JQC Colloquium

Held at Newcastle University on 15th September, 2016

Joint Quantum Centre (JQC) Durham–Newcastle

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The 2D Bose gas, in and out of equilibrium

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The physics of many-body systems strongly depends on their dimensionality. With the realization of quantum wells for example, it has been possible to produce two-dimensional gases of electrons, which exhibit properties that differ dramatically from the standard three-dimensional case.

During the last decade, a novel environment has been developed for the study of low-dimensional phenomena. It consists of cold atomic gases confined in tailor-made light traps, forming thus a thin layer of material particles. In this talk I will present some key aspects of these quantum 2D gases, such as quasi-long range coherence and superfluidity. I will also address some remarkable dynamical features, like the nucleation of random permanent currents in the gas when it is rapidly cooled across the superfluid transition. Finally I will discuss the possibility to simulate quantum-Hall type phenomena with these atomic gases.

JQC Symposium

Held at Newcastle University on 13th September, 2016

Joint Quantum Centre (JQC) Durham–Newcastle
An Inter-University Research Centre dedicated to aspects of quantum science and technology

Non-contact interactions between photons

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Recently, we have shown that photons can interact—strongly—without ever passing through the same region in space[1]. In this talk I will discuss how it is done and what we might be able to do next.

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[1] H. Busche *et al*, in preparation

Meissner effect for an artificial gauge field in multimode cavity QED

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In most realisations of artificial magnetic fields for neutral atoms, the applied field is static with a fixed spatial structure determined by external experimental parameters. Realisations of artificial gauge fields using single mode cavities allow some dynamics, but no freedom of the spatial profile [1, 2]. By using the light field in a multimode cavity we propose a scheme to realise a dynamic, spatially varying, artificial magnetic field acting on a trapped Bose-Einstein condensate. This is possible because in a nearly confocal optical cavity atoms couple to multiple cavity modes [3] resulting in coupled dynamics between the density of the condensate and the local intensity of the light, and hence the magnitude of the effective magnetic field. We simulate the full atomic and cavity light field dynamics, describing two internal states of a neutral atom and including pumping and loss. We show that the effective field leads to a diamagnetic response in the condensate, which in turn changes the distribution of the cavity light field and hence the effective magnetic field. In particular, this multimode cavity QED system allows sufficient freedom to demonstrate the Meissner effect, where the BEC expels the applied artificial gauge field [4].

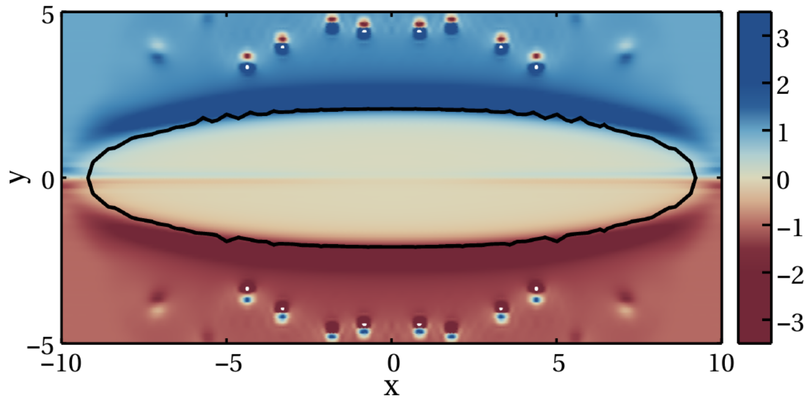

FIG. 1. Colour plot of the effective magnetic field B/B_0 around an atomic condensate shown by black line. The applied field is $\pm B_0$ on either side of the axis $y = 0$. The magnetic field is expelled from the condensate, and increased directly outside it, in agreement with the Meissner effect.

