Poster session I

Tuesday, February 5th, 14:00-16:00
Chair: Martin Ringbauer, Pavel Hrmo, University of Innsbruck

1. **Super- and subradiance of clock atoms in multimode optical waveguides**
   Laurin Ostermann, University of Innsbruck

   The transversely confined propagating modes of an optical fiber mediate virtually infinite range energy exchange between atoms placed within their field, which adds to the inherent free space dipole-dipole coupling. Typically, the single atom free space decay rate largely surpasses the emission rate into the guided fiber modes. However, scaling up the atom number as well as the system size amounts to entering a collective emission regime, where fiber-induced superradiant spontaneous emission dominates over free space decay. We numerically study this super- and subradiant decay of highly excited atomic states for one or several transverse fiber modes as present in hollow core fibers. As particular excitation scenarios we compare the decay of a totally inverted state to the case of $\pi/2$ pulses applied transversely or along the fiber axis as in standard Ramsey or Rabi interferometry. While a mean field approach fails to correctly describe the initiation of superradiance, a second-order approximation accounting for pairwise atom-atom quantum correlations generally proves sufficient to reliably describe superradiance of ensembles from two to a few hundred particles. In contrast, a full account of subradiance requires the inclusion of all higher order quantum correlations. Considering multiple guided modes introduces a natural effective cut-off for the interaction range emerging from the dephasing of different fiber contributions, which limits the maximal possible 1D coupling.

2. **A cesium interferometer for quantum metrology**
   Benedikt Gerstenecker, TU Wien

   The matter-wave properties of atoms and the macroscopic behavior of BECs make interference experiments with ultracold atoms a useful tool for metrology applications. It has been shown that a condensate can be split while controlling the relative phase, realizing a phase-preserving beam splitter. Utilizing this method, high sensitivity to small energy differences can be achieved with BEC interferometry. The procedures developed in the past years lead to the prospect of an integrated matter-wave sensor for high-precision measurements.

   In order to realize such a sensor we are building an experimental setup for cesium interferometry. After achieving condensation in a dipole trap close to the surface of an atomchip by tuning the scattering properties, the single potential well is continuously deformed into a double well. The phase difference accumulated by the two resulting clouds allows for observing atomic interactions and inhomogeneities of ambient fields. We aim at exceptionally high sensitivity by reducing the scattering length of the ultracold atoms via magnetically induced Feshbach resonances and by shielding the experiment against external influences, while still maintaining a very compact setup size employing a commercial "BEC machine" by ColdQuanta. The poster presentation will feature the main objectives and prospects as well as the current status of the experiment. It will also discuss the systematic energy budget to evaluate the challenges and constraints given by ambient and control fields.

3. **Wavelength-scale errors in optical localization due to spin-orbit coupling of light**
   Magister Stefan Walser, TU Wien

   The precise determination of the position of sub-wavelength scale emitters using far-field optical imaging techniques is of utmost importance for a wide range of applications in medicine, biology, astronomy and physics. We theoretically and experimentally show that, for a standard optical imaging system like an optical microscope, the image of an elliptically polarized point-like emitter does in general not coincide with the emitter's real position. Instead, even for perfect, aberration-free imaging with high numerical aperture, the image can in general be shifted. Imaging a single gold nanoparticle in a standard immersion microscopy setup, we experimentally demonstrate this effect and observe shifts up to one optical wavelength. Such shifts can lead to a systematic error in the optical localization of emitters which exceeds the typical precision of super-localization microscopes by far. Moreover, for the case of small numerical aperture, the shift can in principle reach arbitrarily large values. Beyond its relevance for optical imaging, the demonstrated phenomenon may also occur for sources of other types of waves as for instance in radar and sonar imaging.

4. **Superradiant emission from colour centres in diamond**
   Andreas Angerer, TU Wien

   Superradiance is a fundamental collective effect where radiation is amplified by the coherence of multiple emitters. It plays a prominent role in optics (where it enables the design of lasers with substantially reduced linewidths) and quantum mechanics. Resonators coupled to spin ensembles are promising future building blocks of integrated quantum devices that will involve superradiance. As such, it is important to study its fundamental properties within such devices. Here we explore superradiance in a system composed of a three-dimensional lumped element resonator in the fast cavity limit inductively coupled to an inhomogeneously broadened ensemble of nitrogenâĂŞvacancy centres. We observe a superradiant pulse being emitted a trillion times faster than the decay for an individual nitrogen-vacancy centre. This is further confirmed by the nonlinear scaling of the emitted radiation intensity with respect to the ensemble size.

5. **VUV Characterization of 229Th:CaF2 for an optical clock**
   Marion Mallweger, TU Wien

The isomer of Th-229 is the only excited nuclear state known today that could be excited by current laser technology. Owing to its long lifetime, the Th-229m isomer could form a platform of a future nuclear optical clock. Very recently, the LMU Munich experiment has observed the de-excitation of the isomer. The direct excitation of the isomer, however, still is one of the greatest challenges in this field of research.

We aim to directly excite Th-229 doped into a in a CaF2 crystal to observe the radiative decay of the isomer. Firstly, the biggest challenge of using Th-229 in a crystal is the suppression of both the non-radiative decay of the isomer and of crystal-related luminescence. Secondly, photons of the appropriate energy are needed for the direct excitation. The isomer energy is known to lie between 6.3 and 18.3 eV, which puts it in the vacuum ultraviolet (VUV) region. So far, only synchrotron radiation has been explored as a possible light source.

To excite the Th-229 in the crystal, we take a new approach by applying a commercially available excimer lamp. This light source uses a low-energy electron beam to excite noble gases to form excimer molecules. These excimers show a continuous and broad emission spectrum in the VUV region, thus forming are a high-brightness VUV light source. The wavelength can be tuned to span from 110 nm to 200 nm by using different noble gas mixtures. A VUV spectrometer is used for detection and allows for spectral separation of the crystal luminescence from the anticipated isomer signal.

The direct excitation of 229Th might not need the exact matching photon energy. We investigate colour centres created by Thorium in the crystal matrix and excitons of CaF2 that might be able to pump energy into the isomer state. The absorption of these defects Details on the experimental progress along these research lines will be presented.

6. **Wavefront-shaping for electron microscopy**
   Philipp Weber, University of Vienna

   The precise shape of the electron beam is a critical factor for the performance of an electron microscope. The achievable resolution and sensitivity in various imaging modes depend on wavefronts with low aberrations.

   An electron wave passing through an intense laser pulse experiences a ponderomotive potential and accumulates a phase shift. A shaped optical intensity pattern can therefore be used to shape an electron wavefront. Here we propose a wavefront-shaping scheme to correct the spherical aberration of an electron beam.

   A spatial light modulator is used to generate laser pulsed with a tailored wavefront. A pulsed electron beam is synchronized and overlapped with the laser pulses. We discuss a Gerchberg-Saxton algorithm to iteratively adjust the intensity distribution of the light field and thereby the electron wavefront.

7. **Superradiance in ensembles of Strontium-88 with inhomogeneous broadening**
   Georgy Kazakov, TU Wien Bad cavity laser is a laser where the linewidth of the

cavity mode is broader than the gain profile. Frequency of radiation emitted by such laser is robust with respect to fluctuations of the cavity length, what opens the possibility to create a highly stable active optical frequency standard. We will discuss the possibility of creation of such a stangdard on the babsis of forbidden 3P0->1S0 transition in bosonic Sr-88 atoms. Such a transition, generally totally forbidden, can be made slightly allowed in the presence of magnetic field. However, this magnetic field shifts the energy of the 3P0 state, and spatial inhomogenity of this field leads to inhomogeneous broadening of the atomic transition. We consider theoretically influence of such a spatial inhomogenity of the magnetic field, as well as other relevant factors, on the characteristic of the superradiance of ensemble of Sr-88 atoms.

8. **Reaching the optimal sensitivity of non-gaussian spin states using individual sub-level resolution**
   Alexandre Evrard, Laboratoire Kastler Brossel and College de France

   The measurement precision of a quantum sensor can overcome the capabilities of its classical counterpart when its constituants are entangled together. In squeezed states, quantum correlations allow for a reduction of the quantum projection noise below the shot noise limit.

   Measurements are performed on atomic clouds of typically 4e4 atoms and temperature of 1uK and individual sub-level resolution is achieved with Stern-Gerlach imaging. We measure here the sensitivity of non-classical states of the electronic spin J=8 of dysprosium atoms created using light-induced non-linear coupling. We reach the optimal sensitivity of oversqueezed states, well above the capability of squeezed states and about half of the Heisenberg limit.

9. **A cesium interferometer for quantum metrology**
   Maximilian Lerchbaumer, TU Wien

   Caesiums special scattering properties, notably the tunability of its scattering length via magnetically induced Feshbach resonances, make it a promising candidate for BEC matter-wave interferometry but also require us to use a trapping scheme not reliant on magnetic fields.

   Using evaporative cooling and tuning of the scattering length via a magnetic field we will achieve condensation in a dipole trap close to the surface of an atomchip. Then continuously deform the potential well into a double well while controlling the relative phase between the two resulting BECs. The phase difference later accumulated allows observation of atomic interactions and inhomogeneities of ambient fields with very high sensitivity. We aim to further increase this sensitivity by tuning the scattering length and shielding the experiment against unwanted external influences while still maintaining a very compact setup using a commercial self contained UHV chamber with fitting field coils by ColdQuanta.

10. **Quantum advantage for probabilistic one-time programs**
    Marie-Christine RÃűhsner, University of Vienna

One-time programs, computer programs which self-destruct after being run only once, are a powerful building block in cryptography and would allow for new forms of secure software distribution. However, ideal one-time programs have been proved to be unachievable using either classical or quantum resources. Here we relax the definition of one-time programs to allow some probability of error in the output and show that quantum mechanics offers security advantages over purely classical resources. We introduce a scheme for encoding probabilistic one-time programs as quantum states with prescribed measurement settings, explore their security, and experimentally demonstrate various one-time programs using measurements on single-photon states. These include classical logic gates, a program to solve Yao's millionaires problem, and a one-time delegation of a digital signature. By combining quantum and classical technology, we demonstrate that quantum techniques can enhance computing capabilities even before full-scale quantum computers are available.

11. **Matchgate circuits and compressed quantum computation**
Martin Hebenstreit, University of Innsbruck

Although it is believed that quantum computation cannot be classically efficiently simulated in general, there exist certain restricted classes of quantum circuits for which classical simulation is indeed possible. The most prominent example are the Clifford circuits. Here, we consider another such class, the so-called matchgate circuits (MGCs) [1,2]. MGCs can be classically efficiently simulated and moreover, performed as a compressed quantum computation, i.e., the computation can be performed on an quantum computer using exponentially fewer qubits and only polynomial overhead in runtime [3]. We elaborate on and extend recent results [4] on classical simulability of MGCs. To this end, we discuss the notion of magic states in this context.

