Probing Spin-Phonon Coupling at the Quantum Limit using Light-Matter interaction

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In a solid, the most fundamental process by which an excited spin ensemble transfers energy to the surrounding environment is goverened by longitudinal relaxation processes. These processes are usually driven by spin-phonon interaction. However, the so far available methods did not allow us to investigate on spin relaxation at temperatures where quantum effects become relevant.
Here we show a method to study the longitudinal spin-lattice relaxation of nitrogen-vacancy spins in diamond and observe spontaneous emission of phonons. We further develop a theoretical model that describes the fundamental mechanism and calculate the the relaxation rate ab initio based on density functional theory (DFT).

Certifying steerability and joint measurability under restrictive scenarios

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Einstein-Podolski-Rosen steering is a form of quantum correlation intermediate between entanglement and Bell nonlocality. In a bipartite scenario, we say Alice can steer Bob when it is possible for her to prepare Bob's state by interacting only with her share of the system, in such a way that the resulting correlations between her measurements, her outcomes, and Bob's conditioned state exhibit nonlocal properties. From a fundamental and practical point of view, deciding weather a given entangled quantum state is Einstein-Podolski-Rosen steerable or not (i.e. admits a local hidden state model) is a problem of crucial importance. Despite some particular results, no general method was known to decide if an arbitrary quantum state displays EPR steerability in a particular scenario with N measurements of k outputs. Here we apply general methods to solve this problem by providing upper and lower bounds for the amount of white noise required to transform a steerable state into a unsteerable one under restrictive measurement scenarios. Our techniques are also applicable to the study the white noise robustness of the compatibility of N arbitrary unknown qudit measurements with k outputs. We illustrate our methods with several examples and discuss the usefulness of projective measurements, symmetric informationally complete (SIC) measurements, mutually unbiased (MU) measurements, and general positive-operator valued measures (POVMs) in EPR steering and joint measurability.

Strong coupling between nanofiber-trapped atoms and fully fiber-integrated Fabry-Perot microresonator

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No abstract.

Toward single lattice-site imaging of ultracold dipolar molecule quantum gases

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Experiments on ultracold dipolar molecules are close to offering a new platform for the study of many-body physics in lattices. Over the last few years dipolar molecules lattices with more than 30% occupancy have been achieved for weakly bounded RbCs molecules. From here high efficiency stimulated Raman adiabatic passage can be implemented to bring the molecules to deeply bound long lived states. However the spatial distribution of the molecules inside the lattice remains widely unknown. Here we start discussing the implementation of single lattice-site imaging of dipolar molecular quantum gases based on optical microscopy, by analogy with the technique established for ultracold atoms. In particular we address the necessary features of the experimental set-up to allow for this imaging technique, such as specifically designed cell, transport and lattice depth. The realization of optical microscopy for dipolar molecule quantum gases would allow for a better understanding of many-body effects inside the gas and pave the way toward single molecule manipulation.

Relaxation and recurrence of a degenerate one-dimensional Bose gas

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In the last years, cold atomic gases developed into a versatile testbed for the study of many different physical phenomena. In particular, for the investigation of relaxation and thermalization dynamics in isolated quantum systems, they represent a powerful tool and sparked a lot of research activity. In our group we have developed techniques to characterize relaxed states and the dynamics leading to them. Our system is a quantum degenerate 1D Bose gas of 87 Rb that is taken out of equilibrium by coherently splitting it into two parts. During the subsequent evolution we monitor the relative phase field of the two condensates, providing a local probe for the system. The out-of equilibrium dynamics of the system is characterized by a loss of the initial coherence through dephasing and the appearance of a thermal-like steady state. Furthermore, by confining the gases to a box shaped potential we are able to create a system with commensurate energy modes and observe a periodic recurrences of the initial state.

Instability in polariton condensates

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No abstract.

