Poster abstracts

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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].

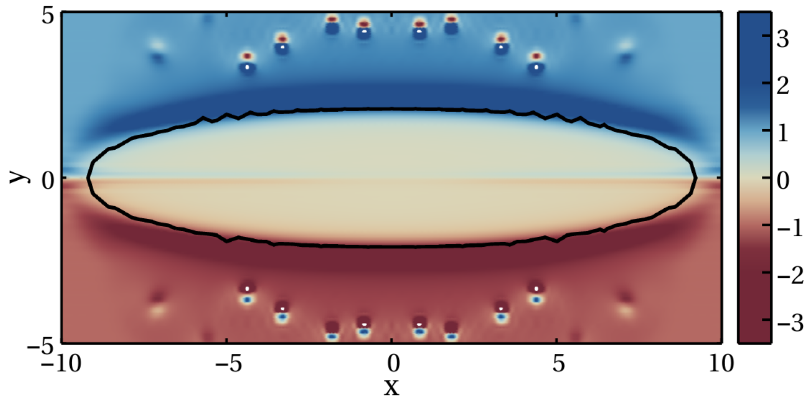

FIG. 1. Colour plot of the effective magnetic field B/B_0 around an atomic condensate shown by black line. The applied field is $\pm B_0$ on either side of the axis $y = 0$. The magnetic field is expelled from the condensate, and increased directly outside it, in agreement with the Meissner effect.

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Cooperativity in lattice monolayers of driven interacting dipoles

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We investigate the cooperative behaviour of regular monolayers of driven two-level dipoles, using classical electrodynamics simulations. The dipolar response results from the interference of many cooperative eigenmodes, each frequency-shifted from the single resonant dipole case, and with a modified lifetime, due to the interactions between dipoles. We show how subradiant behaviour of the dominant eigenmode in a two-dimensional triangular, hexagonal or square dipolar lattice can lead to significant enhancement in the optical extinction of a resonant driving field [1]. Such an enhancement in the optical cross-section is an enticing goal in light-matter interactions, due to its fundamental role in quantum and non-linear optics. Also of interest is the kagome lattice, where the semiregular geometry permits simultaneous excitation of two dominant modes, one strongly subradiant, leading to an electromagnetically-induced-transparency-like interference in a two-level system. The interfering modes are associated with ferroelectric and antiferroelectric ordering in alternate lattice rows with long range interactions [2].

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Stable Hopf solitons in rotating Bose-Einstein condensates

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A Hopfion (or Hopf soliton) is a topological soliton with two independent winding numbers: the first, S, characterizes a horizontal circular vortex embedded into a three-dimensional soliton; and the second, m, corresponds to vorticity around the axis, perpendicular to this circle. Hopf solitons appear in many areas of physics, including field theory, optics, ferromagnets, and semi- and superconductors. In atomic Bose-Einstein condensates (BEC) such a topological solitonic structure results from a superfluid flow of atoms simultaneously quantized in poloidal and toroidal directions.

In our recent paper [1] we suggested an experimentally feasible trapping configuration that can be used to create, stabilize, and manipulate a vortex ring in a controllable and nondestructive manner. In the present work [2] we use a similar trapping potential and a rotating condensate and investigate energetic and dynamical stability of Hopfions in such a setup.

Our theoretical investigations show that Hopf solitons can be both energetically and dynamically stable in a rotating trapped atomic BEC. In the framework of a dissipative mean-field model we investigate dynamics of the Hopfion solutions and their energy landscape depending on the location of the vortex line and ring components within the trap. We reveal several different scenarios of the Hopfion dynamics observed for different values of the rotation rate. It turns out that within a certain interval of rotation velocities a Hopfion may be stable. For rotation rates lower than this interval the vortex line and ring deform and finally reconnect. On the other side of the interval, for high angular velocities, vortex lines are nucleated at the outer edge of the condensate and then reconnect with the vortex ring.

We also investigate stability of Hopf solitons with higher topological charges. All of them are shown to be unstable in the suggested trap geometry. Multiply-charged vortex lines/rings split into singly-charged vortex lines/rings, which then either reconnect with another vortex component or become unstable due to growing Kelvin modes.

It is observed that decay of the Hopfion leads to the formation of a vortex lattice. The kinetic energy of the ring component is transferred via reconnection to the vortex lattice. As is well known, the experimental detection of vortex rings is much more challenging than observation of the holes in the atomic cloud produced by vortex lines. By counting the number of vortex lines in the vortex lattice one obtains clear experimental evidence of the presence of the vortex ring component.

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Dark Solitons in Dipolar Bose-Einstein Condensates

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Typically solitons have three main behaviours: they are of permanent form, they are localised to a region, and they can interact with other solitons (emerging from the collision unchanged, except for a phase shift) [1]. It follows that the solitons interact with each other at short range. We investigate a new form of soliton, existing in a quasi-one-dimensional dipolar Bose-Einstein Condensate (BEC), in which the solitons have modified profiles and develop novel long-range interactions [2]. Dipolar BECs have been generated in several experiments to date [3]. We undertake a quantitative study of a zero temperature weakly-interacting dipolar BEC through numerical simulation of the dipolar Gross-Pitaevskii equation [4]. It is shown that, in the presence of dipolar interactions, dark solitons can develop i) a modified density profile with ripples surrounding the soliton density dip, ii) a non-trivial stability diagram as a function of the dipolar strength, and iii) long-range interactions which scale as z^{-3} , where z is the soliton separation. Further, it is shown that under harmonic confinement the dipolar dark solitons oscillate at a frequency which dependson the interactions [5].

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Interactions between photons in spatially separate media

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While great progress has been made in quantum non-linear optics to achieve interactions at the level of individual photons [1], the idea that photons could interact without ever being in the same place seems impossible.

Rydberg non-linear optics [2] has emerged as a viable approach to induce strong effective interactions between individual photons by coherently and reversibly mapping them into strongly interacting collective Rydberg excitations in cold atomic ensembles. So far, Rydberg-induced photon interactions have been observed between photons propagating in overlapping optical modes inside the same atomic medium. However, thanks to the long-range dipolar character of the interactions, spatial overlap is no fundamental requirement, neither for the photons, nor the media.

Here, we demonstrate interactions between photons in independent optical modes stored in atomic media which are separated by distances on the order of 15 times their optical wavelength [3]. Analysing the statistics of the retrieved photons, we observe a strong suppression of simultaneous retrieval in both modes as the distance between them is reduced and the interaction strength increases. Comparing our results to theory, we find that suppression already occurs at separations above the Rydberg blockade as a result of interaction-induced dephasing [4]. The demonstration of long-range interactions between photons represents a paradigm shift for optics and opens up perspectives, e. g. for all-optical quantum gates [5] and to study strongly correlated many-body dynamics with light.