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Experimental Freezing of mid-Evolution Fluctuations with a Programmable Annealer

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For randomly selected couplers and fields, the D-Wave device typically yields a highly Boltzmann like distribution [1] indicating equilibration. These equilibrated data however do not contain much useful information about the dynamics which lead to equilibration. To illuminate the dynamics, special Hamiltonians can be chosen which contain large energy barriers [2, 3]. We generalize this approach by considering a class of Hamiltonians which map clusters of spin-like qubits (which we will henceforth refer to as 'spins') into 'superspins', thereby creating an energy landscape where local minima are separated by large energy barriers. These large energy barriers allow us to observe signatures of the transverse field frozen. To study these systems, we assume that the these frozen spins are describes by the Kibble-Zurek mechanism [4] which was originally developed to describe formation of topological defects in the early universe. We demonstrate that these barriers block equilibration and yield a non-trivial distribution of qubit states in a regime where quantum effects are expected to be strong, suggesting that these data should contain signatures of whether the dynamics are fundamentally classical or quantum. We *exhaustively* study a class of 3x3 square lattice superspin Hamiltonians and compare the experimental results with those obtained by exact diagonalisation. We find that the best fit to the data occurs at finite transverse field. We further demonstrate that under the right conditions, the superspins can be relaxed to equilibrium, erasing the signature of the transverse field. These results are interesting for a number of reasons. They suggest a route to detect signatures of quantum mechanics on the device on a statistical level, rather than by observing the behavior for specially chosen Hamiltonians, as was done in [2, 5]. Furthermore, our work suggests that devices of this kind may be able to provide a way of studying the Kibble-Zurek mechanism in large and complex systems, which may be interesting in its own right due to the relevance of Kibble-Zurek to aspects of cosmology as well as condensed matter physics. Finally the Ising square lattice with random fields and couplers is known to be an NP-hard problem [6], meaning that this class of Hamiltonians could provide a potential avenue to study the effect of dynamical freezing on computation. A summary of this work can be found on the arXiv [7].

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Recent advances in sensing beyond the quantum limit

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I will give a brief overview of quantum enhanced metrology and recent developments in the field. I will then focus on the advantages of local versus global strategies for estimating multiple parameters simultaneously. While global strategies using entanglement between sensors can lead to enhanced precision, the same advantages can be obtained with mode-separable states and local measurements. This has practical implications because local strategies have better robustness to local estimation failure, more flexibility in the distribution of resources, and comparatively easier state preparation. I will also highlight some intriguing results that have appeared recently and argue that these arise from subtleties in the theory and its interpretation and that more work is needed in understanding the role of bounds and their validity.

Feedback Control in Quantum Transport

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In classical control theory, closed-loop or *feedback control* offers a number of advantages over open-loop control such as disturbance rejection and robustness against component variations. Over the last two decades, significant progress has been made in translating the concept of feedback control into the quantum realm, with the greatest advances coming in the field of quantum optics [1].

In this talk I will review work aimed at bringing feedback control to *quantum transport* [2], by which I mean low-temperature electronic transport in semiconductor nano-structures. Feedback control strategies for quantum systems can be broadly grouped into two classes: *measurement-based* and *coherent* control. Both have been considered in the transport context and both will be discussed here. On the measurement-based side, charge counting provides detailed time-resolved information on the stochastic motion of electrons on the nano-scale. This can be used as the basis for a feedback scheme. One such scheme was recently realised in a quantum dot [3] and was shown to dramatically suppress current fluctuations [4]. Other theoretical proposals include a nano-electric Maxwells daemon [5] and the stabilisation of non-equilibrium pure states [6]. Coherent quantum control employs a controller that is itself a quantum-mechanical system and is a less well-developed field than its measurement-based counterpart. Here I will discuss proposals to use coherent control to optimise current and noise properties of phase-coherent nanostructures [7].

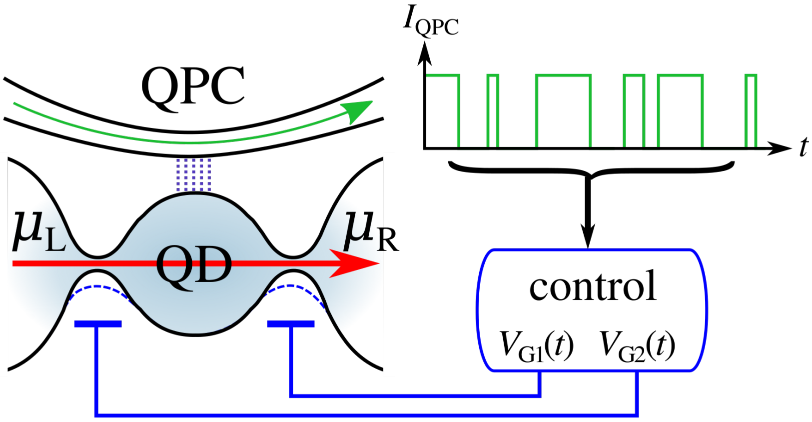

FIG. 1. Schematic of a measurement-based feedback control scheme applied to transport through a quantum dot (QD). The QD is connected to reservoirs (indicated by their chemical potentials μ_{L} and μ_{R}) and the arrow indicates current flow. The occupation status of the QD is detected with a quantum point contact (QPC), whose current gives rise to the time trace, top right. This information is then processed by control circuitry that modulates the gate potentials $V_{\text{G1}}(t)$ and $V_{\text{G2}}(t)$ in response, and in doing so alters the tunnel rates of electrons through the QD. In this way, a feedback loop is set up to control aspects of charge transfer through the dot. Figure from Ref. 2.

