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1–4 September 2015
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7–8 April
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25–29 July
19th International Conference on Non-Contact Atomic Force Microscopy
East Midlands Conference Centre, Nottingham, UK
Organised by the IOP Nanoscale Physics and Technology Group

1–4 August
Summer School on nanoScience@Surfaces
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Organised by the IOP Thin Films and Surfaces Group

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5–8 September
Photon16
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Conference Programme

Tuesday 1 September 2015

11:00 Conference registration
12:20 Lunch
14:00 Welcome
14:10 (keynote) Single photons and nonclassicality
Peter Knight, Imperial College London, UK
15:00 (invited) A quantum-gas microscope for fermions
Stefan Kuhr, University of Strathclyde, UK
15:40 Refreshments
16:00 (invited) Harnessing collective effects for quantum enhanced absorption of light
Erik Gauger, Heriot-Watt University, UK
16:40 Floquet engineering of driven lattice systems
Charles Creffield, Universidad Complutense de Madrid, Spain
17:00 Dark soliton like excitations in a disk shaped Bose-Einstein condensate
Nadine Meyer, University of Birmingham, UK
17:20 Trapping ultracold argon atoms
Peter Edmunds, University College London, UK
17:40 Soliton dynamics in the Gross-Pitaevskii equation: splitting, collisions and interferometry
John Helm, Durham University, UK
18:00 Welcome reception
19:00 Welcome reception concludes
Wednesday 2 September 2015

08:30 Registration

09:00 (keynote) **Attosecond ionisation dynamics and time delays**
Ursula Keller, ETH Zürich, Switzerland

10:00 **Femtosecond electron microscopy of charge motion along the surface of a nanoscale object**
Will Bryan, Swansea University, UK

10:20 **Grassmann phase space theory for fermions**
Bryan Dalton, Swinburne University of Technology, Australia

10:40 Refreshments

11:00 (invited) **Optical Clocks - is now the time?**
Patrick Gill, National Physical Laboratory, UK

11:40 **Quantum-enhanced magnetometry with cold molecules**
Jordi Mur-Petit, Consejo Superior de Investigaciones Científicas, Spain

12:00 **Molecule interference: Not too hot to handle**
Joseph Cotter, University of Vienna, Austria

12:20 Lunch

14:00 (invited) **Quantum correlations in photonic networks**
Ian Walmsley, University of Oxford, UK

14:40 **Grating chips for quantum technologies**
Aidan Arnold, University of Strathclyde, UK

15:00 **On-chip generation and deterministic splitting of degenerate photon pairs**
Alex Clark, Imperial College London, UK

15:20 **Creating 18dB metrologically relevant spin-squeezed states of an atomic ensemble**
Rajiv Krishnakumar, Stanford University, USA

15:40 Refreshments

16:00 (invited) **Introduction to the UK National Quantum Technology Hub in Sensors and Metrology**
Kai Bongs, University of Birmingham, UK

16:40 **Vacuum measurements with a Magneto-Optical Trap: the \( N_{\text{vac}} - \tau_{\text{plot}} \)**
Donatella Cassettari, University of St Andrews, UK

17:00 **Single-photon metrology for quantum technologies**
David Szwer, National Physical Laboratory, UK

17:20 **Sub-100 µm resolution imaging of dc and microwave magnetic fields using atomic vapour cells**
Andrew Horsley, University of Basel, Switzerland

18:00 Buffet Dinner and Poster Session

20:30 Buffet Dinner and Poster Session concludes
Thursday 3 September 2015

08:30  Registration

09:00  (keynote) Real and artificial atoms interacting with photons: From cavity QED to circuit QED
Serger Haroche, ENS / Collège de France, France

10:00  Quantum optics in dense alkali-metal thermal vapours
Ifan Hughes, Durham University, UK

10:20  Orbital angular momentum of light stored and retrieved in cold atoms via FWM and CPO processes
Laurence Pruvost, Université-Paris Sud, France

10:40  Refreshments

11:00  (invited) First generation controlled quantum hardware: What’s it good for, and when can we have it?
Simon Benjamin, University of Oxford, UK

11:40  Minimal ancilla-mediated quantum gates
Viv Kendon, Durham University, UK

12:00  Quantum correlations of light and matter through environmental transitions
Ahsan Nazir, University of Manchester, UK

12:20  Lunch

14:00  (invited) Magnetic induction imaging with atomic magnetometers
Ferrucio Renzoni, University College London, UK

14:40  Observation of localised multi-spatial-mode quadrature squeezing
Vincent Boyer, University of Birmingham, UK

15:00  (invited) Quantum inspired imaging
Miles Padgett, University of Glasgow, UK

15:40  Refreshments

16:00  (invited) Probing physics at TeV by measuring aeV
Ed Hinds, Imperial College London, UK

16:40  (invited) Inertial atom interferometry
Tim Freegarde, University of Southampton, UK

17:20  Interaction of atoms with structured light
Mohamed Babiker, University of York, UK

17:40  Conference close Day 3

18:30  Depart venue for Conference Dinner

19:00  Conference Dinner

22:00  Conference Dinner concludes
Friday 4 September 2015

08:30   Registration
09:00   (keynote) Bates Prize Lecture
          Bates Prize winner
10:00   (invited) Interaction of positrons and positronium with atoms and molecules: scattering, annihilation and binding
          Gleb Gribakin, Queen’s University Belfast, UK
10:40   Refreshments
11:00   (invited) A rigorous relativistic framework for nonlinear electrostatic modes in the high-density quantum plasma regime: shedding new light on an old problem
          Ioannis Kourakis, Queen’s University Belfast, UK
11:40   Detection of azimuthal doppler shift using saturated absorption spectroscopy with optical vortex
          Mitsuoshi Aramaki, Nihon University, Japan
12:00   Frequency combs for demanding applications
          Benjamin Sprenger, Menlo Systems GmbH, Germany
12:20   Closing of the conference
12:30   Lunch
14:00   Laboratory tours commence
16:00   Laboratory tours conclude

All refreshment breaks are proudly sponsored by

PHOTONIC SOLUTIONS
Poster programme

P01. Dominant correlation effects in atomic spectra
Hubert Klar, Duale Hochschule Baden-Württemberg, Germany

P02. Practical quantum optical metrology with a 7-fold enhancement
Paul Knott, University of Sussex, UK

P03. First-principles prediction of the magnetic ordering and the superconducting state in rare earth iron pnictides
Said Abbaoui, University Djillali Liabés, Algeria

P04. Quantum states in the multipole solution of the Maxwell’s equations for the free radiation field
Michele Marrocco, ENEA, Italy

P05. Solitary waves in plasma with pressure variations in both electrons and ions
Samiran Das, Central Institute of Technology Kokrajhar, India

P06. High density sub-Doppler laser cooling of $^{40}$K using grey molasses on the D$_2$-Line
Graham Bruce, University of St Andrews, UK

P07. Towards rotation sensing with a Bose-Einstein condensate
Graham Bruce, University of St Andrews, UK

P08. Progress towards a molecular fountain for measuring the electron’s electric dipole moment
James Bumby, Imperial College London, UK

P09. Many-body localisation in modular systems of quantum spin chains
Emil Khabiboulline, California Institute of Technology, USA

P10. Towards a cold gas ring laser with coherent dispersion control
Balazs Megyeri, University of Birmingham, UK

P11. Quantum simulation of a lattice gauge theory
Pedro Nevado Serrano, University of Sussex, UK

P12. Magnetic field and density effects on the streaming instability in magnetized electron-positron plasmas
Young-Dae Jung, Hanyang University, Korea

P13. An improved experiment to measure the electron electric dipole moment with ytterbium fluoride
Jack Devlin, Imperial College London, UK

P14. Superfluid in rotating helical pipe
Alexey Okulov, Russian Academy of Sciences, Russia

P15. Quantum carburettor effect for photon number shifting
Jennifer Radtke, University of Strathclyde, UK
P16. A portable magneto-optical trap for public engagement events
Philip Ireland, University of St Andrews, UK

P17. Phase-engineered light patterns for ultracold atom experiments
David Bowman, University of St Andrews, UK

P18. Talbot-enhanced maximum-contrast interferometry and coherence in Bose-Einstein condensates
Aidan Arnold, University of Strathclyde, UK

P19. Creation of ultracold RbCs molecules in the rovibrational ground state
Avinash Kumar, Durham University, UK

P20. A hybrid atom-photon-superconductor quantum interface
Jonathan Pritchard, University of Strathclyde, UK

P21. Towards laser spectroscopy of trapped antihydrogen
Steven Jones, CERN, Switzerland

P22. Quantum properties of light and matter in quantum optical lattices for ultracold atoms
Santiago Francisco Caballero Benitez, University of Oxford, UK

P23. An AC MOT for atoms and molecules with complex level structures
Kyle Jarvis, Imperial College London, UK

P24. Ultracold collisions of highly magnetic Erbium isotopes: How much chaotic are they?
Jordi Mur-Petit, Consejo Superior de Investigaciones Científicas, Spain

P25. Measurement of K-shell X-ray production cross sections in Ti due to 0.3 – 0.7 MeV/u $^{28}$Si and $^{63}$Cu ions
Mandlenkosi Msimanga, Tshwane University of Technology, South Africa

P26. Toward a charged-wire storage ring for high-field-seeking Rydberg atoms
Alan Suganuma, University College London, UK

P27. Single-shot, phase-insensitive readout of an atom interferometer
Andrew Mackellar, University of Strathclyde, UK

P28. Towards the production of a quantum gas near a tapered optical nanofibre
Rhys Jenkins, Swansea University, UK

P29. Towards ultracold CsYb molecules for quantum simulation
Stephen Hopkins, Durham University, UK

P30. Security against jamming of ghost imaging
Wojciech Roga, University of Strathclyde, UK

