Precision measurements – the noisier the better!

Klaus Mølmer
Aarhus University, Denmark

Quantum systems provide time and frequency standards and they can be used as sensitive probes of inertial effects, weak electromagnetic fields, etc. Much effort has gone into the optimization of measurement schemes based on the preparation, evolution and final detection of the state of a quantum system, where, e.g., squeezing and entanglement can be used to reduce measurement uncertainty and hence increase sensitivity.

In this talk, I shall discuss the analysis of a different - but experimentally very common - scheme for precision probing, where one monitors signals emitted from a single quantum system rather than the system itself. This is the typical situation, e.g., in spectroscopy, where we can use a quantum optical master equation to obtain the density matrix of the system and predict the mean optical signal properties as function of any system parameter, and thus infer its value from experimental data.

In reality the signal record fluctuates with time, and while this imposes measurement uncertainty, it also imposes measurement back action. On average, the system that emits the signal is governed by the master equation, but subject to a given detection record, it is constantly “quenched” and obeys a stochastic evolution. I shall present an analysis that takes this “permanently transient” dynamics explicitly into account and which yields much more information than the one based on only mean signal values.

With detection of atomic fluorescence signals as an example, I shall demonstrate how photon counting and homodyne detection yield different sensitivity to the atomic and field parameters, while none of them exceed a general, theoretical sensitivity limit that we shall infer from the general quantum theory of measurements.

Magnetic Resonance at the Quantum Limit

Yuimaru Kubo
OIST Graduate University, Japan

The detection and characterization of paramagnetic species by electron-spin resonance (ESR) spectroscopy has numerous applications in chemistry, biology, and materials science. Most ESR spectrometers rely on the inductive detection of the small microwave signals emitted by the spins during their Larmor precession into a microwave resonator in which they are embedded. Using the tools offered by circuit Quantum Electrodynamics (QED), namely high quality factor superconducting micro-resonators and Josephson parametric amplifiers that operate at the quantum limit when cooled at 20mK [1], we report an increase of the sensitivity of inductively detected ESR by 4 orders of magnitude better than the state-of-the-art, enabling the detection of 1700 Bismuth donor spins in silicon with a signal-to-noise ratio of 1 in a single echo [2].

We also demonstrate that the energy relaxation time of the spins is limited by spontaneous emission of microwave photons into the measurement line via the resonator [3]. This constitutes the first observation of the Purcell effect for spins, and a first step towards circuit QED experiments with magnetically coupled individual spins.

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Adiabatic Crossing of Many-body Resonances

Emanuele Dalla Torre
Bar Ilan University, Israel

In periodically-driven quantum many-body systems we find a low-entanglement eigenstate of the dynamics analogous to the ground state of static systems. This state can be reached by adiabatically lowering the frequency, until a non-equilibrium quantum phase transition occurs. We exemplify this method with a one-dimensional spin chain: we find that the transition has a non-trivial topology and is associated with a Kibble Zurek scaling; this effect is an example of genuine non-equilibrium universality. Thanks to the low entanglement, the non-integrable case can be numerically studied by means of t-DMRG: this opens new perspectives in the study dynamical instabilities and many-body delocalization in driven systems.

Controlling Hybrid Quantum Systems for Sensing and Information Processing

Jason Twanmley
Macquarie University, Australia

Quantum engineering is become a heterogeneous endeavour requiring one to bring together very different types of physical subsystems so as to achieve an overall functionality which is impossible using each subsystem alone. A classic example related towards achieving the DiVincenzo Criteria 6&7 - on interconnecting static and flying qubits. In this talk we describe how, in theory, hybrid quantum devices can be designed to be useful for gravimetry, photon quantum non-demolition measurement, and building a quantum network between spatially distant superconducting chips, e.g. a quantum internet. These designs intermix superconducting, optical, solid-state and mechanical quantum subsystems.

Extraordinary properties of light including the Quantum spin Hall effect of light

Franco Nori
RIKEN, Japan

Maxwell's equations, formulated 150 years ago, ultimately describe properties of light, from classical electromagnetism to quantum and relativistic aspects. The latter ones result in remarkable geometric and topological phenomena related to the spin-1 massless nature of photons. By analyzing fundamental spin properties of Maxwell waves, we show that free-space light exhibits an intrinsic quantum spin Hall effect—surface modes with strong spin-momentum locking. These modes are evanescent waves that form, for example, surface plasmon-polaritons at vacuum-metal interfaces. Our findings illuminate the unusual transverse spin in evanescent waves and explain recent experiments that have demonstrated the transverse spin-direction locking in the excitation of surface optical modes. This deepens our understanding of Maxwell's theory, reveals analogies with topological insulators for electrons, and offers applications for robust spin-directional optical interfaces.

K.Y. Bliokh, D. Smirnova, F. Nori, Quantum spin Hall effect of light, Science 348, 1448-1451 (2015). Highlighted in a Perspectives [Science 348, 1432 (2015)].

Symmetry properties, density profiles and momentum distribution of multicomponent mixtures of strongly interacting 1D Fermi gases

Anna Minguzzi
CNRS, France

We consider a mixture of up to six components for a strongly interacting Fermi gases confined to a one-dimensional geometry by in a tight atomic waveguide. The fermions are confined by a harmonic potential in the longitudinal direction and interact by very strong repulsions with the other components of the mixture. In the limit of infinitely strong repulsions the ground state displays a large degenracy. We use an exact solution to identify the wavefunction which corresponds to the ground state at finite, large interactions, as well as the excited states. We determine the partial density profiles of each component of the mixture, and find partial spatial separation in the case of an imbalanced mixture.

We further characterize the wavefunctions by their symmetry, introducing a suitable transposition-class sum operator, and we find that the ground state has the most symmetric configuration compatible with its component imbalance, thus providing an exemple of generalization of the Lieb-Mattis theorem to the case of mixtures of more than two fermionic components. Finally, we obtain the momentum distribution for each component of the mixture and study in particular the high-momentum tails, which are a signature of the strongly correlated regime.

This work is done in collaboration with Jean Decamp, Pacome Armagnat, Bess Fang, Mathias Albert and Patrizia Vignolo

Quantized Conductance in Neutral Matter

Tilman Esslinger
Institute for Quantum Electronics, Switzerland

The observations of quantized steps in electric conductance have provided important insights into the physics of mesoscopic systems and allowed for the development of quantum electronic devices. Whilst quantized conductance should not rely on the presence of electric charges, it had not been observed for neutral, massive particles. I will report on recent experiments in which we observed quantized conductance in the transport of neutral atoms [1]. We used high-resolution imaging to shape the potential of a quantum point contact and a quantum wire between two reservoirs of quantum degenerate fermionic lithium atoms. I will further report on recent findings in spin and particle conductance measurements through a quantum point contact in a regime of strong atom-atom interactions [2].

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Two-body momentum space correlations in a one-dimensional Bose gas

Isabelle Bouchoule
Institut d'Optique Graduate School, France

Analyzing the noise in the momentum profiles of single realizations of one-dimensional Bose gases, we present the experimental measurement of the full momentum-space density correlations, which are related to the two-body momentum correlation function. Our data span the weakly interacting region of the phase diagram, going from the ideal Bose gas regime to the quasicondensate regime.

We show experimentally that the bunching phenomenon, which manifests itself as super-Poissonian local fluctuations in momentum space, is present in all regimes. The quasicondensate regime is however characterized by the presence of negative correlations between different momenta, in contrast to Bogolyubov theory for true Bose condensates, predicting positive correlations between opposite momenta. We will present analytical predictions for quasi-condensates, that compare well with the data lying deep into the quasi-condensate regime. Data lying in the crossover between the quasi-condensate and the ideal gas regimes are in good agreement with ab-inhitio Quantum Monte Carlo simulations.

Vortex dynamics in coherently coupled Bose-Einstein condensates

Alexander Fetter
Stanford University, U.S.A.

In classical hydrodynamics, straight vortices move with the local fluid velocity. This description can be rewritten in terms of forces arising from the interaction with other vortices. Two such positive vortices experience a repulsive interaction and precess in the positive (counterclockwise) sense around their common centroid. A similar picture applies to vortices in a two component Bose-Einstein condensate (BEC) coherently coupled through rf Rabi fields. Unlike the classical case, however, the rf Rabi coupling induces an attractive interaction, and two such vortices with positive signs now rotate in the negative (clockwise) sense. This picture is extended to a single vortex in a two-component trapped BEC (a "half-quantum vortex"). P. Massignan and colleagues at ICFO (Barcelona) are exploring numerical simulations of many of these configurations.