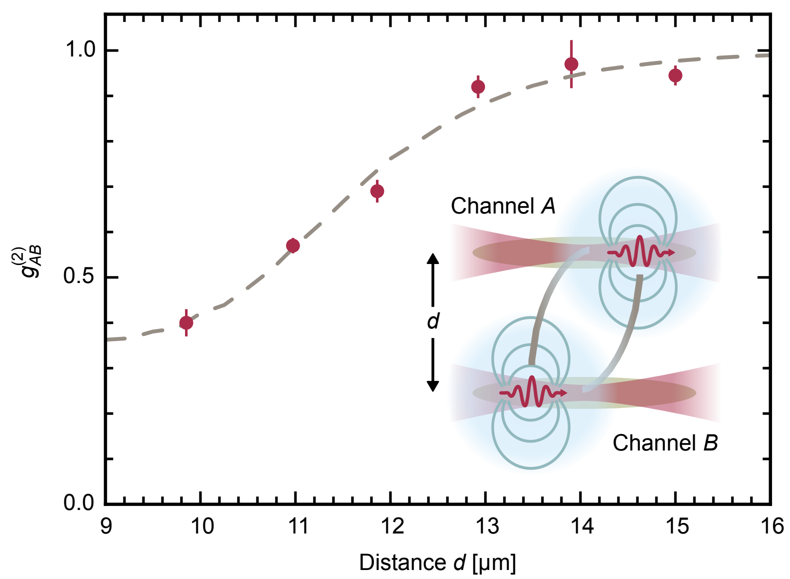

FIG. 1. Observation of spatial correlations and suppression of simultaneous retrieval of photons stored as collective Rydberg excitations in non-overlapping side-by-side atomic media as a result of interaction-induced dephasing.

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Comparative study of numerical techniques for rotating ultra-cold atomic gases

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Modelling of a mixture of Bose condensate and thermal cloud of atoms requires two completely distinct formalisms. The condensate and thermal cloud mixture can be treated by applying the Zaremba-Nikuni-Griffin (ZNG) approach [1], where the evolution of the condensate part is obtained by solving the Gross Pitaevskii equation [2] within the mean field approximation and the thermal cloud is treated by classical point particles obeying momentum and force conservation principles in a Boltzmann distribution [3]. In absence of an analytical solution of both the Gross Pitaevskii and Boltzmann equation, existing methods rely on special numerical techniques with different orders of accuracy, speed and ease of implementation [4, 5]. We have performed a comparative study between these algorithms in the context of rotating condensates and condensates trapped in a ring trap. The numerical methods have been implemented in user friendly python scripts. A package containing the collection of these scripts has been developed which can be used to simulate problems related to mixture of condensate and thermal cloud or each component separately. Fig. 1 shows the example of numerical calculations for the evolution of a wave packet of condensate cloud evolving in a ring potential in presence of a dipole barrier at a fixed position in the ring. The details of such studies will be presented during the conference.

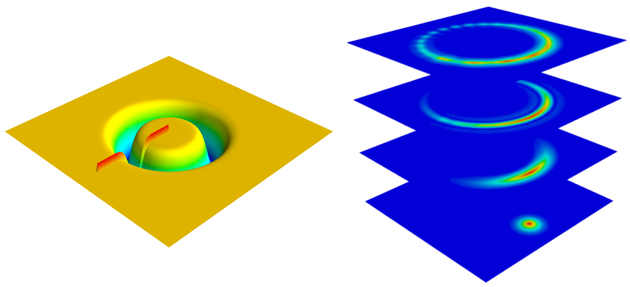

FIG. 1. Evolution of a condensate wave packet in a magnetic ring potential across a repulsive dipole barrier. (a) Potential landscape of the physical problem, (b) probability distribution of the initial condensate wave packet (T=10 nK) as a function of time (upwards).

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Controlled polarization of two-dimensional quantum turbulence in atomic Bose-Einstein condensates

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We propose a scheme for generating two-dimensional turbulence in harmonically trapped atomic condensates with the novelty of controlling the polarization (net rotation) of the turbulence. Our scheme is based on an initial giant (multicharged) vortex which induces a large-scale circular flow. Two thin obstacles, created by blue-detuned laser beams, speed up the decay of the giant vortex into many singly-quantized vortices of the same circulation; at the same time, vortex-antivortex pairs are created by the decaying circular flow past the obstacles. Rotation of the obstacles against the circular flow controls the relative proportion of positive and negative vortices, from the limit of strongly anisotropic turbulence (almost all vortices having the same sign) to that of isotropic turbulence (equal number of vortices and antivortices). Using the new scheme, we numerically study the decay of 2D quantum turbulence as a function of the polarization. Finally, we present a model for the decay rate of the vortex number which fits our numerical experiment curves, with the novelty of taking into account polarization time-dependence. [1]

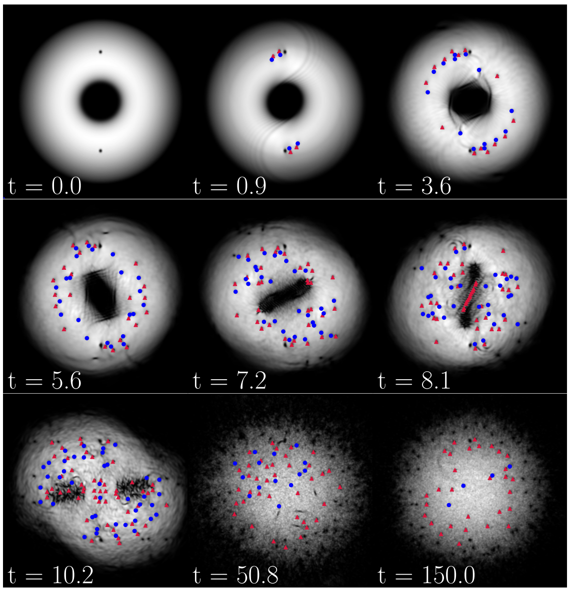

FIG. 1. Density plots of the condensate at different times t for non-rotating obstacles. Regions of large/low density are displayed in white/black respectively. Red triangles and blue circles identify positive-charged and negative-charged vortices respectively. The giant vortex decays by injecting a large number of singly-quantized (positive) vortices into the condensate, whilst the pins generate vortex pairs, as can be clearly seen at time $t = 0.9$.

