References

[1] D. Yang, C. Laflamme, D. V. Vasilyev, M. A. Baranov, and P. Zoller Phys. Rev. Lett. 120, 133601.

[2] Philipp Uhrich, Soumik Bandyopadhyay, Nick Sauerwein, Julian Sonner, Jean-Philippe Bran- tut, Philipp Hauke. arXiv:2303.11343.

Experimental set-up for loading Sr atoms into a hollow-core fibre

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Extended Abstract Online (ID 45)

In our project we develop an experimental setup to trap ^{88}Sr atoms in magneto-optical trap (MOT) and transfer them spatially with assist of optical dipole potential inside a hollow-core fibre. We focus on the delivery of atoms from a preparation area that consists double stage cooling by $^1S_0 -^1 P_1$ and $^1S_0 -^3 P_1$ transitions into the measurement area on the other side of the fibre. We want to experimentally determine the optimal cooling and loading strategy for Sr. During guiding we aim to increase atom lifetime (mostly related to vacuum quality) to the range of 1 s by reducing the heating rate, and employing targeted cooling schemes.

Superradiant two-level laser with intrinsic light force generated gain

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Extended Abstract Online (ID 32)

The implementation of a superradiant laser as an active frequency standard is predicted to provide better short-term stability and robustness to thermal and mechanical fluctuations when compared to standard passive optical clocks. However, despite significant recent progress, the experimental realization of continuous wave superradiant lasing still remains an open challenge as it requires continuous loading, cooling, and pumping of active atoms within an optical resonator. Here we propose a new scenario for creating continuous gain by using optical forces acting on the states of a two-level atom via bichromatic coherent pumping of a cold atomic gas trapped inside a single-mode cavity. Analogous to atomic maser setups, tailored state-dependent forces are used to gather and concentrate excited-state atoms in regions of strong atom-cavity coupling while ground-state atoms are repelled. To facilitate numerical simulations of a sufficiently large atomic ensemble, we rely on a second-order cumulant expansion and describe the atomic motion in a semi-classical point-particle approximation subject to position-dependent light shifts which induce optical gradient forces along the cavity axis. We study minimal conditions on pump laser intensities and detunings required for collective superradiant emission. Balancing Doppler cooling and gain-induced heating we identify a parameter regime of a continuous narrow-band laser operation close to the bare atomic frequency.

Hybrid ion-nanoparticle system

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Extended Abstract Online (ID 89)

Coupling a mechanical oscillator to a qubit provides a means to control the oscillator's motion at the quantum level. Our goal is to couple a levitated nanoparticle oscillator to an atomic ion qubit. Levitated oscillators are highly isolated from the environment and fundamentally unrestricted in the spatial extension of the wave function, allowing tests of quantum mechanics in new mass and size regimes. Trapped ions are long-lived levitated qubits with exquisite state control capabilities, which makes them suitable for use in combination with levitated oscillators. I will present our steps towards realizing such a system. First, we trapped a nanoparticle in a Paul trap in ultra-high vacuum and achieved a quality factor above $10^{1}0$ — the highest quality factor for a nanomechanical oscillator at room temperature. Second, we adapted methods originally developed to detect and control the motion of atomic ions, including self-homodyne detection and sympathetic cooling. Finally, we co-trapped the nanoparticles and an atomic ion using a dual-frequency drive of the Paul trap.

Free-parameter optimisation for efficient shadow tomography

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Verifying properties of large entangled quantum systems represents one of the main challenges in employing such systems for real applications. New methods of verification, attempting to access only partial information about the system, can significantly reduce the consumption both of quantum and classical resources. A good example is the protocol of classical shadows, which utilises the outcomes of randomised measurements to estimate the means value of observable. The standard reconstruction of the estimator from the measurement outcomes, based on the properties of Clifford gates, does not however take into consideration the fact that measurements are usually described by an over-complete set of observables: the reconstruction of the estimator does depend on free parameters which can be varied to further optimise the figure of merit, mainly the variance of the estimator, which determines the expected number of copies needed to achieve an adequate level of accuracy. In this work we show how these free parameters can be used to reduce significantly the resources requested for an accurate estimation of particular local observables in tensor-product states.

Reconfigurable time-bin processor for multi-photon quantum interference.

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Extended Abstract Online (ID 18)

The interference of non-classical states of light is crucial for a wide range of quantum enhanced applications on photonic platforms. However, implementing complex quantum protocols requires an increasing number of physical resources, such as more photon sources, larger interferometers, and multiple detectors. In this talk, I will present the realization and operation of a highly efficient programmable quantum photonic processor, based on time-bin encoding and comprised of a quantum-dot single-photon source, a programmable time-bin interferometer, and one detector. Our time-bin interferometer makes repeated use of a single active, tunable optical element in a loop-based architecture, enabling interference to occur entirely in a single spatial mode. Our approach is thus highly resource-efficient compared to standard spatial encoding, as it does not require active demultiplexing of a single-photon source or building an array of multiple identical emitters. Furthermore, all multi-photon processing is carried out by analyzing the time-tags of a single detector. We program our device for multi-photon interference experiments with varying numbers of photons, and the size of the experiments is increased at will, utilizing a constant number of programmable physical resources. In practice, the experiment size is mainly constrained by source efficiency, allowing us to observe interference of up to 8 photons in 16 modes. Our results can serve as a foundation for a future resource-efficient universal photonics quantum processor.

Cavity QED using atomic mirrors

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Extended Abstract Online (ID 118)

Ordered lattices of neutral atoms can exhibit a collective response to light, offering opportunities for enhanced and controlled light-matter interaction. In particular, a

planar array with sub-wavelength interatomic spacing can act as an efficient mirror, as demonstrated in experiments. In this work, we theoretically study configurations of two parallel atomic mirrors. With the right design, we predict a sharp cavity mode that can be accessed with high cooperativity by additional impurity atoms suspended between the mirrors, allowing for cavity QED applications. We analyze and optimize the performance of such atomic cavities involving different protocols and cavity regimes, both in the ideal case of fixed atoms and allowing for fluctuations of the atomic positions. Finally, we look into the fundamental differences between these systems and conventional optical cavities, and propose ways to leverage the non-linearity of the atoms for additional applications.

Optimal Static Potentials for Robust Macroscopic Quantum State Generation of Levitated Nanoparticles

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Extended Abstract Online (ID 120)

Levitated nanoparticles offer a unique and controlled experimental platform for investigating quantum phenomena at the interface between classical and quantum me- chanics. The ground-state cooling of nanoparticles in optical traps was recently achieved, and the current pursuit is directed towards the preparation of macroscopic quantum superposition states. Due to substantial decoherence in optical potentials, the dynamics must happen either in the absence of an optical potential or within a dark potential. A specific nonharmonic potential has been identified for generating these macroscopic quantum superpositions, yet the optimal potential shape remains unknown.

We address this question by using an optimization approach to determine the optimal static potential shape for robust generation of macroscopic quantum states. Our optimization strategy accounts for inherent noise sources within experimental setups. Given the computational demands of the multiscale simulation of this system, we provide a description of the dynamics that allows for fast computation of key figures of merit. Specifically, we use coherence length and cubicity of the state as indicators for the emergence of nonclassical features. We find that the optimal potential shape varies based on the strength and nature of the noise in the system. Our research shows that optimization can provide valuable insights for enhanced control over quantum features in levitated nanoparticle systems.