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Quantum Turbulence in Superfluid Helium channel flows

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Quantum turbulence can be loosely defined as the most general dynamical motion of a set of discrete quantised vortices in quantum fluids, namely Bose-Einstein Condensates, the B-phase of ^{3}He and superfluid ^{4}He. The observed properties of quantum turbulent flows strongly depend on the characteristics of the quantum fluids investigated, particularly with respect to the range of accessible lengthscales, determined by the ratios of the systems size to the intervortex spacing and the healing length. Here we focus on quantum turbulent flows of superfluid ^{4}He in plane channels where these ratios are respectively 10^3 and 10^8 , hence allowing a robust hydrodynamical description of the flow. Adopting the latter, we numerically simulate the coupled motions of the normal and superfluid components constituting superfluid 4 He, fully modeling the mutual interaction between the two phases. The channel walls play a fundamental role by introducing flow inhomogeneities and engendering the polarization of the superfluid vortex tangle [1].

We recover recent experimental results obtained with new cryogenic flow visualization techniques [2] and predict the normal fluid velocity structure in *pure superflow*, a channel flow where the net flow of the normal component is nominally zero.

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Mean-Field Dynamics and Fisher Information in Matter Wave Interferometry

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There has been considerable recent interest in the mean-field dynamics of various matterwave-interferometry schemes designed for precision sensing. In the field of quantum metrology, the standard tools for evaluating metrological sensitivity are the classical and quantum Fisher information. In this presentation, we show how these tools can be adapted to evaluate the sensitivity when the behaviour is dominated by mean-field dynamics. As an example, we compare the behaviour of four recent theoretical proposals for gyroscopes based on matter-wave interference in toroidally trapped geometries. We show that while the quantum Fisher information increases at different rates for the various schemes considered, in all cases it is consistent with the well-known Sagnac phase shift after the matter waves have traversed a closed path. However, we argue that the relevant metric for quantifying interferometric sensitivity is the classical Fisher information, which can vary considerably between the schemes. [1].

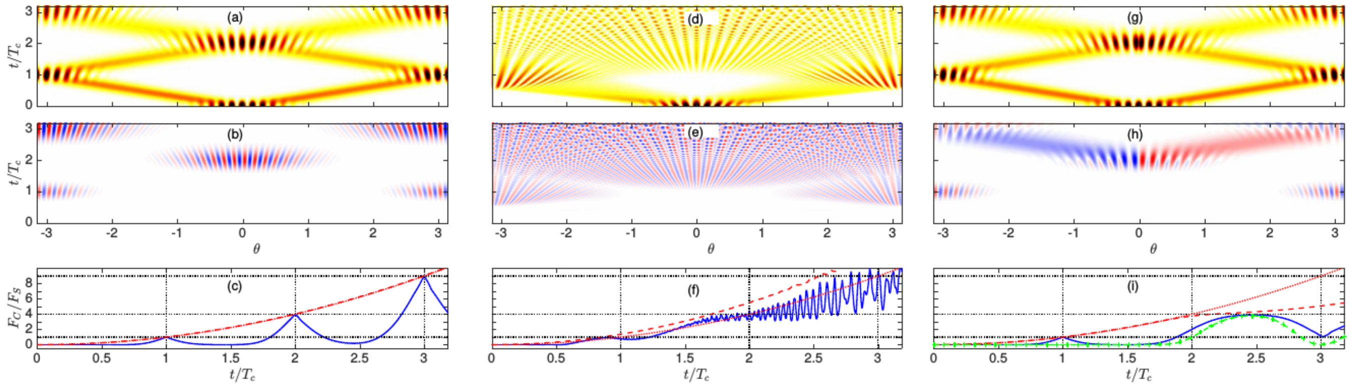

FIG. 1. Density distribution and Fisher information for a variety of matterwave interferometry schemes.