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Algebraic order and quench dynamics in exciton-polariton condensates

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The properties and dynamics of exciton-polariton condensates can, in certain regimes, be described by a stochastic driven-dissipative Langevin equation [1] (complex Ginzbug-Landau equation with noise), as already applied to the Berezinskii-Kosterlitz-Thouless transition [2]. Motivated by our related earlier work in the context of trapped cold atoms [3], we undertake a characterisation of the properties of an incoherently-pumped 2d condensate (focussing on densities and correla-tion functions) in terms of appropriate physical system parameters, extending our analysis to non-equilibrium regimes of experimental relevance [4]. We focus our studies on the out of equilibrium dynamics of a exciton-polariton condensate when cooled through the Berezinskii-Kosterlitz-Thouless phase transition; here bound and free vortices and phonons play a role in the change of the rst-order correlation function and characterize the transition from a disordered to ordered state. Finally, we discuss some preliminary results related to the Kibble-Zurek mechanism in a 2d geometry [5] in which the disordered state is plague with topological defects, and density of topological defects is related to the cooling rate.

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A quantum-enhanced atomic gyroscope with tunable sensitivity

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We study the dynamics of an atomic Bose-Einstein condensate trapped in a rotating anisotropic quasi-2D potential. We find that the system undergoes a quantum phase transition heralded by symmetry breaking at a critical rate of rotation [1]. In the region of this phase transition, the atomic state is highly entangled and dominated by two highly occupied angular momentum modes. This state is shown to have great potential for quantum-enhanced measurements of rotations [2]. By calculating the quantum Fisher information, which quantifies the achievable precision, for different system parameters such as the trap anisotropy and the interaction strength between atoms, we show that the sensitivity can be tuned. In particular, it is possible to alter the width of the Fisher information resonance curve as a function of rotation rate (at a cost of the maximum value) as shown in figure 1. This could be of considerable practical advantage since prior information of the rotation rate may not be well known and so a broad Fisher information curve could be used to get an initial estimate. This could then be continually refined with a boot-strapping method that progressively improves the systems sensitivity as better knowledge of the value of the rotation is obtained. The measurement protocol could be optimized to continually refine the sensitivity of the system to obtain the best overall result. A further interesting aspect we have found is the ability to create a range of different entangled states by varying the trap parameters [2]. Some of these offer known advantages in quantum metrology due to their robustness to a range of different loss mechanisms [3].

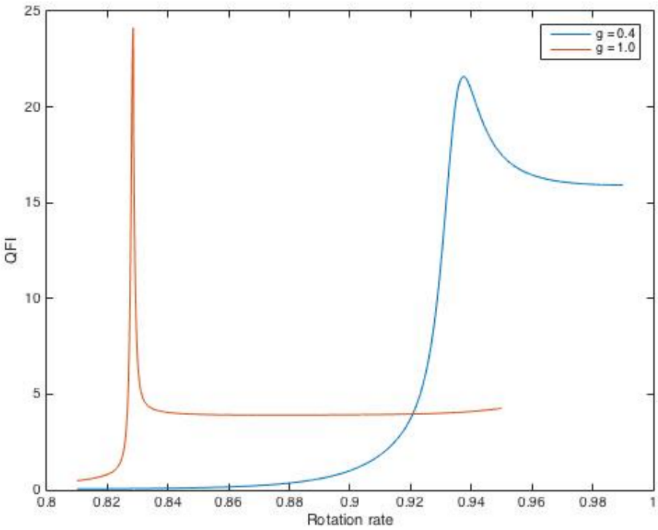

FIG. 1. A figure showing the extremes of the Fisher information curves that can be achieved by altering the parameters being modelled; the largest contributers being the trap anisotropy (constant in this example) and the interaction potential between the bosons. Here we see the larger interaction potential ($g = 1.0$) giving a very sharp peak, and a lower potential ($g = 0.4$) giving a much broader peak. The critical frequency is also dependent on these parameters and as such can be shifted to different rotation frequencies.

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The Wigner SGPE: a stable c-field theory that includes quantum fluctuations

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Classical-field or c-field calculations are a mainstay of simulations of the dynamics and stationary properties of quantum Bose gases at nonzero temperature, allowing for temperatures too high to treat with other methods, strong fluctuations and defects, as well as the study of single experimental realizations. They do however omit any quantum fluctuations. We have derived an extended version of the stochastic GPE (SGPE) that preserves quantum fluctuations, starting from the master equation of Gardiner and Davis [1]. Thus, a very tractable, nonlinear description of the system has been obtained in terms of complexvalued fields, that also includes quantum fluctuations, depletion, shot noise, antibunching, and similar effects, and makes no assumptions of a condensate. In contrast to the usual truncated Wigner approach of adding virtual vacuum noise into the initial conditions, this method preserves quantum fluctuations even into the long-time stationary state.

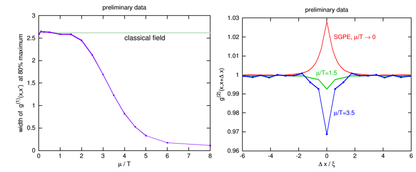

FIG. 1. Correlations in the centre of a trapped 1D gas in the grand canonical ensemble with $\mu = 25\hbar\omega$, obtained with the Wigner SGPE by varying the temperature and interaction strength in such a way that predictions of the SGPE (classical field) model would be unchanged. That is by varying λ such that $g = 0.15\lambda$ in trap units and $k_B T = \mu/\lambda$, while keeping μ constant. The left panel plots the width at 80% maximum of the phase correlation function $g^{(1)}(x, x + \nabla x)$, and shows the onset of a decrease in correlation length mediated by quantum fluctuations. The right panel plots the local density correlation function $g^{(2)}(x, x + \nabla x)$ for several interaction strengths, showing the appearance of antibunching.

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Probing the Stability and Collisions of Dipolar Matter-Wave Bright Solitons

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The achievement of condensation of atomic species possessing permanent magnetic dipole moments adds a new paradigm to the ultracold matter landscape, that of long-ranged anisotropic interactions [1]. The dipole-dipole interaction facilitates a number of novel phenomena, including roton physics, which has recently led to the observation of quantum droplets in these condensates [2]. The study of the nonlinear wave excitations of these systems is expected to provide rich insight into their behaviour, in particular it has been shown for the case of net repulsive interactions that vortices in quasi-2D dipolar condensates exhibit modified density structures due to the presence of the roton [3], while dark soltions, their one-dimensional analogue can form long-lived bound states due to the play-off between the attractive part of the dipolar interaction and the dark solitons effective negative mass [4, 5].