P31. Cavity cooling a single charged levitated nanoparticle
Piergiacomo Zucconi Galli Fonseca, University College London, UK
P32. The Zeeman-Sisyphus decelerator: A new time-independent slowing method for molecules
Moritz Hambach, Imperial College London, UK

P33. Developing a next generation ultrafast electron microscope
Connor Barlow-Myers, Swansea University, UK

P34. Rydberg spectroscopy and dressing in strontium with a high power, narrow linewidth UV laser
Elizabeth Bridge, Durham University, UK

P35. Laser cooling of CaF molecules
Hannah Williams, Imperial College London, UK

P36. Sensitivity improvement to the YbF electron electric dipole moment experiment
Isabel Rabey, Imperial College London, UK

P37. Transporting and storing Rydberg atoms above electrical transmission-lines
Patrick Lancuba, University College London, UK

P38. Adiabatic elimination of a qubit transducer from stochastic quantum dynamics. Quantum jumps monitoring in optomechanical system
Denis Vasilyev, University of York, UK

P39. Rydberg atoms in time-varying electric fields: sensing electrical noise and monitoring many-body interactions
Valentina Zhelyazkova, University College London, UK

P40. Calculation of the exchange splitting of the interaction energy of H₂⁺ based on the multipole expansion of the wave function
Piotr Gniewek, University of Warsaw, Poland

P41. First principles study of the electronic and magnetic structure of intermetallic compounds
Ahmed Benidris, University Djillali Liabés, Algeria

P42. Holography-based device for the study of the topological kondo effect in cold atom systems
Donatella Cassettari, University of St Andrews, UK

P43. A co-trapped barium and ytterbium ion trap experiment for remote entanglement and hybrid quantum networks
James Siverns, University of Maryland, USA

P44. Observation of localised multi-spatial-mode quadrature squeezing in four wave mixing
Joshua Hordell, University of Birmingham, UK

P45. Observation of chiral edge states with neutral fermions in synthetic Hall ribbons
Marie Rider, University of Innsbruck, Austria

P46. Towards a molecular MOT of YbF
James Almond, Imperial College London, UK
P47. *Quantum simulation of the two dimensional compass model with periodic driving fields*
Samuel Fernández Lorenzo, University of Sussex, UK

P48. *Observing the average trajectories of particles in a double slit interferometer*
Joel Morley, University College London, UK

P49. *Dielectric anomaly in H$_2$O ice near 20 K; Evidence of macroscopic quantum phenomena*
Fei Yen, Chinese Academy of Sciences, China

P50. *Dense and cold atomic beam delivered by a 2DMOT repumped and channelled by a Laguerre-Gaussian laser beam*
Laurence Pruvost, Université Paris-Sud, France

P51. *An optical system for high-fidelity coherent quantum control of atomic systems*
Joseph Thom, National Physical Laboratory, UK

P52. *Four wave mixing in CMOS compatible high order ring resonators*
Luigi Di Lauro, University of Sussex, UK

P53. *Quantum key distribution protocol*
Dragos Falie, Politehnica University of Bucharest, Romania

P54. *Burst-mode operation of a 655GHz mode locked laser based on an 11th order microring resonator*
Andrew Cooper, University of Sussex, UK

P55. *Towards strong coupling of single ions to an optical cavity*
Ezra Kassa, University of Sussex, UK

P56. *Non-destructive state detection and identification of molecular ions*
Amy Gardner, University of Sussex, UK

P57. *Terahertz waves for ancient manuscripts conservation*
Luke Peters, University of Sussex, UK

P58. *Ion trap cavity QED - probabilistic ion entanglement for cluster state generation*
Markus Vogt, University of Sussex, UK

P59. *Scalable cryogenic and microwave systems for the creation of high fidelity quantum gates*
Anton Grounds, University of Sussex, UK

P60. *Design of a micro-sized ion trap for cavity-QED*
Jack Morphew, University of Sussex, UK

P61. *Route to ultracold NaK groundstate molecules via the spin-orbit coupled d/D complex*
Zhenkai Lu, Max-Planck Institute for Quantum Optics, Germany

P62. *Dressed potentials for ultracold alkali atoms: Theory and applications*
German Sinuco-Leon, University of Sussex, UK
P63. Tests of quantum Darwinism with the pseudomode method
Graeme Pleasance, University of Sussex, UK

P64. Modifying the potential landscape of a Penning trap
Frances Crimin, University of Sussex, UK

P65. Realisation of the geonium chip – a planar Penning trap
Jonathan Pinder, University of Sussex, UK

P66. Future applications of the geonium chip
Jonathan Pinder, University of Sussex, UK

P67. Quantum information processing using long-wavelength radiation
Joe Randall, University of Sussex, UK

P68. Microfabricated ion traps for scalable quantum computation and simulation
Weikang Fan, University of Sussex, UK

P69. Towards portable ion trap magnetometers
Ethan Potter, University of Sussex, UK

P70. Theory for electrostatic rogue waves in multi-ion plasmas
Ibrahim El-Kamash, Queen’s University Belfast, UK

P71. Non-adiabatic losses from radio frequency dressed cold atom traps
Kathryn Burrows, University of Sussex, UK

P72. A carbon nanotube mechanical oscillator coupled to a radio-frequency electrical resonator
Edward Laird, University of Oxford, UK

P73. The weak measurement process and the weak value of spin for metastable helium
Vincenzo Monachello, University College London, UK

P74. NPL & University of Liverpool Interferometer
Jonathon Coleman, University of Liverpool, UK

P75. Thermodynamic properties of NLTE hydrogen plasma: Role of pressure derivative of partition function
Gurpreet Singh, DAV College Bathinda, India

P76. Sub-100 µm resolution imaging of dc and microwave magnetic fields using atomic vapour cells
Andrew Horsley, University of Basel, Switzerland
Oral abstracts

Tuesday 1 September 2015

(keynote) Single photons and nonclassicality

P Knight
Imperial College London, UK

Quantum Optics has focused for many years on uncovering what is specifically non-classical about light fields, from the early days of quantum mechanics to current work on quantum information processing. Much of this work has concentrated on the role of discreteness, of the limits of the uncertainty relation in governing fluctuations and the nature of quantum correlations beyond what is allowed classically. Progress in identifying, generating and characterizing nonclassical states has been spectacular. Quantum Information Science in part has grown out of this progress: the quantum world allows information to be encoded, manipulated and transmitted in ways quite different from classical physics. I will discuss the formation, propagation and manipulation of single photon wavepackets, explain how these can be used in simple quantum networks (for example in quantum walks and in Boson Sampling), and describe recent work on detecting single photons non-destructively.

(invited) A quantum-gas microscope for fermions

S Kuhr
University of Strathclyde, UK

Single-atom-resolved detection in optical lattices using quantum-gas microscopes has enabled a new generation of experiments in the field of quantum simulation. While such devices have been realised with bosonic species, a fermionic quantum-gas microscope has proven more challenging.

We recently demonstrated single-site- and single-atom-resolved florescence imaging of fermionic potassium-40 atoms in a quantum-gas microscope setup using electromagnetically-induced-transparency cooling [1]. We detected on average 1000 fluorescence photons from a single atom within 1.5 s, while keeping it close to the vibrational ground state of the optical lattice.

Our fermionic quantum-gas microscope will provide the possibility to probe quantities that are difficult to access directly, such as spin-spin-correlation functions or string-order. It would allow the study of out-of-equilibrium dynamics, the spreading of correlations and the build-up of entanglement in many-particle fermionic quantum systems. It could perform quantum simulation of the Fermi-Hubbard model, which is conjectured to capture the key mechanism behind high-temperature superconductors.

(invited) Harnessing collective effects for quantum enhanced absorption of light

E Gauger
Heriot-Watt University, UK

We consider ring-like structures of optically active quantum nanostructures which interact with a common electromagnetic environment as well as experiencing the influence of their condensed matter environment. Often considered detrimental, here the fundamentally present pairwise couplings of such systems prove to be an asset for unlocking light absorption beyond what is possible classically. Suitably engineered systems may support one or more of several distinct effects contributing to quantum enhanced photon absorption: inverting superradiance, breaking detailed balance, and optical ratcheting. Potential practical applications of these effects include improved photon detectors and light harvesting devices.

Floquet engineering of driven lattice systems

C. E Creffield1, F. Sols1 and G. Sierra2
1Universidad Complutense de Madrid, Spain, 2Universidad Autónoma de Madrid Cantoblanco, Spain

When a lattice system is periodically driven at a high-frequency, its dynamics can often be described in terms of an effective static Hamiltonian, which can be derived using the Floquet approach. By controlling the type of driving, novel terms can be induced in this effective Hamiltonian, allowing us to perform “Floquet engineering”. Using the example of ultracold atoms held in optical lattice potentials, we will show how this technique can be used to study systems ranging from number theory to quantum simulation. We will first show how the Hamiltonian can be tuned so that its spectrum mimics the Riemann zeta function [1], allowing the Riemann zeros to be directly observed in currently accessible cold atom experiments. We will then show how the phase of the tunnelling can be controlled, permitting the simulation of synthetic gauge fields [2].

FIG. 1: Floquet quasienergies, showing the formation of the Hofstadter butterfly structure in a driven cold atom system. Black (filled) circles show the bulk states, the red (unfilled) symbols the chiral transporting edge states.

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

N Meyer, H Proud, C O’Neale, M Pera-Ortiz and K Bongs

University of Birmingham, UK

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 $^{87}$Rb. The evolution, dynamics and their premature decay 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 creation of more stable lump structures by varying imprint shapes. Longer lifetimes are crucial for directed and efficient transport on surfaces.

In contrast to formerly performed experiments in elongated BEC traps [4] the soliton like excitation created in the disk shaped Bose-Einstein condensate is dynamically unstable along one degree of freedom leading to the so-called snaking instability. However the collective excitation decays rapidly within a few ms which stands in contrast to numerical simulations of the GPE and prevents the onset of the expected decay into vortices. Investigating the lifetime of soliton like structures in the finite temperature regime shows a prolonged lifetime at lower temperatures. The results are compared to a modified model developed for quasi-1D BECs based on the scattering of thermal excitations [5, 6] and shows reasonable agreement.

