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Atom-Mediated Directional Channeling of Emission into an Optical Waveguide

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Silica optical fibers transmit light almost without loss and are as such prime candidates for the realization of quantum networks where quantum information is carried by optical photons. Tapered optical fibers with subwavelength diameters additionally provide an evanescent field interface between the guided light and other quantum devices. Our experiment employs a two-colour scheme to optically trap a small ensemble of cesium atoms in the evanescent field surrounding a 500-nm diameter nanofiber [1]. The very efficient coupling between the quantum emitters and the guided light together with the ground-state coherence times of the trapped atoms in the ms-range [2] make this system well suited for fiber-integrated quantum information processing. Here, we show that, in addition, the unique properties of the nanofiber-guided modes allow for the directional channelling of light into the waveguide. The coupling ratio between the two emission directions is directly controlled by the quantum state of the trapped atoms. By preparing the atoms in outermost Zeeman states of their hyperfine ground-state [3], ratios higher than 10:1 have been measured.

Quantum Control and Generation of Entanglement

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Generation of entanglement is studied in a controlled environment. The model system of interest is a cavity field interacting with a pair of atoms. The cavity field is heavily damped and it is pumped in order to maintain a steady state field population. Because the cavity field is heavily dumped, we can eliminate it adiabatically first by displacing the density operator, and the master equation describing its evolution[1]. This system is analyzed in the steady state, without making any measurement on the photons leaking through the cavity walls. The ideal physical parameter set for maximum entanglement is investigated. In the second step, we assume a direct measurement on the leaking cavity photons, and observe the evolution of entanglement in a quantum trajectories approach[2]. In the final step a homodyne measurement on the leaking cavity photons is performed. In this scheme the cavity field interferes with a coherent field at a beam splitter, followed by a continuous measurement on the emerging beams[2]. We simulate quantum trajectories approach by applying Monte Carlo method for both direct and homodyne measurement[3]. A feedback mechanism relying on the tuning of the external field is studied. The amount of entanglement is analyzed in all cases with the help of various methods[4].

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Single-ion Faraday rotation and ion-ion entanglement by single-photon detection

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Single-ion Faraday rotation and ion-ion entanglement by single-photon detection'

We present two recent experiments with one and two trapped Barium ions. In the first [1] we could observe Faraday rotation of a probed beam by a single trapped ion. In the second one [2] we were able to entangle two effectively distant ions by a single photon detection triggered process.

Furthermore, we present the development of our new ion trap, which is composed by four main tips and integrated with a hemispherical mirror and a high numerical aperture (0.7) aspheric lens. This new trap will allow us to more than triple our collection of fluorescence light, and to explore a regime where the spontaneous emission of the ion can be reduced drastically.

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Achievable upper bound of extractable work under feedback control

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Recent advances in experimental techniques enables us to deepen understanding of nonequilibrium statistical physics. In particular, feedback control provides a key framework to understand the role of Maxwell's demon. In modern terms, Maxwell's demon is a feedback controller who performs measurement on a system and utilizes the obtained information to extract work beyond the limit set by the second law of thermodynamics.

While the amount of the acquired information sets an upper bound of extractable work under feedback control, this bound does not always give an achievable bound.

In this study, we obtain an achievable upper bound of extractable work for a given feedback control. We find that the amount of information which becomes unavailable through the feedback process lowers the upper bound, which leads to an inequality more stringent than the hitherto known one. Because the obtained upper bound is achievable, it can play a role of a guiding principle for designing the optimal protocol.

Superconducting Vortex Lattices Atom Chip

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In this project we present a concept to implement magnetic lattices created by superconducting vortices for atom trapping.This technique allows the possibility to access fundamental length scales associated with superconducting vortices, the coherence length and London's penetration depth. Accessibility to this parameters plays an important role in building quantum simulators for Hubbard models.

Quasi-Bell states in a strongly coupled qubit-oscillator system and their delocalization in phase space

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We study evolution of bipartite entangled quasi-Bell states in a strongly coupled qubit-oscillator system, and extend it to ultra-strong coupling regime. We assume the presence of a static bias that may be easily generated, say, for the flux qubits. In the context of coupled qubit-oscillator system the non-classical quasi-Bell states are found to be of much interest. They exhibit entanglement of microscopic atomic states and the photonic coherent states that can be regarded as mesoscopic for reasonably large values of the coherent state amplitudes. In the large coupling regime a state of the generic quasi-Bell type becomes the approximate ground state of the combined system. These states are likely to be fruitful for studying quantum phase transitions of qubit-oscillator systems. Using the adiabatic approximation, that relies on the separation of the time scales governed by the high oscillator frequency and the (renormalized) low qubit frequency, the reduced density matrix of the qubit is obtained for the strong coupling domain in closed forms involving linear combinations of Jacobi theta functions. The analytical results based on theta functions are found to be in good agreement with their series counterparts. The time evolution of the entropy suggests that the individual subsystems repeatedly arrive at almost pure states reducing the entanglement and the mixedness to very low values for short time intervals.

On the other hand the reduced density matrix of the oscillator provides a way to study the phase space density functions of the oscillator degree of freedom. In particular, we evaluate the Q-function and utilize this for obtaining closed-form expressions of the first two moments of the quadrature variables as linear combinations of theta functions. Our closed-form evaluations of various physical quantities for strong coupling domain and weak bias are compared with, and found to be good approximations of, their series values. The non-classicality of the quantum state can be studied via the negativity of the Wigner function and the Mandel parameter. For an ultra-high qubit-oscillator coupling strength we study the Wehrl entropy, the Heisenberg uncertainty function, and the complexity that measure the delocalization of the oscillator in the phase space. As it is difficult to analytically determine the Wehrl entropy due to the presence of the logarithmic function in it, the inverse of the second moment of the Husimi distribution is proposed as a measure of complexity of quantum states. A series expression of the complexity is obtained. The long-term time evolutions of the Wehrl entropy and the complexity suggest that for the strong coupling they undergo almost periodic dynamical evolution whose period is proportional to the fourth power of the coupling constant. This is the regime in which the closed form evaluation based on the theta function holds. But for the ultra strong coupling it shows the existence of long-living metastable states with superimposed Markovian fluctuations that resemble white noise.
Preliminary version of this work is availabe in arXiv: 1302.2771v2