Measuring mouse retina response near the detection threshold to direct stimulation of photons with sub-poisson statistics

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Probing the visual system of human and animals at very low photon rate regime has recently attracted the quantum optics community. In an experiment on the isolated photoreceptor cells of Xenopus, the cell output signal was measured while stimulating it by pulses with sub-poisson distributed photons. The results showed single photon detection efficiency of 29+/-4.7% [1]. Another behavioral experiment on human suggests a less detection capability at perception level with the chance of 0.516+/-0.01 (i.e. slightly better than random guess) [2]. Although the species are different, both biological models and experimental observations with classical light stimuli expect that a fraction of single photon responses is filtered somewhere within the retina network and/or during the neural processes in the brain. In this ongoing experiment, we look for a quantitative answer to this question by measuring the output signals of the last neural layer of WT mouse retina using microelectrode arrays. We use a heralded downconversion single-photon source. We stimulate the retina directly since the eye lens (responsible for 20-50% of optical loss and scattering [2]) is being removed. Here, we demonstrate our first results that confirms the response to the sub-poisson distributied pulses.

Coupled Atomic Wires in a Synthetic Magnetic Field

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In this poster, we propose and study systems of coupled atomic wires in a perpendicular synthetic magnetic field as a platform to realize exotic phases of quantum matter. This includes (fractional) quantum Hall states in arrays of many wires inspired by the pioneering work [Kane et al. PRL 88, 036401 (2002)], as well as Meissner phases and Vortex phases in double-wires. With one continuous and one discrete spatial dimension, the proposed setup naturally complements recently realized discrete counterparts, i.e. the Harper-Hofstadter model and the two leg flux ladder, respectively. We present both an in-depth theoretical study and a detailed experimental proposal to make the unique properties of the semi-continuous Harper-Hofstadter model accessible with cold atom experiments. For the minimal setup of a double-wire, we explore how a sub-wavelength spacing of the wires can be implemented using the recently introduced nanoscale ﻁDark stateﻁ optical potentials [Łącki et al. PRL 117, 233001 (2016)]. Due to the significant reduction of length scales, the relevant energy scales in this construction are increased by at least an order of magnitude compared to ordinary optical lattices. Thus, subtle many-body phenomena such as Lifshitz transitions in Fermi gases are rendered observable in an experimentally realistic parameter regime. For arrays of many wires, we discuss the emergence of Chern bands with readily tunable flatness of the dispersion and show how fractional quantum Hall states can be stabilized in such systems. Using for the creation of the optical potentials Laguerre-Gauss beams that carry orbital angular momentum, we detail how coupled atomic wire setups can be realized in non-planar geometries such as cylinders, discs, and tori.

High-dimensional single-photon quantum gates: Concepts and experiments

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Transformations on quantum states form a basic building block of every quantum information system. From photonic polarization to two-level atoms, complete sets of quantum gates for a variety of qubit systems are well known. For multi-level quantum systems beyond qubits, the situation is more challenging. The orbital angular momentum modes of photons comprise one such high-dimensional system for which generation and measurement techniques are well-studied. However, arbitrary transformations for such quantum states are not known. Here we experimentally demonstrate a four-dimensional generalization of the Pauli X-gate and all of its integer powers on single photons carrying orbital angular momentum. Together with the well-known Z-gate, this forms the first complete set of high-dimensional quantum gates implemented experimentally. The concept of the X-gate is based on independent access to quantum states with different parities and can thus be generalized to other photonic degrees-of-freedom.

Generating entanglement between a trapped ion and the time-bin of a photon

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While small-scale quantum computers, e.g., based on trapped ions, are already in existence, scaling up to larger numbers of qubits proves technically challenging. One possible solution to this problem is a distributed quantum computer, consisting of several small-scale quantum computers, linked together in a quantum network. Such linking of separate quantum nodes is also a requirement for building quantum repeaters for long-distance quantum communication. Here, we describe the current status of our quantum node at the Universität Innsbruck: we report on the implementation of a laser beam for addressing single ions in a crystal of multiple trapped ions, and describe a protocol and its implementation for the generation of entanglement between the electronic state of one trapped ion and the time-bin degree of freedom of a single photon. This protocol is an alternative to the more standard encoding of quantum information in the polarization degree of freedom of photons and can thus be used for systems in which well-defined photon polarization can not be achieved.