Observation of antiferromagnetic phase transition in the fermionic Hubbard model

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Extended Abstract Online (ID 141)

The repulsive fermionic Hubbard model (FHM) is central to our understanding of electron behaviors in strongly correlated materials. At half filling, its ground state is characterized by an antiferromagnetic phase, which is reminiscent of the parent state in high-temperature cuprate superconductors. Introducing dopants into the antiferromagnet, the fermionic Hubbard (FH) system is believed to give rise to various exotic quantum phases, including stripe order, pseudogap, and d-wave superconductivity.However, despite significant advances in quantum simulation of the FHM, realizing the low-temperature antiferromagnetic phase transition in a large-scale quantum simulator remains elusive. In this talk, I will present our recent progress on the realization of a low-temperature repulsive FH system in three dimensions, consisting of lithium-6 atoms in a uniform optical lattice with approximately 800,000 sites.Using spin-sensitive Bragg diffraction of light, we measure the spin structure factor (SSF) of the system. We observe divergences in the SSF by finely tuning the interaction strength, temperature, and doping concentration to approach their respective critical values for the phase transition, which are consistent with a power-law scaling in the Heisenberg universality class. Our results successfully demonstrate the antiferromagnetic phase transition in the FHM, paving the way for exploring the low-temperature phase diagram of the FHM.

Towards strong coupling of polar molecules to a superconducting resonator

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Hybrid quantum systems are a well-established tool in quantum science and technology. Building up on our latest results, where we successfully strongly coupled sodium atoms embedded in a noble gas neon matrix to the magnetic field of our resonator, we present a novel concept which aims to couple superconducting resonators to cryogenic crystals (solid hydrogen, Ne, Ar,...) doped with polar molecules (ND3,. . .). By implanting molecules in such noble gas crystals, they can be kept very close to the resonators surface where electric coupling is maximized. Deuterated ammonia has an electric dipole moment of 1.5 Debye and an inversion transition of 1.6 GHz which will be the transition coupled to the microwave resonator. By its nature, the electric field's coupling strength is orders of magnitude greater than the magnetic coupling strength, which allow us to enter the strong coupling regime with a much lower number of implanted impurities.

Vacuum mediated two photon emission by a single atom

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Extended Abstract Online (ID 113)

Single atoms coupled to high finesse optical cavities provide an important platform for quantum information processing, in which single photon qubits can be efficiently generated, stored and processed. Recent cavity manufacturing developments have made it possible that two independent resonators are coupled to the same emitter in the high atom-photon cooperativity regime. So far such a system has enabled the implementation of novel photon receiving and a photon tracking schemes, but the two-cavity mediated photon emission of by single atom was not yet explored. In our recent work we study the situation where a single atom has three energy levels that are coupled to two optical resonators in a ladder configuration.

Controllable Energy Transport and Superabsorption in Large Atomic Ensembles inside a Hollow-Core Fiber

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In contrast to free-space dipole-dipole interaction fiber-mediated dispersive and dissipative collective couplings exhibit a periodic behaviour. We propose to exploit this periodicity in order to facilitate controlled energy transport amongst sub-ensembles arranged inside a hollow-core fiber. Once energy of the system is above a certain threshold, we find a nearly lossless energy transfer from a driven sub-ensemble to a ground state sub-ensemble in the system. This transport is enhanced or suppressed depending on the positions of the ensembles relative to each other and can therefore be controlled. In an extremal case we identify a significantly faster transfer rate, i.e. superabsorption.

TBD

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TBD

Towards interpretable quantum machine learning via single-photon quantum walks

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Variational quantum algorithms represent a promising approach to quantum machine learning where classical neural networks are replaced by parametrized quantum circuits. However, both approaches suffer from a clear limitation, that is a lack of interpretability. Here, we present a variational method to quantize projective simulation (PS), a reinforcement learning model aimed at interpretable artificial intelligence. Decision making in PS is modeled as a random walk on a graph describing the agent's memory. To implement the quantized model, we consider quantum walks of single photons in a lattice of tunable Mach-Zehnder interferometers trained via variational algorithms. Using an example from transfer learning, we show that the quantized PS model can exploit quantum interference to acquire capabilities beyond those of its classical counterpart. Finally, we discuss the role of quantum interference for training and tracing the decision making process, paving the way for realizations of interpretable quantum learning agents.

Precision spectroscopy and quantum information with trapped molecular ions

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Extended Abstract Online (ID 111)

The quantum molecules group at Universität Innsbruck utilizes a range of advances in molecular spectroscopy and quantum logic spectroscopy (QLS) to study molecular rovibrational structure and explore quantum information (QI) in trapped molecules. The efforts of our group are divided into four projects. The first utilizes Raman

rotational control using a CW laser and frequency comb for precision rotational spectroscopy and to explore applications in QI. Novel QI encoding schemes are possible in rotational states of molecules which are not available in atoms. We are developing a dissipative quantum error correction scheme to stabilize a rotational superposition. We aim to demonstrate state preparation, coherent control, and creation of superpositions of rotational states in CaH+ or CaOH+. The second project is pump-probe recoil spectroscopy, where we aim to measure vibrational population dynamics of single molecular ions by mapping them to the electronic state of an atomic ion via QLS. The third project focuses on state-dependent force spectroscopy, where an optical tweezer generates a state-dependent force on a trapped molecular ion. This enables quantum non-demolition measurements of the rovibrational structure. The fourth project involved using the capable platform we have developed to measure one- and two-photon dissociation spectra of CaOH+ molecular ions.

Microscopy with heralded Fock states

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Extended Abstract Online (ID 73)

In the presented work a quantum ghost imaging setup is considered, where Spontaneous parametric down-conversion (SPDC) heralded single photons are used to illuminate a sample. The SPDC-generated photon pairs are described by a biphoton wavefunction which is further propagated through a given optical setup and analyzed at different steps of the propagation path. The analysis includes not only the spatial mode profile investigation but also examining its phase. Analytical expressions for the spatial mode tracking together with the widths of the heralded and non-heralded modes are provided. These analytical results are supported through numerical calculations, and a comprehensive discussion considering practical factors like finite-size optics and single-photon detectors. As a result, it is demonstrated that the diffraction limit can be approached while mitigating photon losses, which leads to an enhanced signal-to-noise ratio - a critical factor for the practical use of quantum light. Furthermore, it is shown that spatial resolution manipulation is possible by careful preparation of the amplitude and phase of the spatial mode profile of the single photon at the microscope objective's input. This is proven to be true for both quantum and classical light. Spatial entanglement of the biphoton wavefunction or adaptive optics can be utilized for this purpose. Analytical formulas describing how the parameters of the incident and focused spatial mode profiles are related are provided.

Multi-photon emission from a resonantly pumped quantum dot

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Extended Abstract Online (ID 44)

Resonance fluorescence of natural or artificial atoms constitutes a prime method for the generation of non-classical light. We experimentally quantify the multi-photon emission statistics in a two-level artificial atom - a semiconductor quantum dot in a micropillar cavity - pumping with a short optical pulse and measuring autocorrelation functions $g(n)(\tau)$ up to the fourth order, for different pumping powers. We measure up to four-photon emitted after a single pumping pulse and, with fine temporally-resolved measurement, we investigate the emission dynamics. We propose a method, based on acquisition gating, to enhance the photon purity while maintaining high brightness.

Unraveling PXP Many-Body Scars through Floquet Dynamics

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Extended Abstract Online (ID Quantum scars are special eigenstates of many-body systems that evade thermalization. They were first discovered in the PXP model, a well-known effective description of Rydberg atom arrays. Despite significant theoretical efforts, the fundamental origin of PXP scars remains elusive. By investigating the discretized dynamics of the PXP model as a function of the Trotter step τ, we uncover a remarkable correspondence between the zero- and two-particle eigenstates of the integrable Floquet-PXP cellular automaton at $\tau = \pi/2$ and the PXP many-body scars of the time-continuous limit. Specifically, we demonstrate that PXP scars are adiabatically connected to the eigenstates of the $\tau = \pi/2$ Floquet operator. Building on this result, we propose a protocol for achieving high-fidelity preparation of PXP scars in Rydberg atom experiments.)