Tuning the Quantum Phase Transition of Bosons in Optical Lattices via the Presence of an Impurity

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Tuning the Quantum Phase Transition of Bosons in Optical Lattices via the Presence of an Impurity

We investigate how a single impurity immersed in a cloud of bosons in an optical lattice changes the location of the quantum phase transition from a Mott insulator to a superfluid [1]. To this end we apply the Ginzburg-Landau theory [2-4] for the underlying Bose-Hubbard model and determine the impact of the presence of the impurity upon the respective Landau coefficients. The results can be physically interpreted in terms of a polaron formed by the impurity and a cloud of bosons. Changing the interaction strength between the impurity and the bosons with the help of a Feshbach resonance allows to tune considerably not only the polaron properties, i.e. its mass and its size, but the quantum phase diagram as a whole.

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Probing Resonances of an Artificial Molecule Coupled to a Transmission Line

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Superconducting circuits with Josephson junctions are promising candidates for developing future quantum technologies. Of particular interest is to use these circuits to study effects that typically occur in complex condensed-matter systems. In this work, we fabricated capacitively-coupled transmon qubits in the gap of coplanar waveguide resonator. The resonance frequency is 7.185GHz and quality factor about 3500 at 40mK.As sweeping the magnetic field, B form -25Gs to 25Gs at 8GHz, we found periodic EM wave transmission peaks in Fano line shape, a signature due to absorption emission of transmon.

Other works,the superconducting single-electron transistors (SETs) and one dimensional Josephson junction array(1D JJ Array) are fabricated on silicon subtsrate . We experimentally studied the transport characteristics of SETs and current flows through the 1D JJ Array affect the SET behaviors. We also observed that the 1D JJ arrays coupled together via AC josephson effect.

Non-Linear Optical Phase response from Collective Strontium Atoms in an Optical Cavity

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Quantum systems where light and matter strongly interact with coherent non-linear dynamics may be used to engineer strongly correlated phases of light-matter couplings. Realization of such systems would provide an ideal platform for applications in quantum metrology, quantum information science, and studies of many-body quantum systems. An example of such systems is a cavity QED system consisting of an ensemble of alkali atoms coupled to an optical cavity [1-2]. It has been proposed to exploit the non-linear phase slopes of cavity QED systems in the bad cavity regime with narrow lined atomic transitions as quantum discriminators to enhance the spectral purity of a laser [3-4].

This collective linewidth narrowing has been reported in the microwave domain using a two-photon optical Raman transition in rubidium [4], but the effect has not been observed in the optical regime yet. For future applications in quantum metrology it is essential to use atomic transitions in the optical regime where the Q-factor is several orders of magnitude larger. Here we present the first experimental results of a non-linear phase response in the optical domain of a cavity QED system consisting of a thermal ensemble of laser-cooled collective strontium atoms.

We perform direct spectroscopy on the narrow optical 1S0−3P1 transition (Linewidth = 7.6 kHz) of 88Sr at 689 nm by trapping about 10^8-10^9 strontium atoms in a standard Magneto Optical Trap (MOT) inside a low finesse cavity with a waist diameter of 1 mm. The cavity is attached on the outside of our vacuum chamber limiting the finesse (F=85) and the cavity length (30 cm). The collective cooperativity denoting the degree of atom-light coupling of the system is C=630, wich places the system in the collective regime. The atoms are cooled down to mK temperatures and their Doppler energy scale is several orders of magnitude larger compared to narrow line width of the optical transition. This system is sensitive to velocity tuned two-photon scattering events and provides a non-linear phase signature of the system which is significantly different from the zero temperature result. By varying the number of atoms and the intra-cavity power experimentally we systematically investigate the non-linear phase signatures relevant for laser stabilization. The relative simplicity of our system opens new possibilities not only for improving the stability of atomic clocks[3], but also for superradiant laser sources[2,4-5], spin glass phase transitions[6-8],
frustration and supersolidity[9].

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Exact heat capacity of non-interacting bosons gas in one and two dimensional boxes

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Using the grand canonical ensemble statistics of non-interacting bosons gas [1] in low dimension as such 1D and 2D boxes, we study the properties of this gas, in particular its chemical potential and heat capacity. These properties have been usually studied in the literature [2] in the case of macroscopic dimensions, where energy levels are very tight. The summations can be replaced by integration over the phase space. In our case, we perform calculations using the exact expressions of energy and the ground state energy is not zero. These considerations are suited for small systems. We study the reduced chemical potential and the heat capacity as functions of the temperature for 1D and 2D by means of different methods.

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Keywords: Quantum statistical mechanics, bosons, Heat capacity.

Reservoir engineering for the preparation of non-classical fields with Rydberg atoms in a cavity

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A superconducting cavity allows us to store a microwave field of several photons without dissipation for a fraction of a second. The coupling of this field to single “circular” Rydberg atoms allows the realization of numerous thought experiments suggested by the founders of quantum mechanics to illustrate its non-intuitive aspects. Our experiment realizes a conceptually simple quantum system which allows us to implement fundamental experiments to understand the quantum logic in a system which is very well controlled on the microscopic level.

During my PhD we will work on the realization of a “reservoir engineering” experiment. The idea is to prepare an artificial dissipative environment whose equilibrium states are non-classical. This artificial environment is created by the controlled interaction of atoms which are successively crossing the cavity. We showed theoretically that when an atom is interacting successively in a dispersive, then resonant, then dispersive way with the cavity mode, states like the Schrödinger cat state, a coherent superposition of classical states, are left invariant by this composite interaction. When a sufficiently large number of atoms cross the cavity in the scale of the photon life time, then the field rapidly converges to a state left invariant by the interaction. The atoms behave like an artificial environment preventing decoherence due to the ordinary dissipation which usually destroys very fast the non-classical states [1].