[1] L. Valiant, SIAM J. Computing 31, 1229 (2002), B. Terhal and D. DiVincenzo, Phys. Rev. A 65, 032325 (2002)

[2] R. Jozsa and A. Miyake, Proc. R. Soc. A 464, 3089 (2008)

[3] R. Jozsa, B. Kraus, A. Miyake, J. Watrous, Proc. R. Soc. A 466, 809 (2010)

[4] D. J. Brod, Phys. Rev. A 93, 062332 (2016)

12. **Characterizing multi-qubit operations in an ion-trap quantum computer**
Alexander Erhard, University of Innsbruck

Quantum computers promise to solve certain problems more efficiently than their classical counterparts. A major challenge towards a large-scale quantum information processor is characterizing and controlling the noise afflicting the processor during an algorithm. We experimentally characterize entangling operations on an ion-trap quantum computer incorporating up to 10 qubits. Our results reveal process fidelities of multi-qubit entangling gates ranging from 99.64(6) % for 2 qubits to 85.6(1.9) % for 10 qubits. Furthermore, the average fidelity per single-qubit gate or two-qubit coupling does not decrease with increasing system size, which is an indispensable requirement for practical quantum error correction

13. **Estimating spatial correlations in a trapped ion quantum information processor**
Lukas Postler, University of Innsbruck

Correlations between different partitions of quantum systems play a central role in a variety of many-body quantum systems, and they have been studied exhaustively in experimental and theoretical research. Here, we investigate dynamical correlations in the time evolution of multiple parts of a composite quantum system. A rigorous measure to quantify correlations in quantum dynamics based on a full tomographic reconstruction of the quantum process has been introduced recently [A. Rivas et al., New Journal of Physics, 17(6) 062001 (2015).]. In this work, we derive a lower bound for this correlation measure, which does not require full knowledge of the quantum dynamics. Furthermore we also extend the correlation measure to multipartite systems. We directly apply the developed methods to a trapped ion quantum information processor to experimentally characterize the correlations in quantum dynamics for two- and four-qubit systems. The method proposed and demonstrated in this work is scalable, platform-independent and applicable to other composite quantum systems and quantum information processing architectures. We apply the method to estimate spatial correlations in environmental noise processes, which are crucial for the performance of quantum error correction procedures.

14. **Constructing k-uniform states and study the graph state representation**
Zahra Raissi, The Institute of Photonic Sciences

A pure quantum state of n subsystems each having local dimension q is called k-uniform state, if all k-qudit reductions of the whole system are maximally mixed. These states form a natural generalization of n qudits EPR and GHZ states which belong to the class 1-uniform states. The k-uniform states are known to play an important role in quantum information processing when dealing with many parties. They are useful for multipartite teleportation and in quantum secret sharing. These states have also deep connections with apparently unrelated areas of mathematics such as combinatorial designs and structures, classical error correcting codes (CECC), and quantum error correcting codes (QECC).

The Schmidt decomposition shows that a state can be at most $n/2$-uniform, i.e., k $<=$ $n/2$. The $n/2$ -uniform states are called Absolutely Maximally Entangled states or AME states for short. We describe that there can be a direct correspondence between a given CECC and k-uniform state of minimal support if there exists a coordinate such that any k symbols of the codewords can be taken as message symbols. One aspect of this connection can provide a framework to develop a stabilizer formalism and produce an orthonormal basis of a given k-uniform state. We also study the description of these k-uniform states within the graph state formalism. We show the graphical representation for the state constructed from a CECC form a bipartite graph.

We propose a systematic method to construct a new set of k-uniform states. This method is not based on the CECCs and can produce a set of k-uniform states that have better parameters compare to the states that are obtained from the CECCs. In an analogous fashion, we construct a set of Pauli strings that generate a stabilizer group that stabilizes this set of k-uniform states. Also, we compare the graphical representation of the k-uniform states constructed from the CECCs and the new set.

15. **Scalable quantum computation - Keeping a qubit alive**
    Lukas Gerster, University of Innsbruck

    Trapped ions are a promising platform to host a future quantum computer. In our setup we use a planar segmented trapping architecture in a cryostat to demonstrate scalable quantum manipulation. The setup has been designed to reduce magnetic field noise and mechanical vibrations, both of which can induce errors. Two species, 40Ca+ and 88Sr+, are co-trapped, allowing for recooling of ion crystals during sequences. We are modifying the setup to host a segmented linear surface trap for supporting multiple trapping sites, and in-vaccum optics with high collection efficiency for high fidelity state readout.

    We further present ion crystal rotation of both single and multi species ion crystals with only few phonons accumulated per rotation, similar to [1]. These operations expand the available toolbox, enabling quantum error correction protocols in the future.

    [1] H. Kaufmann et al, Fast ion swapping for quantum-information processing,

    https://doi.org/10.1103/PhysRevA.95.052319

16. **A hybrid quantum-classical learning agent**
    Sabine Wölk, University of Innsbruck

    In a recent publication [1] a new framework for quantum machine learning was introduced. Building on earlier work on projective simulation [2], it was shown that a generic quadratic speed up for reinforcement learning can be achieved when a learning agent interacts with its environment quantum mechanically. However, this interaction needs to be coupled, at least from time to time, to a classical tester to rank the performance of the agent.

    In this poster, we investigate potential designs for the interplay between classical and quantum mechanical interactions and discuss experimental realizations that seem feasible with state-of-the-art quantum technology.

    [1] V. Dunjko, J. M. Taylor and H.J. Briegel, âĂIJQuantum-enhanced machine learningâĂİ, Phys. Rev. Lett. 117, 130501 (2016)

    [2] G. D. Paparo, V. Dunjko, A. Makmal, M.A. Martin-Delgado and H. J. Briegel, Quantum speedup for active learning agents, Phys. Rev. X 4, 031002 (2014)

17. **Machine learning for designing new quantum experiments**
    Alexey Melnikov, University of Innsbruck

    How useful can machine learning be in a quantum laboratory? Here we raise the question of the potential of intelligent machines in the context of scientific research

(PNAS 115, 1221). We investigate this question by using the projective simulation model, a physics-oriented approach to artificial intelligence. In our approach, the projective simulation system is challenged to design complex photonic quantum experiments that produce high-dimensional entangled multiphoton states, which are of high interest in modern quantum experiments. The artificial intelligence system learns to create a variety of entangled states, in number surpassing the best previously studied automated approaches, and improves the efficiency of their realization. In the process, the system autonomously (re)discovers experimental techniques which are only now becoming standard in modern quantum optical experiments - a trait which was not explicitly demanded from the system but emerged through the process of learning. Such features highlight the possibility that machines could have a significantly more creative role in future research.

18. **Learning and Planning in Quantum Experiments**
    Lea Marion Trenkwalder, University of Innsbruck

    The focus of this work lies on investigating intelligent agents capable of conducting quantum experiments, such as optical table experiments. The task structure of performing optical table experiment can be mapped to navigating on a complex maze. Using the projective simulation platform, we design an agent capable of learning the structure of this maze. Thus, such an agent can simulate experience and plan strategies to create experiments which generate high-dimensional multi-entangled states.

19. **Locust collective motion modelled with Projective Simulation**
    Andrea López-Incera, University of Innsbruck

    Locust collective motion has been widely studied in the literature from the perspective of different scientific disciplines including biology, social science or statistical physics. In this work, we apply Projective Simulation (PS) to model each locust of the swarm as an artificial agent that can process its perceptions to deliberate and perform actions. We study how collective behaviour emerges from the interaction of the individuals with their neighbours and with the surrounding environments.

20. **Rydberg Excitations in Lanthanoid Atoms for Quantum Simulation**
    Arno Trautmann, IQOQI Innsbruck

    We present our design for a novel platform for quantum simulation based on erbium-Rydberg atoms in optical tweezers. Rydberg atoms are promising candidates for quantum simulation due to their extremely strong and long-range interactions, and have been applied already very successfully in alkali atoms. However, the simple electronic structure with only one valence electron limits the possible manipulation of Rydberg states, such as trapping, cooling or direct imaging. The extension to Rydberg states in multi-electron atoms is natural, and recently strontium and ytterbium have been studied. We plan to use erbium atoms, which have two valence electrons in their outer 6s shell and 12 electrons in an open, sub-merged, 4f shell. The properties of Rydberg states in such a complex system are not yet well understood and require intense spectroscopic effort. We here present our design for a new experiment dedicated to the study of these states in controllable arrays of optical tweezers.

21. **Quantum simulation of non-perturbative cavity quantum electrodynamics**
Tuomas Jaako, TU Wien

We propose to simulate the Extended Dicke Model with systems of trapped ions. Especially we concentrate on simulation of the single qubit ultra-strong coupling regime with, on average, repulsive dipole-dipole interactions. In this regime in the ground state of the system the light and matter degrees of freedom are decoupled and at the same time the qubits are highly entangled among themselves. We highlight some experiments that could be done such as an adiabatic preparation of the ground state, and quench-dynamics. Different aspects of the spectrum of the system could be studied by probing either the internal dynamics of the ions or the normal modes of the ion crystal.

22. **Towards Quantum Simulation of 2D Spin Lattices with Ion Crystals**
Dominik Kiesenhofer, IQOQI Innsbruck

Understanding the behaviour of quantum many-body systems is one of the biggest challenges in quantum physics. To address this challenge our goal is the development of a two-dimensional (2D) 100 particle quantum simulator. Our future experiments will combine the proven methodology for realizing spin models in linear ion crystals with a novel approach to extending the systems into two dimensions. The experimental platform will be a 2D crystal of laser-cooled calcium ions held in a radio-frequency Paul trap. The exploration of 2D lattice geometries will overcome difficulties in scaling up one-dimensional trapped-ion systems and enable the experimental investigation of the rich physics of two-dimensional spin models (with frustrated interaction) beyond classical capabilities. I will present a novel micro-fabricated trap design providing unobstructed optical access for addressing and imaging as well as sufficient control for shaping the trapping potential in such a way that laser-ion interactions are not perturbed by the trapâĂŹs driving field. Different novel laser-cooling strategies will be explored to cool all motional degrees of freedom of the ion crystal to millikelvin temperatures or below. We further intend to set up an rf ion trap in a cryostat to create large ion crystals unaffected by collisions with the residual background gas.

23. **Quantum Simulation of spin models using assembled arrays of Rydberg atoms**
Sylvain de Leseleuc, Institut d'Optique Graduate Schools

Single atoms trapped in arrays of optical tweezers and excited to Rydberg states are a promising experimental platform for the quantum simulation of spin models. We have engineered a robust and easy-to-use method to assemble perfectly filled two-dimensional arrays of 87Rb atoms by moving them one by one with a moveable optical tweezers controlled by computer (Science 2016), a technique further enhanced to trap, image and assemble three-dimensional arrays (Nature 2018).

Using the resonant dipolar coupling between two Rydberg atoms (PRL 2015/2017), we implement an XY spin model and notably the Su-Schrieffer-Heeger model (arXiv 2018), known for its fermionic topological phase protected by the chiral symmetry. Here, we studied this topological phase, first at the single-particle level, then with strongly interacting bosons (hard-core bosons). This work paves the way for the study of topological phase of matters with interacting particles.

24. **Experimental Greenberger-Horne-Zeilinger Entanglement Beyond QuBits**
Manuel Erhard, IQOQI Vienna

Quantum entanglement is important for emerging quantum technologies such as quantum computation and secure quantum networks. To boost these technologies, a race is currently ongoing to increase the number of particles in multiparticle entangled states, such as Greenberger-Horne-Zeilinger (GHZ) states. An alternative route is to increase the number of entangled quantum levels. In our recent Nature Photonics article, we overcome present experimental and technological challenges to create a three-particle GHZ state entangled in three levels for every particle. The resulting qutrit-entangled states are able to carry more information than entangled states of qubits. Our method, inspired by the computer algorithm Melvin, relies on a new multi-port that coherently manipulates several photons simultaneously in higher dimensions. The realization required us to develop a new high-brightness fourphoton source entangled in orbital angular momentum. Our results allow qualitatively new refutations of local-realistic world views. We also expect that they will open up pathways for a further boost to quantum technologies.

25. **Entanglement by Path Identity**
Jaroslav Kysela, University of Vienna

Entanglement, being a truly quantum feature, has attracted a lot of attention in the past decades. Despite considerable technological progress, the generation of high-dimensionally entangled states in high rates is nevertheless still difficult. In the photonic case, the nature of the parametric down-conversion in nonlinear crystals leads to limitations of the entanglement generation process in terms of both efficiency and versatility. In this poster we present a genuinely different method of creation of high-dimensionally entangled photonic states. The underlying principle of our approach is the indistinguishability of propagation paths of individual photons. The lack of which-path information together with the mode transformations give rise to the entanglement. Our method is general and enables for generation of multiparty multidimensionally entangled states. The phases and magnitudes in produced states can be set independently and generation of specifically tailored states is thus possible. The scheme is demonstrated for photons, but other systems can be used in principle as well.