Probing non-white models of wavefunction collapse using levitated nanospheres

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Models of dynamical reduction attempt to resolve the famous measurement problem via the introduction of a universal noise field which induces wavefunction collapse. The models make predictions which differ from quantum mechanics; and by this virtue they are testable. However, a number of problems arise when trying to make sense of such theories. In particular, the nature and origin of the putative noise field demand a description. We propose an experiment which would be capable testing models which push past the white noise approximation, invoking noise fields whose spectra are more physically realistic.

High Fidelity Measurement of the Electronic Spin of the Nitrogen–Vacancy Center Using State-Dependent Reflection

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On the basis of its many favorable properties, the negatively charged nitrogen-vacancy (NV-) center in diamond has been presented as a candidate qubit for applications as diverse as quantum-enhanced sensing, quantum communication and even full-scale quantum computation. A common requirement of all such applications is the ability to measure, and in many cases to measure non-destructively, the electronic spin state of the center. However, primary physical constraints of the center inhibiting such measurements include charge-state switching, polarizing decay through a meta-stable state, low optical quantum efficiency, and spectral diffusion in optical transitions. Investigations most commonly use luminescence measurements to determine the electronic state of the center, though the fidelity of a luminescence measurement is inherently limited both by polarizing decay through the meta-stable state of the center and by charge-state switching. Several authors have suggested interaction-free measurements using optical cavities as a path to high-fidelity read-out of the center. The performance estimates resulting from their investigations provide evidence that, though we cannot change the fundamental physical constraints of the center, we may be able to work around them by utilizing a coupled hybrid system. However, common approximations to the NV- center's energy level structure and dynamics must be relaxed before conclusive statements can be made in the high-performance regimes required for large-scale information processing. Here we use a recurrent scattering treatment, interlaced with discretized relaxation, to model the performance of resonant, multi-shot, single-photon measurement. Our central result predicts excellent performance across the strong-coupling regime in the ideal case, and in addition we investigate the effects of source and detection inefficiency, variations in the decay probability through the meta-stable state, as well as estimating the magnitude of error caused by a finite-bandwidth photon source.

Towards the realisation of an atom trap in the evanescent field of a WGM-microresonator

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Whispering-gallery-mode (WGM) resonators guide light by total internal reflection and provide ultra-high optical quality factors in combination with a small optical mode volume. Coupling a single atom to the evanescent field of a WGM microresonator thus allows one to reach the strong coupling regime [1]. Furthermore, such resonators provide chiral light-matter coupling which can be employed for realising novel quantum protocols [2] as well as nonreciprocal quantum devices [3]. However, trapping atoms in the evanescent field of such resonators has not yet been demonstrated, which severely limits the atom-resonator interaction time. We aim to trap single 85Rb atoms in the vicinity of a bottle-microresonator - a highly prolate type of WGM resonator. A standing wave optical dipole trap is created by retroreflecting a tightly focused beam on the BMR surface (method similar to [4]). In order to load atoms into the trap, we employ an FPGA-based electronics which allows us to react in 150 ns to an atom arriving in the resonator field and thus to switch on the dipole trap. We will present first characterizations of our trap.

[1] C. Junge et al. Phys. Rev. Lett. 110, 213604 (2013),
[2] I. Shomroni et al. Science 345, 903 (2014),
[3] M. Scheucher et al. Science 354, 1577 (2016),
[4] J. D. Thompson et al. Science 340, 1202 (2013).