This new method of preparing non-classical states is based on a complex atom-cavity interaction which needs an interaction time impossible to reach with our previous experiment. The atoms were produced in a horizontal beam with a thermal velocity which limited the interaction time with the cavity mode to 0.1ms, much shorter than the lifetime of atoms (30ms) and photons (130ms). Therefore we develop a new experiment in which the atoms will be prepared from a beam of cold atoms launched in a parabolic trajectory in the space between the mirrors. This requires changing preparation method, because the time of flight of the slow atoms from the edge to the center of the cavity is no longer negligible with respect to the lifetime of the atomic state, and the atoms have to be prepared inside the cavity. I will present our first results on circular Rydberg state preparation and manipulation.

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Many-particle entanglement and phase coherence in mesoscopic Bose-Einstein condensates

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Atomic Bose-Einstein condensates (BECs) are highly controllable isolated quantum systems with long coherence times, and offer applications to metrology and quantum information processing. We experimentally prepare non- classical many-body spin states, analyze them by tomographic state reconstruction, and study their decoherence dynamics.

Our system consists of a two-component Rubidium-87 Bose-Einstein condensate, consisting of a few hundred atoms, created on an atom-chip [1]. A state-selective potential tunes the collisional interactions (one-axis twisting dynamics [2]), which allows us to prepare many-particle entangled states [3]. We present our recent results on the preparation of strongly oversqueezed states.

In finite-temperature BECs, interactions with the non-condensed fraction intrinsically limit the phase coherence [4]. We experimentally study these fundamental limits by performing Ramsey spectroscopy with BECs of different temperature and densities.

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Self-avoiding quantum walks

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We review self-avoiding quantum walks. Machida et al [arXiv: quant-ph /1307.6288v2] study the discrete case on a subspace of the complete Hilbert space. The walk can be self-avoiding in the coin and position space separately or simultaneously. Camilleri et al [doi:10.1038/srep04791] describe how to implement a quantum walk with a memory register which then enables it to be self-avoiding but only to some extent depending on the strength of the memory recording and back-action. Furthermore, it provides an elaborate comparison with the classical self-avoiding walk and thus, points out that the quantum version, due to its diffusive characteristics, may have applications in quantum simulation. Next, we consider two alternatives to the completely self-avoiding walk so as to eliminate the need of memory. The non-repeating and non-reversal quantum walks, introduced by Proctor et al [arXiv: quant-ph /1303.1966v3], are both interconnected since the non-repeating walk is obtained when the coin used for the non-reversal one is permuted. The latter refers to a walk whereby the state cannot move back onto the position where it has just been before whereas the non-repeating walk cannot move in the same direction which it previously moved. These have applications in organic chemistry, especially for a process known as polymerisation. After careful analysis of these discrete time quantum walks, we explore the possibility of designing a self-avoiding open quantum walk which is the quantum version of a classical Markov chain but whereby the states are represented by density matrices as explained by Attal et al [J Stat Phys (2012) 147:832–852].

Characterization of Hong-Ou-Mandel Bunched States by Quantum Homodyne Tomography

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We experimentally demonstrate quantum homodyne tomography of Hong-Ou-Mandel bunched states (Two-photon-interfered states).
The states are created by dynamically adjusting emission timings of two heralded single photons using coupled cavities.

A Cavity QED platform for testing classical and quantum random walk models

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An optical cavity allows for the optical manipulation of motional degrees of freedom of atoms (or even generally polarizable particles). We study dynamics in a previously unexplored regime where both cavity pumping and direct pumping of the atom are included and frequency beating is allowed. The corresponding dynamics is non-trivial: the effective time-dependent potential induces a random walk behavior in the classical regime. Immediate generalization to a multitude of driving fields shows the model to be mapped onto the kicked rotor model. Future investigations will take into account the internal degree of freedom of the atom to consider possible implementation of the quantum random walk.

Determination of the universal thermodynamic function of strongly interacting Fermi system with ultracold Fermi gases

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We are investigating the universal thermodynamic property of 2-component strongly-interacting Fermi system with ultracold atomic gases. Because the ultracold atomic system has a universality, our result can be applicable to all low energy s-wave interacting system. We constructed ultracold 6Li atomic system in which the interaction between different spin components can be tuned by applying an external magnetic field, and observed a superfluid transition so far. We are trying to determine the equation of state in the all region of the BEC-BCS crossover and to apply it to many fields.

Simulation of Grover's algorithm with spatially-dependent coupling constant

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We simulate Grover's algorithm in an Ising spin chain quantum computer with spatially-dependent coupling constant. The simulation shows that the tendency of two distinct states to transition from the same initial state is reduced. The fidelity with the ideal result and the probability of finding the target state are also investigated.

Quantum-State Control of a Ferromagnetic Magnon Mode Coupled to a Superconducting Qubit

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1. Background

Recently, transducing a quantum state between a superconducting qubit and an optical mode has been intensively studied to realize long-distance quantum communication. As a candidate for such transducing media, we focus on ensemble of electron spins in ferromagnetic materials. Magnon modes, consisting of ferromagnetic electron-spin ensemble, become macroscopic modes in the long wavelength limit. These modes have advantages of strong coupling and easy mode-matching with an external electromagnetic field.

2. Coupling between a Ferromagnetic Magnon Mode and a Microwave Cavity Mode

Yttrium iron garnet (YIG) is a representative ferrimagnetic insulator, known for its narrow ferromagnetic resonance (FMR) linewidth. We report coherent coupling of a magnon mode in a single-crystal YIG sphere to a microwave mode in a cavity. We couple microwave photons in TE101 mode of the rectangular copper cavity to magnons of the uniform precession mode in a single-crystal YIG sphere mounted in the cavity. As the result of microwave transmission spectroscopy at 10 mK, we obtain the coupling strength of 47 MHz between the cavity and the magnon mode for a sample with a diameter of 0.5 mm, for example. The coupling strength is much stronger than the cavity linewidth of 2.7 MHz and the magnon mode linewidth of 1.1 MHz. An anticrossing is observed, suggesting strong coupling between them [1]. On the other hand, the magnon linewidth shows peculiar temperature dependence below 1 K. We discuss correspondence between such a behavior and the theory of the relaxation due to a bath of two level systems [2].