26. **Experimental few-copy multi-particle entanglement detection**
Valeria Saggio, University of Vienna

The reliable verification of quantum entanglement is an essential task to scale up quantum technologies. Recently, because of technological developments which allow for the experimental realization of quantum devices with increasing complexity, an entanglement verification method that is both reliable and resource-efficient is urgently needed. Although progressively more efficient techniques have been developed, most of these focus solely on minimizing the number of measurement settings. Additionally, in each measurement setting these methods still require many copies of the same quantum state, i.e. many detection events. Recently, a single-shot probabilistic method was proposed [1], wherein it was shown that even a single detection event can be sufficient to verify if a state contains entanglement. In our work [2], we extend this theoretical approach by showing that any entanglement witness can be translated into this probabilistic framework. In this way, entanglement detection can be easily carried out in a resource-efficient way, meaning that any witness operator can be used to reliably certify the presence of entanglement by using only a very low number of copies of the quantum system. To benchmark our theoretical findings, we report the experimental entanglement verification in a photonic six-qubit cluster state generated using three single-photon sources at telecommunication wavelength. We find that the presence of entanglement can be certified with at least 99.74% by using only 20 copies of the state. Additionally, we show that genuine six-qubit entanglement is verified with at least 99% confidence by using 112 copies of state. This novel method entails a significant reduction of resources and provides an easy tool to certify the presence of entanglement in large-scale systems, promising a great impact in future experiments where an efficient and resource-saving approach will be essential for entanglement verification problems in multi-qubit states.

[1] A. Dimić et al., npj Quantum Information, 4(1), 11, (2018).

[2] V. Saggio et al., arXiv:1809.05455 (2018).

27. **Probing the Rényi Entanglement Entropy via Randomised Measurements**
Christine Maier, IQOQI Innsbruck

Entanglement is the key feature of many-body quantum systems, and the development of new tools to probe it in the laboratory is an outstanding challenge. Measuring the entropy of different partitions of a quantum system provides a way to probe its entanglement structure. On this poster, I present the experimental demonstration of a new protocol, for measuring entropy, based on statistical correlations between randomized measurements. The experiment is carried out with a trapped-ion quantum simulator and proves the overall coherent character of the system dynamics and reveals the growth of entanglement between its parts - both in the absence and presence of disorder. Our protocol represents a universal tool for probing and characterizing engineered quantum systems in the laboratory, applicable to arbitrary quantum states of up to several tens of qubits.

28. **Entanglement of stabilizer states**

Matthias Englbrecht, University of Innsbruck

LOCC transformations provide a meaningful order in the set of entangled states. In order to understand the capabilities of stabilizer states under LOCC and thus to find new applications for them, it is essential to characterize their local symmetries. We approach this task by considering graph states, a set of states every stabilizer state can be mapped to by local Clifford operations. We aim to identify the most general form for a local symmetry of these states and to connect the existence of more local symmetries than the stabilizer to the structure of the corresponding graph. We will use the insights gained from these considerations to find new applications for stabilizer states.

29. **Changing SLOCC class using multiple copy transformations**
David Gunn, University of Innsbruck

Multipartite entanglement can be characterised by considering LOCC transformations. The possible LOCC transformations between single copy truly n-partite entangled pure states are known generically. For example, NielsenâĂŹs Theorem provides necessary and sufficient conditions for transformations between truly bipartite entangled pure states. However, for nâĽě4, there are an infinite number of SLOCC classes (states in one SLOCC class cannot be transformed via LOCC into any state in any other SLOCC class, even probabilistically). Moreover, almost all states are isolated (that is, they can neither be reached via LOCC nor reach any other state via LOCC), and therefore the minimal set of states from which all other states can be reached, called âĂŸthe Maximally Entangled SetâĂŹ or MES, is of full measure. We now look to better understand the transformations allows between multiple copies of states. In particular, we investigate whether by using multiple copies, we can change SLOCC classes, thereby opening up transformations not possible in the single copy case.

30. **Entanglement entropies and OTOCs from randomized measurements**
Andreas Elben, IQOQI Innsbruck

In this poster, we discuss statistical correlations of randomized measurements as a new toolbox to access properties of quantum systems beyond standard observables. From a unified point of view, we present first the protocol and recent experimental results on measuring in a trapped ion quantum simulator the 2nd order Renyi entropy of arbitrary (reduced) quantum states in a 10-qubit system - a size inaccessible with state-of-the-art quantum state tomography. We demonstrate the overall coherence of this system, and the generation of bipartite entanglement under quenched time-evolution governed by a long-range interacting spin-spin Hamiltonian, with and without controlled disorder.

Secondly, we propose, based on the same ingredients, a new protocol to access out-of-time ordered correlators (OTOCs), characterizing spreading of information (scrambling) in quantum many body systems. Uniquely, our protocol does not require the implementation of time-reversed evolution and/or additional ancillas.

31. **Wave-particle dualities of many-body quantum states**
Christoph Dittel, University of Innsbruck

We formulate a quantitative theory of wave-particle duality for many-body quantum systems. We introduce measures of the wave and particle characters of many identical bosons or fermions equipped with a tunable level of (in)distinguishability, which we show to satisfy many-body wave-particle duality relations. We analyze the bearing of the latter on measurement statistics and visibilities in general and possibly interacting many-particle dynamics, and, thereby, provide a versatile framework to witness quantum mechanical complementarity on the many-particle level.

32. **Anomalous energy transport and symmetry breaking in microscopic power grids**
Julian Huber, TU Wien

We study the transport of energy through a microscopic network of coupled harmonic oscillators, where energy is injected at one end and extracted at the other end with finite rates. We evaluate the resulting energy currents under the influence of both thermal and quantum noise and describe various transport phenomena that arise from the competition between coherent and incoherent processes and the presence of nonlinear saturation effects. Specifically, we show that such networks exhibit a non-equilibrium phase transition between a noise-dominated and a coherent transport regime. This transition is associated with the formation and breaking of spatial symmetries, which is identified as a generic mechanism that affects many transport properties of active networks. Therefore, our findings have important practical consequences for the distribution of energy over coherent microwave, optical or phononic channels, in particular close to or at the quantum limit.

33. **Cosmic Bell Test using Random Measurement Settings from High-Redshift Quasars**
Dominik Rauch, IQOQI Wien

I present a Cosmic Bell experiment with polarization-entangled photons, in which measurement settings were determined based on real-time measurements of the wavelength of photons from high-redshift quasars, whose light was emitted billions of years ago; the experiment simultaneously ensures locality. Assuming fair sampling for all detected photons, and that the wavelength of the quasar photons had not been selectively altered or previewed between emission and detection, we observe statistically significant violation of Bell's inequality. This experiment pushes back to at least $\sim$7.8 Gyr ago the most recent time by which any local-realist influences could have exploited the "freedom-of-choice" loophole to engineer the observed Bell violation, excluding any such mechanism from 96% of the space-time volume of the past light cone of our experiment, extending from the Big Bang to today.

34. **Satellite-Relayed Intercontinental Quantum Network**
Johannes Handsteiner, IQOQI Vienna

We perform decoy-state quantum key distribution between a low-Earth-orbit satellite and multiple ground stations located in Xinglong, Nanshan, and Graz, which establish satellite-to-ground secure keys with $\sim$kHz rate per passage of the satellite Micius over a ground station. The satellite thus establishes a secure key between itself and, say, Xinglong, and another key between itself and, say, Graz. Then, upon request from the ground command, Micius acts as a trusted relay. It performs bitwise exclusive OR operations between the two keys and relays the result to one of the ground stations. That way, a secret key is created between China and Europe at locations separated by 7600 km on Earth. These keys are then used for intercontinental quantumsecured communication. This was, on the one hand, the transmission of images in a one-time pad configuration from China to Austria as well as from Austria to China. Also, a video conference was performed between the Austrian Academy of Sciences and the Chinese Academy of Sciences, which also included a 280 km optical ground connection between Xinglong and Beijing. Our work clearly confirms the Micius satellite as a robust platform for quantum key distribution with different ground stations on Earth, and points towards an efficient solution for an ultralong-distance global quantum network.

35. **Certification and quantification of multilevel quantum coherence**
Martin Ringbauer, University of Innsbruck

Quantum coherence is one of the fundamental features that mark the departure of quantum mechanics from the classical realm. It manifests whenever a system exists in a superposition of classically distinguishable states, and for many-body systems embodies the essence of entanglement. For gauging the nonclassicality of a system, however, it is important to go beyond the mere presence or absence of coherence. Just like in the case of entanglement, there is a rich structure of multilevel coherence, which might be interesting for applications in quantum information processing and beyond. Using four-dimensional quantum systems we demonstrate a number of ways to experimentally quantify multilevel coherence. In particular, multilevel coherence is found to be the fundamental resource for an elementary quantum information task, which in turn can be exploited to witness the presence of coherence even without knowing what your measurement device is doing.

36. **Hidden Bridge between Quantum Experiments and Graph Theory**
Xuemei Gu, IQOQI Vienna

We present a conceptually new approach to describe state-of-the-art photonic quantum experiments using Graph Theory [1,2]. There, the quantum states are given by the coherent superpositions of perfect matchings. The crucial observation is that introducing complex weights in graphs naturally leads to quantum interference. The new viewpoint immediately leads to many interesting results, some of which we present here. Firstly, we identify a new and experimentally completely unexplored multiphoton interference phenomenon. Secondly, we find that computing the results of such experiments is P-hard, which means it is a classically intractable problem dealing with the computation of a matrix function Permanent and its generalization Hafnian. Thirdly, we explain how a recent no-go result applies generally to linear optical quantum experiments, thus revealing important insights to quantum state generation with current photonic technology. Fourthly, we show how to describe quantum protocols such as entanglement swapping in a graphical way. The uncovered bridge between quantum experiments and Graph Theory offers a novel perspective on a widely used technology, and immediately raises many follow-up questions.

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37. **Chiral Heisenberg Gross-Neveu-Yukawa transition with a single Dirac cone**
Thomas Lang, University of Innsbruck

We present quantum Monte Carlo simulations for the chiral Heisenberg Gross-Neveu-Yukawa quantum phase transition of relativistic fermions with $N = 4$ Dirac spinor components subject to a repulsive, local four fermion interaction in 2+1d. Here we employ a two dimensional lattice Hamiltonian with a single, spin-degenerate Dirac cone, which exactly reproduces a linear energy-momentum relation for all finite size lattice momenta in the absence of interactions. This allows us to significantly reduce finite size corrections compared to the widely studied honeycomb and π-flux lattices. A Hubbard term dynamically generates a mass beyond a critical coupling of $U_c = 6.76(1)$ as the system acquires antiferromagnetic order and SU(2) spin rotational symmetry is spontaneously broken. At the quantum phase transition we extract a self-consistent set of critical exponents $\nu = 0.98(1)$, $\eta_\phi = 0.53(1)$, $\eta_\psi = 0.18(1)$, $\beta = 0.75(1)$. We provide evidence for the continuous degradation of the quasi-particle weight of the fermionic excitations as the critical point is approached from the semimetallic phase. Finally we study the effective "speed of light" of the low-energy relativistic description, which depends on the interaction U, but is expected to be regular across the quantum phase transition. We illustrate that the strongly coupled bosonic and fermionic excitations share a common velocity at the critical point.