We present a comprehensive analysis of the form and interaction of single and multiple dipolar bright solitons across the full parameter space afforded by quasi-one-dimensional attractively interacting dipolar Bose-Einstein condensates (BECs). The key role of the relative phase is explored; in particular for in-phase collisions three regimes of behaviour are identified for increasing dipolar interaction strength: free collisions, short-lived (metastable) bound state formation and soliton fusion (where post collision the solitons wave packet transforms into an irreversible merged state). We further consider the 3D representation of these states supported in a waveguide potential using a variational approach; for certain parameters these 3D solitons are unstable to collapse, and we map out the stability diagram as a function of the interaction and waveguide parameters [6].

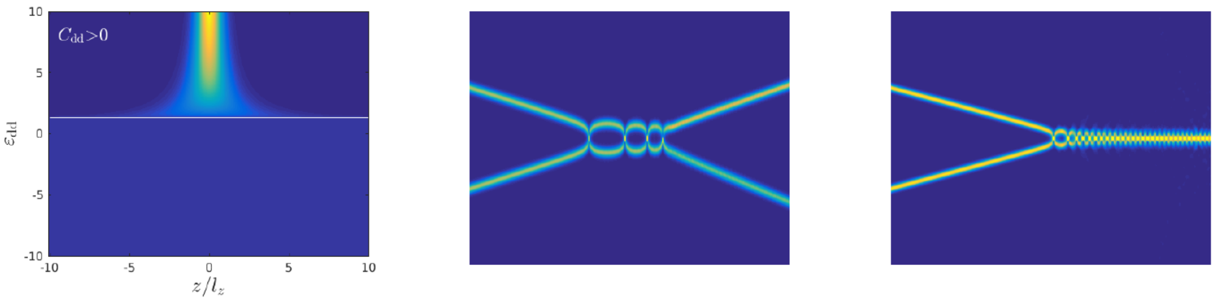

FIG. 1. Pseudocolour density plot showing continuous bright soliton solutions as a function of the dipole-dipole interaction strength. Middle: Short-lived bound state of two bright solitons. Right: For strong dipolar interactions the solitons merge together.

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Analytic models for density of a ground-state spinor condensate

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We demonstrate that the ground state of a trapped spin-1 and spin-2 spinor ferromagnetic Bose-Einstein condensate (BEC) can be well approximated by a single decoupled Gross-Pitaevskii (GP) equation [1]. Useful analytic models for the ground-state densities of ferromagnetic BECs are obtained from the Thomas-Fermi approximation (TFA) to this decoupled equation. The analytic densities are the functions of trapping potential and interaction parameters. Similarly, for the ground states of spin-1 antiferromagnetic and spin-2 antiferromagnetic and cyclic BECs, some of the spin-component densities are zero, which reduces the coupled GP equations to a simple reduced form. Analytic models for ground-state densities are also obtained for antiferromagnetic and cyclic BECs from the TFA to the respective reduced GP equations [1]. The analytic densities thus obtained are in very good agreement with the full numerical solution of the GP equations with realistic experimental parameters as are shown in Fig. 1.

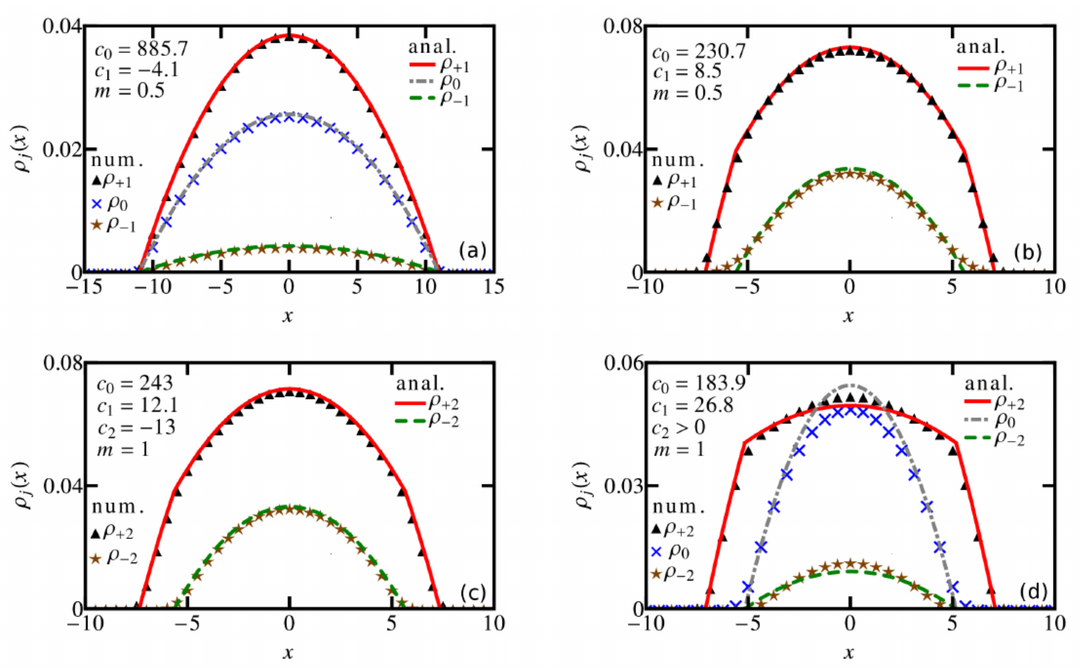

FIG. 1. (a) shows the analytic and numerical densities for a ferromagnetic spin-1 condensate of ^{87}Rb atoms, whereas (b) shows the same for an antiferromagnetic spin-1 condensate of ^{23}Na atoms. In the lower panel: (c) shows non-zero component densities for an antiferromagnetic spin-2 condensate of ^{23}Na atoms, and (d) shows the same for the cyclic phase (obtained by tuning one of the scattering length spin-2 ^{23}Na atoms). Here c_0, c_1 and c_2 are the interaction parameters; $c_0 \propto (a_0 + 2a_2)/3$ and $c_1 \propto (a_2 - a_0)/3$ for spin-1 condensate, whereas $c_0 \propto (4a_2 + 3a_4)/7$, $c_1 \propto (a_4 - a_2)/7$, $c_2 \propto (7a_0 - 10a_2 + 3a_4)/7$ for spin-2 condensate. Here, a_0, a_2 and a_4 are the scattering lengths in total spin $0, 2$ and 4 channels respectively. All the quantities shown in the figures are in dimensionless units.