3. Coupling between a Ferromagnetic Magnon Mode and a Superconducting Qubit via a Microwave Cavity Mode

It is possible to couple coherently a ferromagnetic magnon mode and a superconducting qubit via a microwave cavity mode. We couple a single-crystal YIG sphere and a transmon-type superconducting qubit, both mounted in the rectangular copper cavity, via virtual microwave photons in TE102 mode. By sweeping the magnon frequency, we observed an anticrossing suggesting strong coupling between them. We believe that such a strong coupling allows quantum-state control of the magnon mode in time domain. We are preparing for experiments to generate non-classical states of the magnon mode, such as Fock states and squeezed states.

Reffernces

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Production of a Quantum Gas in a Hybrid 'Dimple' Trap near a Tapered Optical Nanofibre

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In recent years novel techniques have been developed to create an ultracold atomic quantum degenerate gas each with their own advantage: speed, large atom number, simplicity to name a few. Once a quantum degenerate gas has been achieved it can be manipulated to gain information in other areas of physics such as condensed matter by loading a quantum gas into an optical lattice and performing quantum simulations of solid state models [1]. Another approach is to manipulate the ultracold atoms to create a controllable quantum information system [2, 3]. These applications give rise to new technologies and give a greater insight into fundamental quantum physics.

At present we are in the building phase of an experiment. We are working towards the production of a quantum gas and an imaging system for detection of a quantum gas based upon single atom detection with optical tapered nanofibres (TNFs). The presence of a TNF within a cloud of atoms does not impose severe restrictions to laser cooling [4], thus our goal is to incorporate the TNFs into the cold atom experiment by mounting them within close proximity of the trap centre and observe either the atom fluorescing into the nanofibre mode or the interaction of the atom with a resonant nanofibre photon. The scheme can also be extended to simultaneously detect atoms in different internal states.

We have constructed a laser cooling system that is designed to trap Rb and K atoms with magnetic coils capable of creating fields strong enough to reach Feshbach resonances. We have magnetically trapped 87Rb atoms with a field gradient of 1.0 T/m at 140 μK with the magnetic coils capable of producing a maximum field gradient of 2.2 T/m. Currently we are incorporating a hybrid 'dimple' trap technique into the experiment that is designed to produce of a 87Rb BEC.

We have designed an optical dipole system using a 1064 nm distributed feedback laser to seed a fibre amplifier capable of outputting up to 5 W. The dipole beam waist is chosen to be small enough that it will provide phase space densities high enough to rapidly cool the atoms in the trap to the quantum degeneracy regime. With the measured dipole beam waist of 62 μm the trap frequencies are calculated to be 354 Hz along the radial directions of the dipole beam and 32 Hz along the beam propagation axis due to the magnetic confinement. Calculations give values for the trap depth of our system throughout the adiabatic transfer from the dimple trap to a pure optical trap to be U0 = 49 μK and the temperature of the atom cloud at completion of the transfer to the pure optical trap to be 4.9 μK if we assume the relation of Tf = 0.1*U0 /kb as shown in [5]. We will then further evaporatively cool in the pure optical trap towards quantum degeneracy.

Here we present an overview of our TNF work to date and the first results from the hybrid 'dimple' trap technique within our system.

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Second stage laser cooling of thulium atoms

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Our group deals with laser cooling of thulium atoms. Thulium is a rare-earth element with a high ground state magnetic moment (4 μB), so it is attractive for study magnetic dipole-dipole interactions and for quantum simulations. Also, thulium is a promising candidate for optical clock applications.

We propose to use the magneto-dipole transition between two fine-structure sub-levels of the thulium ground state as a clock transition for a lattice optical clock. Its wavelength is 1.14 μm and the linewidth was estimated to be 1.2 Hz. The differential polarizability of the transition is expected to be small, so AC Shtark shift provided by an optical lattice and a black body radiation shift could be minimized.

The dipole trap is going to be loaded by recapture atoms from the magneto-optical trap (MOT). The MOT for thulium atoms is based on two cooling transitions: the strong “blue” transition at 410.6 nm with the linewidth about 10MHz for decelerating of atoms in a Zeeman slower and the first stage cooling and the weak “green” transition at 530.7 nm with the linewidth about 350 kHz for the second stage cooling. It’s worth noticing that for both cooling transitions Lande g-factors of the lower and the upper states are close to each other, therefore sub-Doppler cooling mechanism is effective directly in the MOT.

Currently, the lowest temperature obtained in the MOT is 20 μK. Now we are working at optimization of the cooling process to increase the number of atoms in the MOT and to decrease the temperature of the atomic cloud.

Inhibiting unwanted transitions in population transfer in two- and three-level quantum systems

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We construct fast and stable control schemes for two- and three-level quantum systems. These schemes result in an almost perfect population transfer even in the presence of an additional, unwanted and uncontrollable transition. Such schemes are developed by first using the techniques of ”Shortcuts to Adiabaticity” and then introducing and examining a measure of the scheme’s sensitivity to an unwanted transition. We optimise the schemes to minimise this sensitivity and provide examples of shortcut schemes which lead to a nearly perfect population inversion even in the presence of unwanted transitions.

Behavior of an ultracold Yb-Li mixture in an optical lattice

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Ultracold atomic mixtures consisting of two different species provide interesting research fields. In particular, mixtures of two species with an extreme mass imbalance in optical lattices enable us to simulate many-body systems with impurities which play important roles in real materials.

We here report our recent results on a quantum degenerate mixture of Ytterbium (Yb) and Lithium (Li) in a 3-dimensional optical lattice. We measure coherence properties of a Bose-Einstein condensation of Yb in the optical lattice with and without Li atoms. We also perform high-resolution spectroscopy of Yb in the optical lattice via an ultra-narrow optical transition in both cases with and without Li atoms. The results do not show clear differences in both the coherence properties and the spectra [1]. One of the reasons of these small effects of Li is small spatial overlap of Yb and Li because of a large gravitational sag. To obtain good spatial overlap, we employ an additional optical dipole trap beam.