39. **Testing Foundations of Quantum Mechanics with a Waveguide Interferometer**
Sebastian Gstir, University of Innsbruck

In this work we designed and built an integrated three-path waveguide interferometer in fused silica for measuring so-called higher-order interferences and higher-dimensional phases. These hypothetical higher-order interferences and higher-dimensional phases do not occur in ordinary quantum mechanics or classical electrodynamics and thus the experiment tests the foundations of these theories. In our interferometer miniature mechanical shutters switch the individual arms on and off. Our main goal was to avoid cross-talk between the shutter state in a path and the transmissivity or phase in any other path. Using a laser source we were able to bound the occurrence of any higher-order interferences to be less than 8(12) 10-5, normalized to the expected two-path interference and the occurrence of any higher-dimensional phases to be less than 2

40. **Efficient non-Markovian quantum dynamics using time-evolving matrix product operators**
    Peter Kirton, TU Wien

    In order to model realistic quantum devices it is necessary to simulate quantum systems strongly coupled to their environment. To date, most understanding of open quantum systems is restricted either to weak system-bath couplings, or to special cases where specific numerical techniques become effective. I will present a novel, general numerical approach to efficiently describe the time evolution of a quantum system strongly coupled to a non-Markovian environment.

    By writing the path integral description of the history of the system as a large tensor, we use use matrix product based techniques to develop our method, called 'time-evolving matrix product operators' (TEMPO)[1]. This allows us to efficiently calculate dynamics of generic open systems, making it applicable to simulations of a wide variety of physical systems. I will give an overview of how the TEMPO algorithm works and show the power and flexibility of our method by identifying the BKT localisation transition of the Ohmic spin-boson model and considering a model with widely separated environmental timescales arising for a pair of spins embedded in a common environment.

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41. **Universal dynamics in an isolated one-dimensional Bose gas far from equilibrium**
    Sebastian Erne, University of Nottingham

    Understanding the behaviour of isolated quantum systems far from equilibrium and their equilibration concerns one of the most pressing open problems in quantum many-body physics. Following a strong cooling quench transferring a 3D ultra-cold Bose gas into a one-dimensional quasicondensate, we demonstrate Kibble-Zurek type scaling of the defect density with the quench rate determined through the single-particle momentum distribution for a model of randomly distributed solitonic defects. For the fastest quench rates, the systems, during the course of its relaxation, exhibits universal scaling in time and space, associated with the approach of a non-thermal fixed point. The time evolution within the scaling period is described by a single universal function and scaling exponent, independent of the specifics of the initial state [SE Nature 563 (2018)]. The non-equilibrium evolution features the transport of an emergent conserved quantity in the scaling region, finally leading to the build-up of a quantum degenerate quasicondensate. Our results provide a quantum simulation in a regime, where to date no theoretical predictions are available and establish universal scaling dynamics in an isolated quantum many-body system. This provides a conceptually new access to time evolution far from equilibrium relevant for a large variety of systems.

42. **The positivity problem in quantum many-body systems**
Maria Balanzó-Juandó, University of Innsbruck

Tensor Networks are an ansatz that provides an efficient and scalable description of quantum many-body systems, both from a theoretical and a numerical standpoint. While they have been extremely successful for the description of ground states of one-dimensional (1D) gapped Hamiltonians with Matrix Product States (MPS), our understanding of mixed states is much poorer, both at a theoretical and at a numerical level. Since mixed states are needed to describe thermal states, systems out of equilibrium, dissipative dynamics, the boundary of a pure state in one more dimension, or in general any experimental situation, this is hindering progress in all of these situations. One of the reasons for that is the positivity problem, which is the following.

Any mixed state has the following basic mathematical property: it is represented by a positive semidefinite matrix (that is, a Hermitian matrix with nonnegative eigenvalues), which is normalized to 1, since this guarantees that probabilities for measurement outcomes are well-defined. It is however hard to characterize how this global positivity is translated to the local tensors of the description. Namely, if the positivity is not imposed locally, then this is a challenge for both the numerical and the theoretical description of mixed states with Tensor Networks. On the other hand, if it is imposed, then generally the description is no longer efficient. The positivity problem is thus the difficulty of representing the positivity of the state locally.

43. **Measuring non-classical paths with atom-cavities in the double-slit experiment**
Jessica Oliveira de Almeida, The Institute of Photonic Sciences

An important experiment in understanding many fundamental aspects of quantum mechanics was Thomas Young's double-slit experiment. Even nowadays, it continues to be used, to prove fundamental axioms, such as the Born rule [1]. The Feynman path integral formalism has been essential to calculate probability amplitudes in multiple-slit experiments, furthermore, it showed that the superposition principle is only an approximation to these probability distributions. The reason for that is the naive assumption that the boundary condition of each individual slit is the same as for all slits [2]. The correction term comes from exotic trajectories that include multiple slits in the path integral, which are called the non-classical paths.

There exist many theoretical models that allow to quantify the impact of non-classical paths on optical interferometry [3]. Although some experiments have intended to empirically prove their existence [4], their conclusions remain doubtful. This is because, in order to simulate the exact conditions of such experiments, in the regime where the nonclassical paths are relevant, a very high computational power is required [5]. Consequently, there still exist discrepancies between theoretical models and experiments.

In 2017, it has been shown [6], that it is possib38le to isolate the contribution of the non-classical paths in the double-slit set-up, in which a source of single atoms is coupled to optical cavities located inside each slit. This set-up was first proposed by M. O. Scully et. al., in 1991 [7]. In our work, we demonstrate using atoms-cavity interaction of Jaynes-Cummings type in the double-slit, that the non-classical paths can contribute up to 1% of the total intensity, which provides a significant improvement over the previous analysis.

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94 **Arbitrary d-dimensional Pauli X-Gates of a flying Qudit**
Xiaoqin Gao, IQOQI Wien

High-dimensional degrees of freedom of photons can encode more quantum information than their two-dimensional counterparts. While the increased information capacity has advantages in quantum applications (such as quantum communication), controlling and manipulating these systems has been challenging. Here we show a method to perform lossless arbitrary high-dimensional Pauli X-gates for single photon. The X-gate consists of a cyclic permutation of qudit basis vectors, and, together with the Z-gate, forms the basis for performing arbitrary transformations. We propose an implementation of such gates on the orbital angular momentum of photons. The proposed experimental setups only use two basic optical elements such as mode-sorters and mode-shifters – thus could be implemented in any system where these experimental tools are available. Furthermore the number of involved interferometers scales logarithmically with the dimension, which is important for practical implementation.

95 **Arbitrary d-dimensional Pauli X-Gates of a flying Qudit**
Irati Alonso Calafell, University of Vienna

Among the various approaches to quantum computing, all-optical architectures are especially promising due to the robustness and mobility of single photons.

However, the creation of the two-photon quantum logic gates required for universal quantum computing remains a challenge. Here we propose a universal two-qubit quantum logic gate, where qubits are encoded in surface plasmons in graphene nanostructures, that exploits graphene's strong third-order nonlinearity and long plasmon lifetimes to enable single-photon-level interactions. In particular, we utilize strong two-plasmon absorption in graphene nanoribbons, which can greatly exceed single-plasmon absorption to create a "square-root-of-swap" that is protected by the quantum Zeno effect against evolution into undesired failure modes. Our gate does not require any cryogenic or vacuum technology, has a footprint of a few hundred nanometers, and reaches

fidelities and success rates well above the fault-tolerance threshold, suggesting that graphene plasmonics offers a new route towards scalable quantum technologies.

96 **Quantum non-demolition measurement of many-body Hamiltonians**
Lukas Sieberer, University of Innsbruck

97. **Optimizing Quantum Error Correction Codes with Reinforcement Learning**
Hendrik Poulsen Nautrup, TU Wien

Quantum error correction is widely thought to be the key to fault-tolerant quantum computation. However, determining the most suited encoding for unknown error channels or specific laboratory setups is highly challenging. In my poster, I will present a reinforcement learning framework for optimizing and fault-tolerantly adapting quantum error correction codes. I consider a reinforcement learning agent tasked with modifying a quantum memory until a desired logical error rate is reached. I will showcase the results of some efficient simulations of a surface code quantum memory with about 70 physical qubits which demonstrate that a reinforcement learning agent can determine near-optimal solutions, in terms of the number of physical qubits, for various error models of interest. Moreover, I will show that agents trained on one task are able to transfer their experience to similar tasks. This ability for transfer learning showcases the inherent strengths of reinforcement learning and the applicability of our approach for optimization both in off-line simulations and on-line under laboratory conditions.

Poster session II

Thursday, February 7th, 14:00-16:00
Chair: Martin Ringbauer, Pavel Hrmo, University of Innsbruck

38. **After all, are non-completely-positive maps physical or not? How causal models can clear up conceptual confusion**
Katja Ried, University of Innsbruck

It is widely accepted that the evolution of open quantum systems is a described by completely positive (CP) maps. However, this standard treatment breaks down when the system is initially correlated with its environment, leading to a rich landscape of mathematical complications, overgrown by fundamental arguments about how (if it all) one should interpret these physically. Here we argue that the root of the problem lies in how one defines the evolution of an open quantum system. We illustrate how the definition that is normally assumed gives rise to several - increasingly crippling - pathologies. Instead, guided by the conceptual framework of classical causal models, we propose an alternative approach for describing the evolution of an open quantum system, in a way that avoids the aforementioned mathematical and conceptual problems.

44. **Plasmon Enhanced Third-Harmonic Generation with Graphene Nanoribbons**
Alessandro Trenti, University of Vienna

The so called second quantum revolution is approaching and its importance is highlighted by the recent huge investment of the European Commission in the 1-billion-euro-Flagship-scale initiative in quantum technology. In this context, quantum computing is a really hot topic due to the theoretically envisaged "quantum supremacy" compare to a classical computer. It has already been shown that universal quantum computing is possible using only single-photon sources and detectors, and simple (linear) optical circuits. However, for achieving a scalable quantum computer, the challenge is the realization of a deterministic two-photon logic gate, as photons weakly interact with themselves.

A possibility is to use a strong nonlinear medium, such as graphene. Indeed, among the many interesting graphene's properties, this unique 2D material possesses a strong third-order nonlinear response, which can be made substantial even at the single-photon level. However, although there have been experimental works studying the third-order nonlinearity in planar graphene, there has been no observation of the nonlinear enhancement due to plasmons resonantly interacting in nanostructures.

Here we will report on a study of the third-order nonlinearity in planar graphene and graphene nanoribbons. We will present Third Harmonic Generation (THG) measurements by pumping in the 5-6 μm range, allowing us to access wavelengths which are resonant with the nanostructures. In agreement with theoretical expectations, we measured a strong enhancement (almost 3 orders of magnitude) from the graphene nanoribbons compared to planar graphene. This is due to the tight optical field confiment and the plasmonic resonant enhacement. By gating the nanostructures, that is by shifting the Fermi energy, we also measured a relative factor 5-enhancement in THG signal, which actually proves the resonant plasmonic enhancement origin.

45 **Towards electrically injected parametric down-conversion in Bragg-reflection waveguides**
Alexander Schlager, University of Innsbruck

In the last decade, integrable semiconductor sources of single photons and photon pairs on microscopic chips have been utilized in a variety of quantum experiments. As one of those platforms, Bragg-reflection waveguides (BRWs) made from Aluminium Gallium Arsenide offer parametric down-conversion of laser light into photon pairs in the telecom C-band. In comparison to nonlinear crystals, they benefit from a high nonlinearity and integrability, but do not require operation in vacuum or cryogenic environments like other semiconductor sources.

In the last few years, we have shown high quality polarization and time-bin entanglement of broadband photon pairs from our BRWs, which have been optically pumped by an external laser system. However, in our current work we aim to achieve parametric down-conversion without the need of an external pump. For this purpose, our most recent waveguide structures incorporate an active quantum dot layer capable of lasing by electrical injection.