Higher-order topological Peierls insulator in a two-dimensional atom-cavity system

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Extended Abstract Online (ID 98)

In this work, we investigate a two-dimensional system of ultracold bosonic atoms inside an optical cavity, and show how photon-mediated interactions give rise to a plaquette-ordered bond pattern in the atomic ground state. The latter corresponds to a 2D Peierls transition, generalizing the spontaneous bond dimmerization driven by phonon-electron interactions in the 1D Su-Schrieffer-Heeger (SSH) model. Here the bosonic nature of the atoms plays a crucial role to generate the phase, as similar generalizations with fermionic matter do not lead to a plaquette structure. Similar to the SSH model, we show how this pattern opens a non-trivial topological gap in 2D, resulting in a higher-order topological phase hosting corner states, that we characterize by means of a many-body topological invariant and through its entanglement structure. Finally, we demonstrate how this higher-order topological Peierls insulator can be readily prepared in atomic experiments through adiabatic protocols. Our work thus shows how atomic quantum simulators can be harnessed to investigate novel strongly-correlated topological phenomena beyond those observed in natural materials.

Generating scalable graph states in an atom-nanophotonic interface

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Extended Abstract Online (ID 134)

Measurement based quantum computing paradigm demonstrated that after generating cluster states, just measuring their states can enable universal quantum computation – limiting the propagation of errors. However, it is very difficult to create large-scale cluster states with high fidelity, especially for stationary atomic qubits. Our proposal achieved this through state-carving of neutral atoms coupled to photonic crystal cavities. Single photons are sent into the cavity and are measured upon reflection which effectively collapses the atoms into desired entangled states. Our proposal has high fidelity and optimal generation probability, making it scalable. Finally, we achieved creation of generalized multi-node arbitrary graph states using multi-qubit state-carvings.

Towards a Sagnac photon-pair source for uplink spaceborne QKD

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Extended Abstract Online (ID 71)

With the rising capabilities of quantum computers, quantum communication becomes increasingly critical. Not only are quantum computers required to eventually communicate through quantum channels, but quantum key distribution (QKD) will also become essential for secure encryption at the same time, underscored by the vulnerability of traditional encryption methods to quantum computers. Particularly for globe spanning networks, satellite-based quantum communication is favourable over optical fibers, as reliable quantum repeaters, capable of mitigating optical losses are not available yet. Spaceborne QKD has been demonstrated before, but communication from ground to space is still to be demonstrated. To address this gap, we present construction of a compact Sagnac interferometer for the generation of heralded single photons and entangled photon pairs. This photon source will be integrated into the currently planned Innsbruck quantum optical ground station telescope. Subsequently, this optical ground station equipped with the photon-pair source will then be used for ground to space QKD as the counterpart of quantum satellites.

Non-equilibrium dissipative dynamics of interacting bosonic atoms coupled to an optical cavity

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We investigate the full quantum evolution of interacting bosonic atoms on a chain coupled to an optical cavity, following a quench in the atoms-cavity coupling. We compute the numerically exact time evolution of the coupled dissipative system by employing an extension of time-dependent matrix product state techniques. Our numerical method captures the global coupling to the cavity mode and the open nature of the cavity. Recently, we have shown that fluctuations that go beyond the mean-field elimination of the cavity field play an important role and change the nature of the self-organized steady states. The steady states should be described as mixed states, characterized by an effective temperature determined by the fluctuations. Furthermore, we analyze the timescales and frequencies that

characterize the dissipative dynamics by monitoring several observables throughout the evolution, for both the atomic and photonic degrees of freedom. We supplement our understanding with analytical insights obtained from many-body adiabatic elimination techniques, in which the atoms-cavity fluctuations are treated either exactly or perturbatively. We aim to identify universal features of the atoms-cavity non-equilibrium dynamics which can be observed in current experimental realizations based on ultracold atoms.

Three-Photon Transfer and Inelastic Collisions in ^{84}Sr

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This work describes how we achieve a coherent three-photon transfer between the internal states $^1S_0$ and $^3P_0$ of ^{84}Sr and how two-body inelastic collisions occur between these states. Despite challenges in achieving a complete transfer, we highlight the potential uses for outcoupling atoms into a continuous atom laser beam and for quantum computing. Our method allows us to prepare a high phase-space density cloud of $^3P_0$ atoms. This was previously difficult due to an unfavorable elastic-to-inelastic ratio, making traditional evaporative cooling impractical. Additionally, we pioneer the measurement of inelastic collisional loss rates for $^3P_0$ atoms in ^{84}Sr. Our method opens up new possibilities for realizing quantum degenerate samples in the metastable $^3P_0$ and $^3P_2$ states of alkaline-earth-like atoms.

Cavity-based Quantum Processor: Engineering Entanglement with Programmable Connectivity

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Extended Abstract Online (ID 43)

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. Our goal is to establish an alternative platform for quantum simulation and information processing with full qubit connectivity. The idea is to trap an array of individually addressable atoms inside an optical cavity. The photon-mediated interactions of the atoms in the cavity will enable us to introduce non-local couplings and entangling operations between any two atoms or qbits in the system. We will implement a non-destructive readout scheme that relies on injecting a few-photon field into the cavity. Dissipation and non-destructive measurements open up exciting possibilities to generate highly entangled many-body ensembles, like large GHZ states, in our system. We want to use the quantum processor to address longstanding questions about thermalisation of quantum systems and information scrambling. With its scalability and fully programmable connectivity, our architecture has the potential to open up new pathways for a wide range of fields like quantum optimization, communication and simulation.

Cavity Sub- to Superradiance Transition with Application to Ramsey Spectroscopy

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Extended Abstract Online (ID 42)

Large atomic ensembles coupled to a single optical resonator mode can be steered to strongly enhanced or suppressed collective emission via phase controlled excitation. Employing the Tavis-Cummings model using a second order cumulant expansion approach we predicted that a homogeneously excited ensemble equally distributed between odd and even sites along the cavity mode is extremely subradiant as long as the average excitation remains below 50%, but shows pulsed emission for inversion. The combination of these two properties enables the implementation of an efficient cavity-enhanced Ramsey probing featuring a fast readout and minimal heating with particular advantages for atomic clock transitions. We experimentally confirm the predicted excitation threshold for superradiant emission on a narrow optical transition and apply it in a Ramsey sequence. The minimal heating of the atoms allows for multiple interrogations within one experimental cycle.

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Laughlin-like physics in small subwavelength atom arrays

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Atom arrays offer exciting possibilities of quantum optics, such as harnessing wave interference and collective absorption/emission to e.g. increase the efficiency of quantum optical devices beyond standard limits. The current frontier in array physics is the many-body regime, where complex effects are expected due to interaction between atomic excitations. To find intuitions about the behavior of such systems, one can seek for analogous solid-state systems for which the many-body problem was already thoroughly studied.

In this work, we propose that the low-energy physics of small hexagonal flakes of three-level atoms in magnetic field can be understood in analogy to the fractional quantum Hall systems. It was shown that in arrays of three-level atoms, magnetic field can induce a topologically nontrivial single-particle band structure. If such topological bands are flat enough, they may host fractional quantum Hall states on the many-particle level. Here, we show that at small lattice constant and in presence of parabolic confinement potentials, small hexagonal flakes of honeycomb three-level atom arrays exhibit a characteristic branch in the few-particle spectrum, resembling the edge spectrum on the top of the $\nu = 1/2$ Laughlin state and exhibiting high overlap with model Laughlin states. Although the band structure of an infinite lattice exhibits divergences near the light cone, finite-size effects smooth out these divergencies, and, as a result, small flakes dominated by near-field interaction behave similarly to a topological flat-band system. We evaluate the decay rates of the Laughlin-like states, showing that some of them are highly superradiant, while some exhibit subradiance. Then, we study the behavior of the system under driving by Laugerre-Gauss beams.