Trapping ultracold argon atoms

P D Edmunds and P F Barker
University College London, UK

Thermalising collisions between molecules and laser cooled atoms are a promising general method for dissipative cooling, but typical laser cooled species are reactive and cannot generally be utilised [1]. Trapped noble gas atoms in their ground state appear to be ideal candidates for the sympathetic cooling as they are chemically inert and can be laser cooled to µK temperatures in an excited metastable state.

We describe the dipole trapping of both metastable and ground state argon atoms for sympathetic cooling. Metastable argon atoms are first Doppler-cooled down to ∼80 µK in a magneto-optical trap (MOT) and are loaded into a dipole trap formed within the focus of an optical build-up cavity. The optical cavity’s well depth could be rapidly modulated [2]: allowing efficient loading of the trap, characterisation of trapped atom temperature, and reduction of intensity noise. Collisional properties of the trapped metastable atoms were studied within the cavity and the Penning and associative losses from the trap calculated.

Ground state noble gas atoms were also trapped for the first time by optically quenching metastable atoms to the ground state and then trapping the atoms in the cavity field (shown in figure 1) [3]. Although the ground state atoms could not be directly probed, we detected them by observing the additional collisional loss from co-trapped metastable argon atoms. This trap loss was used to determine an ultra-cold elastic cross section between the ground and metastable states and was shown to lead to type of sympathetic evaporation of the metastable atoms. Using a parametric loss spectroscopy we also determined the polarisability of metastable argon at the trapping wavelength of 1064 nm.

Figure 1: Schematic of the optical cavity. Metastable argon is first cooled in a MOT, and then quenched down to the ground state. Both species can be trapped in the lattice formed within the optical build-up cavity.

Here we investigate the use of BEC bright solitary-waves to perform interferometry, with particular focus on the interactions of bright solitary-waves with narrow potential barriers[1–3].

We first study bright solitons in the GPE as they are split on Gaussian and $\delta$-function barriers in various energetic regimes[1, 2]. We present analytic and numerical results determining the general region in which a soliton may not be split on a finite width potential barrier. Furthermore, we test the sensitivity of the system to quantum fluctuations.

We then study fast-moving bright solitons colliding at a narrow Gaussian potential barrier. In the limiting case of a $\delta$-function barrier[1], we show analytically that the relative norms of the outgoing waves depends sinusoidally on the relative phase of the incoming waves. We use numerical simulations to show that outside the high velocity limit nonlinear effects introduce a skew to the phase-dependence.

Finally, we use these results to analyse the process of soliton interferometry[1, 2]. We develop analyses of both toroidal and harmonic trapping geometries for Mach–Zehnder interferometry, and then two implementations of a toroidal Sagnac interferometer[3], also giving the analytical determination of the Sagnac phase in such systems. These results are again verified numerically.

Wednesday 2 September 2015

(keynote) Attosecond ionisation dynamics and time delays

U Keller
ETH Zürich, Switzerland

The basic motivation is to understand and ultimately control how quanta of energy and charge are transported on an atomic spatial and attosecond (i.e. 10–18 seconds) time scale. In principle, time dependent-processes in quantum mechanics are described by the time-dependent Schrödinger Equation (TDSE). The challenge is that the TDSE in most cases cannot be solved without approximations. Semi-classical models, on the other hand, seem to explain surprisingly well many current attosecond measurements. Attosecond measurements have advanced rapidly with reproducible and high-quality data, allowing for very fundamental tests for our current understanding and models in time-dependent quantum mechanics. Following the “peak” of an electron wavepacket for determining photoionisation time delays, for example, can be very successful but also misleading under certain conditions. In contrast to a light pulse, an electron wavepacket disperses even in vacuum. Since the propagation of the peak of a wavepacket follows by definition the group delay, almost any group delay can be measured during propagation in combination with an appropriate energy-dependent transmission filter. This can explain why in the multi-photon or tunnel ionisation regime the group delay (or correspondingly the Wigner time delay) gives the wrong explanation for the measured delay using the attoclock technique [1, 2], whereas in the single-photon ionisation regime we can show experimentally that the group delay can explain the general trend correctly although it does not capture all the observed features using the attosecond energy streaking technique in coincidence [3].


Femtosecond electron microscopy of charge motion along the surface of a nanoscale object

W A Bryan, A R Bainbridge and C Barlow-Myers
Swansea University, UK

The impact of electron microscopy and diffraction is clearly established, facilitating unprecedented imaging of matter on atomic length scales. Major advances in ultrafast electron microscopy and diffraction over the last decade are bringing about a paradigm shift to using electrons as a time-resolved imaging tool. Much as with femtosecond pulses of x-rays generated by XFELs being employed to image processes on chemical and biological time- and length-scales, ultrafast electron microscopy is moving towards being able to image on atomic time- and length-scales. Our recent results to be presented in Sussex are a step in this direction, using sub-picosecond and sub-micron temporal and spatial resolution to directly observe the response of a nanoscale metal conductor to an applied ultrafast laser pulse.

We have developed and demonstrated time-resolved imaging in a novel instrument which makes use of point projection microscopy (PPM), originally developed as a CW technique by Fink and co-workers in 1989 [1,2]. PPM is closely related to the original holographic scheme of Gabor, and the beauty of PPM lies in its simplicity. Typical PPMs [3,4] are composed of a highly coherent electron source (typically a nanoscale metal tip), the target or object to be imaged and an electron detector. In CW mode, other groups have reported a resolution of 2 nm, however very recent results indicate a single-atom source could resolve to 2 Angstroms.
One of our medium-term goals is to directly observe nanoplasmonic responses in the vicinity of nanorods, nanowires and 2D crystalline planes illuminated with femtosecond laser pulses. As a proof-of-principle, we have made use of two nanoscale metal tips (NSMTs) as source and target as they have a well understood response to laser fields. A Light Conversion Pharos (1028nm, 290fs, 50kHz, 4W) pumped an Orpheus-N NOPA producing 800nm, 20 fs, 0.85W at 50kHz which was actively pointing stabilised. These laser pulses were split 1:10, with the lower energy pulse transmission focused on a tungsten NSMT pointing at a distant MCP + phosphor screen. The tight radius of curvature at the apex of such NSMTs caused a field enhancement which, when coupled with the electric field induced by the laser field, caused tunnelling of bunches of electrons directly into the continuum. The novelty is that this source is operated in single- or few-electrons per pulse, hence the temporal duration of the electron pulses is only defined by the bandwidth of the emission process. Here, we have shown that we can deliver electron pulses with a duration of the order of 100 femtoseconds over 0.3 mm.

A second tungsten NSMT perpendicular to the first and illuminated by the remaining split of the laser output is a perfect test object for temporally resolved electron microscopy. By reducing the separation of the NSMTs to a few hundred microns we formed a low-energy PPM with sub-micron resolution. This configuration allowed the observation of a “wave” of charge along the shank of the second nanotip as the laser pulse delay was varied. This charge wave is initiated by the nanoplasmonic response to the applied laser field, so our observations combine information about how the charge density evolves as a function of space and time. Interestingly, we see the influence of the changing shape of the nanotip taper. Our current efforts are centred on modelling these observations, and novel Monte Carlo results will be presented and discussed, as will future applications of this technique.


Grassmann phase space theory for fermions
B Dalton¹, J Jeffers² and S Barnett³

In both quantum optics and cold atom physics, the behaviour of bosonic photons and atoms is often treated using phase space methods, where mode annihilation and creation operators are represented by c-number phase space variables, with the density operator equivalent to a distribution function of these variables. The anti-commutation rules for fermion annihilation, creation operators suggests the possibility of using anti-commuting Grassmann variables [1] to represent these operators. However, in spite of the seminal work by Cahill and Glauber [2] and a few applications [3, 4], the use of Grassmann phase space methods in quantum-atom optics to treat fermionic systems is rather rare, though fermion coherent states using Grassmann variables are widely used in particle physics. The theory of Grassmann phase space methods for fermions is developed, showing how the distribution function is defined and used to determine quantum correlation functions, Fock state populations and coherences via Grassmann phase space integrals, how the Fokker-Planck equations are obtained and converted into equivalent Ito equations for stochastic Grassmann variables. Unlike the bosonic case, the sign for the drift term in the Ito equation is reversed and the diffusion matrix in the Fokker-Planck equation is anti-symmetric rather than symmetric.

Using the un-normalised B distribution [3, 5] we show the Ito stochastic equations can be solved numerically via c-number stochastic quantities plus averages of products of initial Grassmann stochastic variables determined from the initial quantum state. A major problem in carrying out numerical calculations based on Grassmann phase space theories for fermion systems is now resolved.

Typical applications involving spin conserving collisions between spin 1/2 fermions are presented.
(invited) Optical clocks - is now the time?

P Gill
National Physical Laboratory, UK

This year marks the 60th anniversary of the microwave caesium atomic clock, which has been the basis for the SI second over the last few decades. The advent of laser cooling has underpinned development of cold caesium fountain clocks, some of which now achieve systematic frequency uncertainties of \( \sim 1-2 \times 10^{-16} \). Optical clocks comprise frequency-stabilised lasers probing very weak absorptions in a single cold ion confined in an electromagnetic trap, or similarly weak absorptions in an ensemble of cold atoms trapped within an optical lattice. Certain optical clock systems based on different atomic species now surpass the best performance of Cs fountain primary standards used to realise the SI second, raising the issue of redefinition of the second. These include \(^{27}\text{Al}^+\), \(^{199}\text{Hg}^+\), \(^{171}\text{Yb}^+\) and \(^{88}\text{Sr}^+\) trapped ion systems and \(^{87}\text{Sr}\) and \(^{171}\text{Yb}\) atoms in an optical lattice, where relative frequency uncertainties in the few \(\times 10^{-17}\) to few \(\times 10^{-18}\) have been achieved in certain cases. This presentation will briefly point to leading-edge performance and future developments of optical clocks, the need for remote clock intercomparisons, and the wider spectrum of applications.