Superflows in multicomponent Bose-Einstein condensates

Angela White
OIST Graduate University, Japan

Phase transitions can modify quantum behaviour on mesoscopic scales and give access to new and unusual quantum dynamics. We investigate the phase transition from miscibility to immiscibility in toroidally trapped rotating two-component condensates. We show how in the azimuthally phase separated regime one of the hallmarks of superfluid flow is broken, the condition of quantization of circulation. We find that azimuthally phase separated states exhibit stable rotation for long times, and possess a phase boundary that exhibits classical solid body rotation, despite the quantum nature of superfluid flow. This coexistence of quantum and classical rotation results in the flow pattern following a unique velocity profile, with radial flow developing in regions near the phase boundary, while the atoms in the bulk condensate exhibit the well-know superfluid vortex profile. Furthermore, we show that a transition to radially phase separated states can be driven by two component condensates rotating with a large relative velocity between both of the components, and exhibit intriguing density dynamics.

Dark soliton like excitations in a disk shaped Bose-Einstein Condensate

Nadine Meyer
University of Birmingham, U.K.

Nonlinear systems out of equilibrium give rise to vortex and soliton solutions that play an important role in high speed optical communication[1], energy transport mechanisms in molecular biology[2] and astrophysics[3]. Collective excitations play a paramount role in transport of energy and information and are of special interest. In order to gain a deeper insight in these phenomena well controlled and flexible many body quantum systems at finite temperatures can be used for the simulation of these fundamental collective excitations of the nonlinear Gross-Pitaevski equation (GPE) and their dynamics. The finite temperature regime thereby models systems closer to realistic, everyday life systems in physics and biology.

Here we present the experimental observation of quasi 2D soliton like excitations in a disk shaped Bose-Einstein condensate of 87Rb. The evolution and their dynamics confined in an ultracold atomic system will be discussed.

By using a spatial light modulator (SLM) for optical imprinting, the quantum phase of the Bose-Einstein condensate can be arbitrarily engineered. This versatile method gives rise to a nonlinear particle like matterwave pulses where the dispersion of the soliton like excitation is balanced by the repulsive interatomic interaction. The flexibility of the SLM gives the opportunity for the first creation of Jones Roberts solitons by applying tailored imprints. Their longer lifetimes are crucial for directed and efficient transport on surfaces.

In contrast to formerly performed experiments in elongated BEC traps[4] the dark plane soliton excitations created in the disk shaped Bose-Einstein condensate is dynamically unstable leading to the so-called snaking instability. Here we show both the onset of the expected decay into vortices and the rapid decay of the collective excitation within a few ms possibly due to thermal dissipation. Investigating the lifetime of soliton like structures in the finite temperature regime shows a prolonged lifetime at lower temperatures.

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Towards understanding the collisional dynamics of cold nanoparticles

Kiyotaka Aikawa
Tokyo Institute of Technology, Japan

Cold collisions of atoms and molecules have attracted great interests for decades. Extensive studies on them have found a wide variety of intriguing applications, including evaporative cooling, tuning interatomic interactions, and associating atoms to form ultracold molecules. Recent advances in optomechanical experiments have realized cooling single nanoparticles to the millikelvin regime, opening the novel possibility of exploring their collisional dynamics at unprecedented low energies. In this talk, I will present the efforts towards the experimental investigation on the cold collisions of nanoparticles.

Fast machine-learning online optimization of ultra-cold-atom experiments

Michael Hush
University of New South Wales, Australia

Machine-designed control of complex devices or experiments can discover strategies superior to those developed via simplified models. We describe an online optimization algorithm based on Gaussian processes and apply it to optimization of the production of Bose-Einstein condensates (BEC). BEC is typically created with an exponential evaporation ramp that is approximately optimal for s-wave, ergodic dynamics with two-body interactions and no other loss rates, but likely sub-optimal for many real experiments. Machine learning using a Gaussian process, in contrast, develops a statistical model of the relationship between the parameters it controls and the quality of the BEC produced. This is an online process, and an active one, as the Gaussian process model updates on the basis of each subsequent experiment and proposes a new set of parameters as a result. We demonstrate that the Gaussian process machine learner is able to discover a ramp that produces high quality BECs in 10 times fewer iterations than a previously used online optimization technique. Furthermore, we show the internal model developed can be used to determine which parameters are essential in BEC creation and which are unimportant, providing insight into the optimization process.

Implementing frustrated magnets using Rydberg atoms and ions

Rejish Nath Gopinathan Rejani

Indian Institutes of Science Education and Research (IISER), India

Recent experimental developments in Rydberg dressed atoms and ion crystals opening up new platforms to emulate exotic quantum spin models, in particular, frustrated quantum magnets in which the low energy description is provided by gauge fields. We discuss how the building blocks for such spin models can be designed in cold Rydberg gases and ions by engineering the inter-particle couplings via laser fields. Particular examples for the spin-ice models are considered.

Towards Coherence Measurements of Rydberg Atoms with All-Optical Detection

Lara Torralbo-Campo
University of Tuebingen, Germany

We have developed a non-destructive and time-resolved method to optically detect the population of atoms in a selected Rydberg state (1) as alternative to selective field ionization. This scheme is based on electromagnetically induced transparency (EIT). By monitoring the optical density of the probe laser over time, we can imply the initial population of the Rydberg state. We have tested the new method as proof-of-principle in a cold gas of 87Rb atoms where lifetimes of Rydberg states under various environment conditions were measured (2). This method promises also to provide information regarding the initial coherence of the system. We present the ongoing work towards measurement of the coherence in a Rydberg gas.

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Anomalous broadening in driven dissipative Rydberg systems

Thomas Boulier
JQI, NIST and the University of Maryland, U.S.A.

Due to their strong, long-range, coherently-controllable interactions, Rydberg atoms have been proposed as a basis for quantum information processing and simulation of many-body physics. Using the coherent dynamics of such highly excited atomic states, however, requires addressing challenges posed by the dense spectrum of Rydberg levels, the detrimental effects of spontaneous emission, and strong interactions. It is therefore crucial to explore the consequent deviations between real-life systems and the idealized few-level atoms used in many proposals.

We report the observation of interaction-induced broadening of the two-photon 5s-18s Rydberg transition in ultra-cold 87Rb atoms, trapped in a 3D optical lattice. The measured linewidth increases by nearly two orders of magnitude with increasing atomic density and excitation strength, with corresponding suppression of resonant scattering and enhancement of off-resonant scattering. We attribute the increased linewidth to resonant dipole-dipole interactions of 18s atoms with spontaneously created populations of nearby Rydberg p-states. The dephasing mechanism we observe has significant implications for many-body Rydberg systems in the dissipative regime. In particular, the timescales available for coherent addressing of such systems are dramatically shortened by this effect, hampering many recent proposals to use Rydberg-dressed atoms for quantum simulation of many-body systems. Our results are in the precess of being published, and are available as an arXiv pre-print [Goldschmidt, E. A., et al. "Anomalous broadening in driven dissipative Rydberg systems." arXiv preprint arXiv:1510.08710 (2015)].

Precision spectroscopy and quantum control with coherence diffusion

Yanhong Xiao
Fudan University, China

In an atomic vapor cell with anti-relaxation coating, the ground state coherence can survive wall collisions of more than thousands of times [1]. This offers unique opportunities for precision spectroscopy and quantum control. I will describe a sub-coherence-lifetime spectroscopy technique [2] that gives a linewidth of 0.2 Hz in such cells and allows for high sensitivity magnetometers. Then, I show how one can use the coherence diffusion or transport [3, 4] to spatially split a laser beam of either a coherent state or a squeezed state [5]. Lastly, using atomic coherence as a mediator, we can effective couple spatially separated light modes, and thus construct a parity-time anti-symmetric optical non-Hermitian Hamiltonian [6]. We demonstrate phase transition behaviors and interesting interference phenomenon in this system.

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Practical quantum simulators for quantum field theory

Gavin Brennen
Macquarie University, Australia

An exciting prospect for quantum simulators is to probe physics that is difficult to compute using analytical methods or classical numerical simulations. An especially compelling direction is to simulate quantum field theory. I will discuss two new approaches in this regard. The first is a quantum simulation of 2+1 dimensional U(1) lattice gauge theory using superconducting fluxonium arrays which allows for non destructive measurements of non local order parameters such as space like Wilson loops and 'tHooft strings. The second is a quantum simulation of the holographic principle for a critical 1+1 dimensional conformal field theory. The method uses an encoding based on Daubechies wavelets and can be realized as a multimode entangled Gaussian state of continuous variable systems using e.g. frequency modes in photonic networks.

Directed and controlled quantum walks via generalised PT symmetry

Jingbo Wang
The University of Western Australia, Australia

Parity-Time (PT) symmetric quantum mechanics, although a relatively recent field, has seen a flurry of interest in the past few years due to its ability to analyse seemingly un-physical systems, such as those possessing non-Hermitian Hamiltonians [1]. By redefining the inner-product of Hilbert space, such Hamiltonians produce a real eigenspectrum and conserve probability - neglecting the need for hermeticity altogether. Furthermore, PT-symmetric quantum mechanical structures and systems are beginning to be explored experimentally in photonics [2, 3], suggesting real life applications for a theory that was originally considered largely speculative in nature.