Near-resonant light scattering by an atom in a state-dependent trap

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Extended Abstract Online (ID 36)

The optical properties of a fixed atom are well-known and investigated. For example, the extraordinarily large cross section of a single atom as seen by a resonant photon is essential for quantum optics applications. Mechanical effects associated with light scattering are also well-studied, forming the basis of laser cooling and trapping, for example. Despite this, there is one fundamental problem that surprisingly has not been extensively studied, yet is relevant to a number of emerging quantum optics experiments. In these experiments, the ground state of the atom experiences a tight optical trap formed by far-off-resonant light, to facilitate efficient interactions with near-resonant light. However, the excited state might experience a different potential, or even be anti-trapped. Here, we systematically analyze the effects of unequal trapping on near-resonant atom-light interactions. In particular, we identify regimes where such trapping can lead to significant excess heating, and a reduction of total and elastic scattering cross sections associated with a decreased atom-photon interaction efficiency. Understanding these effects can be valuable for optimizing quantum optics platforms where efficient atom-light interactions on resonance are desired, but achieving equal trapping is not feasible.

SWAP-less Implementation of Quantum Algorithms on Linear Architectures

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We present a procedure based on parity quantum computing to efficiently implement the Quantum Approximate Optimization Algorithm (QAOA) and the quantum Fourier transform (QFT) on n qubits requiring only linear nearest-neighbor (LNN) qubit connectivity. For both algorithms, we obtain improved gate counts and circuit depths compared known proposals. For the QAOA, this is—to the best of our knowledge—the first proposal with a linear circuit depth while not requiring more than n^2 CNOT gates per iteration. Our approach for QFT, requiring only LNN connectivity, surpasses previous QFT implementations even on devices with high qubit connectivity in terms of circuit depth while not the increasing gate count in leading order.

Non-equilibrium Wannier-Stark photon condensate

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Strongly coupled light-matter systems feature nonequilibrium effects, due to common photon loss and gain processes, as well as appreciable photon-photon interactions. Here we introduce a light-matter lattice system composed of an array of driven- dissipative, coupled Kerr cavities with linearly increasing resonant frequencies. The model amounts to a driven-dissipative Bose-Hubbard model in a tilted potential, revealing diverse stationary and non-stationary behaviour. Our key finding is that, under weak on-site interactions, photons condense into localized Wannier-Stark states. Notably, as photon-photon interactions strengthen, a non-stationary regime emerges, marked by periodic Bloch-like oscillations in photon density.

Towards simulation of lattice gauge theories with ultracold ytterbium atoms in hybrid optical potentials

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Gauge theories play a fundamental role for our understanding of nature, ranging from high-energy to condensed matter physics. Their formulation on a regularized periodic lattice geometry, so-called lattice gauge theories (LGTs), has proven invaluable for theoretical studies. Numerical studies on, e.g., their real-time dynamics are however computationally challenging. We report progress on developing a quantum simulator for LGTs using neutral ytterbium atoms. Ytterbium's internal level structure provides a ground and meta-stable clock state pair, and fermionic isotopes further host nuclear qubits. We combine optical lattice and optical tweezer technology that can enable robust and scalable implementation of LGTs. To realize state-selective control, we leverage magic and tune-out wavelengths. We present the first measurements of such wavelengths near the narrow cooling transition at 556 nm and discuss prospects in implementing local gauge invariance.

Rydberg-blockade-based parity quantum optimization

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A major research effort in quantum information science focuses on exploring a potential quantum advantage in the solution of combinatorial optimization problems on near-term quantum devices. A particularly promising platform implementing quantum optimization algorithms is arrays of trapped neutral atoms, laser coupled to highly excited Rydberg states. However, encoding arbitrary combinatorial optimization problems in atomic arrays is challenging due to the limited interqubit connectivity of the finite-range dipolar interactions. Here, we present a scalable architecture for solving higher-order constrained binary optimization problems on current neutral-atom hardware operating in the Rydberg blockade regime. A paradigmatic combinatorial optimization problem directly encodable on such devices is the maximum-weight independent set (MWIS) problem on unit-disk graphs. We extend this approach to generic combinatorial optimization problems by utilizing the recently developed parity encoding of arbitrarily connected higher-order constrained optimization problems. The parity encoding only requires problem-encoding local fields and problem-independent quasi-local interactions among 2 x 2 plaquettes of nearest-neighbor physical qubits on a square lattice geometry. We formulate the required plaquette logic as an MWIS problem, which allows one to build our architecture from small MWIS modules in a problem-independent way, crucial for practical scalability. Furthermore, we provide an efficient method to compensate for the long-range interaction tails of the van der Waals interaction between Rydberg atoms.

Rymax-One: A neutral atom quantum processor to solve optimization problems

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Quantum computers are set to advance various domains of science and technology due to their ability to efficiently solve computationally hard problems. Of particular interest are combinatorial optimization problems, whose solutions could provide the basis for optimal supply chains and vehicle routing. However, achieving such a quantum advantage is still prevented by the quality and scale of the available quantum computing hardware.

Here, we present the recent status of our project Rymax-One – which aims at building a quantum computer specifically designed to solve optimization problems which are intractable on classical devices. To achieve this goal, we are using trapped arrays of ultracold Ytterbium atoms, whose level structure enables the realization of qubits with long coherence times and high-fidelity gate operations to explore the potential of quantum computers to tackle real-world problems.

Coupled spin-phonon dynamics in Rydberg tweezer arrays

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Recent breakthroughs in the domains of quantum simulation and quantum computation are based on the utilization of Rydberg atoms, which interact strongly via dipolar interactions. Concomitant to interactions are mechanical forces, that couple the internal atomic degrees of freedom to the external motional ones. The resulting spin-phonon coupling has been recently exploited to explore polaron physics and to realize artificial molecular systems.

Here we investigate the influence of coherent vibrations on the transport properties of a quantum spin chain that can be studied with Rydberg atoms. We find that coherent spin-phonon interactions dramatically change the way spin domains expand through the lattice. This change is due to resonant spin-phonon scattering between the propagating domain walls and the atoms' vibrational excitations, which leads to the inhibition of spin transport even in a disorder-free translationally invariant system. We also find that the phase coherence of the vibrational excitations manifests macroscopically in an asymmetric expansion of the spin domain, which is detectable in current Rydberg quantum simulators.

Variational measurement-based quantum computation for generative modeling

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Extended Abstract Online (ID 112)

Measurement-based quantum computation (MBQC) offers a fundamentally unique paradigm to design quantum algorithms. Indeed, due to the inherent randomness of quantum measurements, the natural operations in MBQC are not deterministic and unitary, but are rather augmented with probabilistic byproducts. Yet, the main algorithmic use of MBQC so far has been to completely counteract this probabilistic nature in order to simulate unitary computations expressed in the circuit model. In this work, we propose designing MBQC algorithms that embrace this inherent randomness and treat the random byproducts in MBQC as a resource for computation. As a natural application where randomness can be beneficial, we consider generative modeling, a task in machine learning centered around generating complex probability distributions. To address this task, we propose a variational algorithm equipped with controllable parameters that allow to directly adjust the degree of randomness to be admitted in the computation. Our numerical findings indicate that this additional randomness can lead to significant gains in learning performance in certain generative modeling tasks.

Tuning photon-mediated interactions in a multimode cavity: from supersolid to insulating droplets hosting phononic excitations

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Ultracold atoms trapped in laser-generated optical lattices serve as a versatile platform for quantum simulations. However, as these lattices are infinitely stiff, they do not allow to emulate phonon degrees of freedom. This restriction can be lifted in emerged optical lattices inside multimode cavities. Motivated by recent experimental progress in multimode cavity QED, we propose a scheme to implement and study supersolid and droplet states with phonon-like lattice excitations by coupling a Bose gas to many longitudinal modes of a ring cavity. The interplay between contact collisional and tunable-range cavity-mediated interactions leads to a rich phase diagram, which includes elastic supersolid as well as insulating droplet phases exhibiting roton-type mode softening for a continuous range of momenta across the superradiant phase transition. The non-trivial dynamic response of the system to local density perturbations further proves the existence of phonon-like modes.