In this work, we characterize the creation of laser light within our structures by applying varying voltages with an electric pulse generator at different temperatures. By reducing the temperature of the waveguide to -25°C using a dual stage Peltier and a water cooling system, the laser performance can be enhanced. However, to enable parametric down-conversion, the laser spectrum and the phasematching function of the material have to overlap. Therefore, we investigate the spectral properties of the laser and compare them to the nonlinear optical properties of the BRW. By optimizing the structure design and varying the temperature and applied voltage, we can change these spectral characteristics and work towards a fully integrated and bright source of broadband photon pairs at desirable wavelengths for quantum communication.

46. **An optical nanofiber-based interface for solid-state quantum emitters**
Sarah Skoff, TU Wien

In recent years, solid-state quantum emitters have gained increased interest as building blocks for quantum networks, quantum metrology and nanosensors. For all these applications, strong light-matter interactions are essential.

A versatile tool to achieve such interactions is an optical nanofiber, which is the tapered part of a commercial optical fiber that has a subwavelength diameter waist. This allows an appreciable amount of light to propagate outside the fiber in the form of an evanescent wave. We use such optical nanofibers to optically address individual molecules in solids and we will present this fully fiber-integrated system in more detail.

Due to the transverse confinement of the light field provided by the optical nanofiber, the interaction with quantum emitters is already significant. However, this nanofiber-based approach can be combined with a fiber-based cavity to enhance the light-matter interaction even further and we will show the implementation of a resonator that makes it possible to reach the strong coupling regime.

47. **Direct and teleportation-based qubit interfaces between a single ion and near-IR photons**

Stephan Kucera, Universitat des Saarlandes

Quantum networks with trapped ions require interfaces between the nodes and channels and a resource of entanglement for long distance communication. Quantum state teleportation provides a protocol for atom-photon interfaces, alternative to direct quantum state transfer. Here we implement both schemes on a single 40Ca+ ion as quantum node and single photons as channel. Direct quantum state transfer is demonstrated with an atomic qubit encoded in the D5/2 Zeeman sublevels that is mapped onto the polarization qubit of a single 854 nm photon. Furthermore we show the generation of maximally entangled states between the D5/2 Zeeman sublevels and the emitted photon. Compatibility with the low-loss telecom wavelength at 1310 nm is demonstrated by polarization maintaining quantum frequency conversion.

48. **Interacting Rydberg ions**

Chi Zhang, University of Stockholm

Trapped Rydberg ions are a novel approach for quantum information processing [1]. By combining the high degree of control of trapped ion systems with the long-range dipolar interactions of Rydberg atoms [2], fast entanglement gates may be realized in large ion crystals [1,3].

Strong interactions between Rydberg ions rely upon using microwave (MW) fields to introduce large oscillating dipole moments to the Rydberg ions. This requires a profound understanding of the properties of the MW-dressed states in the radio-frequency trap. In our experiment [4], we trap $^{88}Sr^{+}$ ions and coherently excite them to Rydberg states using two UV laser fields [5]. We have observed the Autler-Townes splitting in the MW field, and measured the lifetimes and polarizabilities of the MW-dressed states. Additionally, we recently measured strong interactions between two MW-dressed Rydberg ions in a Coulomb crystal. These are fundamental steps towards a trapped Rydberg ion quantum computer or simulator.

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49. **Ultrafast coherent excitation of a Ca40+ ion**
Daniel Heinrich, IQOQI Innsbruck

Trapped ions are a well-studied and promising system for the realization of a scalable quantum computer. Faster quantum gates would greatly improve the applicability of such a system and allow for greater flexibility in the number of calculation steps.

In this poster we present a pulsed laser system, delivering picosecond pulses at a repetition rate of 5 GHz and resonant to the S1/2 - P3/2 transition in Ca40+ for coherent population transfer to implement fast phase gate operations. The optical pulse train is derived from a mode-locked, stabilized optical frequency comb and inherits its frequency stability.

Using a single trapped ion, we implement different techniques for measuring the ion-laser coupling strength and characterizing the pulse train emitted by the laser, and show how all requirements can be met for an implementation of a fast phase gate operation.

50. **Polarization gradient cooling of one- and two-dimensional ion crystals**
Christian Roos, IQOQI Innsbruck

We present our recent results of polarisation gradient cooling of one- and two-dimensional crystals of up to 50 Ca+ ions. Sisyphus cooling is achieved by two counter-propagating laser beams in lin-$\perp$-lin configuration that are blue-detuned from the $S1/2 \leftrightarrow P1/2$ transition at 397nm. We measure the mean phonon number between 1 to 2 for all the motional modes except the COM mode where the laser cooling competes with a high motional heating rate.

In addition, we assess the ion crystal by measuring the cross-correlations between the ion pairs. In the first experiment, we excite the ions on a narrow transition and correlate the electronic states of individual ions after a projective fluorescence measurement. We observe a built-up of classical correlations followed by a decay whose dynamics is governed by the thermal occupation of the axial modes of motion. In the second experiment, we measure correlations between finding ions in either one or the other of the two Zeeman ground states after polarisation gradient cooling. Analysis of these pairwise correlations enables precise characterisation of the axial trapping potential.

51. **Enhancing Optical/Electron Phase Microscopy for Biological Applications**
Thomas Juffmann, TU Wien

Caesium's special scattering properties, notably the tunability of its scattering length via magnetically induced Feshbach resonances, make it a promising candidate for BEC matter-wave interferometry but also require us to use a trapping scheme not reliant on magnetic fields.

Using evaporative cooling and tuning of the scattering length via a magnetic field we will achieve condensation in a dipole trap close to the surface of an atomchip. Then continuously deform the potential well into a double well while controlling the relative phase between the two resulting BECs. The phase difference later accumulated allows observation of atomic interactions and inhomogeneities of ambient fields with very high sensitivity. We aim to further increase this sensitivity by tuning the scattering length and shielding the experiment against unwanted external influences while still maintaining a very compact setup using a commercial self contained UHV chamber with fitting field coils by ColdQuanta.

52. **Energy determination of the Th-229 nuclear clock transition**
Benedict Seiferle, University of Vienna

There is only one nuclear excited state that allows to be driven with a laser, namely the first excited nuclear state in Th-229. Its energy has been measured indirectly to be 7.6(5) eV (160 nm), the uncertainty, however, is still too large for a direct laser excitation in a Paul trap and thus impedes further developments. The most prominent application is a nuclear optical clock, which uses a nuclear transition instead of an atomic transition for time keeping.

Therefore, a major goal has been a precise energy determination of the excitation energy.

The poster presents ongoing experimental efforts as well as first results of a first direct energy measurement of the first nuclear excited state in Th-229.

53. **A direct nuclear laser excitation scheme for Th-229m**
Lars von der Wense, LMU Munich

There is only one nuclear excited state that allows to be driven with a laser, namely the first excited nuclear state in Th-229. Its energy has been measured indirectly to be 7.6(5) eV (160 nm), the uncertainty, however, is still too large for a direct laser excitation in a Paul trap and thus impedes further developments. The most prominent application is a nuclear optical clock, which uses a nuclear transition instead of an atomic transition for time keeping.

Therefore, a major goal has been a precise energy determination of the excitation energy.

The poster presents ongoing experimental efforts as well as first results of a first direct energy measurement of the first nuclear excited state in Th-229.

54. **Prospects for a Cesium interferometer with tunable interactions**
Stephanie Manz, TU Wien

The matter-wave properties of atoms and the macroscopic behavior of BECs make interference experiments with ultracold atoms a useful tool for metrology applications. It has been shown that a condensate can be split while controlling the relative phase, realizing a phase-preserving beam splitter. Utilizing this method, high sensitivity to small energy differences can be achieved with BEC interferometry. The procedures developed in the past years lead to the prospect of an integrated matter-wave sensor for high-precision measurements.

In order to realize such a sensor we are building an experimental setup for cesium interferometry. After achieving condensation in a dipole trap close to the surface of an atomchip by tuning the scattering properties, the single potential well is continuously deformed into a double well. The phase difference accumulated by the two resulting clouds allows for observing atomic interactions and inhomogeneities of ambient fields. We aim at exceptionally high sensitivity by reducing the scattering length of the ultracold atoms via magnetically induced Feshbach resonances and by shielding the experiment against external influences, while still maintaining a very compact setup size employing a commercial "BEC machine" by ColdQuanta.

The poster presentation will feature the main objectives and prospects as well as the current status of the experiment. It will also discuss the systematic energy budget to evaluate the challenges and constraints given by ambient and control fields.

55. **Long Baseline Molecular Interferometry**
Yaakov Fein, University of Vienna

Matter-wave interferometry has a range of both applied and fundamental physics research applications, including ruling out modifications to quantum mechanics [1], tests of the equivalence principle [2], and measuring molecular properties [3].

I will show results from the new Long Baseline Universal Matter-wave Interferometer (LUMI) in Vienna, a near-field three-grating interferometer with a baseline of two meters. The long baseline is designed to allow interference with particles beyond 100,000 amu and makes it particularly sensitive for metrological applications.

At LUMI we have shown interference and electric and magnetic deflection studies of various atoms and molecules, from barium to tailored biomolecules. I will discuss the techniques required to see interference at this scale, and I will outline the efforts underway to break the current mass record of matter-wave interferometry [4].

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56. **Cavity and circuit QED in the non-perturbative regime**
Daniele de Bernardis, TU Wien

We study a generic cavity-QED system where a set of (artificial) two-level dipoles is coupled to the electric field of a single-mode LC resonator. This setup is used to derive a minimal quantum mechanical model for cavity QED, which accounts for both dipole-field and direct dipole-dipole interactions. The model is applicable for arbitrary coupling strengths and allows us to extend the usual Dicke model into the non-perturbative regime, which can be associated with an effective finestructure constant of order unity. In this regime we identify and characterize three distinct classes of normal, superradiant and subradiant vacuum states and study the transitions between them. Our findings reconcile many of the previous, often contradictory predictions on this topic and provide a unified theoretical framework to describe ultrastrong coupling phenomena in a large variety of physically very different cavity-QED platforms.

57 **The Roentgen-term and surprising effects in basic in atom-light interaction**
Matthias Sonnleitner, University of Innsbruck

In these exciting times where lasers control atoms with ever increasing precision, it becomes necessary to remember small effects which could previously be safely neglected. Because if we want to probe fundamental physics using atoms and lasers, we urgently need to understand how subtle features in basic atom-light interaction might affect our measurements.

One of these subtle effects is the Roentgen term which describes the interaction between an atom and the magnetic component of a radiation field. Its physical interpretation is that a moving electric dipole (the atom) appears to have a magnetic dipole moment in the laboratory frame such that it can interact with magnetic fields as well.

Although this Roentgen interaction is usually very weak it has been shown, for example, that it must be included in the calculation of emission patterns of moving atoms [1]. A simple extension of these calculations leads to the surprising result, that an excited two-level atom moving through vacuum appears to experience a spurious friction force in first order v/c. At first this seems to be in obvious contradiction to other calculations showing that the interaction with the vacuum does not change the velocity of an atom. Even worse, it appears to be in contradiction to the principle of relativity. It can be shown, however, that this is a side effect of the surprising appearance of $E = mc^2$ in non-relativistic atomic physics [2,3].

More importantly however, the Roentgen term leads to additional forces between atoms and lasers. These forces appear whenever there is some time-modulation in the atom-light coupling, for example, if the light intensity or phase is modified or if the laser frequency is detuned from the atomic transition [3,4]. We will discuss the characteristics of these Roentgen forces and explore their magnitudes in basic processes, such as an atom interacting coherently with a plane-wave laser field. We shall also study some peculiar results, such as forces acting perpendicular to the propagation axis of circularly polarized laser beams.