As such, this makes PT-symmetric quantum mechanics a superb framework for the investigation of directed continuous time quantum walks (CTQWs) and CTQWs with sinks/traps - both of which result in a non-Hermitian Hamiltonian [4, 5]. Previous work by Salimi and Sorouri [6] have already shown the feasibility of so called Pseudo-Hermitian methods applied to directed 3-vertices graphs. In this study, we extend this to more general Generalised-PT methods [7] and more complex graphs, with applications in network analysis [8], electron transport in the FMO complex [9], as well as potentially protein folding simulation [10]. Together with X. S. Ma and P. Xu at Nanjing University, we are also exploring the possibility of implementing non-Hermitian PT-symmetric Hamiltonians experimentally to simulate quantum walks on directed graphs.

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Controlling and Probing non-Abelian Emergent Gauge Potentials in Spinor Bose-Fermi Mixtures

Phuc Nguyen Thanh
RIKEN, Japan

Gauge fields, typified by the electromagnetic field, often appear as emergent phenomena due to geometrical properties of a curved Hilbert subspace, and provide a key mechanism for understanding such exotic phenomena as the anomalous and topological Hall effects. Non-abelian gauge potentials serve as a source of non-singular magnetic monopoles. Here we show that unlike conventional solid materials, the non-abelianness of emergent gauge potentials in spinor Bose-Fermi atomic mixtures can be continuously varied by changing the relative particle-number densities of bosons and fermions [1]. The non-abelian feature is captured by an explicit dependence of the measurable spin current density of fermions in the mixture on the variable coupling constant. Spinor mixtures also provide us with a method to coherently and spontaneously generate a pure spin current without relying on the spin Hall effect. Such a spin current is expected to have potential applications in the new generation of atomtronic devices.

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Probing cold 87Rb using ultrathin optical fibres

Sile NicChormaic
OIST Graduate University, Japan

Optical nanofibres (ONFs) have recently emerged as very useful tools for probing and trapping cold atoms, due to the functionality of such fibres in the development of atom-photon hybrid quantum systems. For example, ONFs have been shown to be highly efficient tools for demonstrating nonlinear optics phenomena in atomic media [1, 2]. This arises from the very high evanescent field intensities that can be achieved due to the very tight light confinement within very small mode areas over the length of the nanofibre. Exploiting this phenomenon we have studied quantum interference effects using an optical nanofibre surrounded by cold 87Rb atoms via 2-photon processes at 780 nm and 776 nm. We have observed frequency up-conversion for a 776 nm probe power as low as 200 pW, asymmetric Autler-Townes (A-T) splitting for 20 nW of 780 nm coupling power, and EIT. These power levels are several orders of magnitude lower than those used in free space experiments and provide an all-optical switching technique at the few-photon level.

We also present our recent progress towards ONF-based atom trapping schemes [3,4], which rely on engineering the optical nanofibres by (i) selection of the taper profile to enable higher order mode propagation [3], or (ii) through focussed ion beam milling [4] of nanostructures in the nanofibre. In one study we consider modal interference in few-mode ONFs in order to generate optical potentials around the fibre. In another experiment, we have considered atom trapping by removing the central part of the ONF, thereby creating a slot region rendering the system equivalent to two parallel optical waveguides. This increases the coupling interaction between the fibre-guided modes and atoms near the fibre surface and can also be extended to submicron scale colloidal particle trapping.

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Coherent Control of a Hybrid Optocapillary Resonator and an Experimental Demonstration of a Ripplon Laser

Tal Carmon
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We fabricate a hybrid resonator where the optical resonance is coupled to the capillary resonance. We then control this resonator to operate at the non-resolved sideband regime. Pump interference with capillary Stokes-scattering is therefore resonantly enhanced to allow experimental demonstration of coherent generation of capillary waves. The capillary waves mediates our laser emission similar to charge oscillations mediating Raman lasers. We experimentally record kHz-rate capillary waves that are coherently generated by light and makes audio files containing the sound that they produce.

Relatedly and in more details, energy exchange between light and sound was first suggested by Brillouin in 19221. After Townes established the “phonon maser” theory, coherent generation of intense hypersonic waves was observed together with stimulated Brillouin Scattering.

It is therefore natural to repeat these experiments, but with capillary-waves instead of sound waves. Here we experimentally demonstrate stimulated capillary-scattering and coherent excitation of capillary modes. We do so by fabricating a special type of liquid-walled microcavity that not only contains an optical mode, but also co-hosts a capillary resonance. Our micro-spherical resonator is made of a low-viscosity liquid that is also highly transparent so that its capillary quality-factor [Qcap] is 18 while its optical one [Qopt] is 10 million. We then control our hybrid optocapillary-cavity to operate at its non-resolved sideband regime where energy transfer from light to capillary oscillations (Stokes) is preferred over the reversed one. Coherent capillary-resonance at audio-band rates (kHz) is optically excited at pump threshold of 77 μW, while generating stimulated capillary-scattering. Our device might extend its impact beyond just ripplon lasers.

Possible unexplored areas that will be accessible with optocapillary cavities include sideband-cooling and coherent-control of capillaries.

Bose-Einstein Condensation of Photons and Periodic Potentials for Light

Martin Weitz
University of Bonn, Germany

Bose-Einstein condensation has been observed in several physical systems, including cold atomic gases, exciton-polaritons, and magnons. Photons usually show no Bose-Einstein condensation, since for Planck's blackbody radiation the particle number is not conserved and the photons at low temperatures vanish in the system walls. I here describe experiments with a dye-filled optical microresonator experimentally observing Bose-Einstein condensation of photons. Thermalization is achieved in a number conserving way by photon scattering off the dye molecules, and the cavity mirrors provide both an effective photon mass and a confining potential. I will also report on recent work realizing periodic lattice potentials for the photon gas.

Correlations and energy transfer in many-body localized systems

John Goold
The Abdus Salam Centre for Theoretical Physics, Italy

The phenomenon of many-body localization (MBL) in disordered quantum many-body systems occurs when localization survives in the presence of interactions. Since its inception a decade ago it has received a significant amount of interest and its study is currently blossoming into a vibrant research field with experiments up and running in both ion traps and optical lattices. In this talk I will introduce the total correlations, a concept from quantum information theory capturing multi-partite correlations, to the study of this phenomenon. We demonstrate that the total correlations of the diagonal ensemble provides a meaningful diagnostic tool to pin-down, probe, and better understand the MBL transition. In the second part of the talk I will discuss results on energy transfer dynamics in quenched MBL systems. In all cases I will demonstrate the phenomenology numerically using a one dimensional system of interacting Fermions on a disordered lattice.

Boosting performance of a quantum heat engine with an interacting-Bose gas as a working medium

Juan Diego Jaramillo
National University of Singapore, Singapore

We study a quantum heat engine operating in an Otto cycle with a working medium comprised of a Bose gas with inverse square two-body interactions. We report the conditions under which many-particle effects enhance the optimal power output per cycle and the associated engine efficiency. In particular, we report for a large number of weakly interacting bosons in the thermodynamic limit a quantum enhancement of the engine efficiency by up to 50 percent with respect to the single-particle case.

Spin control in quantum dot by fast and robust Landau-Zener type passage

Yue Ban
Shanghai University, China

An analytical approach of the inverse engineering by using a single variable is proposed in order to control the charge qubit of a double quantum dot. The corresponding driving electric field is derived correspondingly. Furthermore, the fluctuations in the driving field and the phase errors in the system are checked. Fast and robust quantum gates are constructed based on the protocol.

Quantum and classical control of single photon states via a mechanical resonator

Sahar Basiri Esfahani
The University of Queensland, Australia

We describe quantum interference of one and two photon states at a controlled beam splitter with a transmitivity/reflectivity that can be varied by exciting a single bosonic degree of freedom representing a mechanical resonator. When the mechanical resonator has a small coherent amplitude it acts as a quantum control, entangling the optical and mechanical degrees of freedom. As the coherent amplitude of the resonator increases we recover single photon and two-photon interference via a classically controlled beam splitter. This mechanically induced coherent photon conversion scheme provides a new route to use opto-mechanics to produce multiquanta comples photonic states with applications in photonic quantum information processing.

A Quantum Optomechanical Interface in the Unresolved Sideband Regime

James Bennett

EQuS, The University of Queensland, Australia

A key operation in the control of multimode quantum systems is the state swap. For instance, the ability to perform a light-to-matter state swap enables one to build quantum memories and reliable repeaters. These are anticipated to be crucial for potential future information distribution and processing networks [1].

Cavity optomechanics provides a promising platform for such interfaces. It combines the benefits of optical information transmission with the flexibilitiy of mechanical oscillators, which may readily be functionalised so as to interact with diverse types of physical systems [2]. For example, an oscillator within a magnetic field gradient may be coupled to a spin [3].

Traditional optomechanical schemes are capable of performing optical-to-mechanical state swaps in the regime where the cavity linewidth is small compared to the mechanical frequency (the resolved sideband regime). Here we consider the opposite limit, which is a natural operating situation for low-frequency devices. In this unresolved sideband case it is possible to generate optomechanical quantum non-demolition (QND) interactions by using pulsed illumination [4]. These have been proposed previously to permit one-way state transfer between light and a matter system [5,6,7].