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Thermal solitons in a quasi-1D Bose gas as revealed by studying static structure factor

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We study, within a framework of the classical fields approximation [1, 2], the static structure factor of a weakly interacting Bose gas at thermal equilibrium. As in a recent experiment [3], we find that the thermal distribution of phonons in a three-dimensional Bose gas follows the Planck distribution. We find as well a disagreement between the Planck and phonon distributions in the case of an elongated quasi-one-dimensional systems. We attribute this discrepancy to the the existence of spontaneous dark solitons (i.e., thermal solitons) in an elongated Bose gas at thermal equilibrium [4, 5].

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Controlling the Rotational and Hyperfine State of Ultracold ^{87}Rb^{133}Cs Molecules

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The formation of ultracold heteronuclear molecules opens up many exciting areas of research spanning precision measurement, quantum computation, quantum simulation, ultracold chemistry and fundamental studies of quantum matter. Long-lived, trapped samples of molecules with full quantum control of the molecular internal state are crucial to many of these applications. Here we demonstrate coherent microwave control of the rotational and hyperfine state of ultracold, chemically stable ^{83}Rb ^{133}Cs molecules. We create up to 4000 molecules in the rovibrational and hyperfine ground state at a temperature of 1.2 μK and a density of 10^{11} cm^{-3} using magnetoassociation on a Feshbach resonance [1] followed by optical transfer using stimulated Raman adiabatic passage [2–4]. Optical frequency comb measurements of the STIRAP transition frequencies are used to accurately measure the binding energy of the molecule [5]. We then use precision microwave spectroscopy of the rotational transition to probe the rich hyperfine structure of the molecule. Finally, we exploit coherent Rabi oscillations to transfer the total population of molecules between hyperfine levels and report measurements of the collisional lifetime for molecules in a single hyperfine level of both the ground state and the first rotationally excited state [6].

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Matterwave interferometric measurement of the condensate mean field.

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Atom interferometers allow the measurement of forces and fields through detection of the differential phase shifts induced in the atomic wavefunction by the interaction. This general feature offers great potential in the area of applied physics, with next–generation measurement devices tantalising close to realisation.

Here, we instead discuss the use of a Bose–Einstein condensate (BEC) matterwave interferometer for measurement of the dynamics of the interfering medium itself. Using the technique of contrast interferometry we have devised a method for probing the evolution of mean–field energy following the release from the trapping potential. GPE simulations are compared to experimental data, showing that our system has the potential for measuring in a parameter space.

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Towards a Quantum Degenerate Mixture of Cs and Yb

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The formation and study of ultracold polar molecules leads to many fascinating areas of study, including quantum computation and the behaviour of degenerate quantum gases of molecules. This experiment aims to produce ground state CsYb molecules, using techniques such as magneto-association across Feshbach resonances [1] and Stimulated Raman Adiabatic Passage (STIRAP) [2]. The extra valence electron in ytterbium means that CsYb will have both electric and magnetic dipole moments in the ground state, unlike bi-alkali molecules which have just an electric dipole moment. This additional degree of freedom in experiments makes it possible to explore interesting phenomena such as spin dependent interactions in lattices [3].

I will present the development of our two-species apparatus for the production of degenerate mixtures of Cs and Yb. I will then demonstrate the capability of the two-species apparatus in producing cesium BECs containing 4×10^4 atoms and large ytterbium BECs containing in excess of 2×10^5 atoms. I will also discuss our next steps towards the creation of CsYb molecules, such as photoassociation spectroscopy of CsYb and preparation of Yb in the metastable state to allow the search for novel anisotropy induced Feshbach resonances in a dual species mixture of ground and excited state atoms [4, 5].

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Fresnel Holography for Atomic Waveguides and Miniaturised Rotation Sensing

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The progress and practicality of quantum technologies, such as rotation sensing, are contingent on the miniaturisation and portability of existing ultra-cold atom technologies [1] and the exploration of new alternative techniques. In response to this, we are aiming to integrate existing atom trap grating chips [2] with new novel Fresnel Zone Plate (FZP) hologram chips (as shown in figure 1 [3]) to create a compact Bose-Einstein condensate interferometry device.

Due to the potential for sub-wavelength scales of microfabrication, FZPs are exciting, miniaturised, candidates for the production of static cold-atom trapping potentials useful to atomtronics, interferometry, and the study of fundamental physics. This has been demonstrated through computational simulations of the optical properties of these zone plates compared to spatial light modulators [3]. We are realising this technology for testing, prior to implementation within a compact BEC interferometry device.

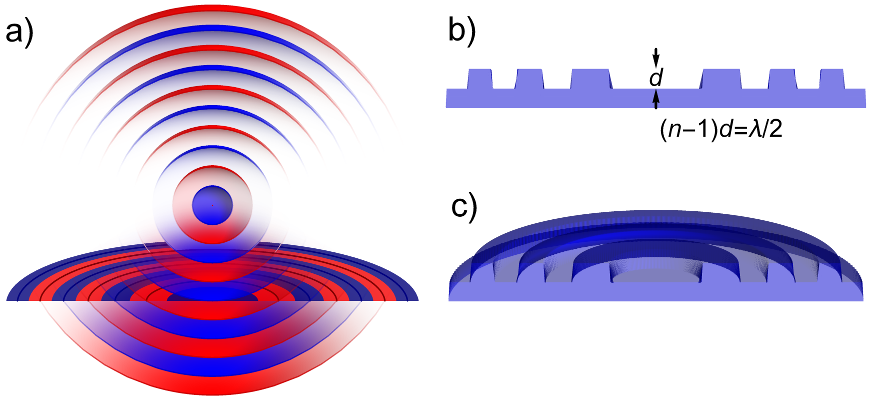

FIG. 1. A demonstration of a basic Fresnel Zone Plate used to produce a single focus. In (a) spherical light wave phasefronts (separated in phase by steps of π) emanating from a focused light beam form a distinctive Fresnel phase pattern when intersecting a plane. This phase pattern can then be binarised to produce a transmission hologram as shown in (b) and (c). In these holograms, an equivalent phase pattern is recreated from refractive index n material, with half-wavelength steps in optical depth $(n-1)d$.

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Creating Feshbach Resonances for Ultracold Molecule Formation with Radiofrequency Fields

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We show that radiofrequency (RF) radiation may be used to create Feshbach resonances in ultra-cold gases of alkali-metal atoms at desired magnetic fields that are convenient for atomic cooling and degeneracy. For the case of 39K+133Cs, where there are no RF-free resonances in regions where Cs may be cooled to degeneracy, we show that a resonance may be created near 21 G with 69.2 MHz RF radiation. This resonance is almost lossless with circularly polarized RF, and the molecules created are long-lived even with plane-polarized RF.