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58. **Observation of Multimode strong coupling of laser-cooled atoms to fiber-guided photons**
Aisling Johnson, TU Wien

We report on the observation of multimode strong coupling between a cloud of cold atoms and a nanofiber-based fiber ring resonator.

This novel regime of light-matter coupling is reached when the collective coupling strength between a cloud of laser-cooled Cesium atoms and the light field exceeds the free spectral range (FSR) of the resonator, leading to strong coherent coupling of the atoms with more than one longitudinal resonator mode simultaneously [1]. The mode cross-section of our resonator containing an optical nanofiber is independent of its length, such that using a 30 m long fiber ring resonator yields an exceptionally small free spectral range of 7.1 MHz, while at the same time having large collective coupling strengths [2]. The measured transmission spectra provide clear experimental evidence for multimode strong coupling of the loaded cavity, measured for increasing couplings until values as large as twice the FSR. We further characterised the atom-resonator system by measuring photon statistics at the output of the cavity. In this regime of cavity QED atoms can mediate interactions between photons in different resonator modes, through which we envision to employ for the generation of novel non-classical photonic states.

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59. **Chiral cavity quantum electrodynamics with whispering-gallery-modes**
Michael Scheucher, TU Wien

Whispering-gallery-mode (WGM) microresonators provide a powerful system for the investigation of cavity quantum electrodynamics because they allow one to combine both, strong coupling between quantum emitters and light as well as low optical loss, in the same system. Furthermore, due to the strong confinement of the light in these resonators, a strong longitudinal polarization component of the electric field occurs that oscillates in quadrature to the transversal component. Most significantly, the emerging transverse photon spin is intrinsically coupled to the direction of propagation of light. When the resonator field is coupled to a polarization-dependent emitter, such as a spin-polarized atom, this gives rise to chiral light–matter interaction.

This poster will summarize the results obtained within the SFB-FoQuS, where we studied chiral light–matter interaction that occurs when coupling single rubidium atoms to a bottlemicroresonator. By making use of the chiral light–matter interaction, we have demonstrated a strong optical Kerr nonlinearity that imprints a photon number dependent phase shift close to the maximum value of pi at the level single photons. Furthermore, we realized a new class of nonreciprocal devices, including a fiber integrated optical diode as well as a circulator that are controlled by a single atom.

Our results demonstrate that chiral light–matter interaction offers a plethora of possible application for future quantum optical networks and information processing

60. **Heating in Nanophotonic Traps for Cold Atoms**
Daniel Hümmer, IQOQI Innsbruck

We describe how the motion of an atom in a nanofiber-based optical trap is coupled to vibrations of the fiber. Predictions of atom heating rates based on this theory are compatible with experimental observations.

In recent years, it has become feasible to trap ensembles of individual atoms in the near-field of photonic nanoscale structures, such as tapered optical fibers. In the latter setup, evanescent fields surrounding a light-guiding nanofiber create an optical trapping potential a few hundred nanometers from the fiber surface [1,2]. In experiments, a finite life-time of atoms in such fiber-based optical traps is being observed [3]. One effect which may lead to the loss of a trapped atom is the heating of its center of mass motion by thermal vibrations of the fiber itself. This effect is significant, because the fiber has a temperature of several hundred Kelvin.

We present a theoretical description of the effective interaction between the center of mass of the atom and vibrations of the fiber. The latter adiabatically change the optical fields surrounding the fiber, both by displacement of the fiber surface , and by strain-induced inhomogeneity and anisotropy of the electric permittivity. In consequence, the optical potential fluctuates, leading to an effective atom-phonon coupling. We derive a quantum description of the exchange of phononic excitations between a trapped atom and the fiber itself. The resulting model may be generalized to optical near-field traps based on other waveguide geometries.

We quantify the coupling and estimate life-times for atoms in optical fiber traps, using parameters of existing experimental setups [1]. It turns out that the atom only couples to the three fundamental phonon bands without frequency cutoff: longitudinal, torsional, and flexural modes. The interaction is dominated by radiation pressure, while the photoelastic effect can be neglected. The heating of the atom in turn is dominated by coupling to the flexural modes, because their density of states (DOS) diverges in the low frequency limit, while the DOS of the other two bands is constant. This result holds true even when considering that the tapered region of the fiber acts as a resonator for torsional modes. For the setup in [1], we predict ground state heating rates of atoms on the order of 300 Hz in radial and azimuthal direction of the trap, while heating in axial direction is smaller by orders of magnitude. This prediction is in good agreement with experimental observations [3].

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61. **Studying collective effects in 3D waveguide QED with frequency and time-domain resolved spectroscopy**
Aleksei Sharafiev, IQOQI Innsbruck

Collective behavior of coupled quantum emitters has been studied extensively theoretically starting from seminal Dicke's paper. Experimentally however many of the theoretical predictions have never been checked since it requires sophisticated experimental techniques. The recently appeared platform of 3D cQED offers unique opportunities in controlling independent qubits and their respective couplings control as well as long coherence times. We experimentally realized a system, which allows to investigate frequency chirping in a Dicke physics model, as well as to study cooperative behavior against collective noise and parameters spread. We study the system dynamics in frequency, as well as time-domain and compare it to theoretical predictions.

62. **An ion-trap quantum network node**
Josef Schupp, IQOQI Innsbruck

Our project aims to 1. simultaneously entangle three remote trapped-ion quantum network nodes, 2. convert the photons to telecom wavelength via single-photon frequency conversion. Each network node consists of ions coupled to a high-finesse optical cavity, distributed over the Technik campus of the University of Innsbruck with a separation of up to 400 meters.

In this poster we present the third node of the planned quantum network, built at the IQOQI Innsbruck: An ion-cavity system optimized for quantum networking: high efficiency and rate of photon collection.

We aimed to build a near-determinisitic on-demand source of light (photon) - matter (ion) entanglement, and our progress so far is reported. This includes the key steps in achieving coupling of our high-finesse, near-concentric cavity to a single trapped 40Ca+ ion. The chosen parameters and low losses of the cavity allowed for us to build an on-demand single-photon source with a maximum photon output probability of 85% limited by mirror losses. To date we have achieved up to 58%. Most recent results include ion-photon entanglement, both at the photon's natural wavelength of 854nm as well as after photon conversion to 1550nm.

As a next step we want to investigate different possibilities to transfer the entanglement to the other ion-cavity systems. Furthermore, the high rate and efficiency of the ion-cavity system together with the high efficiency and low noise characteristics of the frequency conversion setup should allow us to demonstrate ion-photon entanglement over a distance of 50km.

63. **Quantum simulation of non-perturbative cavity quantum electrodynamics**
Yunfei Pu, University of Innsbruck

An ion-based quantum interface is a promising building block for future quantum networks. The successful realization of entanglement swapping [1] and error correction [2] in an ion chain demonstrates the advantage of distributing long-distance quantum entanglement via an ion-based quantum repeater. In addition, compatibility with state-of-the-art quantum logic units based on ions makes an ionic quantum network an ideal choice for distributed quantum computation.

We are working on the experimental implementation of transferring an arbitrary quantum state between two distant ion-based quantum interfaces, which is an important step towards an ion-based quantum network. Here the two ionic quantum interfaces are located in two labs 400m apart, and the ion-photon interaction is enhanced by a high finesse cavity at each site. In this experiment, we will first convert the quantum state of ion 1 to a photonic state by means of a cavity-assisted Raman transition [3]. After transmission through a 400m fiber between two labs, the photonic qubit will be absorbed by ion 2, accomplishing the state transfer process. Furthermore, for higher photon mapping efficiency and fidelity, a heralded absorption scheme is discussed.

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64. **Controlled photon generation and absorption in ion-cavity systems for quantum networks**
Maria Galli, University of Innsbruck

Understanding the behaviour of quantum many-body systems is one of the biggest challenges in quantum physics. To address this challenge our goal is the development of a two-dimensional (2D) 100 particle quantum simulator. Our future experiments will combine the proven methodology for realizing spin models in linear ion crystals with a novel approach to extending the systems into two dimensions. The experimental platform will be a 2D crystal of laser-cooled calcium ions held in a radio-frequency Paul trap. The exploration of 2D lattice geometries will overcome difficulties in scaling up one-dimensional trapped-ion systems and enable the experimental investigation of the rich physics of two-dimensional spin models (with frustrated interaction) beyond classical capabilities. I will present a novel micro-fabricated trap design providing unobstructed optical access for addressing and imaging as well as sufficient control for shaping the trapping potential in such a way that laser-ion interactions are not perturbed by the trap's driving field. Different novel laser-cooling strategies will be explored to cool all motional degrees of freedom of the ion crystal to millikelvin temperatures or below. We further intend to set up an rf ion trap in a cryostat to create large ion crystals unaffected by collisions with the residual background gas.

65. **Quantum network with fiber cavities**
Yueyang Zou, University of Innsbruck

The fiber cavity system is a platform that designed for being part of the study of the entanglement between nodes of a quantum network. Here we present the characterization of fiber mirrors and a wheel ion-trap design for use in cavity QED experiments with trapped ions. We expect to study the atom-cavity coupling in strong coupling regime, and coherent state mapping of photons out of the fiber cavity.

66. **A cesium interferometer for quantum metrology**
Benedikt Gerstenecker, TU Wien

The matter-wave properties of atoms and the macroscopic behavior of BECs make interference experiments with ultracold atoms a useful tool for metrology applications. It has been shown that a condensate can be split while controlling the relative phase, realizing a phase-preserving beam splitter. Utilizing this method, high sensitivity to small energy differences can be achieved with BEC interferometry. The procedures developed in the past years lead to the prospect of an integrated matter-wave sensor for high-precision measurements.

In order to realize such a sensor we are building an experimental setup for cesium interferometry. After achieving condensation in a dipole trap close to the surface of an atomchip by tuning the scattering properties, the single potential well is continuously deformed into a double well. The phase difference accumulated by the two resulting clouds allows for observing atomic interactions and inhomogeneities of ambient fields. We aim at exceptionally high sensitivity by reducing the scattering length of the ultracold atoms via magnetically induced Feshbach resonances and by shielding the experiment against external influences, while still maintaining a very compact setup size employing a commercial "BEC machine" by ColdQuanta.

The poster presentation will feature the main objectives and prospects as well as the current status of the experiment. It will also discuss the systematic energy budget to evaluate the challenges and constraints given by ambient and control fields.

67. **Direct loading of levitated nanoparticles in a Paul trap in high vacuum**
Dmitry Bykov, University of Innsbruck

A clean method of loading nanoparticle in a Paul trap is necessary in order to achieve levitation in ultra-high vacuum (UHV). The latter is an essential condition for building extremely high quality factor mechanical oscillators. Direct loading of the particles at low pressures is challenging due to conservative nature of the trapping potentials and reduced gas damping. We demonstrate a mechanism that allows us to overcome these limitations. The method is based on laser induced acoustic desorption (LIAD) of nanoparticles from a metallic foil and temporal control of the Paul trap potential. The potential is switched on with a delay relative to the desorption of the particles and at the exact moment in which the launched particles are crossing the center of the trap. We demonstrate high efficiency of the overall process and support the results with numerical simulations. The method can potentially be extended to ultra-high vacuum.

68. **New regimes of light-matter interaction in levitated nanoparticles**
Carlos Gonzalez-Ballestero, IQOQI Innsbruck

Entanglement is the key feature of many-body quantum systems, and the development of new tools to probe it in the laboratory is an outstanding challenge. Measuring the entropy of different partitions of a quantum system provides a way to probe its entanglement structure. On this poster, I present the experimental demonstration of a new protocol, for measuring entropy, based on statistical correlations between randomized measurements. The experiment is carried out with a trapped-ion quantum simulator and proves the overall coherent character of the system dynamics and reveals the growth of entanglement between its parts - both in the absence and presence of disorder. Our protocol represents a universal tool for probing and characterizing engineered quantum systems in the laboratory, applicable to arbitrary quantum states of up to several tens of qubits.