2D arrays of ion traps for quantum information processing & High-temperature superconducting traps

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Ion traps are a promising tool for quantum simulators and quantum computers [1]. Microfabricated surface traps offer the possibility to miniaturize ion traps, which is a possible route towards a scalable quantum computer. However, the proximity of the ions to the surface of the trap leads to motional heating, the origin of which is not well understood [2].
To investigate different sources of motional heating, we operate a surface ion trap made of YBCO, a high-temperature superconducting material. The trap is designed in such a way that Johnson noise is the dominant source of motional heating above the critical temperature Tc ≈ 85 K, whereas below Tc it is negligible compared to other noise sources. Using a local heating element, we adjust the temperature of the trap chip and observe the superconducting transition by measuring the motional heating rate of a trapped ion.
We also report on the status of a second project, where we have realized a microfabricated 2D array of individual RF point traps. While linear chains of trapped ions are used for quantum simulation of 1D spin systems [3], such 2D arrays of ion traps may allow to extend the range of accessible simulations to systems with more than one spatial dimension, because of the physical arrangement of the individual trapping sites.
Our array consists of 16 individual trapping sites with a 100 µm pitch. This inter-ion distance may be reduced while maintaining a stable trap by varying the RF amplitude on electrodes between two adjacent trapping sites [4]. In this way, coherent operations mediated by the Coulomb interaction should become possible. We report on our progress towards operating the system at cryogenic temperatures and present designs for a new generation of 2D arrays based on parallel linear surface traps.

[1] R. Blatt, C.F. Roos, Nature Phys. 8, 277 (2012)
[2] M. Brownnutt et al., Rev. Mod. Phys. 87, 1419 (2015)
[3] C. Monroe et al., Proceedings of the International School of Physics ‘Enrico Fermi,’ Course 189, pp. 169-187 (2015)
[4] M. Kumph et al., New J. Phys. 18, 023047 (2016)

PT -symmetric systems in open quantum system

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The phenomenon of PT-symmetric breaking in classical systems with balanced loss and gain is associated with a sharp transition from a purely real to complex eigenvalue spectrum of the underlying dynamical matrix. Over the past years this phenomenon has been extensively studied, for example, using coupled optical modes, where however, the system is always in a large amplitude classical state. In this work we study for the first time the effect of PT-symmetry breaking in the quantum regime where the effects of non-linearities and intrinsic quantum noise become important. We investigate the stationary behaviour of non-linear PT-symmetric systems in the quantum regime, where we observe an unconventional transition from a high-noise symmetric state to a parity-broken lasing state with strongly reduced fluctuations. We illustrate these effects here for a specific physical system of coupled mechanical resonators with optically induced gain and loss, but the described mechanisms will be essential for a general understanding of the steady-state properties of acutual PT-symmetric systems in the quantum regime.

Towards trapping of neutral atoms in surface-induced potentials

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There is growing interest to trap atoms and nanoscale dielectric bodies close to surfaces. We explore the possibility of using physisorption states to trap neutral atoms at atomic distances. These states are located in the potential well formed by attractive dispersion forces and Pauli repulsion, and thus do not depend on externally applied fields. We consider a physisorbed atom orbiting a thin, clean dielectric or metallic fiber at cryogenic temperatures in high vacuum. The physisorption potential confines the atom in radial direction, giving rise to discrete vibrational levels of its center of mass. We model the thermalization of the vibrational state through coupling to the phononic modes of the cylinder. Moreover, we quantitatively describe a procedure for loading this 2-dimensional trap from an atom beam, as well as a way to measure the population of different trap states. This setup can serve as a proof-of-principle for the controlled trapping of neutral atoms in purely surface-induced potentials. Further possible applications include measuring forces at the nanometer scale, or even quantum friction.

Blue detuned cavity cooling

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We investigate blue detuned cavity cooling of a single particle. The solutions of the coupled differential equations, derived by solving the wave equation with source terms allow predictions for the intracavity field and the particle motion. Moreover, the efficiency of the cooling mechanism is investigated for different parameters of the pump detuning with respect to the atomic transition and cavity eigenmode.