Quantum-enhanced magnetometry with cold molecules

J Mur-Petit
Consejo Superior de Investigaciones Científicas, Spain

One of the more promising practical applications of quantum information science lies in the field of quantum sensing, where certain quantum-correlated states are used to measure physical observables with reduced uncertainties with respect to the standard quantum limit [1]. In the last few years, a number of experiments with atomic samples have used external control fields to create such squeezed states [2,3,4]. In particular, a particular class of many-particle squeezed state with cold atoms has been utilised to measure a magnetic field with quantum-enhanced resolution [4]. On the other hand, it is known that paramagnetic molecules present higher sensitivity than atoms to low-frequency electromagnetic fields [5]. In this talk, I will discuss the possibility of realising similar quantum-enhanced magnetometry protocols using ensembles of cold molecules, and the sensitivities we can expect [6].

Molecule interference: Not too hot to handle

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Matter-wave interferometry helps to probe the foundations of quantum physics and can be used to make precise measurements of particle properties and fundamental constants.

All interferometers require a beam splitter capable of dividing and recombining the wave function whilst maintaining a well defined phase difference. Optical phase gratings are used as beam splitters for a wide variety of large, complex molecules in both far-field diffraction [1] and in near-field Kapitza-Dirac-Talbot-Lau interferometry [2] (KDTL). Recently, this has enabled quantum interference with particles consisting of more than 800 atoms and with a combined mass exceeding $10^4$ amu to be observed [3].

The rich internal structure of molecules makes their interaction with an optical grating more complex. Although the dominant beam splitting mechanism in the KDTL interferometer occurs through a phase grating interaction, photon absorption can still occur and play an important role in the diffraction process. If the absorbing molecule has a sufficiently complex internal structure then the energy of any absorbed photon can rapidly be redistributed across many internal degrees of freedom, heating the particle. By transferring the photon energy into vibrational excitation no optical photons can be emitted and therefore no which-path information is revealed. The result is that spatial coherence can be preserved.

Here, we describe some recent experiments in the KDTL interferometer[4]. By implementing a pseudo-random time-of-flight technique we have improved our velocity resolution by an order of magnitude over our previous experiments. This has enabled us to study a three component beam splitting mechanism which occurs only for complex molecules in a standing light wave. We observe matter-wave phase modulation induced by the electric dipole interaction between a polarisable molecule and the laser field. In addition, the absorption of photons induces a matterwave amplitude modulation which increases the internal temperature of the molecule. Each absorption event also splits the molecular wave function into a coherent superposition of momentum states which arise from the indistinguishability of the photon propagation directions in the standing light wave. We find that center-of-mass coherence can be maintained even when the internal energy and entropy of the interfering particle are substantially increased by the absorption of photons. This may lead to the realisation of temperature labelling interferometers for particles that neither ionise, fragment nor reradiate upon absorption.

Figure 1: An ensemble of molecules with temperature $T_0$ diffracts at a standing light wave. The periodic dipole potential they experience distributes the ensemble into different orders separated by even multiples of the photon momentum, $2m\hbar k$. The absorption of $n$ photons increases the temperature of the molecule, $T_n = T_0 + n\delta T$. Those
molecules which absorb populate different orders, namely those with odd integer multiples of the photon momentum, $m\hbar k$. This results in a series of overlapping, position synchronous interference patterns with different internal temperatures.


(invited) Quantum correlations in photonic networks

I A Walmsley¹, J Nunn¹, S Kolthammer¹, M Barbieri², A Datta³, D Saunders¹, P Ledingham¹, E Poem¹, B Metcalf¹, P Humphreys¹, X Jin⁴, T Bartley⁵, T Champion¹, J Munns¹, G Donati¹ and M Vidrigin¹

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A scalable photonic quantum network will facilitate the preparation of distributed quantum correlations among many light beams, allowing a new regime of state complexity to be accessed, and enabling new quantum-enhanced applications. Such a network can be constructed by means of linear optical operations on pure-state quantum light beams, measurement by efficient photodetectors, and storage in a photonic quantum memory. I will discuss progress in preparation, manipulation and detection of distributed quantum correlations as well as some recent applications in metrology and secure distributed computation models.

Quantum networks allow the distribution of quantum-correlated states of light among multiple nodes. Typically these nodes allow some sort of signal processing, again at the quantum level. Indeed, in the earliest proposals, the purpose of the network was to connect quantum computers [1]. Other applications include communications and sensing [2]. Quantum optics offers an important platform for exploiting non-classical phenomena to enhance information processing technologies. Central to all these protocols is the preparation and characterization of correlations between multiple distinct optical modes that cannot be exhibited by classical fields.

Photons are particularly promising for networking for many of the same reasons that optical interconnections are a vital technology for classical communications: large bandwidth, ease of manipulating signals and minimal dephasing between modes. However, a characteristic that makes photons useful for transporting information – their lack of interaction with other photons – also makes it difficult to perform the quantum operations needed to process information. Some years ago, an approach to this problem was proposed in the context of photonic quantum computing [3]. This approach made use of quantum measurements to synthesise effective nonlinear interactions between photons, and has proven to be a practical means to effect controlled logical operations on single photons [4].

There remain a number of challenges, aside from the technical barriers of propagation losses and inefficient detectors, to which solutions are being developed [5]. First, such operations are intrinsically non-deterministic, and thus any device based upon them is intrinsically non-scalable, unless a means to effectively store the output from one operation is available so that subsequent operations can be performed upon the resulting state. One way to achieve this is by means of a photonic quantum memory [6]. This is a device that can store a quantum state of light for an arbitrary period and recall it with high efficiency and fidelity on demand. Second, certifying that such correlations exist is crucial in identifying suitable resources, or indeed to verify that such resources retain their quantum signature after propagation [7].

Grating chips for quantum technologies
A S Arnold, J P McGilligan, S Ingleby, P F Griffin and E Riis

University of Strathclyde, UK

Laser cooled atomic samples have resulted in profound advances in frequency metrology, however the technology is typically complex and bulky. Micro-fabricated diffractive optical elements (DOEs) [1] can greatly facilitate the miniaturisation of magneto-optical traps (MOTs) for use in ultra-cold atom technology (Fig. 1). Portable devices should be feasible with accuracy vastly exceeding that of equivalent roomtemperature technology, with a minimal footprint. Laser cooled samples will be ideal for measurement devices e.g. portable atomic clocks and magnetometers and, moreover, they hold great potential for longerterm breakthroughs exploiting e.g. optical lattices for all-optical clocks and Bose-Einstein condensates for atom interferometry. Here we will discuss next generation diffractive optical elements (DOE) and demonstrate quantum based measurements on samples of ultra-cold atoms created using our miniaturised optical setup [2].

Figure 1: A diffractive optical elements (DOE) can transform a single circularly-polarised input beam into all required beams for an intensity-balanced magneto-optical trap [1]. This kind of chip was used to sub-Doppler cool atomic gases and subsequently load them into a magnetic trap.
On-chip generation and deterministic splitting of degenerate photon pairs

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Indistinguishable pairs of photons are traditionally generated using spontaneous parametric downconversion (SPDC) in bulk-nonlinear crystals. However, to make this technology scalable, integrated sources of indistinguishable photons are required that can be utilised on-chip with photonic circuits [1]. Unlike bulk SPDC sources in which degenerate photons are spatially separated and thus easy to split, on-chip photon sources produce photons collinearly and the deterministic splitting of degenerate photons is challenging [2]. In this case, photons can only be deterministically split using time-reversed Hong-Ou-Mandel (HOM) interference, in which a pair is created in one of two waveguides followed by a 50:50 coupler, where the pair splits into two single photons. Such a quantum splitter requires tuning of the relative phase of photons from the two waveguides [3].

Here we demonstrate deterministic splitting using an integrated silicon-on-insulator Sagnac loop, with degenerate photons created by spontaneous four-wave mixing in a ring resonator coupled to the loop (Fig. 1a). We show that 89% photons are split and a HOM interference using the split photons exhibits 94% visibility, verifying the deterministic splitting and indistinguishability of the photons. This Sagnac configuration automatically sets the phase correctly, and uses a single ring in clockwise and counter-clockwise directions to ensure perfect spectral overlap. With our approach we offer compactness and minimise fine-tuning. This will allow convenient scaling for more elaborate circuits requiring multiple sources which are intrinsically stable.

Fig. 1 (a) Experimental setup. Pump wavelengths $\lambda_{p1}$ and $\lambda_{p2}$ are coupled to separate input ports of the Sagnac circuit and create photon pairs in the ring resonator. After splitting pairs are observed in coincidence at the outputs A and B. (b) HOM dip using split photons, with a Lorentzian fit line and the background level of accidental coincidences.

Two synchronised pump pulses at $\lambda_{p1}$=1540.8 nm and $\lambda_{p2}$=1558.1 nm, tuned to two resonances of the ring are injected into separate inputs of the chip via grating couplers, and reach a multi-mode interference (MMI) coupler. After splitting pairs are observed in coincidence at the outputs A and B. (b) HOM dip using split photons, with a Lorentzian fit line and the background level of accidental coincidences.

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corrected visibility 94%. Both exceed the threshold of 50% possible for classical light sources or probabilistically split photon pairs.


Creating 18dB metrologically relevant spin-squeezed states of an atomic ensemble

R Krishnakumar, O Hosten, N Engelsen and M Kasevich
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Without any quantum engineering, the resolution with which a physical signal (e.g. a phase shift on an atomic state) can be measured is limited by the counting statistics of independent probe particles. This so called “shot-noise” can be overcome by entangling the probe particles, for example via ‘squeezing’ [1] [2], increasing the signal-to-noise ratio.