Monolithic source for narrow-band photon pairs using down-conversion in ppKTP

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We present first results and future prospects for a photon-pair source based on spontaneous parametric down-conversion (SPDC) in a periodically poled monolithic KTP crystal cavity. By proper engineering of the cavity parameters and phase-matching, it is possible to tune the source for interfacing with atomic systems and particularly with quantum memories. By putting the cavity end mirrors directly on the 2x1x3.5 mm^3 non-linear crystal we have build a photon-pair source that is set to a dedicated signal and idler wave- length of 895 nm with a bandwidth of 250 MHz and a cavity finesse of 90 while retaining a tuneability of 20 GHz. The source emits photon pairs at a rate of 40 kcts/s with an heralding efficiency of 38%, limited by the current choice of collimation op- tics. We plan on interfacing our source with a ladder-type EIT warm vapor quantum memory to explore synchronizing the probabilistically generated photons to a fixed clock rate. In addition to investigating typical parameters of quantum memories such as efficiency and maximum storage time, we will measure the attainable two-photon interference between a photon retrieved from the memory and one directly from the source.

Conventional and unconventional Dicke models: Multistabilities and nonequilibrium dynamics

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The Dicke model describes the collective behavior of a sub-wavelength–size ensemble of two-level atoms (i.e., spin-1/2) interacting identically with a single quantized radiation field of a cavity. Across a critical coupling strength it exhibits a zero-temperature phase transition from the normal state to the superradian phase where the field is populated and and the collective spin acquires a nonzero x-component, which can be imagined as ferromagnetic ordering of the atomic spins along x. Here I introduce a variant of this model where two sub-wavelength–size ensembles of spins interact with a single quantized radiation field with different strengths. Subsequently, I restrict myself to a special case where the coupling strengths are opposite (which is unitarily equivalent to equal-coupling strengths). Due to the conservation of the total spin in each ensemble, the system supports two distinct superradiant states with x-ferromagnetic and x-ferrimagnetic ordering, coexisting with each other in a large parameter regime. The stability and dynamics of the system in the thermodynamic limit are examined using a semiclassical approach, which predicts non-stationary behaviors due to the multistabilities. At the end, I also perform small-scale full quantum-mechanical calculations, with results consistent with the semiclassical ones.

Optical Quantum Information Encoder: Implications for Quantum Computing Applications

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Extended Abstract Online (ID 62)

Optical photons, as powerful carriers of quantum information, enable secure long-distance transmission via satellites or fibers [1]. A quantum optical encoder store information as stationary excitations, where the embedded information can be manipulated using just single-qubit and two-qubits gate operations for Quantum Computing applications. In this study, we focus on transferring non-classical optical multi-mode squeezed states, characterized by maximal entanglement, to a network of stationary qubits. Utilizing the Jaynes-Cumming model and separability criteria [2], we calculate the entanglement transfer within qubits initially in ground state exposed to multi-mode squeezed radiation. We also obtain conditions that perform maximum entanglement transfer. Our findings demonstrate the 90% efficiency in entanglement transfer for a three-qubit quantum encoder. Additionally, nearly complete entanglement transfer is achieved through the utilization of quantum state tomography techniques.

References

[1] S.K. Liao, W. Q. Cai, W. Y. Liu, et al., Nature 549, 43–47 (2017) .

[2] M. Horodecki, P. Horodecki, R. Horodecki, Physics Letters A 223 (1), 1-8 (1996) .

Diffusion models: from quantum circuit synthesis to experiment generation

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Quantum computing has recently emerged as a transformative technology. Yet, its promised advantages rely on efficiently translating quantum operations into viable physical realizations. In this work, we use generative machine learning models, specifically denoising diffusion models (DMs), to facilitate this transformation. Leveraging text-conditioning, we steer the model to produce desired quantum operations within gate-based quantum circuits. Notably, DMs allow to sidestep during training the exponential overhead inherent in the classical simulation of quantum dynamics—a consistent bottleneck in preceding ML techniques. We demonstrate the model's capabilities across two tasks: entanglement generation and unitary compilation. The model excels at generating new circuits and supports typical DM extensions such as masking and editing to, for instance, align the circuit generation to the constraints of the targeted quantum device. Given their flexibility and generalization abilities, we envision DMs as pivotal in quantum circuit synthesis but also in many other platforms, from qudit processor and measurement-based computation to quantum optic experiments.

Probing the emergent physics of quasi-1D Bose gases

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Extended Abstract Online (ID 25)

Over the past decade, one-dimensional (1D) ultracold gases trapped on atom chips have proven a powerful platform for studying the emergent physics of quantum many-body systems. Using techniques of in-situ imaging and matter-wave interference, along with advances analysis techniques, transport and higher-order correlation functions on the emergent scale can be probed. I will present an overview of the capabilities and limitations of these approaches, focusing, in particular, on recent results regarding transport:

In a series of experiments, a fully adjustable 1D potential was employed to perform highly controlled quenches, where measurements of the subsequent dynamics facilitate testing the predictions of transport theories such as Generalized Hydrodynamics (GHD). Indeed, following quenches of a single momentum mode of the condensate, a surprisingly good agreement with GHD predictions was found, even at relatively high energies. In highly energetic 1D systems, 3D scattering events are known to break integrability and drive the system towards thermalization. However, as identified by the Bethe Ansatz, the elementary excitations of the 1D Bose gas are actually fermionic; the slow relaxation observed (in agreement with 1D GHD) can be explained via an emergent Pauli blocking of the non-integrable scattering and is thus an indication of the underlying quasi-particle statistics.

A stochastic approach to exact dynamics and tunneling in the generalized open Dicke Model

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As a fundamental model of quantum optics, the Dicke model has been known and studied for a long time. Recently, however, interest in this model has been revived by the emergence of numerous Cavity QED experiments that allow the controlled realisation of the Dicke model (and its generalised versions) over a wide parameter regime. In the thermodynamic limit $N \to \infty$ the mean-field solution of the Dicke model becomes exact. However, to study the emergence of genuine quantum effects in the dynamics of these systems at finite N, a description that goes beyond mean-field theory is required. Here, we present a novel open-system method that allows us to push the boundary for the exact numerical solution of the model up to a mesoscopic number of atoms ($N \approx 500$) and to investigate the deficiencies of a mean-field description in this regime. We explore in which parameter regions true quantum effects, such as tunneling, become relevant for the dynamics and observable in experiments.

Polarization control of radiation and energy flow in dipole-coupled nanorings

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Collective optical excitations in dipole-coupled nanorings of sub-wavelength spaced quantum emitters exhibit extreme sub-radiance and field confinement facilitating an efficient and low-loss ring-to-ring energy transfer. We show that energy shifts, radiative lifetimes, and emission patterns of excitons and biexcitons in such rings can be tailored via the orientation of the individual dipoles. Tilting the polarization from perpendicular to tangential to the ring dramatically changes the lifetime of the symmetric exciton state from superradiance to subradiance with the radiated field acquiring orbital angular momentum. At a magic tilt angle all excitons are degenerate and the transport fidelity between two rings exhibits a minimum. Further simulations suggest that, for certain parameters, the decay decreases double-exponentially with the emitter's density. Disorder in the rings' structure can even enhance radiative lifetimes. The transport efficiency strongly depends on polarization and size, which we demonstrate by simulating a bio-inspired example of two rings with 9 and 16 dipoles as found in biological light harvesting complexes (LHC). The field distribution in the most superradiant state in a full LHC multi-ring structure shows tight sub-wavelength field confinement in the central ring, while long-lived subradiant states store energy in the outer rings.

Synthetic nanoscale quantum emitter rings for efficient excitation transport

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Extended Abstract Online (ID 8)

Nature is abundantly engineering complex rings of chromophores in light- harvesting complexes (LHCs) utilized for photosynthesis. They absorb and transport solar

energy to the photosynthetic reaction centers with high efficiency. These bio-rings could be modeled as sub-wavelength rings of optical dipoles that support extremely sub-radiant collective eigenmodes and show efficient excitation energy transfer [1-4]. To explore possibilities for synthetic LHCs, we will present a theoretical investigation tackling bio-inspired state-of-the-art nanoscale coupled ring geometries of quantum emitters, featuring the signature optical properties of the natural LHCs. Our study expects to find promising applicability in the thrust areas of artificial light harvesting and designing inter-node lossless links utilized in quantum networks.