We show that combining three QND interactions with local mode rotations allows one to perform two-way optical-to-mechanical state swaps [8]. These are not limited to Gaussian states. Our scheme requires only open-loop control, is deterministic and measurement-free. Furthermore, controlling the mean photon number in each pulse permits squeezing of the transferred states by a desired amount.

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SAP beyond STIRAP: interactions, higher dimensions and shortcuts

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The spatial adiabatic passage (SAP) technique has been proposed to accurately control the external degrees of freedom of trapped particles in a robust manner, i.e., without requiring an accurate control of the system parameters. In its most basic form, it is a analogue of the quantum-optical stimulated Raman adiabatic passage (STIRAP) technique, and transfers an atom between the ground states of two spatially-separated traps.

Adiabatic passage of neutral atoms in space allows to consider situations that possess more degrees of freedom than usually found on optical systems. Among these additional degrees of freedom are access to higher dimensionalities, the possibility to create and control finite (angular) momentum states, the presence of interactions in many-particle systems and the ability to add external fields. Here we will discuss all of these and show that they allow to extend the range of quantum states that can be accessed significantly.

While adiabatic techniques allow to obtain high fidelities and are robust against noise and errors, their adiabatic nature is often considered to be an obstacle, as it prevents experimental implementation. For spatial adiabatic passage, however, we will show that a shortcut to adiabaticity exists, which can be experimentally implemented with existing technology.

Quantum simulations and quantum measurements via quantum walks

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Firstly, we experimentally investigate a photonic quantum walk (QW) and observe typical phenomena known from the wave propagation in periodic structures as ballistic spreading. We introduce site-dependent phase defects to the QW which is realized by adding fully controllable polarization-independent phase shifters and observe localization [1,2] and oscillations of the photons [3], and as well as collapse and revival of the coherent information which is encoded in the polarization and spatial modes of photons [4], and Landau-Zener tunneling for strong phase gradients.

Secondly, we experimentally show that QWs are capable of performing generalized measurements on a single qubit [5]. Our demonstration employs a novel photonic QW with site-dependent coin rotation for realizing a generalized measurement. The key experimental advance for realizing a QW-based generalized measurement is the application of site-dependent coin rotations to control the coin's internal dynamics and, thereby, effect the evolution of the walker. Thus, we have demonstrated a new and versatile approach to generalized qubit measurements via photonic QWs.

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Irreversible entropy production in mesoscopic quantum systems out of equilibrium

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Every finite-time transformation results in some production of entropy, which signals the occurrence of irreversibility. Quantifying the amount of irreversible entropy produced is a goal of paramount importance, being a fundamental quantity for the characterisation of non-equilibrium processes. It is also a task of practical interest, since its minimisation improves the efficiency of thermal machines. So far, nanoscale systems have been used for the experimental study of classical out-of-equilibrium thermodynamics; for instance, fluctuation theorems have beee tested in a variety of classically operating systems such as a single-electron box, a two-level system driven by a time-dependent potential, and a levitated nanoparticle undergoing relaxation. However, irreversible entropy production arising from quantum dynamics has not been experimentally addressed so far. In particular, irreversible entropy production in non-equilibrium large-scale quantum systems has remained unobserved.

We developed a theoretical framework to quantify the rate of entropy produced by an open quantum system --- consisting of coupled quantum harmonic oscillators --- in a non-equilibrium steady state. We compare the theoretical predictions with experimental measurements coming from two different platforms: a cavity-optomechanical device and a Bose-Einstein condensate (BEC) with cavity-mediated long-range interactions.

Both the micro-mechanical resonator and the BEC, being coupled to a high finesse cavity, are hence subject also to optical losses. We found excellent agreement between the experimental data and the predictions of our framework. Key features of our setups, such as the cooling of the mechanical resonator and signatures of a structural quantum phase transition in the condensate are reflected in the entropy production rates. This demonstrates the possibility to explore non-equilibrium thermodynamics in driven mesoscopic quantum systems, and paves the way to a systematic experimental assessment of the implications of out- of-equilibrium processes on such systems.

Creating giant oscillating molecular dipoles by highly correlated electronic and nuclear motion

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The dynamics of molecular properties is always associated to the quantum superpositions of Hamiltonian eigenstates. While the nuclear wave function encodes the molecular structure, given by the shape or the geometry, the electronic distribution is responsible for the chemical properties. The correlation between electronic and nuclear motions generally manifest as smooth changes of the electronic distribution with respect to changes in the nuclear coordinates, which is the result of the different time scales of electronic and nuclear motions, i.e., of the widespread validity of the Born-Oppenheimer approximation. To date, most of the studied dynamical processes in molecules involve superposition of vibrational states belonging to the same electronic state. In the present work, we use ultrashort laser pulses to prepare wave packets containing quantum superpositions of both electronic and nuclear degrees of freedom, such that the motion of both electrons and nuclei is highly correlated and occurs in the time-scale of the nuclear motion.

In particular, using the molecular Hydrogen ion as a benchmark, we show how the molecule reacts to very strong nonresonant fields as a molecular antenna. However, only by preserving the coherence of the electronic and nuclear motion with very specific pulse conditions (or static fields) below the onset of ionization, it is possible to create huge oscillating dipoles with amplitudes of the order of 40 Debye. This has potential applications in controlling the reactivity of a molecule, which is greatly influenced by the electronic density, and in generating electromagnetic radiation of specific frequencies.

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Time-optimal control of nonlinear two-level system

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Nonlinear two-level systems with relevance for Bose-Einstein condensates and nonlinear optics are considered and the minimal time $T_{\rm min}$ to drive an initial state to a given final state is investigated. Surprisingly, for a large class of systems the nonlinearity is canceled by an unconstrained time-optimal driving and $T_{\rm min}$ becomes independent of the nonlinearity. For unconstrained and constrained driving explicit expressions are derived for $T_{\rm min}$, the optimal driving, and the protocol.

Generation of a planar squeezed state in a cold atomic ensemble

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Production of squeezed states is of great interest for quantum metrology [1] and allows production of exotic highly entangled spin states [2], a powerful resource for quantum simulators.

However, while canonical variables such as quadratures of the radiation field can be squeezed in at most one component, a planar quantum squeezed (PQS) state, where two orthogonal spin components are simultaneously squeezed can be achieved due to the angular momentum commutation relations. Such states have recently attracted attention due to their potential applications in atomic interferometry and quantum information [3, 4].

Here we report the generation of a PQS state by coherently rotate the collective spin of a cold atomic ensemble of more than one million atoms [5].

We induce spin squeezing through quantum non-demolition (QND) measurements [1] and a coherent rotation by an external magnetic field that rotates a coherent spin state on a plane.

This allows us to successively measure and squeeze two components of the atomic spin, while maintaining a large spin polarization (coherence) in the plane.

We observe 3dB of spin squeezing and quantum enhanced sensitivity in the estimation of the magnetic field for any angle in the rotation plane, and detect entanglement by using generalized spin squeezing inequalities [3,4].

Our results are consistent with theoretical predictions [3] using covariance matrix techniques [6] with realistic experimental parameters, including technical noise contributions from the number of atoms, gradients and fluctuations of the magnetic field.

As we recently proposed [7], the production of squeezed states and their coherent control with magnetic fields is also a promising resource to rigorously observe quantum mechanical effects at the macroscopic scale through the violation of Leggett-Garg inequalities.

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A quantum platform using Rydberg atoms in magnetic lattices

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We present our recent results of research of atomic ensembles in twodimensional array of Ioffe-Pritchard type magnetic traps[1]. Clouds of cold 87Rb atoms are loaded in an array of magnetic lattices separated by 10 m lattice spacing, which is comparable to the dipole blockade radius between Rydberg atoms. We present measurements on Rydberg excitation in the vicinity of the chip surface, showing massive stray electric fields due to surface adsorbates. We also show results of our attempts to remove surface adsorbates by illumination with UV light.

Multi-partite Entanglement detection for many-atoms systems

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We propose a novel method of evaluating the squeezing of quantum fluctuations in an atomic ensemble for an inhomogeneous laser-atom interaction. We find that our method gives a lower bound on separability of a quantum state when compared to the widely used definition of squeezing parameter ξ^2. Furthermore, we show that measure of entanglement in an atomic ensemble in terms of ξ^2 can be erroneous, particularly if the ensemble is not homogeneous for laser-atom interaction. As a remedy we develop procedures that allow us to determine both if and how much the system is entangled. We give explicit bi-partite and multi-partite entanglement measures for atomic ensembles. We also provide a comparison of our method for entanglement measure to an experiment related to quantum metrology that utilizes entanglement.

Controllable non-local solitary wave structures in dipolar condensates

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The recent achievement of condensation with atoms possessing significant magnetic dipole moments [1-3] affords a new opportunity to explore the interplay of magnetic effects with the coherent nature of the condensate. The ability to precisely control the condensate's dimensionality and interactions by tuning the scattering length of the many particle atomic system allows the creation and probing of long-lived solitary wave structures [4,5].