Squeezing has been achieved in in various settings, such as in optics and superconducting microwave circuits where states squeezed in excess of 12dB have been created [3] [4]. Similarly, spin-squeezing in atomic ensembles [5] has been achieved of over 10dB [6]. However these demonstrations so far have been on either a proof of principle level or not suited towards our primary focus of practically improving the precision of state-of-the-art atomic sensors, particularly atomic clocks and atom interferometers, which have a wide range of applications from fundamental experiments such as tests of general relativity [7] to more technology oriented applications such as precision timing systems [8] and inertial sensors [9].

We present an experiment in which we create spin-squeezed states of an ensemble of half-million Rubidium 87 atoms at an unmatched value of 18.5dB below shot noise, using the magnetically insensitive “clock states”. We demonstrate the utility of the prepared states by directly measuring a small microwave-induced rotation on our atomic system. These spin-squeezed states are created by first cooling and trapping the atoms in a 1560nm optical lattice inside an optical cavity and then making a quantum non-demolition measurement using a 780nm probe light.

In order to show that the spin-squeezed states produced in our experiment can be used to directly improve the precision of atomic clocks, we have demonstrated a clock operating at 10.5dB below the shot noise limit (currently limited by our microwave source phase noise). In addition, our system has the unique setup where the probe light is homogeneously coupled to the atoms across the different lattice sites (due to our probe light being double the frequency of our trapping light). This allows for free-space measurements, e.g., with fluorescence imaging, to be made while still taking advantage of the metrological gain from the squeezed state, which is what we are planning to demonstrate in the future.

(invited) Introduction to the UK National Quantum Technology Hub in Sensors and Metrology

K Bongs
University of Birmingham, UK

The UK National Quantum Technology Hub in Sensors and Metrology focuses on the platform of cold and thermal atoms as well as ions. It aims at the translation of precision sensor technology for gravity, rotation, magnetic fields, electromagnetic fields and time into applications, fostering the creation of a Quantum Technology industry in this area. It will deliver mass production scalable underpinning technology components, demonstrate their functionality in precision sensor prototypes and evaluate their value in real-world application challenges set by our industry partners. This talk will provide an overview of our activities, aims and collaboration opportunities.

Vacuum measurements with a Magneto-Optical Trap: the $N_{eq} - \tau$ plot

D Cassettari, L Torralbo-Campo, G D Bruce, R W G Moore, L A Lee, E A Findlay and G Smirne
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The capture of $N$ atoms from background vapour in a Magneto-Optical Trap (MOT) obeys an exponentially-decaying growth as a function of time $t$:

$$N(t) = N_{eq} [1 - \exp (-t/\tau)]$$

By plotting the values of the equilibrium number of trapped atoms $N_{eq}$ as a function of the loading time-constant for varying vacuum conditions, useful information can be gained about the experimental setup. We use this approach for two different purposes: to characterise MOT-loading using the light-induced atomic desorption technique and to measure vacuum pressure using a MOT.

In recent years, light-induced atomic desorption (LIAD) of alkali atoms from the inner surface of a vacuum chamber has been employed in cold atom experiments for the purpose of modulating the alkali background vapour. This is beneficial because larger trapped atom samples can be loaded from vapour at higher pressure, after which the pressure is reduced to increase the lifetime of the sample. Using $N_{eq} - \tau$ curves we present an analysis, based on the case of rubidium atoms adsorbed on pyrex, of various aspects of LIAD that are useful for this application. Firstly, we study the intensity dependence of LIAD by fitting the experimental data with a rate-equation model, from which we extract a correct prediction for the increase in trapped atom number. Following this, we quantify a figure of merit for the utility of LIAD in cold atom experiments and we show how it can be optimised for realistic experimental parameters [1].

Secondly, the lifetime of an atom trap is often limited by the presence of residual background gases in the vacuum chamber. This leads to the lifetime being inversely proportional to the pressure. We use this dependence to estimate the pressure and to obtain pressure rate-of-rise curves by performing $N_{eq} - \tau$ analyses. These pressure-rise curves are commonly used in vacuum science to evaluate the performance of a system. We observe different rates of pressure increase in response to different levels of outgassing in our system. Therefore we suggest that this is a sensitive method which will be useful in applications of cold atom systems, in particular where the inclusion of a standard vacuum gauge is impractical [2].

Single-photon metrology for quantum technologies
D Szwer, C Chunnilall, G Lepert, P Patel and A Sinclair
National Physical Laboratory, UK

Industrial technologies based on the production, manipulation, and detection of single and entangled photons are emerging. Quantum key distribution (QKD) is one of the most commercially advanced quantum technologies, and among the first to directly harness the peculiar laws of quantum physics.

For the commercialisation of quantum technologies to be successful, customers will need proof that the equipment they buy conforms to specification. This is especially important for security-related applications such as QKD. QKD enables future-proof encryption (the key needs to be hacked at the time of creation) and is guaranteed to be secure by the laws of physics (any attempt at eavesdropping will be detected), but only if it faithfully implements the protocol for which security was proved. For instance, if the mean photon number is different from that prescribed, or the qubit states have extra discriminating information, the system becomes vulnerable to undetectable eavesdropping.

The National Physical Laboratory (NPL) is developing metrology (using both traditional and quantum approaches) for the quantum devices used in these technologies, so that they can be calibrated in a way that is traceable to primary SI standards [1]. Our initial focus has been on phase-encoded QKD [2]. The primary standard for optical power is the cryogenic radiometer, which is typically realised using ~0.1 mW of free-space, visible wavelength, monochromatic radiation. Single-photon emitters and receivers for QKD, which are fibre-coupled and operate in the 1550 nm spectral region, need to be calibrated at powers 10⁹ to 10¹⁶ times lower than this. I will describe how we can perform such measurements in an SI-traceable manner, and how they can be adapted to real-time measurements of QKD modules which use the decoy-state protocol [3].

Finally I will discuss future efforts to extend metrology to more advanced optical quantum information technologies, such as those that use entangled photon pairs.

[1] C. J. Chunnilall et al., Traceable metrology for characterizing quantum optical communication devices, Metrologia 51 (6), S258-S266 (2014)

Sub-100 µm resolution imaging of dc and microwave magnetic fields using atomic vapour cells
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Alkali vapour cells are among the best sensors for electromagnetic fields, with applications in physics, medicine, and defence. We have developed techniques for imaging dc [1] and microwave [2,3] magnetic fields using vapour cells, detecting the respective fields through Ramsey and Rabi oscillations on atomic hyperfine transitions. The parallel nature of our dc imaging technique could be advantageous in measurements requiring high spatial and time resolution, such as in microfluidics in chemistry and biology. For microwave fields, there are currently no established imaging techniques. Microwave devices form an essential part of modern technology, finding applications in telecommunications, defence, and scientific instrumentation. Our technique could prove transformative in the design, characterisation, and debugging of such devices, and is already being employed in the characterisation and debugging of high-performance vapour cell atomic clocks [1,4].
We present results from a new imaging system providing spatial resolutions below 100 µm, an order of magnitude improvement from previous experiments [2]. More importantly, our vapour cell allows imaging of fields as close as 150 µm above structures of interest, through the use of extremely thin external cell walls. This is crucial in allowing us to take practical advantage of the high spatial resolution, as feature sizes in near-fields are on the order of the distance from their source. We demonstrate our system through the imaging of dc and microwave fields above a selection of devices.

Our spatial resolution, sensitivity, and approach distance are now sufficient for characterising a range of real world devices at fixed frequencies. However, the development of a broadband microwave imaging technique is essential for wider applications. We also present progress on a frequency-tunable setup, where we use a 0.8 T solenoid to Zeeman shift the hyperfine ground state levels, allowing us to image microwaves at any frequency, from sub-GHz to 10s of GHz.

Figure 1: Experimentally obtained images of the microwave magnetic field at several positions above a microwave circuit. The central signal line of the circuit is shown in red, and the ground planes are in orange.

Real and artificial atoms interacting with photons: From cavity QED to circuit QED
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ENS / Collège de France, France

Cavity Quantum Electrodynamics (CQED) studies the interaction of atoms with photons stored in cavities. In the microwave domain, it consists in coupling large electric-dipole-carrying Rydberg atoms to a very high Q superconducting cavity. With this system, fundamental tests of quantum physics have been realised, including the generation and reconstruction of Schrödinger cat states of light and the observation of their decoherence. Basic quantum information procedures have also been demonstrated. During the last decade, microwave CQED has been extended into a new domain of mesoscopic physics called "Circuit QED", where artificial two-level atoms made of superconducting Josephson junctions interact with high Q radio-frequency resonators. These systems, based on well-developed solid-state technology are very promising for quantum information science. Atomic CQED and Circuit QED bear strong similarities and also present some marked differences which will be illustrated by recent experiments performed in both fields.

Quantum optics in dense alkali-metal thermal vapours
I G Hughes, C S Adams, E Bimbard, J Keaveney and D J Whiting
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Many of the work-horse techniques of contemporary atomic physics experiments were first demonstrated in hot vapours. These media are ideally suited for quantum-optics experiments as they combine (I) a large resonant optical depth; (II) long coherence times; (III) well-understood atom-atom interactions. These features aid with the simplicity of both the experimental set up and the theoretical framework. We have studied experimentally and theoretically the absorption and dispersion of alkali-metal atomic vapours [1-3]. Our model includes the effects of dipole-dipole interactions [4] and calculates the absolute susceptibility that enables quantitative predictions in the vicinity of the D lines. The model was a crucial component in our experimental measurement of the cooperative Lamb shift [5], the first measurement of this phenomenon, 40 years after its prediction. In a related experiment we measured the refractive index of high-density Rb vapour in a gaseous atomic nanolayer, thereby answering the question of what is the theoretical maximum refractive index of an atomic vapour [6]. We will present ideas and preliminary data of how to generate heralded single photons with a dense thermal ensemble.
Orbital angular momentum of light stored and retrieved in cold atoms via FWM and CPO processes

L Pruvost
Université-Paris Sud, France

Laguerre-Gaussian laser modes are ring of light having a helical phase and carrying an orbital angular momentum (OAM). This quantity is quantified by an integer \( \ell \) and the Laguerre-Gaussian mode basis constitutes a way to encode the information. In the context of quantum information, we have explored processes allowing storage and retrieval of the OAM using a cold atom sample as memory.