We also present our current efforts to establish the control of inter-species interaction via Feshbach resonances. Feshbach resonances between Yb and Li in the ground states are too narrow to finely tune the interaction [2]. However, there exist anisotropically induced Feshbach resonances between Yb atoms in the excited $^3P_2$ state and in the ground state with reasonably broad width [3]. Resonances between Yb in the excited $^3P_2$ state and Li in the ground $^2S_{1/2}$ state can be also reasonably broad. Now we strive to study the properties of predicted Feshbach resonances [4] between Yb($^3P_2$) and Li($^2S_{1/2}$).

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Measurement of Microwave Photon-number Distribution Using Superconducting Qubit

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A superconducting LC circuit including a non-linear inductor called a Josephson junction realizes an effective two-level system, known as a superconducting qubit (SC qubit). Since the qubit possesses a large dipole moment due to its large size, it is coupled with microwave (MW) photons strongly, behaving like an atom in a cavity. Therefore, the system, which consists of the SC qubit and a resonator, is well studied in the field known as the Circuit Quantum Electrodynamics (Circuit QED).

The circuit QED is very fascinating to investigate not only quantum infor-mation processing but also quantum optics. Especially, because of the large dipole mo-ment, the SC qubit in the resonator or the cavity can reach the strong dispersive regime where the ac-Stark shift per photon is larger than decoherence rates of the qubit, leading to observation of qubit transitions depending on number of photons. Here, we present the SC qubit spectra reflecting photon-number distribution of thermal, coherent and squeezed-vacuum states.

Towards dipolar quantum magnetism in ultra-cold gases

Anna Kowalczyk

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Ultra-cold atoms allow us to control and manipulate the internal and external states of atoms and offer a unique tool to model quantum systems. Specifically, Bose-Einstein condensates (BEC) with additional spin degrees of freedom (so-called spinor condensates) can be used to explore quantum magnetism phenomena. We aim to produce spinor BECs in an optical lattice at ultra-low magnetic field. In this regime, magnetic dipole interactions dominate the system and will allow us to study quantum many body phenomena and create dipolar quantum magnets. At ultra-low magnetic field ferromagnetic contact interactions, coupled with a cigar-shaped trap geometry, will cause multiple spins to couple to each other and align creating a single large spin for the whole atomic ensemble. The goal of our research is to investigate dipolar interactions using these large spin ensembles in order to understand dipolar quantum phases and dynamics, as well as affording the potential to build very sensitive magnetometers and gravimeters.

Toward experimental verification of fluctuation theorem in superconducting qubit

Yuta Masuyama

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By combining the fluctuation theorem in thermodynamics with information theory, it is stated that information can be converted into free energy by feedback, i.e.,“Maxwell's demon”. There are, however, no reports on experimental verification of the “quantum version”of Maxwell demon because it requires a controllable quantum system. In this presentation, we report on our approach to the realization of the quantum Maxwell demon with superconducting quantum circuit, one of the ideal tools available now due to its ability to implement projective measurement, quantum non-demolition measurement, and feedback control in quantum regime.

A Species-Specific Optical Lattice for Single Cesium Atoms

Daniel Mayer

University of Kaiserslautern, Germany

In the diploma-thesis presented here, a species-specific optical lattice for the transportation of single Cesium atoms has been set up and characterized. The optical lattice is formed by two counter-propagating, linearly polarized laser beams creating an one dimensional standing wave. The laser wavelength is tuned to the so-called magical wavelength of Rubidium, where the dipole-potential for Rubidium vanishes, yielding a blue detuning and therefore repulsive atom-light-interaction for Cesium. By manipulating the frequency difference between both laser beams, the controlled transport of Cesium atoms in the moving interference pattern is realized. In future experiments this transportation system will be used for the controlled doping of Rubidium Bose-Einstein-Condensates with single Cesium atoms.

For the deterministic preparation of the light frequency a dual-channel, radio-frequency driver for acousto-optical modulators (AOM) has been constructed. The signal generation is based on direct digital synthesis and the whole setup is operated by a microcontroller. The system offers two phase-stable signals with tuneable frequencies which are translated to the laser-frequency by an optical setup featuring two AOM. The prepared laser beams are transported to the vacuum chamber by optical fibers and subsequently focussed on the location of the atoms.

First fluorescence images proof the successful transportation of single Cesium atoms in the optical lattice and lifetime measurements point to phase-noise being the main heating effect. The mostly digital AOM driver allows thereby for reproducible and precise transportation of the single atoms over distances of some hundred micrometers.

Non-Markovianity and System-Environment Correlations in a Microscopic Collision Model

Ruari McCloskey

Queen's University Belfast, United Kingdom

We show that the use of a recently proposed iterative collision model with inter-environment swaps displays a signature of strongly non-Markovian dynamics that is highly dependent on the establishment of system-environment correlations. Two models are investigated; one in which such correlations are cancelled iteratively and one in which they are kept all across the dynamics. The degree of non-Markovianity, quantified using a measure based on the trace distance, is found to be much greater for all coupling strengths, when system-environment correlations are maintained.

Realization of a quantum gas microscope of ytterbium atoms

Martin Miranda

Tokyo Institute of Technology, Japan

A quantum gas microscope is a high numerical aperture microscope capable of single-site detection of neutral atoms trapped in a two-dimensional optical lattice. In recent years, rubidium atoms were trapped in a two-dimensional optical lattice and observed using a high numerical aperture microscope, providing a novel tool to study interacting many-body quantum systems and creating quantum simulators [1,2].

Our group focuses on the development of a quantum gas microscope using ytterbium atoms. Ytterbium atoms have zero electronic spin, and thus, provide much longer coherence time compared to that of alkali atoms, and are a good candidate for a quantum computer [3].