We investigate theoretically the form and interaction of bright and dark solitary waves in dipolar condensates, over the full parameter space of the quasi-one dimensional system. The solitons themselves develop a dipolar character, introducing novel long-range soliton-soliton interactions, in addition to the well-known short-range interaction between solitons. For dark solitons with dipoles polarized perpendicular to the axis of the condensate, unconventional bound states are found. Remarkably it is shown that these bound sates also behave as solitons, preserving their form when interacting with other bound dark solitons [6].

We also present the equivalent bright solitary wave solutions, investigating their mutual interaction as a function of both the polarization and strength of the dipole-dipole interaction, as well as exploring the important role that their relative phase plays during collisions. Our simulations are found to be in good agreement with a particle model for the bright solitons dynamics. Opportunities for creating novel soliton crystals and super-solitons will also be discussed.

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Engineering Many-Body Systems with Quantum Light Potentials and Measurements

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Interactions between many-body atomic systems and light in cavities induce new atomic dynamics, which we show can be tailored by projective light measurement backaction, leading to collective effects such as density-density interactions, perfectly-correlated atomic tunneling, superexchange, and effective pair creation and annihilation. These can be long- and short-range, with tunable strengths, based on the optical setup. We demonstrate that the measurement backaction also results in the generation of multiple many-body spatial modes of the atoms, with nontrivial spatial overlap and multipartite entanglement properties. We show this provides a framework to engineer states such as multimode generalizations of parametric down-conversion and Dicke states, and to enhance quantum simulations of novel physical phenomena, including reservoir models and dynamical gauge fields, beyond current methods. Furthermore, we propose how the modes can be used to detect and measure entanglement in quantum gases.

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Non-Equilibrium Thermodynamics of Harmonically Trapped Bosons

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Trapped ensembles of bosonic atoms represent an ideal candidate to simulate some of the most interesting aspects in the phenomenology of out-of-equilibrium quantum systems. I will focus on harmonically trapped bosons and use the framework of non-equilibrium thermodynamics to the study the role quantum features play in setting the dynamic and static properties of the systems when the Hamiltonian parameters are suddenly quenched [1]. Through a combination of analytical and numerical approaches I explore the non-trivial dynamics that arise from the interplay between the quenched trap frequency and an induced quench of the inter-particle interactions which can result in interesting quantum phenomena such as Anderson's Orthogonality catastrophe and the creation of breathing modes. I will further show some qualitative evidence for the relationship between the creation of entanglement and the (irreversible) work performed on the system. This highlights interesting connections between the degree of inter-particle entanglement and their non-equilibrium thermodynamics.

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Coherent manipulation of Andreev states in superconducting atomic-size contacts

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The absorption of a photon by a superconductor is usually an incoherent process in which a Cooper pair is broken into a pair of independent quasiparticles. Here we show that in an atomic-size contact between two superconductors it is possible to coherently excite a pair into a discrete localized bound state. By coupling the contact to the electromagnetic field of a microwave resonator we perform time resolved experiments of this particular excitation. Lifetimes of several microseconds are measured for the excited state of the localized pair. Decoherence times of several tens nanoseconds are measured for coherent superpositions of states, which can increase up to a microsecond with an echo sequence. Single shot measurement of the quantum state of the pair is achieved when using a large number of photons in the resonator.

Quantum Trajectory Thermodynamics with Discrete Feedback Control

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Stimulated by the development of the nonequilibrium statistical physics in small systems in the last two decades, there are renewed interests in the thermodynamics of information processing, represented by the feedback control processes, at the nano and even the atomic scale. For classical systems, the fundamental thermodynamic variables, such as work and heat, and information gain have been well understood at the level of individual trajectories. On the other hand, there have been few progresses in the quantum aspects of the thermodynamics of information, due to the difficulty to consistently define the thermodynamic variables and information gain along a single quantum trajectory.

Only recently, it is found that the quantum jump trajectory (QJT) approach, originally developed in quantum optics, provides the most natural basis to define the thermodynamic variables in the quantum context. Based on such QJT approach, we construct a systematic framework to study the thermodynamics at the trajectory level in a nonequilibrium open quantum system under discrete feedback control. Within this framework, we derive the quantum versions of the generalized Jarzynski equalities, which can be regarded as refined Landauer's principles. One of the generalized Jarzynski equalities shows qualitative difference from its classical counterpart. These fluctuation theorems are verified in a coherently driven two-level open quantum system, which demonstrates a quantum Maxwell's demon. A possible experimental scheme to test our findings in superconducting qubit systems is discussed.

Confined quantum Zeno dynamics of a watched atomic arrow

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In the quantum world, the coherent Hamiltonian evolution of a system can be blocked by a series of frequent measurements. This is the Quantum Zeno Effect (QZE), it has been successfully demonstrated in many experiments on various physical systems.

A more general phenomena can be obtained if the measurement has a degenerate eigenvalue. In this case, the system is no longer frozen in the initial state but it evolves coherently in the subspace corresponding to the result of the measurement, giving rise to a Quantum Zeno Dynamics (QZD). We have studied QZD on a Rydberg atom. We use a well polarized radiofrequency field field to manipulate the state of the atom inside the Stark level manifold. The atom behave like a large spin (J= 25). By measuring a specific level with a continuous selective measurement, we can confine the atomic state evolution and have observe the generation of deterministic nonclassical state like Schrodinger's cat of an angular momentum pointing in two opposite classical directions. We are building a new experiment where the atomic beam will be produced from an atomic fountain. We would like to couple the Rydberg atom to the mode of a superconducting cavity. Our well polarized radiofrequency field allows us to prepare into the circular state atom that are stationary in the center of the cavity mode. This would drastically increase the interaction time with the field, opening the way to new generation of cavity QED experiment with atoms.

Quantum Zeno effect in parameter estimation

Alexander Holm Kiilerich
Aarhus University, Denmark

The quantum Zeno effect freezes the evolution of a quantum system subject to frequent measurements. We apply a Fisher information analysis to show that because of this effect, a closed quantum system should be probed as rarely as possible, while a dissipative quantum system should be probed at specifically determined intervals to yield the optimal estimation of parameters governing the system dynamics. With a Bayesian analysis we show that a few frequent measurements are needed to identify the parameter region within which the Fisher information analysis applies.

A universal scheme for indirect quantum control

David Layden
University of Waterloo, Canada

The goal of indirect quantum control is to coherently steer a quantum system solely by acting on a quantum actuator to which it is coupled. This approach to quantum control is convenient in numerous physical settings, as it allows one to avoid direct addressing of the system—and any associated difficulties—altogether. While it is known in principle that control of the actuator typically yields universal control of the system, the practical details of how such indirect control can be achieved are less clear. This deficiency has led to a number of implementation- and model-specific indirect control schemes, in lieu of a general recipe applicable to any physical setting. Here, we present such a recipe, in the form of an open-loop control scheme which implements arbitrary unitary operations on the system by exploiting open dynamics in the actuator. As an example, we show how our scheme can be used to indirectly control a nanomechanical resonator via an addressable qubit.

Self-assembled spin chains of strongly interacting cold atoms

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Physicists today are able to manipulate cold atoms in optical traps to such a degree of accuracy that a lot of interesting models can be simulated. Specifically, it is possible to realize the Heisenberg spin chain model using cold strongly interacting atoms in a one-dimensional trap. By tuning the geometry of the trap, it is possible to engineer the local exchange coefficients and obtain self-assembled spin chain Hamiltonians. We have developed an efficient computational method that provides the link between the geometry of the confining trap and the spin chain Hamiltonian. We suggest that our method can be used as a powerful theoretical tool for realizing many spin chain models with cold trapped atomic gases.

Sideband cooling of capillary waves.

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We control an optocapillary resonator to operate at its non resolved sideband region. As a result, anti-Stokes scattered light coherently interferes with the pump laser annihilating ripplons and cooling down thermal capillary waves. We employ a novel light-mater interaction exclusive to liquid surfaces that was recently discovered in liquid walled optical microcavities.

We provide experimental results, showing that the cooled sideband exhibit oscillations that are 6 times smaller in amplitude when compared to the heated sideband control group. While sideband cooling of gasses and acoustical waves was widely studied, this is the first time on capillary waves are cooled and could potentially lead to a new platform for quantum studies in the future.

Fast coherent control of quantum systems with counter-diabatic and fast-forward protocols

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Various external control schemes of the dynamical evolution of quantum many-body systems have been proposed. The control schemes rely on coherence and interference effects embedded in the quantum dynamics of the system, and vary in efficiency, generality of application, and sensitivity to perturbations. For example, they have been used to realize high fidelity (sensibly perfect fidelity) for quantum computing and to enhance the efficiency of chemical reactions (higher fidelity). In this talk, an assisted adiabatic control of vibrational population transfer of a molecule in dense liquid and a novel fast control of Bose-Einstein condensates (BEC) are discussed.