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Condensate losses and oscillations induced by Rydberg atoms

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Using the theoretical approach based on the classical fields approximation [1], we numerically analyze the impact of a single Rydberg electron onto a Bose-Einstein condensate. Both $S-$ and $D-$ Rydberg states are studied. The radial size of $S-$ and $D-$states are comparable, hence the only difference is due to the angular dependence of the wavefunctions. We find the atom losses in the condensate after the excitation of a sequence of Rydberg atoms. Additionally, we investigate the mechanical effect in which the Rydberg atoms force the condensate to oscillate. Finally, we compare numerical results to experimental data [2].

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Rydberg spectroscopy and dressing using narrow linewidth transitions in strontium

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Alkaline-earth metal atoms such as strontium are interesting systems for studying ultracold Rydberg physics, where the divalent nature results in the existence of both singlet and triplet Rydberg levels. Advantages of the second valence electron in these atoms include narrow-line optical cooling via the long-lived triplet states, detection using autoionisation [1], along with alternative possibilities for trapping [2] and Rydberg dressing [3].

Previously we have studied Rydberg dynamics on the singlet transitions [1, 4], while more recently our development of a high power, widely tunable laser at 319 nm [5] allows for excitation via the narrow inter-combination lines to the triplet Rydberg levels. The laser outputs over 100 mW, with a linewidth and long-term drift of < 100 kHz and gives access to a large range of Rydberg states from $n \approx 30$ to $n \geq 100$. Additionally a GPS-referenced optical frequency comb can be used to measure the long term frequency stability of the laser and make absolute frequency measurements of the atomic transitions. Here comparisons to previous measurements in two-electron atoms show a large increase in accuracy [6–8]. Another direction of our experiment is to study Rydberg dressing in strontium, a process whereby off-resonant excitation to the Rydberg states results in weakly dressing the ground state atoms with some Rydberg character [9, 10]. In this talk we will present recent spectroscopy results, along with progress towards Rydberg dressing in our system.

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Stable two-dimensional solitons in spin-orbit-coupled Bose-Einstein condensates and optical waveguides

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Until recently, it was commonly believed that two-dimensional (2D) mean-field models of atomic and optical waves with cubic attractive interactions could not produce stable fundamental solitons in the free space, due to the occurrence of the *critical collapse* in the same setting. Solitons with embedded vorticity (*vortex rings*) are subject to a still stronger instability against azimuthal perturbations which split the rings. A novel finding is that the spin-orbit coupling (SOC) of the Rashba type gives rise to *stable* 2D solitons in the pseudo-spinor (two-component) Bose-Einstein condensate (BEC) [1]. It was also found that the SOC in the 2D system may be *emulated* in optics by the temporal dispersion of the linear coupling in dual-core planar waveguides with the Kerr self-focusing nonlinearity, which leads to the prediction of stable 2D spatiotemporal solitons ("light bullets") in the dual-core waveguide [2]. The stabilization is explained by the fact that the SOC terms break the specific scaling invariance of the 2D nonlinear Schrödinger/Gross-Pitaevskii equation, lift the respective degeneracy of the soliton family, and thus create otherwise missing ground states in the form of 2D solitons, which combine zero-vorticity and vortex terms. The talk aims to give an overview of these results, in the fields of BEC and nonlinear optics alike. In the former case, effects of the SOC terms of the Dresselhaus type have been recently investigated too, with a conclusion that they tend to destroy the solitons. In the application to optics, the SOC-emulating terms may be combined with those emulating the parity-time PT symmetry (mutually balanced linear gain and loss in the cores of the dual-core waveguide), with a conclusion that 2D solitons have their stability region in the combined SOC-PT system too.

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A Travelling Wave Zeeman Decelerator

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A large number of applications in both physics and chemistry require the desirable properties of ultracold molecules [1]. An example of particular interest is the quantum simulator [2]. Various methods have been developed to obtain molecules with the desired properties. One such method is a travelling wave Zeeman decelerator. This form of Zeeman decelerator was pioneered by the groups of Narevicius and Vanhaecke [3] [4]. Since then we have made modifications to the Vanhaecke-group design which have helped to improve effectiveness of the decelerator. The technique traps paramagnetic atoms or molecules in the minima of a travelling 3D magnetic potential that is initially set moving at the mean velocity of the molecular packet. As the forward velocity of the magnetic potential is decreased, any molecules trapped within are also decelerated. During the prototyping phase, using a decelerator just 12 cm long, we were able to detect velocity bunching and some deceleration of the metastable argon. In order to decelerate the species of interest to a standstill the decelerator must be made longer. We envision that the decelerator will ultimately be about 1 m in length. This will allow us to achieve the trapping of large numbers of molecules at temperatures in the region of a few tens of mK. Further cooling methods will be required to reach the K, ultracold regime. One possible method would be to sympathetically cool the molecules with laser cooled atoms [5].