To increase the numerical aperture of the system, we introduced a solid immersion lens (SIL) between the Yb atomic cloud and the objective lens. Atoms were transported to the surface of the solid immersion lens using a system comprised by three optical dipole traps and the optical accordion technique. After being transported, a pancake-shaped two-dimensional condensate was created near the surface of the SIL [4]. Later, two optical accordion beams (1080nm wavelength) were retro-reflected, trapping the atoms in a square lattice with a 540 nm period. Fluorescence image with single-site resolution of the atoms trapped in the two-dimensional optical lattice was successfully obtained.

Details in the creation of the two-dimensional optical lattice and the fluorescence imaging method will be further discussed in the poster presentation.

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Monte Carlo Study of Phase Transition on Fractals with Ising, XY, and Heisenberg Model

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Phase transitions of spin dynamic system on fractal structures are investigated with Monte Carlo Simulation.

Phase Transition on conventional 1D, 2D and 3D lattices were intensively investigated with different model Hamiltonians, which lead to some important postulates as to which order parameters are responsible for the existence or absence of phase transition in such systems. Recently, the investigation of phase transition has been extended to fractal structures in order to further support or against the existing postulates. In this talk, I will discuss the details of the computational procedures and results of our Monte Carlo simulation, the properties of fractal structures, and important order parameters in phase transitions.

(additional talk)
Calculations of energy eigenvalues of arbitrary Hamiltonian with Simple Harmonic Oscillator ladder operators

In elementary quantum mechanics, it is well known that position and momentum operators can be neatly described with ladder operators in Simple Harmonic Oscillator basis. The ladder operators can be expressed in matrix form, suggesting that position and momentum operators, and therefore any Hamiltonian which is made of these operators can be also expressed in matrix form. Calculating eigenenergies of Hamiltonian is then reduced to the business of calculating eigenvalues of the corresponding Hamiltonian matrix. This novel matrix method outperforms other conventional methods such as WKB method and perturbation method, in terms of both easiness of implementation and the efficiency and accuracy of computation.

In this talk, I will discuss the details of theoretical aspects of this matrix method and the procedures and results of numerous calculations for many different Hamiltonians. The potential issue and limit of this method are also discussed.

Optical Dipole Trap of cold fermionic strontium gas at magic wavelength

Musawwadah Mukhtar

National University of Singapore (NUS)/Centre for Quantum Technologies (CQT), Singapore

We present our work on trapping cold strontium gas of fermionic isotope ^{87}Sr. The dipole trap laser is set at so-called magic wavelength where the associated difference in Stark shift is zero for the transition ^{1}S_{0}-^{3}^P_{1} of narrow intercombination line. This idea has been fruitful for atomic clock. Here, we are interested in the realization of artificial gauge field with strontium atoms where precise tuning of the laser frequency is a crucial issue.

Nonequilibrium Equalities Derived from Lebesgue's Decomposition

Yuto Murashita

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Nonequilibrium equalities are exact equalities in statistical mechanics valid even far from equilibrium unlike the linear-response relations. These equalities enable us to deal with nonequilibrium phenomena in a qualitative manner and attract considerable attention as a new formulation of nonequilibrium statistical mechanics.

However, most of the integral fluctuation theorems cannot be applied to singularly irreversible processes such as free expansion. This is because the initial probability distribution in the free-expansion process has vanishing probability in a certain region of phase space. The entropy production of the process is defined via the ratio of the final probability to the initial probability. Therefore, the vanishing initial probability makes the entropy production divergent. This is the reason why nonequilibrium equalities are inapplicable to the strongly irreversible situations.

The above discussion is about the standard thermodynamics, in which we do not have access to microscopic degrees of freedom. Thanks to technological advances, we can now gain information of microscopic degrees of freedom through measurements and control the system as we want based on the acquired information. Under this feedback control, nonequilibrium equalities are extended. However, when we conduct high-precision measurements such as projective measurements, probability vanishing regions arise due to the measurements, which again makes nonequilibrium equalities inapplicable.

We identify the mathematical origins of these inapplicability based on Lebesgue’s decomposition theorem and derive new nonequilibrium equalities applicable to the above situations. Inequalities derived from the obtained equalities impose stronger restrictions on the averaged entropy production than the corresponding conventional second laws in certain systems.

Classical Realization of Dispersion Cancellation by Time-Reversal Method

Kazuhisa Ogawa

Kyoto University, Japan

We propose a classical optical interferometry with intense coherent input light reproducing dispersion-insensitive Hong-Ou-Mandel interferograms.

We use a time-reversed HOM interferometer and suitably post-process the measurement data to reproduce the interferograms. This interferometry is derived by our systematic scheme based on the time-reversal symmetry of quantum mechanics.

We also experimentally demonstrate dispersion cancellation by using this interferometry. The results achieve high-visibility interferograms with high signal conversion efficiency owing to the simplicity of our setup. This technique can be applied to practical metrological technology such as optical coherence tomography.

Realization of Dynamic Squeezing Gate

Hisashi Ogawa

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It is one of the biggest goals in the field of quantum optics to control quantum states of light and realize a quantum computer. For universal continuous-variable quantum information processing (CVQIP), at least one non-Gaussian (3rd or higher order) operation is required. For building such a quantum operation, a dynamically controllable 2nd-order quantum gate (squeezing and phase-space rotation) is necessary for a feedforward in teleportation-based non-Gaussian quantum gate. However, 2nd-order quantum gates in previous experiments were not applicable to such use because their squeezing parameters and input states were fixed.

In this report, we demonstrate a dynamic squeezing gate for a dynamically changing input using a one-way quantum computation scheme.

Wave packet dynamics of atomic condensate in a harmonic trap

Shun Ohgoda

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Wave packet dynamics of atomic condensate has become a desirable target for analyzing many quantum phenomena in both theory and experiment because of its controllability and versatility. In this study, we focus on two topics includ-ing 1.quantum-classical correspondence in collective excitation of vortex lattice and 2. dynamics of ultra cold fermions in an optical lattice. 1.Bose-Einstein Condensate(BEC) makes a triangular vortex lattice by rotating itself in a harmonic trap.