Two dimensional quantum repeater

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We present a scheme of quantum repeater based on the DLCZ protocol and aimed to distribute 3 GHZ state between 3 parties. Comparable with the original DLCZ 1D scheme 2D one has a built-in filtering mechanism, which allowed to reach better fidelities for same distances.

Continuous Measurement of an Atomic Current

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No abstract.

Flexible resources for Quantum Metrology

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Quantum Metrology allows to perform measurements which are quadratically more precise than classically possible. However, the hurdle of implementing the necessary quantum probe states and measurements, which vary drastically for different metrological scenarios, is usually not taken into account. We show that for a wide range of tasks in metrology, the 2D cluster state can serve as a flexible resource that allows one to efficiently prepare any required state for sensing, and perform appropriate (entangled) measurements using only single qubit operations. Crucially, the overhead in the number of qubits is less than quadratic, thus preserving the quantum scaling advantage.

Growing, probing and characterizing a crystal of ultracold bosons and light

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The non-linear coupled particle light dynamics of an ultracold gas in the field of two counter propagating laser beams can lead to the dynamical formation of an ordered lattice structure as presented in Phys. Rev. X 6, 021026 (2016). Here we present in depth studies of the initial growth of this spontaneous crystallization with emphasis on clear experimentally observable signatures as compared to single beam matter wave superradiance. While, at least theoretically, optimal non-destructive observation of the growth dynamics and the hallmarks of the crystalline phase can be performed by analyzing the scattered light, monitoring the evolution of the particles momentum distribution via Time-of-Flight probing is usually the experimentally more accessible choice. In this work we show that this can be sufficient to unambiguously identify the crystal. As a clear crystallization signature we study the properties and stability of the spatial locking between the two standing laser waves creating the crystal potential. Moreover, we study possibilities of reversible adiabatic ramping into the crystalline state and back rather than the spontaneous growth from fluctuations.

Ultrasensitive Inertial and Force Sensors with Diamagnetically Levitated Magnets

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We theoretically show that a magnet can be stably levitated on top of a punctured superconductor sheet in the Meissner state without applying any external field. The trapping potential created by such induced-only superconducting currents is characterized for magnetic spheres ranging from tens of nanometers to tens of millimeters. Such a diamagnetically levitated magnet is predicted to be extremely well isolated from the environment. We therefore propose to use it as an ultrasensitive force and inertial sensor. A magnetomechanical read-out of its displacement can be performed by using superconducting quantum interference devices. An analysis using current technology shows that force and acceleration sensitivities on the order of 10^{-23} N / $Hz^{1/2}$ (for a 100 nm magnet) and 10^{-14} g / $Hz^{1/2}$ (for a 10 mm magnet) might be within reach in a cryogenic environment. Such unprecedented sensitivities can be used for a variety of purposes, from designing ultra-sensitive inertial sensors for technological applications (e.g. gravimetry, avionics, and space industry), to scientific investigations on measuring Casimir forces of magnetic origin and gravitational physics.

Swarming fish and learning machines

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The collective behaviour that arises when a group of individuals interact - be they swarming fish or rioting humans - is an intriguing phenomenon with implications for biology, sociology and many other disciplines, but more recently it has also become a topic of interest in the field of artificial intelligence. By training artificial agents to solve tasks that require collective behaviour, one can gain insights both into the mechanisms that give rise to such behaviour in a natural setting and into the capabilities of the artificial agents. We are particularly interested in the performance of agents that use reinforcement learning with projective simulation (PS), due to the role that this paradigm plays in quantum machine learning. I will present results illustrating how PS agents can come to exhibit collective behaviour and discuss possible improvements to the PS framework that facilitate this process.

On the gravitational properties of a quantum object in a spatial cat state

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No abstract.