A single-mode external cavity diode laser using an intra-cavity atomic Faraday filter

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The interaction between atoms and light is of essential importance in many areas of physics, and a quantitative understanding of this interaction is therefore beneficial for a variety of reasons, both from the point of view of fundamental physics and for designing applications. Here we discuss a particular application of atom-light interactions; Faraday filters, which are high-contrast, ultra-narrow bandpass filters that utilises the birefringent and dichroic properties of atomic media in an applied magnetic field. Faraday filters are used in a wide variety of experiments spanning many fields. Recently we have incorporated a Faraday filter into a laser system, creating an atomically-stabilised laser that has a stable output frequency over both short- and long-term measurements.

Adiabatic and quantum walk searching

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Adiabatic quantum search and quantum walk search algorithms can both efficiently implement the task of finding a marked item in unsorted data. Like Grover's original quantum search algorithm, both provide a quadratic speed up over classical searching. We show that adiabatic and quantum walk searching can both be viewed as instances of quantum annealing. They use the same Hamiltonians and initial states, but employ very different annealing schedules. This suggests that the optimal strategy may lie in between the two, using an annealing schedule which takes advantage of the underlying mechanisms of both. We present numerical studies that interpolate between adiabatic and quantum walk searching, revealing the structure of possible trade-offs between high success probability and time to reach the marked state, see for example, figure 1. We find that the optimal algorithm is dependent both on hardware and intended application and can be the adiabatic schedule, random walks, or indeed intermediate algorithms which take advantage of the mechanisms of both, as is the case in figure 1. The spectrum of the search Hamiltonian can easily be produced in real quantum annealing hardware [1], furthermore, in principle the annealing schedules studied here could be implemented on the same hardware if faster controls were available [2].

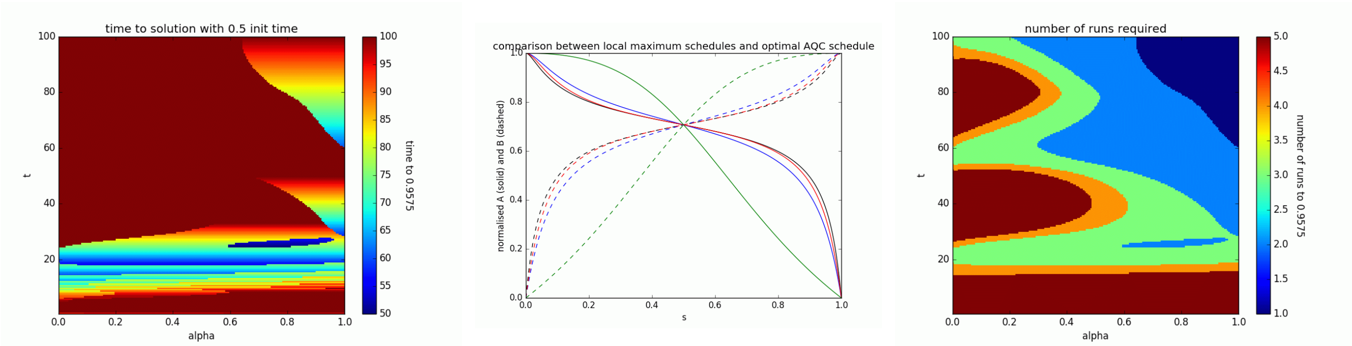

FIG. 1. Left: Time to reach a probability of 0.9575 of finding the target state once in multiple repeated runs given an initialization time of 0.5. The y-axis is the annealing time while the x-axis is an interpolation parameter α such that $\alpha = 0$ corresponds to a random walk and $\alpha = 1$ corresponds to an optimal quantum annealing schedule. All times above 100 are displayed in the same colour. Right: The number of repeated runs required to reach the target state with a probability of 0.9575. All points requiring more than 5 runs are shown the same color. Centre: Interpolation of normalized annealing schedule with driver strength $A(s)$ as solid lines and problem Hamiltonian strength $B(s)$ as dashed lines. The random walk schedule would be flat lines (not shown), while the optimal AQC schedule is shown in green, other colours are interpolations between the two extremes. $A(s)$ and $B(s)$ determine the time-dependent Hamiltonian $\hat{H}(s) = A(s)\,\hat{H}_0 + B(s)\,\hat{H}_m$, where $\hat{H}_m$ is the marked state Hamiltonian specifying the problem.

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Critical Dynamics in Quenched 2D Atomic Gases

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Non-equilibrium dynamics across phase transitions is a subject of intense investigations in diverse physical systems. One of the key issues concerns the validity of the Kibble-Zurek (KZ) scaling law for spontaneous defect creation. The KZ mechanism has been recently studied in cold atoms experiments [1, 2]. Interesting open questions arise in the case of 2D systems, due to the distinct nature of the Berezinskii-Kosterlitz-Thouless (BKT) transition [3]. Our studies rely on the stochastic Gross-Pitaevskii equation. We perform systematic numerical simulations of the spontaneous emergence and subsequent dynamics of vortices in a uniform 2D Bose gas, which is quenched across the BKT phase transition in a controlled manner, focusing on dynamical scaling and KZ-type effects. By varying the transverse confinement, we also investigate the extent to which such features can be seen in current experiments [4].

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Dude, where's my bound state?

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How do theoreticians find bound states? We present a guide to the process used in the programs BOUND and FIELD with illustrative cartoons.

Hydrodynamics in an interacting Bose gas

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In general, normal-phase Bose gases are well described as an ideal gas. In particular, hydrodynamic flow is usually not observed in the expansion dynamics of normal gases, and is more readily observable in Bose-condensed gases. However, by preparing strongly-interacting clouds, we observe hydrodynamic behaviour in normal-phase Bose gases, including the maximally hydrodynamic unitary regime. By monitoring the energy flow between different axes, we reveal the microscopic origin of the development of non-isotropic aspect ratios in interacting clouds. Comparison to a collisional model based on the Boltzmann equation [1] shows excellent agreement at weak interactions. We also observe a deviation at unitarity consistent with a suppression of thermalisation rate predicted for resonant scattering. [2].