To sweep away around at the center of it, Tokachenko mode which oscillates in the azimuthal direction is excited. We simulated this oscillation by two methods: one is intended to solve Gross-Pitaevskii equation; the other is supposed to solve the classical equation of motion assuming quantized vortices are mass point including vortex-vortex interaction. We could conrm collective excitation oscillating in the
azimuthal direction for both calculations. 2.Ultra cold atoms in an optical lattice make band structure because of the periodicity. Due to this structure, we can observe various phenomena (e.g. Bloch oscillation and localization of wave packet).

Recent experiments deal with either ultra cold bosons or fermions. Here we study coherent excitation of non-interacting fermions in an optical lattice in the presence of the harmonic trap.

Numerical simulations with quantum trajectories of the dynamics of two trapped interacting bosonic atoms

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Universitat Autònoma de Barcelona,

Efficient and fast numerical tools to simulate many-body quantum systems are essential to properly describe the quantum dynamics of matter at an atomic level. Nevertheless, as the wave function of a quantum system is defined in the configuration space, to simulate the exact quantum dynamics of a 'simple' two-particle system requires 6 dimensions, which is far from today's best computer capabilities [1]. In this work, we will discuss how to deal with this problem by applying Oriol's algorithm [2] to the de Broglie-Bohm trajectories [3,4] of many-body quantum systems.

The de Broglie-Bohm formulation of quantum mechanics assumes that the wave function acts as a guidance wave for the quantum point particles, allowing introducing quantum trajectories. While the statistical predictions of the de Broglie-Bohm formulation of quantum mechanics are exactly the same as the standard formulation of quantum mechanics, i.e., the orthodox or Copenhagen formulation, it provides an alternative and sometimes gainful mathematical framework to describe quantum systems [5].

In fact, it has been recently shown by X. Oriols [2] that the quantum trajectories of the de Broglie-Bohm formulation of an N-particle quantum system can be derived from N-coupled single-particle pseudo-Schrödinger equations, which, after some reasonable approximations, can be efficiently numerically solved. In this work, we will review Oriol's algorithm for cold atom systems and eventually apply it to investigate the dynamics of a quantum system formed by two interacting bosonic atoms trapped in an optical potential.

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One-dimensional Waveguides for Quantum Computation in Decoherence-Free Subspaces

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Photonic crystals are one of the most promising implementations for manipulating light at the nanoscale [1]. The possibility of engineering photonic bandgaps can be used to mold the flow of light confining it to effective one and 0-dimensional systems. Its combination with atomic systems, with recent experimental implementations [2], provides a very versatile platform for future quantum technologies, e.g., mediating strongly long-range interactions between atomic qubits [3].

These long-range interactions have already been proposed to mediate entanglement between a set of atoms placed close to these structures [3] or study atomic self-organization [4]. In this work, we show how to take further take advantage of it to induce decoherence-free-subspaces (DFS) [5]. By placing a set of atoms we can define a set of logical qubits which evolve unitarily protected from dissipation. The interaction of the atoms with an external laser field can, under certain conditions, lead to operations defining a universal set of quantum gates. We derive these conditions, introduce the necessary approximations and discuss the intrinsic and physical limitations of this system.

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Ramsey spectroscopy with squeezed light

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Ramsey's method of using two spatially separated optical fields has stood as one of the most successful spectroscopic techniques. As the advantages of the entanglement and squeezing played more and more important role in improving the precision of measurements, Wineland et al proposed and demonstrated the application of atomic squeezed spin states to the reduction of quantum noise in Ramsey spectroscopy and they approached the Heisenberg limit. On the other hand, Agarwal and Scully showed that the classical light field in the Ramsey setup can be replaced by nonclassical one leading to the enhancement of the signal-to-noise ratio. The Ramsey technique has been combined with coherent population trapping techniques to probe the clock transitions with much higher accuracy, one as can surpass the limits set by collisions and saturation effects. In view of the widespread applications of the Ramsey spectroscopy, we propose a Ramsey spectroscopic scheme using two atom excitation joint detection and squeezed light field. We are able to achieve a higher resolution using this scheme. We note that the advantages of using squeezed light in optical interferometers are well-known.

Direct Fibre Coupling of Nitrogen-Vacancy Centres

Sarah Reisenbauer

Technische Universität Wien, Austria

At present many new application fields arise from nitrogen-vacancy centre research - be it in quantum information and communication technologies, in quantum metrology or even in life sciences. Most applications and experiments require the possibility of reliable high efficiency measurements of the nitrogen-vacancy centre fluorescence light. For achieving that in our experiment we directly fibre couple the nitrogen-vacancy centre fluorescence light. Our method shows excellent stability in fluorescence measurements as in optically detected magnetic resonance experiments for magnetometry applications. The compactness of the setup allows to easily insert it into a cryogenic environment.

Realization of cavity QED on an optical nanofiber part 1: Cavity realization and characteristics

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We demonstrate the realization of cavity QED conditions for quantum emitters (QEs) on the surface of an optical nanofiber using a unique composite photonic crystal cavity technique. We achieve the Purcell (weak coupling) regime of cavity QED, realizing enhancement of more that 5 times for spontaneous emission from a quantum dot into the nanofiber guided modes.

In Part 1, we detail the principles and realization of the composite photonic crystal cavity. An external grating with a central defect was designed using the finite difference time domain method. The grating was then manufactured using an electron beam and etching technique, using the optimal design parameters. The grating was then combined with an optical nanofiber realizing a composite photonic crystal cavity (CPCC). The optical characteristics of the cavity were measured by coupling a broadband source (superluminescent diode) to the cavity and measuring the transmitted spectrum. Cavity resonance quality factors (Q-factors) between 1000 and 4000 were achieved, with tuning of the Q-factor and cavity resonance possible by changing the nanofiber diameter at the grating mounting position. These values are competitive with those typically seen in monolithically fabricated photonic crystal nanobeams, implying that cavity QED conditions should be readily achieved at the nanofiber surface.