69. **Detection, charging and cooling of a levitating nanosphere in a Paul trap**
Lorenzo Dania, University of Innsbruck

The field of levitated optomechanics studies the interaction between light and the mechanical motion of mesoscopic objects that are suspended by means of magnetic, optical, or electrodynamic traps. The lack of a clamping structure drastically reduces mechanical and thermal coupling with the environment, making these physical systems particularly suitable as ultrasensitive force detectors and as a test bench for quantum mechanics in new regimes.

In our experiment, we use a Paul trap to levitate a charged glass sphere that is 300 nm in diameter. We use an ultra-high-vacuum compatible technique to load a nanosphere into the trap. Furthermore, we have developed a method to control the electric charge of the trapped particle, which allows us to tune its oscillation frequency as well as to measure its mass precisely. Here we also report on the observation of cooling of the particle's secular motion by means of feedback cooling, reaching a few K starting from room temperature. In future work, in order to reach quantum regimes, we plan to couple the center-of-mass motion of the nanoparticle and a single calcium ion to an optical cavity. Such a system offers new opportunities for levitated optomechanics, including new cooling schemes in the unresolved sideband regime and non-linear dynamics.

70. **Quantum State Tomography of Levitated NanoparticlesÂă**
Talitha Weiss, IQOQI Innsbruck

Levitated nanoparticles are outstanding systems to study fundamental aspects of quantum physics at relatively large scales. This is due to the high isolation from the environment that is achieved by the levitation and currently experiments are approaching the quantum ground state. However, when it comes to measuring the quantum state of a nanoparticle, the advantageous isolation of the system turns into a challenge. We want to develop a simple measurement scheme to verify the successful preparation of genuine quantum states. To this end, we study if the continuous measurement of light scattered from the nanoparticle could reveal sufficient information about the quantum state. We investigate the motion of a nanoparticle in a quartic potential, where the nonlinearity is the key to identify deviations in the time evolution of quantum and a classical state even if only the position is continuously monitored. Furthermore, we use neural networks to identify an initial state based on the measurement record and study their potential for performing full quantum state tomography. We hope that these approaches will eventually allow us to fully reconstruct the quantum state of the nanoparticle and obtain the best estimate of the quantum state depending on the so-far collected measurement results at any given time. This will also be useful for quantum feedback protocols in order to prepare the levitated particles in interesting quantum states in the first place.

71. **Quantum measurement and control of levitated nano-particlesÂă**
Liam Walker, University of Strathclyde

Considerable developments are being made in controlling quantum systems through a combination of measurement and feedback. By appropriately interpreting the measurement information and characterising the resulting disturbance, we can determine how to perform feedback in such a way as to drive the system into low-temperature and potentially highly non-classical states [1].

We have been interested specifically in using feedback to prepare and manipulate quantum states of motion of levitated nano-particles. Strong permanent magnets have been shown capable of producing sufficiently large trapping potentials for levitated particles about a micron in diameter [2]. This parameter regime differs from previous work with trapped ions or other nano-mechanical resonators in high-frequency trap systems. In particular, to outpace environmental heating these systems typically need to be controlled on a time-scale comparable to the trap frequency. This poses an interesting challenge, for which we have developed a theoretical framework for preparing states of motion with visible quantum properties.

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72. **Dissipative Photon Blockade and Environment Induced Rabi Oscillations in the Optomechanical Boson-Boson Model**
Yuri Minoguchi, TU Wien

We introduce the Boson-Boson model (BBM) as a natural generalization of strong coupling optomechanics, where a cavity is coupled to a unstructured bath of mechanical modes via the radiation pressure force. In contrast to the much celebrated Spin-Boson model (SBM), where the bath is only a source of decoherence our numerical and analytical results suggest that in the BBM the role of the bath is more ambivalent and can induce photonic nonlinearities and be considered a resource for producing non-classical states of light as well as lead to photonics Rabi oscillations.

73 **Towards matter-wave interferometry experiments with nanoparticles**
Pietro Vahramian, University of Vienna

Dielectric nanoparticles are promising objects for the observation of high-mass matterwave interference [1] beyond the current mass record of 10,123 amu, which was obtained in near-field diffraction with tailored organic molecules [2].

It has been proposed that Talbot diffraction of 10^6 amu silicon nanospheres might be observed [3], if they could be trapped and cooled to 20 mK and evolve freely for about 100 ms. Diffraction would occur at a pulsed-laser UV grating, as routinely used in our cluster interferometry [4].

Here, we propose that free-fall experiments with silicon nanorods might allow us to push the limit by 1-2 orders of magnitude further [5,6]. Compared to SiO2, silicon has a better polarizability-per-mass ratio and nanorods exhibit a 2-5 times higher polarizability optical response compared to nanospheres of the same mass and volume.

Because of their asymmetric shape, nanorods are new and interesting objects for quantum-nanooptomechanics, here in the mass range between 105 and 10^7 amu. If they can be cooled to the ground state of an optical trap, we predict a clear path to orientational delocalization and even quantum revivals as an interference effect in the rotational degrees of freedom [7-9].

All these experiments require nanoparticle cooling to low temperatures in ultra-high vacuum. Active feedback cooling is currently state of the art for particles above 10^8 amu while passive cavity cooling is expected to lead the way towards ground state cooling even at 10^7 amu and about 10 μK or below [5].

For that purpose, the reduced coupling of small particles needs to be compensated by cavities of high finesse and small mode volume. We demonstrate that open access microcavities with a length of 130 um and radius of curvature of 1.3 mm and a mode volume of 7 pl are an ideal platform to detect and manipulate nanoparticles [5]. We report on our most recent chip-based arrays of high-finesse open-access microcavities with F = 500,000 [10]. This is a crucial step towards the realization of cold sources for matter-wave interferometry with nanoparticles.

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74. **Spin dynamics of dipolar fermions in an optical lattice**
Manfred Mark, University of Innsbruck

We present an experimental study of a spinor dipolar gases, using for the first time highly magnetic fermionic atoms in a three-dimensional optical lattice. We use the fermionic isotope of erbium, ^{167}Er, loaded in the lowest band of a deep lattice with a central region of unit filling. We detail the preparation scheme for producing a sample with a specific Zeeman sublevel within the manifold of 20 spin states. We report on the spin dynamics after quenching onto the resonance condition for magnetization-conserving spin-flip operators.This flip-flop dynamics is driven by dipolar offsite interactions in competition with super-exchange interactions in the deep three-dimensional lattice. The resonance condition can be tuned via the quadratic Zeeman effect in combination with quadratic light shifts. The high degree of control achieved in our dipolar spinor system opens fascinating prospects for the exploration of quantum dipolar magnetism and spin-ordered phases.

75. **Antiferromagnetic self-ordering of a Fermi gas in a ring cavity**
Elvia Colella, University of Innsbruck

We explore the density and spin self-ordering of driven spin-$1/2$ collisionless fermionic atoms coupled to the electromagnetic fields of a ring resonator. The two spin states are two-photon Raman-coupled via a pair of degenerate counterpropagating cavity modes and two transverse pump fields. In this one-dimensional configuration the coupled atom-field system possesses a continuous $U(1)$ translational symmetry and a discrete $\mathbb{Z}_2$ spin inversion symmetry. At half filling for sufficiently strong pump strengths, the combined $U(1) \times \mathbb{Z}_2$ symmetry is spontaneously broken at the onset of a superradiant phase transition to a state with self-ordered density and spin structures. We predominately find an antiferromagnetic lattice order at the cavity wavelength. The self-ordered states exhibit unexpected positive momentum pair correlations between fermions with opposite spin. These strong cavity-mediated correlations vanish at higher pump strength.

76. **Static and dynamic properties of a repulsive Bose-Fermi mixture**
Isabella Fritsche, University of Innsbruck

We explore the density and spin self-ordering of driven spin-$1/2$ collisionless fermionic atoms coupled to the electromagnetic fields of a ring resonator. The two spin states are two-photon Raman-coupled via a pair of degenerate counterpropagating cavity modes and two transverse pump fields. In this one-dimensional configuration the coupled atom-field system possesses a continuous $U(1)$ translational symmetry and a discrete $\mathbb{Z}_2$ spin inversion symmetry. At half filling for sufficiently strong pump strengths, the combined $U(1) \times \mathbb{Z}_2$ symmetry is spontaneously broken at the onset of a superradiant phase transition to a state with self-ordered density and spin structures. We predominately find an antiferromagnetic lattice order at the cavity wavelength. The self-ordered states exhibit unexpected positive momentum pair correlations between fermions with opposite spin. These strong cavity-mediated correlations vanish at higher pump strength.

77. **Accurate projective two-band description of topological superfluidity in spin-orbit-coupled Fermi gases**
Lauri Antero Toikka, University of Innsbruck

The interplay of spin-orbit coupling and Zeeman splitting in ultracold Fermi gases gives rise to a topological superfluid phase in two spatial dimensions that can host exotic Majorana excitations. Theoretical models have so far been based on a four-band Bogoliubov-de Gennes formalism for the combined spin-1/2 and particle-hole degrees of freedom. Here we present a simpler, yet accurate, two-band description based on a well-controlled projection technique that provides a new platform for exploring analogies with chiral p-wave superfluidity and detailed future studies of spatially non-uniform situations.

J. Brand, L. A. Toikka, and U. Zulicke SciPost Phys. 5, 016 (2018)

78. **Production of degenerate Fermi mixtures of dysprosium and potassium atoms**
Vincent Corre, University of Innsbruck

We report on the realization of a mixture of fermionic 161Dy and fermionic 40K where both species are deep in the quantum-degenerate regime. Both components are spin-polarized in their absolute ground states, and the low temperatures are achieved by means of evaporative cooling of the dipolar dysprosium atoms together with sympathetic cooling of the potassium atoms. We describe the trapping and cooling methods, in particular the final evaporation stage, which leads to Fermi degeneracy of both species. Analyzing cross-species thermalization we obtain an estimate of the magnitude of the inter-species s-wave scattering length at low magnetic field. We demonstrate magnetic levitation of the mixture as a tool to ensure spatial overlap of the two components. The properties of the Dy-K mixture make it a very promising candidate to explore the physics of strongly interacting mass-imbalanced Fermi-Fermi mixtures.

79. **Quasi-Particles in Flat Energy Bands**
Stuart Flannigan, University of Strathclyde

An interesting single particle effect exhibited by the Lieb lattice is a dispersionless "flat" energy band produced from destructive interference on the lattice.

We want to exploit the recent advances in the field of atomic physics and quantum optics and use ultra-cold atoms in an optical lattice to investigate how interactions between multiple atoms change this novel single particle behaviour.

We propose a scheme to load non-interacting fermions into the flat band with a completely filled lower energy band and move on to investigate interaction induced dispersive states, in the form of two atom bound states for both bosons and fermions, using the recently developed uniform matrix product state excitation ansatz.

80. **Dissipative preparation of fermionic spin-entangled states in ultracold atoms**
Jorge Yago Malo, University of Strathclyde

The generation of entangled states in AMO systems with high fidelity poses important challenges to ongoing experiments, and for its wide variety of applications ranging from quantum simulation to metrology. A promising route to overcome some of these challenges is to make use of dissipative dynamics, engineering the coupling between a system and its environment in analogy with techniques in quantum optics. In this work we propose a new scheme for preparing spin-symmetric many-body states by using the statistics of fermionic atoms in an optical lattice coupled to a BEC reservoir [1].