References

[1] M. Moreno-Cardoner, D. Plankensteiner, L. Ostermann, D. E. Chang, and H. Ritsch, Phys. Rev. A 100, 023806 (2019).

[2] J. A. Needham, I. Lesanovsky, and B. Olmos, New J. Phys. 21, 073061 (2019).

[3] M. Moreno-Cardoner, R. Holzinger, and H. Ritsch, Opt. Express 30, 10779 (2022). [4] V. Scheil, R. Holzinger, M. Moreno-Cardoner, and H. Ritsch, Nanomaterials 13, 851 (2023).

Chirality Dependent Photon Transport and Helical Superradiance

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Extended Abstract Online (ID 11)

Chirality, or handedness, is a geometrical property denoting a lack of mirror symmetry. Chirality is ubiquitous in nature and is associated with the non-reciprocal interactions observed in complex systems ranging from biomolecules to topological materials. Here, we demonstrate that chiral arrangements of dipole-coupled atoms or molecules can facilitate the unidirectional transport of helical photonic excitations without breaking time-reversal symmetry. We show that such helicity dependent transport stems from an emergent spin-orbit coupling induced by the chiral geometry, which results in nontrivial topological properties. We also examine the effects of collective dissipation and find that many-body coherences lead to helicity dependent photon emission: an effect we call helical superradiance. Our results demonstrate an intimate connection between chirality, topology, and photon helicity that may contribute to molecular photodynamics in nature and could be probed with near-term quantum simulators.

Measurement-based quantum computation from Clifford quantum cellular automata

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Measurement-based quantum computation (MBQC) is a paradigm for quantum computation where computation is driven by local measurements on a suitably entangled resource state. Here, we show that MBQC is related to a model of quantum computation based on Clifford quantum cellular automata (CQCAs). Specifically, we show that certain MBQCs can be directly constructed from CQCAs which yields a simple and intuitive circuit model representation of MBQC in terms of quantum computation based on CQCA. We apply this description to construct various MBQC-based Ansätze for parameterized quantum circuits, demonstrating that the different Ansätze may lead to significantly different performances on different learning tasks. In this way, MBQC yields a family of Hardware-efficient Ansätze that may be adapted to specific problem settings and is particularly well suited for architectures with translationally invariant gates such as neutral atoms.

Spin- and momentum-correlated atom pairs mediated by photon exchange and seeded by vacuum fluctuations

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Extended Abstract Online (ID 105)

Engineering pairs of massive particles that are simultaneously correlated in their external and internal degrees of freedom is a major challenge, yet essential for advancing fundamental tests of physics and quantum technologies. In this work, we experimentally demonstrate a mechanism for generating pairs of atoms in well-defined spin and momentum modes. This mechanism couples atoms from a degenerate Bose gas via a superradiant photon-exchange process in an optical cavity, producing pairs via a single or two discernible channels. The scheme is independent of collisional interactions, fast and tunable. We observe a collectively enhanced production of pairs and probe inter-spin correlations in momentum space. We characterize the emergent pair statistics, and find that the observed dynamics is consistent with being primarily seeded by vacuum fluctuations in the corresponding atomic modes. Together with our observations of coherent many-body oscillations involving well-defined momentum modes, our results offer promising prospects for quantum-enhanced interferometry and quantum simulation experiments using entangled matter waves.

Influence of direct dipole-dipole interaction on the optical response of 2D materials in inhomogeneous infrared cavity fields

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Extended Abstract Online (ID 58)

The interaction between light and matter can be strongly enhanced by using nanopho- tonic cavities that localize light at the nanoscale. For example, the strong coupling between the cavity modes and vibrational modes of molecules results in the forma- tion of vibrational polaritons [1],[2],[3], which can have a significant impact on the physical and chemical properties of the system [4],[5]. Our work considers a 2D material formed, by a self-assembled molecular mono- layer or by a single layer of a Van der Walls material, coupled to an infrared nanophotonic cavity, potentially reaching the strong coupling regime. These systems are often modelled using classical harmonic oscillator descriptions or c-QED Hamiltonians that neglect the direct dipole-dipole interactions within the 2D material [5]. However, important effects can arise from these direct interactions, such as the emer- gence of new collective modes. To include these effects, we diagonalize the full Hamiltonian of the system (2D material and nanophotonic cavity), including the di- rect dipole-dipole interactions within the 2D material and their interaction with the nanocavity. The main effect of considering direct dipole-dipole interactions on the optical properties of the hybrid system for homogeneous or slowly varying cavity fields is the renormalization of the effective energy of the bright collective mode of the 2D material that couples with the nanophotonic mode. However, we find that, for situations of extreme field confinement, fully including the direct interactions within the 2D material becomes critical to correctly capture the optical response, with many collective vibrational states participating in the response. Further, we derive a simple analytical equation which establishes the criteria for the need of dipole-dipole inter- actions in the description of the hybrid system beyond the standard renormalization [6].y

Design of a New Apparatus for Dipolar Quantum Gases Strongly Coupled to Cavity QED

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Extended Abstract Online (ID 107)

Strong light-matter coupling can be used for exploring exotic quantum many- body phases, arising from the competition between dipolar and light-mediated long-range interactions, as well as for attaining control of chemical reactions. At the Fritz Haber Institute, we are designing a new apparatus for studying ultracold dipolar atoms and molecules strongly coupled to a cavity QED. We report on our efforts to create a quantum gas of dysprosium atoms in a preliminary version of the apparatus.

Collectively enhanced ground-state cooling in subwavelength atomic arrays

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Extended Abstract Online (ID 40)

Closely spaced arrays of emitters exhibit light-induced dipole-dipole interactions, resulting in modified radiative properties and the emergence of collective resonances with a narrowed linewidth. These modifications significantly impact the optomechanical response of the array. In this work, we theoretically demonstrate the implications of these collective resonances on laser cooling techniques. Our findings reveal a novel approach to leverage collective resonances for enhanced cooling of the motional degrees of freedom of atoms in subwavelength arrays. Notably, the collective line-narrowing effect allows for ground state cooling, even in the case of bare atomic transitions within the unresolved sideband regime. This work contributes to the understanding of how collective resonances can be harnessed to achieve unprecedented control over the cooling dynamics in nanoscale systems.

Optical integration with femto-second laser written waveguides

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Current trapped ion quantum computing systems usually make use of free-space optics to deliver the light to the ions. This practice makes the setups susceptible to drifts and vibrations and limits the number of ions which can be manipulated.

For a scalable system it is thus necessary to increasingly integrate optical elements from external components directly into the ion trap. We use femto-second laser pulses to write single-mode and polarization-maintaining waveguides directly into borofloat glass. Unlike other materials used in CMOS technology, borofloat glass is transparent for ultraviolet light required for the manipulation of $^{40}Ca^{+}$ ions. Henceforth, a microstructured surface trap was realized featuring two of these waveguides, one for 397nm light and one for 729nm light. In parallel, we build up an integrated cryogenic quantum computing system to enable fast trap testing and to investigate the quality of the light delivery to the ions.

Quantum entanglement at the origin of classical radiation

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We introduce a new family of collective spin states which, although being quantum entangled states, are surprisingly responsible for the emergence of classical macroscopic response to light. We call these states coherently radiating spin states (CRSS), study their entanglement properties, the way they are produced, and how they may underlie collective radiation. In particular, we show that CRSS are naturally realized in superradiance and underlie the dissipative Dicke phase transition, hence predicting the optimal scaling of spin squeezing in superradiance, and its classical-like radiation. In a realistic system, where individual decay competes with collective radiation, we show how the system exhibits quantum jumps between CRSS and a non-entangled state. More generally, CRSS emerge as ground states of a collective spin Hamiltonian. CRSS thus provide a promising concept for studying many-body spin systems in various platforms, with applications ranging from quantum metrology and lasing to phase transitions.