Adiabatic dynamics of a quantum system is useful when external field-generated variation of the Hamiltonian is used to manipulate the system's evolution. However, an adiabatic process must be carried out very slowly. In such slow processes decoherence caused by interaction with an environment can degrade the fidelity of the control. Recognition of this restriction has led to the development of control protocols, which we call assisted adiabatic transformations or shortcut to adiabaticity [1].

Benefit of using the assisted adiabatic transformations is not only avoidance of unwanted nonadiabatic transitions. It has been shown that the alternating transport of a BEC generated by the fast-forward driving field suppresses the influence of a fluctuating random potential on the BEC [2]. It was also shown that the auxiliary field suppresses a influence of background states and enhance the efficiency of population transfer when it is applied to a selective vibrational population transfer of isolated polyatomic molecules [3].

In this talk, we show that the counter-diabatic field enhances the efficiency of population transfer in vibrational levels of a molecule in dense liquid suppressing the influence of collisions of atoms surrounding the molecule. We examined a four-state system that models the ground and the first three vibrational levels of HCl in dense fluid Ar [4]. The collisions, whose effect is represented by fluctuations in the energy levels, severely degrade the efficiency of STIRAP generated population transfer. Long pulse control (adiabatic control) cannot improve the control efficiency (even decrease the efficiency) in contrast to simple three-state system because of the fluctuations in the energy levels. Provided that our model of a HCl molecule embedded in dense fluid Ar captures the essential qualitative features of the influence of collisions on a controlled coherent dynamical process, the results of our study show that there is a range of field strengths and pulse durations under which STIRAP + CDF control of population transfer has greater efficiency than does STIRAP generated population transfer. It is thereby implied that other assisted diabatic processes may be useful for the control of quantum dynamics in non-isolated systems. This research was conducted in collaboration with Dr. Stuart A. Rice.

In the second half of this talk, we show a novel control of the phase of wave function using the fast-forward protocol. In the fast-forward protocol, we specify the form of the wave function of the intermediate state with an additional phase, and then derive the driving field. We utilize this property to manipulate the phase of the order parameter of a BEC to realize a state with interesting properties.

If we have enough time we also report recent progresses in our experimental research on manipulation of photon state in the coplanar microwave resonator with inelastic electron tunneling in SINIS junctions.

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Parameter Estimation in Strongly Correlated Systems at Thermal Equilibrium

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In This work we deal with estimation of Hamiltonian couplings in strongly correlated systems (e.g. magnetic field strength in the XY Hamiltonian), in thermal equilibrium. To this end we first use tools from quantum metrology and find the ultimate precision of estimation allowed by quantum mechanics. Then we suggest some protocols/observable (for instance in the XY model the collective angular momentum) using which one may achieve a reasonably precise estimation, compared to the ultimate bound.

Specially we prove the optimality of the collective angular momentums in the estimation of an external magnetic field. In this case we show that the quantum Fisher information, a measure of the distance of quantum states in the parameter space, is equal to the magnetic susceptibility (up to a constant), which is a welknown physical quantity.

We observe that in some phases thermal fluctuations lead to a better estimation, and explain why it happens.

Finally we propose how to make the estimation more efficient, when having control over an internal parameter for example the spin-spin correlations.

Non-linear optomechanical coupling of a membrane to a cavity

Mathias Mikkelsen
OIST Graduate University, Japan

In this study we consider the optomechanical set-up consisting of a membrane placed in a cavity. The standing wave of light in the cavity couples with the membrane, changing its position by imparting momentum, which then changes the resonance frequency of the cavity thus creating a back-action effect. Through the side-band cooling technique significant progress towards reaching the quantum ground state of the oscillating membrane has been achieved[1, 2]. However, so far previous theoretical work on the system has assumed a linear optical coupling to the membrane (1 photon interaction) and it is therefore of considerable interest to see whether adding a non-linear optical coupling (2-photon interaction) gives rise to any new phenomena. In this study we derive the general analytical equations which describes the non-linear system using the Quantum Langevin formalism and present some preliminary numerical results showcasing the effect of the non-linear coupling. For example we find that the non-linear system exhibits bi-stability at vastly different parameter ranges compared to the linear system and that the nonlinear system can display enhanced cooling in certain parameter regimes.

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Laser-induced Kondo effect and topological phases in ultracold alkaline-earth atoms

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Kondo effect is a ubiquitous phenomenon in condensed matter physics. For example, the Kondo effect plays a central role in many heavy-fermion materials, leading to plethora of intriguing phenomena such as quantum criticality. In this presentation, we propose that the laser excitation in ultracold atoms coherently induces a novel Kondo effect which cannot be realized in usual solid-state systems. Motivated by recent development of manipulation techniques of ultracold alkaline-earth atoms, we consider a two-orbital model of ultracold SU(N) fermions coupled with external laser. We show that optical transitions between the two orbitals induce effective hybridization between them and result in the emergence of the Kondo effect. Since the laser field strongly couples with the spin degrees of freedom of atoms, the laser-induced Kondo state shows some "anomalous" properties, such as spin-selective renormalization of effective masses and peculiar dependence on the polarization of the laser. Furthermore, we demonstrate that the optically induced Kondo effect can be used to manipulate a topological phase transition from a Haldane-like phase to the Kondo state, when we focus on a one-dimensional version of this system.

Fast control of topological vortex formation in BEC by counter-diabatic driving

Mikio Nakahara
Kinki University, Japan

Fast creation of a single vortex in BEC of alkali atoms at a prescribed position and time is still challenging even though various methods to create single and multiple vortices have been proposed and demonstrated. Topological vortex formation is advantageous in this respect over other methods in that the position and the time of vortex formation is highly controllable. This method requires inversion of the bias magnetic field along the axis of the condensate, which leads to unwanted atom loss due to non-adiabatic transitions when the bias field crosses zero. It is the purpose of this work to propose a scheme that enables a fast creation of a vortex in much shorter time than needed for adiabatic control time by introducing the counter-diabatic field to avert the atom loss. We further introduce a gauge transformation so that the required magnetic field is generated by manipulating the current of the Ioffe bars, which makes our proposal experimentally feasible.

Manipulating the Squeezing Properties of a Degenerate Parametric Amplifier with Coherent, Time-Delayed Feedback

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Recent developments in experimental conditions have shifted theoretical interest from measurement-based to the more efficient coherent feedback setups [1]. Quantum squeezing of light is an important and topical example to investigate in this context. Enhanced optical squeezing on resonance has been reported for a degenerate parametric amplifier (DPA) with a coherent feedback loop [2, 3], however a time-delay that is comparable to the inverse cavity decay rate has not been considered. This theoretical work addresses the intriguing influence of time-delayed, coherent feedback on the output squeezing spectrum of a DPA in a simple system.

In our setup both mirrors of the DPA cavity are partially transmitting, which is a more practical setup compared to previous proposals. The output field on one side is directly fed back to the input channel of the other side and homodyne detection is performed on the output field of that side. We investigate a wide variety of different operating conditions, including the effects of loss and phase shift in the feedback loop as well as detuning from the cavity resonance. For a given pump strength, as a consequence of time-delay, we find a substantially modified region of stability, which can be interpreted as a shift of the parametric oscillation threshold. With suitable choices of time-delay and measurement parameters, we also find dramatically enhanced squeezing, relative to a conventional one-sided DPA without feedback, in sidebands that are offset from the cavity resonance frequency.

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Quantum metrology with a partly unknown generator

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Quantum metrology aims to estimate a parameter encoded in the state of a quantum system by a unitary transformation. We have studied a scheme in which the generator of the transformation is not entirely known a priori but can vary according to a probability distribution with variable spread, centered about a design value. We have compared the situations where the optimal and design measurements are carried out. In both cases, when using a maximally correlated input state, with n sequential applications of the transformation, the 1/n (Heisenberg) scaling of the mean square error is retained for all spreads of the generator probability distribution until a uniform spread is reached where the error scales as 1/n^(1/2), as expected classically. This highlights the robustness of quantum enhancements in phase and magnetic field estimation scenarios with fluctuating generators, and can be relevant for experimental applications.

Dynamics of large vortex lattice carrying Bose-Einstein condensates

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We examine the dynamics of a rapidly rotating Bose-Einstein condensate with a large vortex lattice subjected to differing perturbations. The first work shows a delta kicked condensate, with an optical lattice matching the vortex lattice structure. This generates superlattice structures in the density. The second work involves manipulating the vortex lattice order via direct engineering of the wave function phase.

Towards the investigation of collective scattering in nanofiber-trapped atomic ensembles

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Nanofiber-based atom-light interfaces are promising candidates for quantum information processing and communication (QIPC) applications. The key component is a nanofiber-based optical dipole trap which stores laser-cooled atoms in the evanescent field around the fiber [1, 2]. In this evanescently coupled atom-waveguide system, a single trapped atom can scatter close to 10 % of a weak resonant light field out of the fiber. The light scattered from the array of trapped atoms into the free space can interfere such that the resultant emission has a well-defined angular distribution about the fiber axis. Moreover, when the atomic array has the right periodicity the fiber-guided light shows reflection and transmission properties similar to those observed for a conventional fiber Bragg grating. However, the distinct polarization properties of the fiber-guided light give rise to some interesting effects [3]. We plan to study these collective scattering phenomena in a new experimental apparatus.