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Low-energy states in the lowest Landau level for rotating two-component Bose gases

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In a previous work [1] we have shown that one can use the composite fermion (CF) approach to find very good approximations to the lowest energy eigenstates of a rotating dilute two-component atomic Bose gas in the lowest Landau level. In particular, the CF approach surprisingly yields very good results also for low angular momenta, far from the quantum Hall regime. In the low L regime, the number of seemingly distinct candidate wave functions tends to be orders of magnitude larger than the number of linearly independent ones, precluding efficient application of the approach. Here we present a subset of CF wave functions that give good approximations to the ground state and low-lying excited states, and for which we have identified all linear dependence relations. The subset is used to study vortex formation and structure for $L \leq N_1 \cdot N_2$, the product of the number of particles of each species.

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Cloud Shape of Dipolar Fermi Gases

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In a recent time-of-flight (TOF) expansion experiment for ultracold polarized fermionic erbium atoms it was shown that the Fermi surface has an ellipsoidal shape [1]. It was also observed that the Fermi surface follows a rotation of the dipoles, which is induced by changing the direction of the external magnetic field, keeping the major axis always parallel to the direction of maximal attraction of the dipole-dipole interaction. Here we present a theory for determining the cloud shape in both real and momentum space by extending the work of Ref. [2], where the magnetic field is oriented along one of the harmonic trap axes, to an arbitrary orientation of the magnetic field. In order to analyze the cloud shape within TOF dynamics, we solve analytically the corresponding Boltzmann-Vlasov equation by using a suitable rescaling of the equilibrium distribution [3]. The resulting ordinary differential equations of motion for the scaling parameters are solved numerically in the collisionless regime at zero temperature and turn out to agree with the observations in the Innsbruck experiment [1].

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Towards quantum simulation using fermionic KCs ultracold molecules

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There is great interest in the use of ultracold polar molecules confined in optical lattices for quantum simulation of complex many-body problems. The objective of our work is to realise a system of ultracold fermionic KCs molecules in a 1D optical lattice consisting of an array of 2D pancake traps. Such a system will enable a wide range of future investigations, including the study of novel regimes of interlayer superfluidity [1]. To create polar molecules we will use magnetoassociation on an interspecies Feshbach resonance [2] followed by transfer to the rovibrational ground state using stimulated Raman adiabatic passage (STIRAP). Here we describe our progress towards this ambitious goal.

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Diffusion of Quantum Vortices

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Symmetry breaking and the formation of topological defects through the Kibble-Zurek mechanism at the transition of 3He to its superfluid phase is perhaps the best experimental analogy to the series of symmetry-breaking phase transitions in the early universe. In the Grenoble-Lancaster experiment [Nature 382.6589 (1996): 332-334] a region of superfluid 3He is thermalised by a neutron capture event, then quenched through the superfluid phase transition by the surrounding fluid. This forms a localised area of quantised vorticity which spreads into the surrounding fluid. We simulate the spread of a region of quantised vortices with the point vortex model and the Gross-Pitaevskii equation in 2D.

Noise-correlation spectroscopy across superfluid-Mott insulator transition: separating G1 and G2

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For systems of cold atoms in a lattice, noise correlation spectroscopy is usually performed by time-of-flight (TOF) imaging and can be exploited to have information about the lattice spacing or, more generally, to probe ordering. Imaging the system after expansion is necessary when, as is often the case, the optical resolution is insufficient to detect the features of the correlation function g2 *in-situ*.

Also, the expanded density profile influences less the measured g2 structure. This is completely true for deep lattices, while it is not if the density interference peaks after the expansion are still visible; indeed, the combination of the atomic density profile with the background noise can give rise to spurious g2 peaks. In principle, performing g2 spectroscopy on an infinite number of images would cancel the information about the average density profile, but in practice this is evidently not the case. So, to extract g2 from TOF images also in case of low lattice depths, we apply a technique inspired by the work of the group of Spielman and Porto [1]. In practice, we mask the TOF density, replacing the regions containing the interference peaks with properly synthesized noise, generated from a Poissonian random number generator (as what dominates is the atomic shot noise), i.e. we smoothen away all interference peaks. This "trick" allows us to definitely separate g1 and g2 even in the case of low lattice height. We present here the technique, show some tests to verify its validity and apply it to extract g2 features of a ^{87}Rb Bose-Einstein condensate loaded in a three-dimensional optical lattice, exploring the whole regime from the Superfluid to the Mott Insulator regime.

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Collapse and revival of the monopole mode of a degenerate Bose gas in an isotropic harmonic trap

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We present experimental observations and analysis of the monopole (breathing) mode of a finite temperature Bose-Einstein condensate confined in an isotropic harmonic trap. Experiments are performed in a modified time-averaged, orbiting potential trap recently developed by D. S. Lobser et al. [1]. We observe non-exponential collapse of the amplitude of the condensate oscillation followed by a partial revival. This behavior is identified as being due to beating between two eigenmodes of the system that correspond to in-phase and out-of-phase oscillations of the condensed and non-condensed portions of the gas. We perform finite temperature numerical simulations of the system dynamics using the Zaremba-Nikuni-Griffin methodology [2], and find good agreement with the data and the two mode description. Furthermore, we compare the results of these simulations to additional simulations done in the classical field formalism.

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Miscibility in anisotropic trapped dipolar condensates

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We are reporting a work performed within an exact full three-dimensional (3D) numerical approach, on miscible-immiscible transitions between components of a coupled dipolar Bose-Einstein condensate (BEC). Within a more general perspective of possible applications to coupled dipolar or non-dipolar condensed systems, the main focus was concentrated on the atomic ^{168}Er-^{164}Dy mixture, subject to a 3D anisotropic trap. By first considering stability regimes of binary dipolar BECs in terms of the harmonic trap-aspect ratio and corresponding number of atoms (N_1 and N_2), we explore dipolar as well as non-dipolar coupled systems. Certain non-trivial structures of the condensed mixture are verified in the density oscillations of dipolar atomic components (given by $|\phi_1|$ and $|\phi_2|$), as exemplified in Fig. 1. The characteristics of the condensed coupled system are evidenced, for different dipolar and contact parameters, through the densities displayed in 3D surface plots where one can visualize the transitions from miscible to immiscible phases. In order to measure the immiscibility, we consider the overlap between the densities, defined by $\eta \equiv \int |\phi_1||\phi_2| d\mathbf{x}$, such that η goes from 0 (complete immiscible) to 1 (complete miscible).