The first presented case uses the delayed four-wave mixing (FWM) process. To complete some previous observations, we have demonstrated that the OAM beam can be retrieved along a direction which differs from the incident writing one [1]. The experiment, done in collaboration with Tabosa’s group (Recife) has been performed in cold Cs atoms of a MOT, using a delayed FWM process on a \( \Lambda \) atomic system excited by \( \sigma^+/\sigma^- \) lasers, one - the writing beam - carrying an OAM with a topological charge \( \ell \) from 0 to 3. The phase structure is stored into the Zeeman coherence grating induced by the incident writing beams and is restored when a reading beam is switched on.

The second case uses the coherent population oscillation (CPO) obtained with linear polarised laser beams [2]. We show that the CPO is more robust against magnetic field, allows storage/retrieval along the writing beam direction or not and, allows to compose OAMs during the nonlinear process.


(invited) First generation controlled quantum hardware: What's it good for, and when can we have it?

S Benjamin
University of Oxford, UK

The effort to develop practical quantum technology is ramping up worldwide, with several governments (including the UK) recently announcing hundreds of millions of dollars worth of investment. Is this premature? Or are we now sure that complex quantum systems can be adequately controlled, and sufficiently scaled, that they can be useful? I will argue for a "yes" by reviewing recent achievements in experiments, architecture theory and applications. Then I will frame what I believe is the key open question facing the field: what will be the use of the first generation machines, with only 100s or 1000s of components? Big enough to be beyond classical simulation, yet too small to be true fault tolerant computer, I argue these machine must be "error robust" in order to be useful.

Minimal ancilla-mediated quantum gates

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Most physical implementations of quantum gates employ some sort of ancilla system to control the register qubits and mediate between them. The original Cirac-Zoller gate is of this form [1]. Use of an ancilla can simplify the experimental requirements, and more recent work has been done to find the simplest forms of ancilla-mediated gates under various restrictions. There are two approaches: the ancilla can be measured after interacting with the qubits to enact the gate [2], or the entire process can be unitary [3]. If the ancilla is measured, the outcomes of the measurements determine a possible correction that must be applied to the qubits, similar to measurement-based quantum computing. The unitary version is deterministic and requires no corrections, but generally requires an extra interaction between the ancilla and the qubits for each gate. Higher dimensional ancillas can also be used [4], with some extra efficiencies for certain gate sequences.

In the most minimal form of ancilla-mediated quantum gates [5], universal quantum computation is achieved through repeated use of a single fixed interaction between the ancilla and register qubits, with the gate sequence determined by the order of the interactions and the preparations (|0⟩ or |1⟩) of the ancillas. The measured and unitary single qubit gates are almost time-reversals of each other, see figure 1. Both use an interaction of the form SWAP.CZ

\[
\begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 0 & -1
\end{pmatrix}
\]

(see [2, 4] for details). In the measured version, the measurement outcome randomly determines the gate, and a small amount of classical computation must be used to carry the measurement result forward to correct the gate if it was not exactly as required. In contrast, the unitary version first chooses to prepare the ancilla in either the zero or one state, thereby selecting the gate deterministically.
Figure 1: Schematic comparison of measured (left) and unitary (right) ancilla-mediated quantum gates. The interaction (zig-zag line) is SWAP.CZ plus some single qubit unitaries on the ancilla only, and \( i \in \{0, 1\} \) determines the gate. The ancilla state \(|\varphi_i\rangle\) is not entangled with the register qubit so can be recycled or discarded.


Quantum correlations of light and matter through environmental transitions

A Nazir\(^1\) and J Iles-Smith\(^{1,2}\)

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We show that quantum light-matter correlations may be generated through interactions with a thermal environment in cavity QED systems. This is true even in regimes that can be described semiclassically in the absence of such an environment, for example when the emitter-cavity coupling strength is dominated by cavity losses. This behaviour, which can be probed experimentally through the cavity emission properties, heralds a failure of the semiclassical approach, and challenges the notion that coupling to a thermal bath supports a more classical description of the system.

(invited) Magnetic induction imaging with atomic magnetometers

F Renzoni

University College London, UK

We demonstrate magnetic induction imaging with an all-optical atomic magnetometer. Our instrument creates a conductivity map of conductive objects. Both the shape and size of the imaged samples compare very well with the actual shape and size. Given the potential of all-optical atomic magnetometers for miniaturization and extreme sensitivity, the proof-of-principle presented in this talk opens up promising avenues in the development of instrumentation in magnetic induction imaging. Ongoing work in the context of specific applications is discussed.

Observation of localised multi-spatial-mode quadrature squeezing

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Optical measurements, including optical imaging, are ultimately limited by the quantum fluctuations of the electromagnetic field. When light comes from the quietest of the lasers, that is to say it is in a coherent state, these fluctuations produce the so-called quantum noise level, or shot-noise. It is however possible to squeeze the noise below the quantum noise level on one of the quadratures at the expense of the other quadrature. To benefit those optical imaging applications where the full field-of-view is captured at once, the squeezing must extend to all
transverse spatial modes. A special case of such multi-spatial-mode squeezing is realised when the field is squeezed locally at all points of its transverse profile.

In principle, all optical parametric amplifiers, such as nonlinear media supporting parametric down-conversion or four-wave-mixing, can generate local squeezing provided the nonlinearity is strong enough. In the case of parametric down-conversion in a crystal however, the nonlinearity tends to be small and using a cavity to enhance it usually results in a single spatial mode to resonate and therefore to be squeezed. Here we report using instead resonant four-wave-mixing in an atomic vapour to generate single-pass large gain and realise local squeezing. The signature of the multimode nature of the squeezing is shown in Fig. 1, where the quantum field fluctuations are analysed by a narrow local oscillator in an homodyne detector arrangement. A significant level of squeezing is recorded for a range of positions of the local oscillator much larger than the waist. More than 75 independently squeezed locales are observed.

Multi-spatial-mode squeezed light used as illumination in certain super-resolution imaging schemes should lead to improved optical resolution beyond the quantum noise limit.

Figure 1. The homodyne detection of a squeezed state leads to reduced noise on the balanced photo-current $i$ below the shot noise, as measured by a spectrum analyser (SA). For a hypothetical multi-spatial-mode squeezed state (MSM) the LO could have any shape or position.


(invited) Quantum inspired imaging

M Padgett

University of Glasgow, UK

QuantIC is one of four hubs created by EPSRC - our focus is the application of quantum science to new imaging techniques and their application to solve real world problems. This talk will present a sub set of this work, namely the application of both quantum and classical correlations to imaging. One system uses IR illumination to create visible light images from only a few thousand photons whilst another system uses only a single pixel detector to create a video camera for imaging gas leaks.
(invited) Probing physics at TeV by measuring aeV

E Hinds

Imperial College London, UK

Experiments using laser-cooled atoms and molecules can search very sensitively for new physics through measurements of ato-eV energies. I will discuss two example of this. (i) Measurements on cold molecules already provide strong constraints on the electric dipole moment of the electron, which in turn constrain theories of new particle physics up to ~10 TeV and place severe pressure on super-symmetric theories. With the advent of molecular laser cooling, this reach can now be extended up to 100 TeV. (ii) Atom interferometry can measure exceedingly small forces between an atom and a test mass in high vacuum. This measurement is sensitive to light scalar fields, thought to be responsible for the dark energy that drives the accelerating expansion of our universe. In particular we can probe how these fields couple to matter at energies almost up to the Planck scale. I will discuss the current status of both topics and the prospects for improvement.

(invited) Inertial atom interferometry

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Atom interferometry uses atomic quantum states instead of the separated paths of an optical interferometer, and pulses of light act as its beamsplitters and mirrors. As with its optical analogue, interference between the superposed trajectories results in fringes that depend upon the landscapes through which the atoms have passed. As atoms have mass, and potentially charge and a magnetic moment, these trajectories can be sensitive to the atom’s inertial motion and the gravitational, electric and magnetic fields through which the atoms move.

When the ‘beamsplitters’ of an atom interferometer change the atom’s momentum – as is the case when they are travelling laser beams – the difference in kinetic energy between the two interferometer states gives a velocity dependence to the interferometric phase [1]. The interferometer can be used not only to determine the atomic velocity, but also to impart a velocity-dependent impulse which, if appropriately adjusted, can cool a cloud of atoms [2, 3]. A pair of velocity-dependent interferometer sequences, used differentially, is sensitive to a change in velocity, and hence can be used to measure the interferometer’s acceleration [1], rotation [4] or the gravitational field to which it is exposed.

Atom beamsplitters and mirrors are unfortunately themselves sensitive to the atom’s velocity, and to variations in the optical intensity and differences in Zeeman sub-state. The errors introduced by systematic perturbations can to an extent be corrected using the NMR technique of composite pulses [5, 6]. If fidelity can be maintained, this should allow the interferometric sensitivity and cooling efficiency to be enhanced by amplifying the impulse [7, 8], increasing the area encompassed by the interferometer [9], or interleaving extra mirror and beam splitter pulses to form a momentum state quantum computer that allows algorithmic cooling as the mechanical effect of a computational sequence [10].

Interaction of atoms with structured light

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The interaction of atoms with laser light at near resonance with an atomic transition involves the creation of optical forces which act on the atomic centre of mass leading to atomic cooling and trapping and culminating in the creation of Bose-Einstein condensates [1].