To prepare these states, which have important applications, e.g., in metrology [2], we can take advantage of the corresponding spatial anti-symmetry of the state. At low energies, the spatial symmetry of s-wave two-body collisions makes it possible to dynamically filter out the desired spatial and spin symmetries. Previously, proposals suggested to use this combined with two-particle loss to achieve spin symmetric states, at the cost of a significant decrease in the particle number [3]. Here, we propose a scheme that uses Raman coupling between bands and dissipation induced by a BEC reservoir in order to filter the spin states, while maintaining the total particle number.

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81. **Roton mode in dipolar quantum Bose gases**
Lauriane Chomaz, University of Innsbruck

Ultracold gases of highly magnetic atoms realize a fantastic platform to study few- and many-body effect under the influence of long-range and anistropic interactions in the quantum regime. The roton mode, an elementary excitation of minimal energy at finite momentum, underlying strong correlations on short distances, is an emblematic example. First discovered in superfluid helium He-II, roton excitations have been proven to be absent in ultracold gases with weak short-range interactions. Since 2003, a roton mode has been predicted in dipolar quantum gases, even without the need for strong interactions, but it remained long unobserved. Here I will report on our first observation of such a roton mode using BECs of erbium atoms trapped in a cigar-shaped geometry. In a first set of experiments, we reveal the existence of the roton mode via the privileged exponential growth of its population after quenching to the instability regime. In a second set of experiments, we more recently probed the excitation spectrum of a stable BEC in a large range of momentum, employing the powerful technique of Bragg spectroscopy. Here we observed the emergence and subsequent softening of the roton excitation when tuning the interaction to the dominant dipolar regime.

82. **Cavity-induced emergent topological spin textures in a Bose-Einstein condensate**
Stefan Ostermann, University of Innsbruck

The coupled nonlinear dynamics of ultracold quantum matter and electromagnetic field modes in an optical resonator exhibits a wealth of intriguing collective phenomena. Here we study a ■ type, three-component Bose-Einstein condensate coupled to four dynamical running-wave modes of a ring cavity, where only two of the modes are externally pumped. However, the unpumped modes play a crucial role in the dynamics of the system due to coherent back-scattering of photons. On a mean- field level we identify three fundamentally different steady-state phases with distinct characteristics in the density and spatial spin textures: a combined density and spin wave, a continuous spin spiral with a homogeneous density, and a spin spiral with a modulated density. The spin-spiral states, which are topological, are intimately related to cavity-induced spin-orbit coupling emerging beyond a critical pump power. The topologically trivial density-wave–spin-wave state has the characteristics of a supersolid with two broken continuous symmetries. The transitions between different phases are either simultaneously topological and first order, or second order. The proposed setup allows the simulation of intriguing many-body quantum phenomena by solely tuning the pump amplitudes and frequencies, with the cavity output fields serving as a built-in nondestructive observation tool.

83. **Observing the quantization of orbital angular momentum with toroidal Bose-Einstein condensates**
Filip Bartolomiej Kialka, University of Vienna and University of Duisburg-Essen

We propose an experiment to observe quantum recurrences of a weakly-interacting BEC evolving in a toroidal trap. This quantum interference effect, which is caused by the quantization of the orbital angular momentum [1–2], demonstrates a macroscopic superposition sustained over millisecond time scales. We calculate the revival time and fidelity for a configuration similar to the state-of-the-art ring traps [3–5] and quantify the influence of imperfections such as interatomic interactions, trap tilt and inhomogeneity, as well as beyond mean-field effects. Our results suggest that quantum recurrences could be observable even in the presence of realistic imperfections.

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84 **Atomic double twin beams**
Filippo Borselli, TU Wien

In our experiment a one-dimensional Bose-Einstein condensate (BEC) of Rubidium atoms is engineered to become a source for pairs of entangled atoms.

We start from around 1000 atoms, condensed in an elongated BEC sitting in the transverse vibrational ground state of an harmonic trap created below an atom-chip.

Using radio-frequency dressing, we apply a series of deformations of the initial trap and finally reach a double-well configuration with the atoms sitting in the second excited state. The correct parameters for the series of deformations applied on the initial trap have been derived using an optimal control algorithm. Interactions within atoms lead to the emission of particles either in the first excited state or in the ground state, which are almost degenerate. Since the emitted atoms need to conserve both energy and momentum, they can only be emitted in pairs of opposite momentum along the longitudinal direction, where the potential is shallow. The motional state is thus expected to be an entangled state made of the superposition of a momentum correlated pair sitting in the first excited state and a momentum correlated pair in the ground state. The trap is then switched off after a certain holding time and the free-falling atoms are detected using a time-of-flight fluorescence imaging system.

85 **Tunable quantum matter in confined dimensions**
Bodhaditya santra, University of Innsbruck

The interplay between strong interactions and confinement to low dimensional geometry amplifies the effects of quantum fluctuations and correlations. One dimensional (1D) quantum systems are unique candidates for exploring exotic many-body phases at low dimensions with promising applications in nanoelectronics, sensing and quantum information processing.

In this poster, I will present the results on the crossover from the Tonks-Girardeau (repulsive interactions) gas to the super-Tonks-Girardeau (attractive interactions) gas [1] using a tunable quantum gas of Cesium atoms loaded in optical lattices. I will also present the dynamics of impurity atoms immersed in 1D quantum liquids. Due to the strong quantum correlations, the impurity atoms show Bloch oscillations even in the absence of a lattice [2]. Finally, I will present the status of our potassium (K) - Cesium (Cs) quantum mixture experiment and a strategy to produce dipolar molecules with long range interactions in optical lattices [3].

[1] E. Haller et al., Science 325, 1224 (2009)

[2] E. Meinert et al., Science 356, 945 (2017)

[3] M. GrÃűbner et al., PRA 95, 022715 (2017)

86 **Towards ultracold dipolar KCs molecules**
Michael Grösner, University of Innsbruck

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87. **Towards Pairs of Momentum Correlated Metastable Helium Atoms**
Kahan Dare, IQOQI Innsbruck

We report on the progress towards creating pairs of metastable helium atoms correlated in their momenta via an atomic four-wave mixing process. We first produce of a Bose-Einstein condensate of 10^6 metastable helium atoms in the crossed optical dipole trap. The BEC is put into a superposition of two counter-propagating states through a 2-photon Raman process. As the BEC splits into these counterpropagating states, collisions can occur which give rise to momentum correlated pairs due to the conservation of momenta. Pairs are then detected with an ultrafast delay-line detector allowing full 3D reconstructing of the momentum space distribution of atoms. We demonstrate the ability to tune the distribution of the atomic population between various diffraction orders. This will be used to directly demonstrate momentum entanglement in a scenario equivalent to the Einstein-Podolsky-Rosen gedanken experiment.

88. **Towards weak measurements on Bose-Einstein Condensates**
Mira Maiwöger, TU Wien

On our atomchip based cold atom experiment BECs are magnetically trapped and typically imaged after some time of flight. Manipulating the internal state of a fraction of atoms in the trapped BEC such that they leave the trap allows to probe the same cloud of ultracold atoms more than once and to perform weak measurements on the system. Here we present first data where this scheme was applied to a BEC split in a double well potential in order to measure the relative phase between the condensates by imaging only few outcoupled atoms.

89. **Towards ultracold RbSr molecules in an optical lattice**
Severin Charpignon, University of Amsterdam

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90. **Quantum Engineering of a Low-Entropy Gas of Heteronuclear Bosonic Molecules in an Optical Lattice**
Deborah Capecchi, University of Innsbruck

Ultracold heteronuclear molecules offer a new platform for the study of quantum physics. On one hand, they share with ultracold atoms the flexibility of control and manipulation; on the other, they introduce tuneable long-range anisotropic interaction, due to their dipolar character. However, the pathway to the realization of low-entropy ultracold samples of heteronuclear molecules is not straightforward. In our experiment the key to engineer samples of RbCs molecules, is to start from the creation of degenerate quantum gases of Rb and Cs and to combine them in an optical lattice. This procedure makes use of advanced (quantum) experimental techniques including quantum phase transitions in the lattice, coherent transport, Feshbach resonances and stimulated Raman adiabatic passage (STIRAP). In this poster, we discuss the full quantum engineering process and the currently achievable molecular samples. In addition, we show experimental characterization of fundamental physics phenomena arising from the investigation of the individual techniques, like the effects of the excited lattice bands on the stability of the atoms in the optical lattice. The understanding of the process, including all involved techniques, will improve the control over the creation of the molecular samples, which in turn can be used to study ultracold chemistry and to simulate the extended Hubbard model in the presence of disorder.

91. **Quantum Engineering of a Low-Entropy Gas of Heteronuclear Bosonic Molecules in an Optical Lattice**
Philipp Ilzhöfer, IQOQI Innsbruck

Over the last years, lanthanide atomic species, namely erbium and dysprosium, have become one of the working horses in the field of ultracold atoms. Their large magnetic moments of 7μB and 10μB for erbium and dysprosium, respectively, give rise to the long-range, anisotropic dipole-dipole interaction and thus, experimentally unexplored phenomena in both bulk as well as lattice systems are within reach.

We present our new experimental apparatus for heteronuclear mixtures of erbium and dysprosium. Recently, we have demonstrated not only a two-species magneto-optical trap in a novel open-top five-beam configuration, but also simultaneous evaporative cooling down to double degeneracy. Up to now, we were able to produce double dipolar Bose-Einstein condesates for five different isotope combinations as well as one degenerate Bose-Fermi mixture. Additionally, we will present first measurements for the interspecies scattering length, which is presently unknown.

92. **Quantum Engineering of a Low-Entropy Gas of Heteronuclear Bosonic Molecules in an Optical Lattice**
Chen Li, Atominstitut

We study the relaxation of ultracold Bosons (Rb-87) in one dimension [1] in a setting similar to the original Newton's cradle experiment [2]. We start with a BEC in a 2D red-detuned optical lattice (a lattice of 1D tubes) with little heating (<0.01 $\hbar\omega_\perp$ / sec) and little loss (4% 7%/sec). We excite the atoms to oscillate and collide in the 1D tubes by coherent pulses and observe the oscillations for up to 4.8 seconds (400 oscillations). Tuning the energy put into the longitudinal motion we can probe the onset of relaxation in the cross over between 1D and 3D. We observe dephasing of the oscillations and then relaxation (=gaussification of the momentum distribution) even for samples where the energy put into the system is not sufficient to excite transverse motion (initial collision energy < 0.5 energy needed for transverse excitations). The final state follows the statistical (non-degenerate) description of a classical 1D gas of Bosons. Investigating the population of the transverse excited states by band mapping we verify that the 2-body collisions involving atoms in transverse excited states contribute greatly to the relaxation process. We conjecture that the relaxation is triggered by the very small excitations produced by heating. Meanwhile, evaluating the 3-body virtual collisions [3] and longitudinal confinement [4], we get relaxation rates in the similar scale with the 2-body process in our experimental case.

For the next step, we will continue the experiments on non-equilibrium 1D Bose gases with Lithium-6 molecular BEC in Vienna. Thanks to the wide Feshbach resonance of Li6, we can easily tune the system from weak repulsive interaction to strong repulsive interaction (Tonks-Girardeau gas), and go across the confinement induced resonance to achieve super-TG gases in the attractive interaction regime. Moreover, we can also study the dynamical properties of strongly correlated Fermi atoms, including spin-balanced / imbalanced Fermi gases (s-wave interaction) and fully-polarized Fermi gases (p-wave interaction).

[1] C. Li et al., arXiv 1084.01969 (2018).

[2] T. Kinoshita et al., Nature, 440, 900 (2006).

[3] I. Mazerts et al., Phys. Rev. Lett., 100, 210403 (2008); S. Tan et al., Phys. Rev. Lett., 100, 090404 (2010).

[4] I. Mazets, Eur. Phys. J. D 65, 43 (2011).

93. **Phonon excitations in a one dimensional Bose gas**
Federica Cataldini, TU Wien

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