Our novel experimental setup offers distinct advantages over previous nanofiber-based atomic trap setup. We use a glass vacuum chamber to host the tapered nanofiber, allowing a much higher optical access. This also enables us to place our magnetic coils much closer to the fiber in order to obtain stronger and more uniform magnetic fields and field gradients. Using rectangular shaped coils, and by appropriate choice of the longitudinal and transverse field gradient, we plan to generate cigar shaped atomic cloud that essentially covers the entire nanofiber waist. This ensures a larger number of atoms trapped and hence a higher optical depth and stronger collective effects. Using state-insensitive trapping [4] and ground state cooling [5] we will try to increase the coherence time of the trapped atoms. The setup also hosts two absorption imaging setups to image the atomic cloud in two orthogonal directions perpendicular to the fiber waist. This arrangement will be used to estimate the temperature of the atomic cloud by time of flight measurement as well as to estimate the total number of atoms trapped.

As a first step, we plan to observe the directed scattering of the nanofiber-guided resonant probe light by the periodic atomic array. Owing to the glass vacuum chamber, we can observe this directed emission by intercepting the scattered radiation at a particular angle to the nanofiber axis which can be pre-determined from the experimental parameters. This effect can possibly be used to increase the success rate of the write step of a nanofiber-based implementation of the DLCZ protocol [6] where not only the overall probability of spontaneous Raman scattering into the fiber is enhanced, but also the directionality of emission.

Owing to spin-orbit coupling [7], the directed coherent emission as well as backscattered radiation depends strongly on the polarization and direction of the propagating guided modes in the fiber. In particular, by achieving a Bragg resonance condition with a moderately large atomic lattice the coherent emission into the forward and backward propagating modes are drastically changed: the light polarized in-plane (out-of-plane) with the atomic array is weakly (strongly) reflected [3]. With our experimental setup we plan to study such collective scattering effects in nanofiber-trapped atomic ensembles.

As an extension to the experiment, we plan to impose a desired periodicity of the trapping potential. This can be achieved by overlapping an external standing wave of an appropriate wavelength at a certain angle with the nanofiber to create the desired trapping potential.

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Quantum walk and 2D phase

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This poster reflects the work I have done for my current rotation. The primary goal of this rotation project was to implement the quantum walk in 1D and investigating the effect of phase branch on the final interference, so far we have developed a MATLAB code to investigate the dynamics of a particle in different number of wells.

In classical system, the probability distribution of finding particle with random movement approaches to a Gaussian distribution[1]. However for quantum system, the movement of the particle is determined by its spin, when its spin is up $|\uparrow\rangle$, particle moves to the right and if $|\downarrow\rangle$ particle moves to the left. Its movement can be formalised by a shift operator $S= |\uparrow\rangle\langle\uparrow| \otimes |x + 1\rangle\langle x| + |\downarrow\rangle\langle\downarrow| \otimes|x - 1\rangle\langle x|$and a coin (Hadamard) operator to rotate the spin of particles. The existence of the superposition in each step of walk creates an interference of states in later steps which is totally different from classical random walk. The Hilbert space of the whole system, particle $\{|\Psi x\rangle|x \in 0 \cup Z+\}$ plus coin operator $C(\theta)$ is $Hc\otimes HS$ where HC and HS are the Hilbert spaces of quantum coins and nodes of the graph respectively.[2]

We have chosen ultra-cold atom which trapped in simple harmonic oscillator. The dynamic of angular momentum of single atom in a ring trap create an interference which could be potential candidate for implementing quantum walk and investigating the effect of phase branch cut on it.[3]

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Creating vortex rings in BECs in artificial magnetic fields

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Artificial gauge fields are versatile tools that allow to control the dynamics of ultracold atoms in Bose-Einstein condensates. Here we discuss a method of artificial gauge field generation stemming from the evanescent field of the curved surface of an optical nanofibre. The exponential decay of the evanescent fields leads to large gradients in the generalized Rabi frequency and therefore, in turn, leads to generation of geometric vector and scalar potentials around nanofibre. We perform numerical simulations of two-dimensional GPE using the artificial gauge fields originating from the fundamental HE$_{11}$ mode, and show that they lead to the generation of vortex rings.

A Single Atom Probe for Ultracold Gases

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Combining a single atom with an ultracold quantum many-body system opens the pathway for a controlled implementation of impurities in the many body system, acting as a model for condensed matter simulation. On the other hand, the single atom can probe the properties of the strongly correlated many-body state non-destructively and locally, facilitating the study of the decoherence of a Bose-Einstein condensate (BEC), its phase fluctuations, or local and time-resolved thermometry.

Here, we present a quantum gas system, comprising a BEC of Rubidium (Rb) atoms in combination with single neutral Cesium (Cs) atoms. Our hybrid system will be employed to study the coherent interaction of the single Cs impurities with the Rb many-body system.

Experimentally, we show the deterministic immersion of single or few Cs atoms in an ultracold, thermal Rb cloud, where the dynamics of the Cs probe within the Rb bath is determined. Therefore, we pin the Cs atoms after a certain interaction time with an optical lattice and thereby freeze the dynamics. This allows for studying the interaction with time and spatial resolution. Also, we measure the Cs thermalization with a revisited release-recapture thermometry technique.

Besides utilizing the single atom as a local probe for a thermalized Rb system, thermometric measurements of non-equilibrium states can be performed, which have attracted much interest in the community recently.

Uncertainty limits of the Poincaré sphere

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Polarisation is the characteristic of choice in numerous experiments at the forefront of quantum mechanics such quantum teleportation, quantum dense coding and quantum cryptography. This stems from the fact that polarisation is a robust degree of freedom which can be easily and cheaply manipulated and transformed. In classical optics, the Stokes parameters are used to describe the polarisation status of light which are formally equivalent to the angular momentum operators. However, the classical definition of the degree of polarisation as the length of the Stokes vector proves insufficient in the quantum domain where one can encounter “hidden polarisation”, i.e., states that appear unpolarised but are found to possess polarisation structure via higher order correlation measurements. Thus, not only is it essential to consider quantum fluctuations of Stokes operators to arrive at an operationally adequate description of polarisation in the quantum domain, from the aspect of metrology quantum fluctuations of angular momentum or Stokes operators, and hence their uncertainty relations, also play a crucial rule, defining the ultimate limit to the resolution of interferometric measurements. In the present work, we study the second order statistics to arrive at non-trivial limits for the uncertainty relation for the Stokes observables and detail the states that reside within these limits.

Although progress has been made recently in defining non-trivial uncertainty limits for the SU(2) group, not much work has been done to describe the behaviour of the intermediate states bounded by these limits. We systematically calculate the sum variance for all states on the Poincaré sphere for N=2 and N=3 manifold and present permissible uncertainty volume for all pure states. We demonstrate that all states on the same orbit, i.e., reachable via a SU(2) transformation, have the same variance. Moreover we show, counter to expectation, that the maximum uncertainty limit is the same for pure and mixed states.

Generalized Geometric Quantum Speed Limits

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In recent years there has been an intense theoretical and experimental research activity to understand on one hand fundamental concepts in quantum mechanics, such as uncertainty and the arrow of time, and to devise on the other hand efficient schemes for the implementation of quantum information and communication technologies. A basic question which combines and underpins both areas of research is: "How fast can a quantum state evolve under an open or closed system dynamics?" Progress towards answering such a question has led to the derivation and interpretation of so-called time-energy uncertainty relations, and to the associated establishment of quantum speed limits, intended as lower bounds setting the minimum time evolution between two distinct quantum states. Establishing general and tight quantum speed limits is crucial to assess how fast quantum technologies can ultimately be, and can accordingly guide in the design of more efficient protocols operating at or close to the ultimate bounds, with timely applications to quantum optimal control, quantum metrology, quantum computation and transport phenomena in many-body systems.

However, past results have included different, apparently unrelated approaches to quantum speed limits, and sometimes tailored to specific settings, i.e. only closed system evolutions, or based on particular functionals of distinguishability. Therefore, there remained a fundamental gap in obtaining a satisfactory answer to the general question posed above.

In this work we provide a breakthrough for the study and applications of quantum speed limits. We approach the problem from a general information theoretic point of view and we adopt a geometric formalism to construct an infinite family of quantum speed limits valid for closed and open system evolutions. Our work is based on the observation that, in quantum theory, there is not a unique bona fide measure of distinguishability on the state space; by properly formalizing speed limits as arising from all possible contractive Riemannian metrics, we exploit the full potential of quantum mechanics in order to derive bounds which are tighter than any previously established one in some relevant instances (e.g. for open system evolutions), and to demonstrate the optimality of previously proposed bounds in some other instances (e.g. for closed system evolutions). We show in particular how our approach incorporates and unifies all the previous specialized results, interpreting them under a new comprehensive framework, and allowing us to reach significantly beyond. From the physical point of view, our investigation is the first to highlight the role of classical populations versus quantum coherences in the determination and saturation of the speed limits. This provides readily useful prescriptions to guide the optimization of quantum protocols in order to reduce their speed of execution in practical realizations.