If the laser light is an optical vortex, the vorticity and the spatial mode structure of the light have led to additional effects, including the generation of an optical torque which imposes rotational effects on the atomic centre of mass and leads to the cooling and heating of the rotational atomic motion, along with the axial motion [2]. Interesting effects in this context include optical spin-orbit coupling effects on atoms, orbital angular momentum transfer, quadrupole interactions and surface optical vortex generation. Experiments on sodium atoms in a Gaussian and a doughnut LG mode have led to the realisation in the laboratory of a long lived atomic current circulating in the high intensity region and so forming a superfluid in the doughnut ring [3].

Our recent investigations have focused on the effects of the Gouy phase [4] on atomic cooling and trapping in Laguerre-Gaussian light. We have found that since the Gouy effect is based on an axial phase of opposite sign to the normal phase associated with propagation along the vortex core, it amounts to an effective axial wave vector of the LG mode. A direct consequence of the inclusion of the Gouy phase in the interaction of LG light with atoms is that the recoil energy experienced by the atom on emission and absorption of light is modified. The reduced axial wave vector means that the recoil energy is decreased and this influences the extent of the axial centre of mass fluctuations. We show how the Gouy phase modifies both the trapping and cooling of the atomic axial motion, while the azimuthal motion is unaffected. The inclusion of the Gouy phase has significant implications for a number of the effects discussed so far involving atomic centre of mass motion in optical vortices involving coplanar multiple beams and a parallel ordered set of modes forming an optical vortex bunch.

Bates Prize winner

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Positron interactions with matter are important in several contexts: astrophysical, with a key question of matter-antimatter asymmetry; condensed matter, where positrons are widely used as probes; fundamental, e.g., in relation to the production of antihydrogen at CERN; and medical, such as PET (Positron Emission Tomography), used in particular as a control diagnostic in heavy-ion therapy. Positron collisions with atoms and molecules is also a challenging theoretical and experimental problem which produced a number of puzzles and surprises over the years.

The interaction of low-energy positrons with many-electron atoms is characterised by very strong electron-positron correlation effects. In addition to the usual polarisation of the atom by the charged projectile (which also affects electron-atom scattering), virtual positronium (Ps) formation provides additional attraction. It makes the positron-atom correlation potential stronger than its electron-atom counterpart. This attraction gives rise to positron virtual and bound states, and provides for the possibility of resonances. Another correlation effect, related to virtual Ps formation, is the enhancement of the electron density at the positron due to their Coulomb attraction at short range. This results in up to an order-of-magnitude enhancement of the annihilation rate over the independent-particle-approximation values.

Many-body theory proves to be an ideal tool for treating these correlation effects. It provides a near-complete understanding of positron interaction with noble gases at low energies (i.e., below the Ps formation threshold), yielding excellent agreement with experiment for positron scattering and annihilation rates [1] and gamma-ray spectra [2], and establishing accurate fractions of positron annihilation with core electrons. The corresponding enhancement factors reveal simple scaling with the orbital ionisation energy [2], which can be used to improve positron annihilation calculations in molecules and solids.

Understanding of the positron-atom problem provides a basis for unravelling the much more complex problem of positron annihilation in polyatomic molecules, where positron binding and vibrational Feshbach resonances (VFR) gives rise to orders-of-magnitude enhancements of annihilation rates [3]. VFRs have been crucial for the experimental measurements of the positron-molecule binding energies for over 70 species. While most of these molecules are nonpolar, quantum chemistry calculations have only been able to confirm positron binding to strongly polar molecules, which is a relatively simple problem to analyse [4]. A similar effect also opens the prospect of using electronic Feshbach resonances in open-shell atoms [5,6] to finally confirm positron binding to neutral atoms, predicted about 20 years ago.

Positronium scattering at first appears to be a much more challenging problem. However, experiment uncovered a surprising similarity between the Ps and electron scattering cross sections at equal velocities for v=0.5-2 a.u., for a range of atomic and molecular targets. The impulse approximation provides quantitative understanding of this effect in the intermediate-energy regime [7], while the picture of Ps scattering at low energies is quite different [8].

(invited) A rigorous relativistic framework for nonlinear electrostatic modes in the high-density quantum plasma regime: shedding new light on an old problem

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A rigorous self-consistent relativistic two-fluid model has recently been proposed for electron-ion plasma dynamics, avoiding various types of simplifying hypotheses, or/and misconceptions adopted in the past [1]. Electrons are treated as a degenerate fluid, governed by an appropriate equation of state. The ion fluid is also allowed to be relativistic, but is cold, “classical” (non-degenerate) and subject only to an electrostatic potential. This presentation will take the form of a brief review of recent results based on this model [1-4].

A linear investigation [2] reveals the existence of two types of harmonic modes, including a low-frequency acoustic mode and a high-frequency modified Langmuir type mode, roughly in qualitative agreement with the classical electron-ion picture. Periodic nonlinear modes are also shown to exist, via a pseudopotential method [3].

Exact stationary-profile solutions (solitary waves) are presented, at the ionic scale [1] and also at the high-frequency (electron) scale [4]. A tedious parametric analysis provides conditions for the existence of stationary-profile modes, in terms of characteristic relativistic parameters, associated with the (ultrahigh) particle density. Low-frequency excitations are of the solitonic (pulse) type [5], while high-frequency modes take the form of envelope solitons [4]. The propagation characteristics of these new modes are briefly reviewed.

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Detection of azimuthal doppler shift using saturated absorption spectroscopy with optical vortex

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The Doppler shift is caused by the additional phase change by the relative movement of an observer to the wave source. As shown in Fig. 1 (a), the plane wave, which is commonly used for laser spectroscopy, has the flat wave front. Therefore, the induced Doppler shift is limited in the propagating direction of the laser beam. On the other side, since the optical vortex (OV) has twisted wave front (see Fig. 1 (b)), the motion in the light field causes the Doppler shift in all the three-dimensional directions [1]. It is described as follows:

$$\delta_{LG} = -\left[ k + \frac{kr^2}{2(z^2 + z_R^2)} \left( \frac{z^2}{z^2 + z_R^2} - 1 \right) - \frac{(2p + m + 1)z_R}{z^2 + z_R^2} \right] V_z - \frac{kz}{z^2 + z_R^2} V_R - \left( \frac{m}{r} \right) V_\phi$$

(1)

where $V_z$, $V_R$, and $V_\phi$ are the axial, radial and azimuthal velocity components of the atom, $m$ is the topological charge, $r$ is the radius from the singular point. Since the phase of OV changes linearly with the azimuthal angle around the beam center, the center of OV is a phase singularity, and the intensity is zero. We neglect the $V_R$ component, since it is much smaller than the other components. Our current study aims to detect the azimuthal Doppler shift by using the OV laser. Since the $V_z$ and $V_\phi$ components will be mixed into a Doppler spectrum, development of a decomposition method is required. We performed a modified saturated absorption spectroscopy to obtain the azimuthal Doppler signal.

Fig. 1: Wave front of (a) plane wave and (b) optical vortex.

Fig. 2: Experimental setup of OV laser spectroscopy.
Figure 3 shows the experimental setup for OV laser spectroscopy. An external cavity diode laser (ECDL) was tuned at 697 nm for the excitation of an argon metastable generated in a plasma. The laser beam is separated into the pump laser and the probe laser. The probe laser is converted to OV by a computer generated hologram displayed on the spatial light modulator (SLM). The images of the OV probe laser were recorded while the wavelength of the ECDL was scanned. The saturated absorption spectra are constructed using variation of the intensity at each pixel. Figure 3(a) shows a picture of OV probe laser. Since the pixels which are located near the dark phase singularity should be used for the spectroscopy, the picture was taken with long exposure time to increase signal level. The 7 pixels are used to construct the saturated absorption spectra shown in Fig. 3(b). Although the plane-wave pump laser cancels the Vz-Doppler component, the azimuthal Doppler shift remains in the saturated dip. Therefore, the saturated dip is composed of the homogeneous broadening and the Vφ-Doppler broadening. Since the Vφ-Doppler effect depends on the radial position, the variation of the dip width gives the information of the azimuthal Doppler shift. The concept of optical vortex spectroscopy and some results of the proof-of-concept experiment will be presented.


**Frequency combs for demanding applications**

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Abstract Frequency Combs are optimised for demanding applications that require hands-off operation, improved robustness to environmental challenges and at the same time ultimate performance. Such applications include operation as clockwork for optical clocks, calibration of astronomical spectrometers and frequency combs designed for use on board of sounding rockets.

Optical frequency combs from mode-locked femtosecond lasers have revolutionised the art of measuring the frequency of light. Today they are used in a wide variety of applications such as optical clocks, distance measurements, trace gas sensing and attosecond physics, to name a few.

Ever increasing demand for stability and accuracy of time and frequency signals require improved oscillators and frequency references. Today’s best clocks rely on narrowband optical transitions and use a frequency comb as clockwork. As their relative stabilities and accuracies both enter into the range of $10^{-18}$, the frequency comb as clockwork needs to keep pace. Here we present an all polarisation-maintaining (PM) and fully phase-locked Er:fiber frequency comb with ultra-high stability and accuracy. An integrated phase noise below 70 mrad (100 Hz – 2 MHz) is reached for the full frequency comb. The locked beat signals exhibit an Allan variance below $10^{-16}$ at 1 s, averaging down below $10^{-19}$ at 1000 s. The modified Allan variance even reaches $3\times10^{-18}$ within 1 s which by far surpasses the stability of today’s best atomic clocks.