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Photon Bose-Einstein condensates: near-equilibrium photon fluids

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Bose-Einstein condensation (BEC) is a universal phenomenon which occurs when a system of identical bosons at thermal equilibrium occupy the ground state in enormous numbers. By optically pumping a 1.5-micron long, dye-filled resonator, we can reach thermal equilibrium of photons and a define a ground state. Thus, a quantum gas of light can be achieved at the room temperature.

Thermal equilibrium is broken by the dissipation in the system, through both pumping and decay of excitations. I will present observations of two circumstances when the equilibrium description description breaks down. First, inhomogeneous pumping, where failure to reach equilibrium shows up in the spatial distribution of light [1]. Secondly, increasing the number of excitations creates an unusual fragmented, multimode condensate, as witnessed by the first-order spatio-temporal correlation function, $g^{(1)}(t-t', \mathbf{r}, \mathbf{r}')$, measured by interferometry [2]. I will also describe a microscopic quantum-optic model of the thermalisation and condensation process that produces photon BEC [3], which we have used to explain the multimode phase.

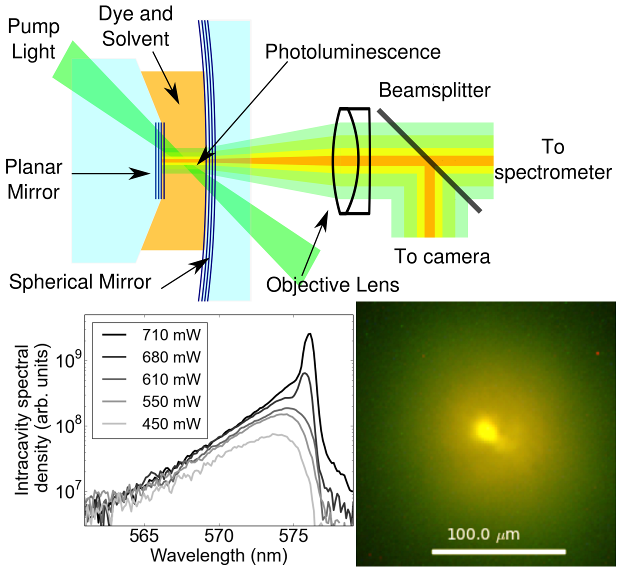

FIG. 1. Top: experimental setup for demonstrating Bose-Einstein condensation of photons. The mirrors are separated by about 1.5 μm. Lower left: the intracavity spectrum, which is compatible with a Bose-Einstein distribution at room temperature, showing macroscopic occupation of the ground state for sufficient pump power. Lower right: a real-colour image.

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Non-trivial topological phases in dissipative systems with dipolar exchange interactions

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In this talk, I will explore the topological properties of a finite long-range interacting system of atoms trapped in a two dimensional lattice where the interactions are based on the exchange of virtual photons between a ground ($J = 0$) and three excited states ($J = 1$). In this system, the interactions go beyond the typical near field $1/r^3$ and I will show how the consideration of the far field components (that decay as $1/r^2$ and $1/r$) gives rise to interesting changes in the topological properties of the system. Moreover, I will elaborate on the effect of dissipation on the topological properties of this open quantum system.

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Soliton and topological physics with microcavity polaritons

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In this talk I will review a number of results on observation of half-light half-matter solitons existing in microcavities and planar waveguides with strong exciton-photon coupling. These devices operate at the record low powers and exhibit giant levels of nonlinear response, while their response time is in the pico-second range. Technology allows to pattern these devices and create lattice and other potentials of the required geometry. Thus many condensed matter phenomena predicted and observed in real solids can be engineered in these strongly nonlinear micron scale devices. In particular, I will report our recent results on interplay of the spin-orbit coupling and nonlinear effects leading to novel topologically protected quasi-solitons in polariton topological-insulators [1–7].

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