In Part 2, we will discuss the realization of enhanced spontaneous emission from a quantum dot into the nanofiber guided modes using the CPCC. Our results pave the way for enhanced light-matter interfaces on optical nanofibers, with clear applications to quantum networks.

Decoherence Effects on the Non-locality of Symmetric States

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Entanglement is a crucial resource for quantum information processing. It refers to the intrinsic property of a quantum state not to be decomposable to product states. The notion of entanglement is relatively well understood in the bipartite case; however for a higher number of qubits it exhibits a more complex behavior. Indeed, multipartite states can be entangled in many different ways and belong to different entanglement classes such as the so-called GHZ and W-type of classes. Entanglement gives rise to the notion of non-locality, which is the ability of spatially distributed events to be correlated in a way impossible to be reproduced by classical shared randomness (or equivalently by a local hidden variable model).

Many tools using non-locality have been developed to separate ``quantum" from ``classical" features of physical systems. Bell inequalities, such as the well-known CHSH inequality in the bipartite case, are the common mathematical tools used for this purpose. A Bell inequality is an inequality composed of joint probabilities, which, if violated, proves the presence of non-classical correlations, thus providing an experimental tool to detect such correlations between space-like separated systems.

However, in any practical application, the non-local properties of quantum states can be degraded due to decoherence experienced by physical systems. Decoherence describes the leakage of information due to the interaction of a quantum system with its environment. Such noise effects become particularly pronounced in many-particle systems because of the complex nature of interactions for all subsystems. Little is known about the relation between noise and non-locality in the multipartite case. Recently, a Bell inequality, which is maximally violated by the W state for a large number of qubits in the asymptotic limit, has been developed ; however, this feature vanishes when decoherence is taken into account, as the non-local correlations become increasingly fragile for a high number of qubits.

In this work, we are interested in the non-locality of n-qubit symmetric states in the presence of decoherence. Our analysis is based on recently developed Bell inequalities using Hardy's paradox. We examine these non-local tests for noise models that are relevant from a practical point of view, namely amplitude and phase damping. To characterize the robustness of the states under study, we define the fidelity threshold, that is, the fidelity under which we cannot observe non-locality for a given Bell test. We compare this threshold for several symmetric states and for both types of noise. We also demonstrate that the measurement basis choice is crucial for the resistance to noise. Indeed, in some cases we find that the optimal basis choice in terms of violation is not the the basis choice which leads to the highest robustness, and in fact, there is an optimal violation shift when the quantity of noise increases. When compared to another non-local test, our test exhibits a surprisingly resistant behavior to phase damping for the W state; indeed, the fidelity threshold scales as 1/sqrt{n} where n is the number of qubits of the W state. Finally, we consider alignment errors typically present in experimental systems, which lead to increased fidelity thresholds.

In conclusion, we have examined non-locality in the complex multipartite case from a practical point of view, using a Bell test based on Hardy's paradox. Our techniques can be easily extended to other non-local tests. Beyond establishing robustness criteria for multipartite states, these techniques can also be used to demonstrate the feasibility, for instance, of tasks such as discrimination of multipartite entanglement classes in a device-independent manner.

Universal relations in strongly-interacting p-wave systems

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Tan relations connect the physical quantities and the asymptotic behaviors of correlation functions of 2-component Fermi gases, which hold universally regardless of the magnitude of the scattering length, the temperature, the number of particles, and so on. In such a system, the only relevant interaction is inter-component s-wave scatterings, and a quantity called "contact" plays an essential role in the relations. The situation significantly changes, however, when we consider a single component Fermi gas. The Fermi statistics prohibits s-wave scattering between particles and scattering in a p-wave channel is the dominant interaction. In this case, the centrifugal barrier requires a finite range of the interaction, which makes the existence of universal relations like Tan's more nontrivial.

The poster presentation is composed of two parts. In the former, I review Tan relations of 2-component Fermi systems. The origin of the asymptotic behavior of correlation functions is discussed. In the latter, I discuss the p-wave cases, where I show a possibility of universal relations for p-wave systems in spite of the seemingly non-universal nature of the p-wave systems.

Tonks-Girardeau gas in different potential traps by exact diagonalization

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We have computed the second-quantized many-mode Hamiltonian for bosons trapped in different one-dimensional potentials and diagonalized it for a small number of atoms. We have observed the transition from the BEC to the Tonks-Girardeau gas, i.e. the fermionization process, as we increase the interaction between the atoms. We calculate the one-body density matrix, the two-body correlations, the momentum distribution, the natural orbitals and their occupations, for the different potentials and interaction strengths. We compare the process of fermionization between the different potentials, with special attention to the largest occupation of the natural orbits, the build up of quantum many-body correlations between different spatial parts of the system, and the energy of the ground and excited states.

Optimal transport of cold atoms in anharmonic traps

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Efficient transport of cold atoms in harmonic trap has been proposed by using shortcuts to adiabaticity, based on Lewis-Riesenfeld dynamics invariants. In this paper, we design optimal trajectories to transport cold atoms in anharmonic traps, combining an invariant-based inverse engineering with optimal control theory. Since the actual optical traps are Gaussian but not harmonic, we bound the relative displacement between the trap center and the center of the mass of transport mode, and find the optimal trajectories for minimizing the anharmonic perturbation energy with high fidelity.

Decoherence in Spinor Superfluidity

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Last year, Scott Beattie et al experimentally studied persistent currents in spinor condensates. The persistent current was created in a toroidal two-component Bose gas with two different spin states (PRL 110,025301). This experiment gives a very intriguing experimental result: a decoherence of spin can lead to the destruction of superfluidity. We try to find a reasonable explanation about it. Recently, we find a promising model which is commonly used in quantum information: a system plus its surrounding harmonic heat bath.A decoherence mechanism is utilized in this model to distribute to the vanishing of the off-diagonal elements of the reduced density matrix of the system. We try to expand this model into a many body system and to consist with the experiment.