Dynamical phases and technological applications of atom-cavity systems

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While dissipation is in general perceived as a destructive feature of a quantum system, it can also be utilized to engineer nontrivial states, often in conjunction with pushing a system out of equilibrium. We study various non-equilibrium phases in an ultracold quantum gas coupled to a high-finesse optical cavity. We utilize both effective models, such as the three-level Dicke model, and numerical methods to characterize the emerging phases ranging from time crystals to dark states. We put forth the first experimental realization of a limit cycle in an atom-cavity system and explain its origin using bifurcation theory, which also enables us to understand the system's route to aperiodic dynamics. Finally, we propose to use the atom-cavity system to create a quantum rotational sensor not only for static high precision frequency measurements but also for inertial measurements and navigation.

Quantum simulation of effective field theories using one-dimensional Bose gases

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Extended Abstract Online (ID 129)

Ultra-cold quantum gases are reliable analog quantum simulators, as they are highly tunable and well isolated from their environment. Here, I will present the quantum field simulation of the Klein-Gordon model using a pair of quasi-one-dimensional tunneling-coupled Bose gases on an atom chip. After briefly introducing our atom chip experiment and the theoretical framework, I will discuss measuring the von Neumann entropy in the experiment and verifying the area law of quantum mutual information. Then, I will explain the post-quench propagation of information on a simulated inhomogeneous metric, where we observe the dynamics of correlations on curved light cones.

Dark state transport between unitary Fermi superfluids

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Electromagnetically induced transparency (EIT), or dark states from the atomic perspective, has profound applications in quantum sciences. Here, in a two-component, unitary Fermi gas, we realize a spin-selective dark state using a Lambda system within the D2 transition manifold of lithium-6 at high magnetic field. The dark state is created in a 2-micrometer region employing an EIT scheme within a one-dimensional channel connecting two superfluid reservoirs. We show that, while

without the dark state resonance, spontaneous emission suppresses the non-Ohmic superfluid signature of the transport [1], the fast current is recovered on resonance by the transport of the atoms in the dark state. Varying the two-photon detuning uncovers an asymmetry in the transport, originating from the two-photon dipole potential around the resonance. This work opens perspectives for optical manipulation of fermionic pairing.

References

[1] M. Huang, J. Mohan, A. M. Visuri, P. Fabritius, M. Talebi, S. Wili, S. Uchino, T. Giamarchi, and T. Esslinger, Physical Review Letters 130.20 (2023): 200404.

Motivating quantum-enhanced metrology with an ion-based optical atomic clock

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Extended Abstract Online (ID 69)

The extraordinary accuracy of optical atomic clocks is currently motivating the future redefinition of the SI second in terms of an optical frequency. The $^{171}Yb^{+}$ ion is an excellent candidate due to its very low sensitivity to external field perturbations, and the presence of a strongly forbidden electric octupole transition with a natural linewidth at the nHz level [1]. The $^{171}Yb^{+}$ ion is also particularly sensitive to variations in the fine structure constant, enabling tests of fundamental physics beyond the Standard Model [2, 3].

The ytterbium single-ion optical clock at the National Physical Laboratory has recently achieved a fractional systematic uncertainty of 2.2×10^{-18}. With its fractional instability of $2 \times 10^{-15}/\sqrt{\tau}$, it would take several weeks of measurement to reach the systematic floor. The quantum-projection-noise-dominated instability of ion-based optical clocks is proportional to $1/\sqrt{N}$ for N ions. While increasing the number of ions would improve the instability according to $\sqrt{N}$, entangling the ions could offer an instability proportional to $1/N$ [5], enabling metrology beyond the standard quantum limit. This poster will present an overview of the ytterbium ion optical clock at NPL for metrology and fundamental physics, and discuss possibilities for quantum-enhanced operation.

References

[1] R. Lange et al., Lifetime of the $^2F_{7/2}$ level in Yb^+ for spontaneous emission of electric octupole radiation, Phys. Rev. Lett. 127 213001 (2021)

[2] N. Sherrill et al., Analysis of atomic-clock data to constrain variations of fundamental constants, New J. Phys. 25 093012 (2023)

[3] B. M. Roberts et al., Search for transient variations of the fine structure constant and dark matter using fiber-linked optical atomic clocks, New J. Phys. 22 093010 (2020)

[4] V. Giovannetti et al., Quantum Metrology, Phys. Rev. Lett. 96 010401 (2006)

Dynamic control of fermionic many body quantum systems

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Extended Abstract Online (ID 84)

In open interacting many body quantum systems, the competition between various energy scales and the coupling to an external bath lead to rich phase diagrams and interesting phenomena. In our work, we investigate the many body dynamics of the self ordering phase transition present in atomic systems coupled to quantum light. We consider ultracold interacting fermionic atoms confined in a 1D optical lattice globally coupled to the field of a dissipative cavity mode. It provides a perfect playground to study the steady states and dynamic self-ordering processes of these complex systems. We develop a quasi-exact numerical method based on time dependent MPS methods, as well as an analytic approach going beyond the mean field level by incorporating fluctuations in the coupling between atoms and cavity field.

Hamilton-Jacobi-Bellman equation for Rydberg-blockade processes

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Extended Abstract Online (ID 140)

We address the time-optimal control problem of globally driven Rydberg atoms by deriving the Hamilton-Jacobi-Bellman equation for the optimal time over the state space. Using a generalized method of characteristics, we extract the optimal trajectories of the atomic system and the corresponding controls. We demonstrate this method by reproducing the known results of the CZ and C-phase gates, and we apply it to compute the optimal pulses for the universal quantum computation scheme introduced in [Phys. Rev. Lett. 131, 170601]. Through these analyses, we

propose the utilization of the Bellman principle of optimality as a general approach to address optimal control problems in Rydberg-atom-based quantum computing.

All-optical superconducting qubit readout

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Extended Abstract Online (ID 75)

The rapid development of superconducting quantum hardware is expected to run into significant I/O restrictions due to the need for large-scale error correction. Classical data centers rely on fiber-optic interconnects to remove similar networking bottlenecks. In the same spirit, ultra-cold electro-optic links have been used to generate qubit control signals, or to replace cryogenic readout electronics. So far, these links suffered from low efficiency, low bandwidth, or breaking of Cooper pairs. In this work, we realize electro-optic microwave photonics at millikelvin temperatures to implement a radio-over-fiber qubit readout that does not require any active or passive cryogenic microwave equipment. We demonstrate all-optical single-shot-readout by means of the Jaynes-Cummings nonlinearity. Importantly, we do not observe any direct radiation impact on the qubit state. This compatibility between superconducting circuits and telecom wavelength light is not only a prerequisite to establish modular quantum networks, it is also relevant for multiplexed readout of superconducting photon detectors and classical superconducting logic.

Effects of time delays on superradiant decay in chiral waveguide QED

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Coupling atoms to a waveguide can give rise to a multitude of collective dynamical phenomena. One of the most striking is superradiance, the cooperative decay of distant excited atoms under emission of a short burst of radiation with a peak intensity scaling superlinearly with the number of emitters. A key assumption underpinning the theoretical description of waveguide-mediated superradiance is that the time taken by photons to travel between atoms can be neglected. Here, we examine the role of non-negligible retardation times in the collective decay of two-level atoms chirally coupled to a linear waveguide. We derive a master

equation which fully accounts for retardation, and solve its dynamics using Matrix Product State (MPS) methods and the Truncated Wigner Approximation (TWA). We demonstrate that time delays can suppress the characteristic scaling of the peak emission rate and give rise to a "plateau" effect associated with an effective maximum number of atoms participating in the superradiant decay. Beyond this, we explore to what extent retardation may affect the coherence properties of the emitted field and give rise to novel features in the emitter dynamics.