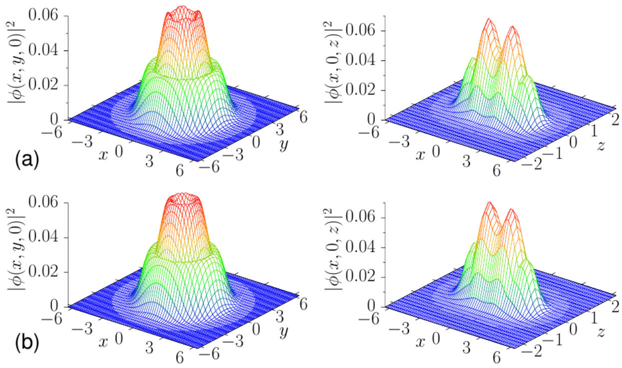

FIG. 1. 3D surface plots for the pure dipolar coupled ^{168}Er-^{164}Dy mixture, confined in a stable pancake-type condensate, where the internal (reddish) structure is dominated by the ^{168}Er component, and the surrounding (greenish) structure dominated by the ^{164}Dy component. Within a partially mixed phase such that $\eta = 0.77$, with about the same dipolar parameters but different number of particles, as the number of atoms is increases from $N_1 = 2700, N2 = 40$ (lower panels) to $N_1 = 3000, N_2 = 60$(upper panels), one can observe some nontrivial biconcave structure oscillations emerging in the coupled condensate.

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Real-time Terahertz Imaging and Cooperatively Enhanced Terahertz Detection using a Hot Rydberg Vapour

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Rydberg atomic states couple to strong, narrowband electric dipole transitions spanning the Terahertz (THz) frequency regime, making them ideal tools for detecting THz radiation. Here we use THz-induced optical fluorescence from a hot caesium Rydberg vapour to image THz fields in real-time [1]. In our scheme Rydberg atoms emit optical photons in proportion to the local THz intensity, and so a camera image of the green-glowing vapour reveals a map of the THz field. Using this technique we image a THz standing wave, with nodes and anti-nodes perpendicular to the laser beam. If we excite a higher density of Rydberg atoms, inter-atomic interactions generate a wealth of non-linear dynamics including intrinsic optical bistability and a non-equilibrium phase transition [2]. When the THz field exceeds a critical intensity threshold the vapour undergoes a phase transition to a collective state characterised by bright-orange fluorescence and increased transparency. Hysteresis in the response means that even a transient THz field ($50\,\mu$s) can permanently alter the collective state of the vapour. To linearise the vapour response we force the system to alternate between the two stable states by cycling the excitation laser frequency and we find that the fraction of time spent in each state is proportional to the THz intensity. Using this protocol we demonstrate a cooperatively enhanced detector with noise equivalent power $\simeq 10\,\mu W m^{-2} Hz^{-1/2}$.

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Towards precision sensing of atom-surface interactions and rotation using Bose-Einstein condensates

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We report on the controlled formation of a bright matter-wave soliton [1] from a Bose-Einstein condensate of ^{85}Rb [2] which is observed to propagate over a distance of ∼1.1 mm in 150 ms with no observable dispersion. We demonstrate reflection from a broad Gaussian barrier of both the soliton and a repulsive condensate, finding excellent agreement with 3D Gross-Pitaevskii equation calculations in both cases. Additionally, we observe splitting of a low incident velocity soliton at a narrow attractive potential well, resulting in quantum reflection of ∼25% of the atoms. A further fraction is confined to the well (∼10%) whilst the remainder is transmitted. These results enable new experimental studies of bright matter-wave soliton dynamics to elucidate the wealth of existing theoretical work and to explore an array of potential applications including novel interferometric devices [4, 5], the realisation of Schrödinger cat states [6, 7], and the study of short-range atom-surface potentials [8]. Such measurements of the interactions between an atom and a solid surface are of fundamental interest as a potential method of establishing new bounds on short range corrections to gravity due to exotic forces beyond the standard model [9].

Furthermore, we report on the formation and decay of vortex lattices in repulsive ^{87}Rb BECs, focussing on quantifying order in the vortex lattice [10]. Inducing vortices in a BEC is a milestone towards future rotation experiments in ring trap geometries featuring two-components flowing in opposite directions, which can be utilised for Sagnac interferometry. Such two-component atom interferometers are robust against atom-atom interactions, provided that the scattering lengths of each component are roughly equal [11]. The ability to control ultracold atoms with unprecedented precision makes them elegant sensors of both interactions (e.g., with a surface) and of external forces. Using non-destructive Faraday imaging we can take multiple in-situ images of the same atomic cloud without causing measurable pertubation. We intend to use this method to further study soliton dynamics. Our goal is to use BECs as sensitive probes of both atom-surface interactions and as rotational sensors.

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Heralded single photons from a hot atomic vapour in a strong magnetic field

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We will present on coherent phenomena in the (large magnetic field) hyperfine Paschen-Back regime of a hot atomic vapour in a diamond energy level scheme. Previous experiments on electromagnetically induced transparency [1] and absorption [2] have shown the benefits of applying large magnetic fields, such as the isolation of pure 3-level systems in hot atomic vapours and the resulting reduction of deleterious interferences usually caused by nearby resonances with degenerate states. We will display recent results on four-wave mixing and heralded single photon generation in this regime, with particular emphasis on the dynamics of the heralded single photons.

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Decay of Macroscopic Quantum Self-Trapping due to Vortex Ring Generation and Thermal Fluctuations

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Josephson effects are an important macroscopic quantum phenomenon, strikingly demonstrated by the flow of particles through a weak link between two quantum fluids exhibiting a different phase of the wave function. In the case of dilute, weakly-linked Bose-Einstein condensates confined in a double-well potential, the presence of interactions may also give rise to a macroscopic quantum self-trapping regime [1], in which one well is always more populated than the other, despite the underlying density oscillations, while the relative phase between the two condensates increases linearly in time. This may give rise to the generation of vortex rings in the barrier region [2], which may enter in the superfluid region causing dissipation via phase slippage and a drop in the superfluid current as recently observed in experiments at LENS [3]. Here we report -both at zero and finite temperatures- our numerical simulations of the transition from the Josephson to the dissipative regime, which depends on the ratio of the tunneling to the on-site energy.

Simulations based on the Gross-Pitaevskii equation are found to compare favourably to experimental results, and we use this to analyse both the time evolution of the population imbalance for different barrier heights and initial population imbalance between the two wells, and the connection between the population imbalance decay and the vortex ring nucleation. In appropriate parameter regimes, we find a decay of macroscopic self-trapping due to the propagation of the vortex ring in the bulk. Our analysis is further extended to finite temperatures, by coupling the Gross-Pitaevskii equation self-consistently to a quantum Boltzmann equation for the thermal cloud ("ZNG" model) [4], where such features are found to arise naturally by means of the additional dissipation introduced into the system by the (fully dynamical) thermal cloud.

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