For more details, please check the reference arXiv:1507.05848

Ultrafast control in quantum structures via geometrical optimization

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The selective preparation of arbitrary states by means of laser protocols is a paramount goal of quantum control, one that has primary importance in quantum engineering, particularly in quantum information or quantum computation processes. Quantum optimal control theory is especially well designed to find the optimal pulses. There are general quantum controllability theorems that can be used to non-constructively establish the feasibility of the enterprise [1] while the study of the quantum landscapes can provide additional details regarding the topological features of the optimal solutions [2]. In this work we will move between quantum control designs and quantum controllability, analyzing the general features of some quantum control schemes assuming certain constrained controllability criteria. To that end we will use the Rayleigh-Ritz variational approach applied not to Hermitian operators (observables) whose value is minimized, but to the time-evolution operator, maximizing transition probabilities. This approach is equivalent to a geometrical optimization of the dynamics where the time evolution operator is replaced by an ordinary rotation in a subset of the Hilbert space.

In particular, we will be concerned with intrinsic properties of the dynamics of systems with composite structures (manifolds of sublevels), which pose several interesting problems from the point of view of controlling the system dynamics. With a larger number of levels participating in the dynamics, a multilevel structure should offer more control opportunities at the expense of our ability to manipulate the wave function within the substructure. However, as shown, such multi-level structures often give raise to Stark effects that actively block population transfer. Only by cleverly engineering the quantum state of the system, and not by a brute force approach, can one invert the population between states in a multilevel structure such as a molecule. In particular, using a novel scheme termed parallel transfer, we will show that one can achieve ultrafast population inversion with minimal pulse intensities and practically overcome the tyranny of the pulse area theorem, as long as all initial sublevels can be accessed [3]. On the other hand, in preparing arbitrary superposition states one needs to have full controllability on to both the initial and the final manifold of sublevels [4].

As examples of the wide use of the principles underlined, we will apply the ideas of parallel transfer and geometrical optimization to quite general problems as ultrafast electronic absorption [3], preparation of specific superposition states [4] or the control of isomerization reactions.

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Towards Coherent Quantum Noise Cancellation

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Optomechanical detectors have reached the standard quantum limit in position and force sensing where backaction noise starts to be the limiting factor for sensitivity [see e.g. Aasi et al., Class. Quant. Grav. 32, 074001 (2015), Purdy et al., Science 339, 801 (2013)]. A strategy to circumvent measurement backaction, and surpass the standard quantum limit, has been suggested by M. Tsang and C. Caves [Phys. Rev. Lett. 105 123601 (2010)] and is called "Coherent Quantum Noise Cancellation" (CQNC). CQNC can be viewed in different ways: First, it is a backaction cancellation scheme where radiation pressure noise is coherently cancelled in the readout quadrature by means of an anti-noise process. It can also be viewed as a quantum non-demolition (QND) measurement with a negative mass oscillator as a reference system (the relative position is a QND variable as the backaction only contributes to the sum of the momenta). Or it can be viewed as Coherent Control: Fluctuations in the output phase quadrature due to fluctuations in the amplitude quadrature of the cavity field are counteracted by a coherent control loop. If all involved parameters can be perfectly tuned, the backaction-free measurement will only be limited by intrinsic (shot) noise.

Our scheme [Wimmer et al., Phys. Rev. A 89, 053836 (2014)] consists of an optical meter cavity with a micromechanical oscillator subject to radiation pressure noise, and a coherent controller given by a second "negative mass" oscillator, a detuned ancilla cavity. The coupling of the light to the micromechanical oscillator will be matched by a beam splitter and a two-mode-squeezing process coupling the light to the ancilla cavity. We present our measurement scheme and a set of experimentally feasible parameters to realise it.

High precision, quantum-enhanced matter-wave interferometry

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Atom interferometry is a leading precision measurement technology, which is remarkable given the low fluxes of current state-of-the-art devices relative to conventional and cheap photon sources (e.g. a laser pointer). However, further improvements would allow for some truly exciting fundamental science, such as tests of the weak equivalence principle, searches for quantum gravitational effects, and the measurement of gravitational waves. Unfortunately, the obvious route towards increased sensitivity - namely, increasing the flux - is unavailable due to considerable technical barriers. Hence, developing atom interferometers that operate below the standard quantum limit (SQL), which have a better 'per atom sensitivity' than current devices, is of great interest.

However, a superb 'per atom sensitivity' has no practical use if the total number of atoms is low and there is no possibility of surpassing current state-of-the-art atom interferometers. This is unfortunately the case for many existing proposals where the requisite entanglement required for quantum-enhanced metrology is generated via large interatomic interactions.

Here I will discuss two quantum-enhanced atom interferometry schemes that are capable of high precision. The first is a hybrid atom-light interferometer, where the requisite squeezed atomic state is generated by mapping the quantum state of squeezed light to an atomic field. Since the squeezing is generated independently of the atomic source, in principle this technique gives high flux (relative to state-of-the- art atomic sources), weakly-interacting squeezed atomic states in targeted motional states - ideal for free-space atom interferometry (e.g. gravimetry). The second scheme exploits spin-exchange collisions to outcouple pairs of number-correlated atoms from a large Bose-condensed source and uses rf coupling to interfere them via a 'beamtritter' operation. In contrast to an SU(1,1) interferometer - which is Heisenberg-limited, but only with respect to the small number of number-correlated atoms outcoupled - this scheme utilises all the atoms in the initial source.

Quantum fluctuation theorems and power measurements

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We discuss transient fluctuation theorems in quantum systems, i.e., quantum Jarzynski equality and Tasaki-Crooks relation [1-4]. In these quantum fluctuation theorems, work is defined by the projective energy measurements at the beginning and the end of the force protocol. Here we consider how the quantum fluctuation theorems are modified if we determine the amount of work by continuous measurements of power as is usually done in the classical systems [5]. We show that, for the power-based work, the quantum fluctuation theorems do not hold in general due to the non-commutativity between the Hamiltonian and the power operator. This conclusion still holds even if the continuous measurements are weak.

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Consistency test for quantum process tomography

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To create and control complex quantum systems, we need to achieve knowledge about the involved quantum states and quantum processes. Typically this task can be accomplished by quantum state/ process tomography.

Quantum processes are in general described by completely-positive maps. However, when performing quantum process tomography, often non-positive maps appear. There exists several reason for the emersion of non-positive maps in quantum process tomography: (i) statistical errors due to the limited number of measurements, or systematic errors such as e.g. (ii) misaligned measurements or (iii) initial correlation of the system and the environment [1,2]. Distinguishing statistical from systematic errors helps us to improve our experiment.

In this contribution we will discuss the reasons for the appearance of not completely-positive maps. Furthermore, we introduce methods to distinguish statistical and systematic errors in process tomography based on methods from state tomography [3]. We illustrate our methods by applying them to trapped ions.

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Investigating non-Abelian character of Majorana zero modes using a photonic quantum simulator

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Majorana zero modes (MZMs) exhibit a fundamental property of non-Abelian statistics, which makes them potentially useful as ideal quantum bits to manipulate certain topological quantum tasks. Rapid theoretical developments have greatly reduced the technological requirements and made it possible to experimentally observe MZMs. However, until now, only a few positive signatures of the formation of MZMs have been reported in solid-state systems, and there has been no investigation of their crucial non-Abelian aspects. Here, we experimentally investigate the non-Abelian character of MZMs in the Kitaev chain model using a photonic quantum simulator. Through the Jordan-Wigner transformation, the geometry phases of the braiding of two MZMs can be directly obtained in an optical system. The local phase-error immunity of MZMs is further studied. This work will be useful for the study of quantum non-Abelian statistics and may provide a novel way to investigate topological quantities of quantum systems.

Ultimate precision limit and optimal probe states for quantum parameter estimation

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Measurement and estimation of parameters are essential for science and engineering, where the main quest is to find out the highest achievable precision with given resources and design schemes to attain it. With recent development of technology, it is now possible to design measurement protocols utilizing quantum mechanical effects, such as entanglement, to attain far better precision than classical schemes. This has found wide applications in quantum phase estimation, quantum imaging, atomic clock synchronization, etc, and created a high demand for better understanding of measurement protocols based on quantum mechanical effects. I will present a general framework for quantum mechanical metrology which relates the ultimate precision limit to the geometrical properties of underlying quantum dynamics. This framework provides efficient methods for computing the ultimate precision limit and optimal schemes to attain it. It also provides an analytical formula of the precision limit with arbitrary pure probe states, which spares the need of optimization required in previous studies. It is also shown that with noiseless dynamics a universal time scaling emerges as a fundamental property under the optimal feedback scheme, this restores an intuition that has been recently questioned in the field, that time is always a valuable resource.

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