Strongly interacting lattice fermions with synthetic dimensions: from universal Hall response to Hall voltage measurement

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Extended Abstract Online (ID 35)

We report on the first quantum simulation of the Hall effect for strongly interacting fermions. By performing direct measurements of current and charge polarization in an ultracold-atom simulator, we trace the buildup of the Hall response in a synthetic ladder pierced by a magnetic flux, going beyond stationary Hall voltage measurements in solid-state systems. We witness the onset of a clear interaction-dependent behavior, where the Hall response deviates significantly from that expected for a non-interacting electron gas, approaching a universal value. Our system, able to reach hard to compute regimes also demonstrates the power of quantum simulation for strongly correlated topological states of matter.

By further applying an additional potential gradient along the synthetic dimension, we have implemented the first measurement of the Hall voltage in an atomic quantum simulator with strongly interacting ultracold fermions, and performed a systematic study of the Hall voltage as a function of the atom number. The observed sole dependence on particle fillings and remarkable robustness with respect to ladder geometries will enable new investigations of the exotic transport properties in the strongly correlated regime.

Beyond mean-field dynamics in multi-level cavity QED

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The distinctive advantage of quantum information is the non-local nature of information stored in the correlation functions of entangled particles. One of the leading platforms for generating non-local models are the cavity QED experiments. Within a microwave resonator photonic modes can couple to the collective degrees of freedom of the atomic ensembles, leading to captivating emergent phenomena. Notably, light-induced spin-exchange interactions, crucial for quantum simulations, were directly observed in an experiment involving a spin-1 bosonic ensemble (Davis et al., 2019) and characterised in a quench setup. The dynamics after the quench has been studied theoretically within the mean-field approach (Valencia-Tortora et al., 2023), indicating that tuning of the atomic intra-level correlations leads to a novel asynchronized chaotic phase. We extended the study of the nonequilibrium behaviour of a 3-level bosonic system in a cavity by employing a self-consistent variational scheme based on the two-particle irreducible functional integral techniques. As a result, we obtain non-perturbative analytical equations for dynamical Green's functions characterising the system and are able to probe the role of quantum fluctuations in the onset of chaos.

Work with Hossein Hosseinabadi and Jamir Marino.

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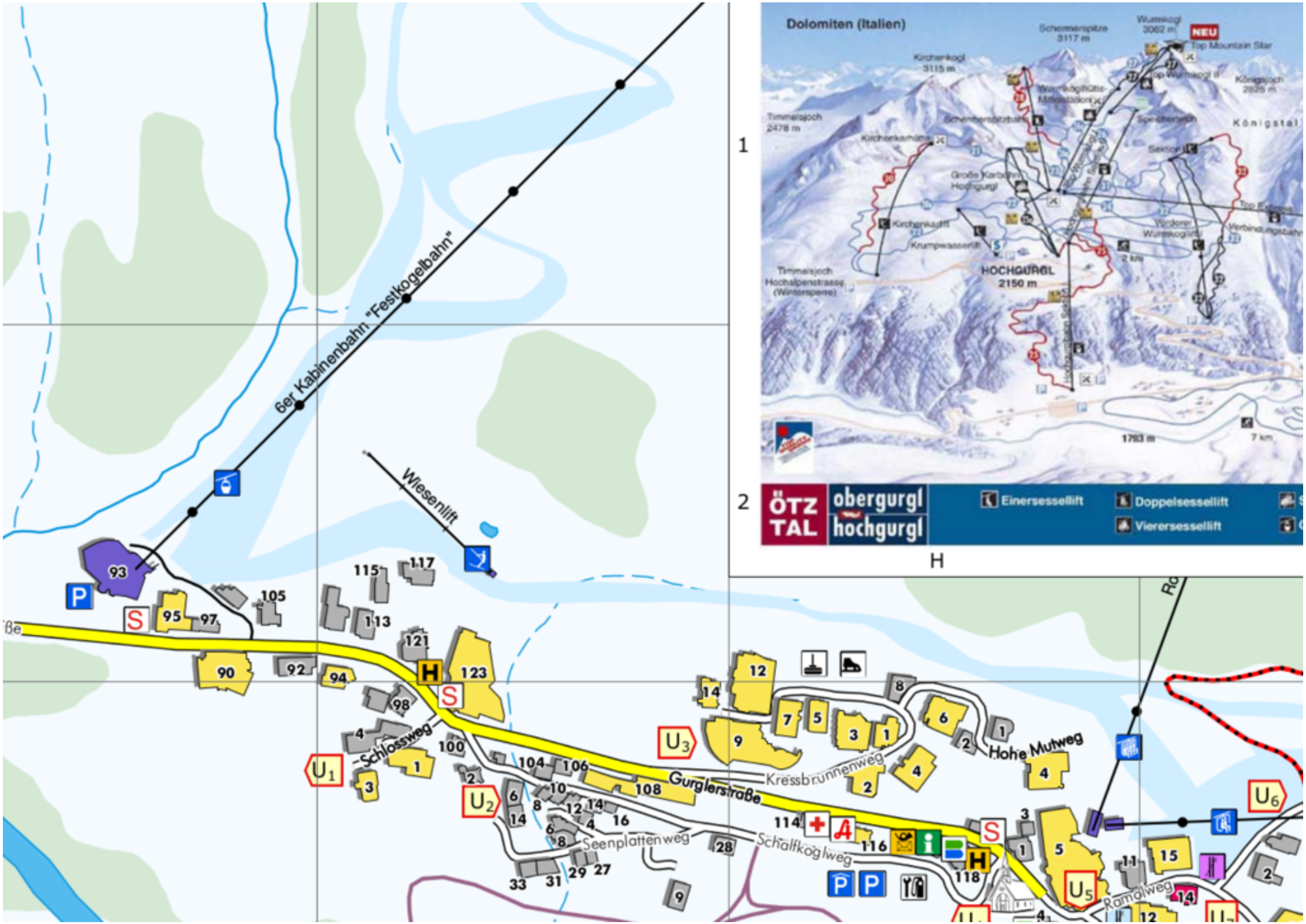

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			Quantum Optics	Quantum Austria Excellence	BeyondC SFB	Quantum Austria Excellence	Quantum Information	
07:15-8:15	Breakfast		Intro Rektor 8:00		Woman's Breakfast			
08:15-08:45	Invited		Rempe	Morigi	Polzik	Lukin	Northup	return bus
08:45-09:15	Invited		Yelin	Kollath	Chang	Meyer	Will	return bus
09:20-9:40	Hot topic		Holzinger	Kuhn	Cerf	Köhl	Dür	
09.40-10:15	Coffee							
10.15-10:45	Invited		Briegel	Donner	Acin	Weiss	Müller	return bus
10.45-11:05	Hot topic		Malz	Weld	Yao	Zwettler	Agresti	return bus
11:10-11:30	Hot topic		Zenesini	Walther	Bock	Kroeze	Haslinger	
11.35-11:55	Discussions				Rozema		SFB Poster Award	
12.00-15.30	**Lunch Break**							
15.30-16:15	**Coffee + Cake**	BUS						
16:15-16:45	Invited	BUS	Schnabel	Rotter	SFB	Steinberg	Cornish	
16.45-17.05	Hot topic	BUS	Dayan	Schäffer	Business	Guo	Vukics	
17:10-17:30	Hot topic	BUS	Gietka	Hunger	Meeting	Keßler	Pick	
17:35-17:55	Hot topic	BUS	Juffmann	Cetina		Jäger	Prüfer	
18:00-18.30	**Discussions**							
18.30-20:00		Dinner	Dinner	Dinner	Conference	Dinner	Dinner	
20.00-21.00		Dinner	Posters1	Posters1	Dinner	Posters2	Posters2	
21.00-22.00		Dinner	A-K	A-K	UZO	L-Z	L-Z	