Another application that is currently attracting a lot of attention is the calibration of astronomical spectrographs with frequency combs. In astronomy the need for ever more precise measurements of spectral lines has led to a point...
where the classical calibration sources – spectral lamps – are not sufficient any longer. The unparalleled accuracy provided by the regularly spaced lines (or modes) of frequency combs opens up new pathways, such as the detection of Earth-like extrasolar planets through radial-velocity measurements or the direct observation of the accelerated cosmic expansion. The comb lines must however be resolved by the spectrograph, which requires large mode spacings of typically 15 - 30 GHz. Spectral broadening followed by flattening techniques are applied. The resulting light can now be coupled to the spectrograph as reference light. Recent successful applications include calibration of the HARPS spectrograph at ESO’s La Silla observatory and KIS’ VTT spectrograph in Tenerife.

For space application a small, robust and 100% maintenance-free system with low power consumption is mandatory. The FOKUS experiment (Faserlaserbasierter Optischer Kammgenerator unter Schwerelosigkeit) is using a Menlo Systems frequency comb to compare two different species of atomic clocks with each other. Such a setup is testing Einstein’s general theory of relativity that predicts that gravity has the same influence on all clocks no matter how the clock is realised. Eventually such experiments will lead to new theories of gravity and will completely change our understanding of the world. This system has been launched on board the German Space Agency’s TEXUS 51 sounding rocket mission from the Esrange space center on April 23, 2015 at 09:35 CEST in Kiruna, Sweden. The flight lasted for approx. 20 min with around 6 min in zero gravity, reaching an altitude of 260km. The clock comparison was successfully completed during the entire zero gravity phase. This demonstrates the robustness and high technology readiness level of Menlo’s frequency combs, enabling future comb applications on rockets, in space as well as in other harsh environments. At the same time this is the first demonstration of a fully operational frequency comb system in space. The FOKUS experiment is a collaborative effort between Menlo Systems, the Max-Planck-Institute of Quantum Optics, Garching, the Ferdinand Braun Institute, Berlin and the University of Hamburg.
Poster abstracts

P01. Dominant correlation effects in atomic spectra
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The spectrum of two-electron atoms (He-like) has been analysed using hyperspherical coordinates within Macek’s adiabatic expansion technique. It is well known that this method works well for not too high double excitation because close to threshold for double escape an infinity of strongly coupled channels occurs.

We modify the adiabatic wave equation by an additional term, introduce correct boundary conditions, and derive along these lines a novel fictitious force acting between the electrons. This force has nothing to do with electrostatic charges, but emerges from the diffraction of an electron wave from a potential ridge. This has been foreign to all previous treatments of electron-atom or electron-ion scattering, and repairs a shortcoming of the Born-Oppenheimer method.

That force leads to unusual features.

(i) It breaks spontaneously the electron exchange symmetry, i.e., the spin is no longer conserved.
(ii) The electron-ion potentials (here e- He+) are different for incoming and outgoing flux. This breaks time reversal symmetry.

We solve analytically the modified channel equation near the threshold, and arrive at the following observations:

(i) The trajectory of an incoming electron is turned towards the top of the potential ridge, i.e., the net interaction between the electrons is attractive. The fictitious force overcompensates the Coulomb repulsion. This type of wavefunction corresponds to Wannier’s classical converging trajectory.
(ii) The outgoing electron is turned away from the ridge corresponding to Wannier’s classical diverging solution. The net e-e interaction is now repulsive. This mode of motion creates a cusp in the ionisation cross section and suppresses high double Rydberg resonances; both in agreement with he observation.
(iii) In both incoming and outgoing solutions, respectively, the total electron momentum is nearly equal to zero. Such a motion is typical for a Cooper pair.

Therefore, we identify threshold ionisation by electron impact as decay of a Cooper pair. Below threshold the incoming wave is reflected at a turning surface emerging from a centrifugal barrier, and the following outgoing wave is reflected at an outer turning surface produced by the net coulomb interaction on the potential saddle.

This temporary electron-electron binding mechanism is not an artefact for two electrons. Three electrons may form a breathing Cooper triple. Results will be presented at the conference.

P02. Practical quantum optical metrology with a 7-fold enhancement
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Quantum metrology aims to harness the power of quantum mechanics to make ultra-precise measurements. A crucial advantage of quantum metrology is that it provides high precision with a significantly lower particle flux. This is an important requirement for many applications such as in biological sensing [1], where disturbing the system can damage the sample, or in gravitational wave detection [2], where the lasers in the interferometer interact with the mirrors enough to degrade the measurement [3]. It is known that an interferometer that utilises a stream of...
independent particles is capable of measurement precision at the shot noise limit, 1/Jn, where n is the total number of particles used in the probe state. However, by making use of quantum mechanical properties this can be improved to the "Heisenberg limit", 1/n, for example by using highly entangled NOON states [4] or squeezed states [5, 6].

Indeed, the most commonly used optical quantum states employ either squeezing or entanglement to enhance measurements, but here we utilise both these techniques to create squeezed-entangled states. We then use the quantum Fisher information (QFI) to show that 7-fold improvements can be gained over states that use squeezing or entanglement in isolation. Motivated by practicality we also look at the squeezed cat-state, which has recently been made experimentally [7], and shows further precision gains, including a 3-fold improvement in the QFI over the optimal Gaussian state. We then simulate a phase readout scheme which involves mixing the two modes at a beam splitter, followed by photon counting at the outputs, as shown in Fig. 1. Finally, we demonstrate a robustness to loss for small photon numbers, allowing us to conclude that the squeezed cat-state can give a significant precision enhancement in optical quantum metrology in practical and realistic conditions.

FIG. 1: This scheme can be used to measure a phase - using the input quantum state |input⟩, which we take here to be a squeezedentangled state. The phase information can be obtained by mixing the states at a 50:50 beam splitter, and counting photon numbers at the outputs.


P03. Theoretical investigation of the magnetic ordering and the superconducting state in rare earth iron pnictides
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The discovery of new superconductors based iron has opened a new horizon for high temperature superconductivity. Iron is usually associated to the magnetism, which is actually an antagonist element to the superconductivity. Recent studies show that the magnetism and superconductivity can coexist in these compounds that present an ideal platform for studying the relationship between these two electronic orders. A considerable number of magnetic superconductors has been examined in the past two decades [1]. Recently, iron-based superconductors RTPnO type (R = La [2], Pr [3], Nd [4], Sm [5], Gd [6], Tb, Dy [7], Ho [8]; T = Fe; Pn = P, As [9]) have been studied by several research groups. The parents of the superconducting compounds crystallize in a tetragonal structure formed
by layers T - Pn and R-O alternately arranged. It was observed in LaFePO compounds [10] and LaNiPO [11] that T - Pn layers play a major role in the appearance of high critical temperatures. This observation was confirmed by a theoretical analysis of the energy band structure based on the theory of density functional (DFT), revealing that the hybridization of Fe 3d orbitals with 4p orbitals of Pn contributes to the Fermi surface [12]. With the change of T element, the electronic and magnetic properties of RTPnO compounds vary such that one finds an anti-ferromagnetic (AFM) insulator for T = Mn [13], a superconductor for T = Fe and Ni [14] and a metal ferromagnetic for T = Co [15]. The SmFePO compound with the ZrCuSiAs structure was reported by [16] using different experimental methods. This compound was identified as a superconductor with a critical temperature below 3K and shows an AFM order below a Néel temperature of 5K, which confirms the possibility of the coexistence of magnetism and superconductivity. The main objective of this work is to identify the microscopic origin of superconductivity in the iron pnictides by providing the key parameters of this property and to discuss the possibility of the coexistence of magnetism and superconductivity in those systems. The study of the electronic structure, in particular the nature of the Fermi surface, is a fundamental step to obtain details on the mechanism of this phenomenon. In addition, understanding the influence of the 4f orbitals of the rare earth element on the magnetic structure is also a major objective in this work. The superconductivity and magnetic phenomena of the rare earth iron pnictides RFePO (R = rare earth) are analysed using ab initio density functional theory in the local density approximation (LDA) with the on-site Hubbard Ueff parameter.

Figure 1: The calculated band structures of the paramagnetic tetragonal compounds RFePO (R = La, Sm) with experimental lattice parameters.

[1] Cava et al., 1994; Eisaki et al., 1994; Lynn et al., 1997; Shirotani et al., 1997; Namiki et al., 2007; Wu et al., 1987; Hor et al., 1987; Yang et al., 1989; Tokura et al., 1989; Lynn et al., 1990; Sumarlin et al., 1992
[2] Kamihara et al., 2006, 2008; Ren et al., 2008], Ce [Ren et al., 2008; Chen et al., 2008; Zhao et al., 2008
[3] Ren et al., 2008; Baumbach et al., 2009; Bhoi et al., 2008; Zhao et al., 2008; Kimber et al., 2008
[4] Ren et al., 2008; Baumbach et al., 2009;Kito et al., 2008; Qiu et al., 2008
[5] Ren et al., 2008; Kamihara et al., 2008; Chen et al., 2008; Fratin et al., 2008; Tropeano et al., 2008
[6] Cheng et al., 2008;Yang et al., 2008
[7] Bos et al., 2008; Yang et al., 2009
[8] Yang et al., 2009
[9] Lee et al., 2008, 2009
P04. Quantum states in the multipole solution of the Maxwell’s equations for the free radiation field

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Classical electrodynamics built on the multipole approach to the Maxwell’s theory of light for the empty space has the potential for reproducing fundamental aspects of quantum optics. Field quantization and discrete energy levels are found without the use of the correspondence principle that is fundamental to the conventional connection between the classical field modes and quantum harmonic oscillators. Results are given for Fock states, vacuum field and photon statistics of chaotic and coherent light. Quantum optics has at its heart the quantization of the free radiation field and the description of the electromagnetic field in terms of Fock (or number) states [1-3]. The quantization procedure is very popular and starts off by expanding the classical field in terms of plane waves. In the second part, the procedure requires the connection of the classical field modes to quantum harmonic oscillators and, by doing that, the outcome is that the electromagnetic field is described in terms of photon-number or Fock states, whose energy is made of a countable number of energy shots (photons) plus a vacuum contribution made of half a shot (zero-point energy).

In this work, we describe a new approach to the quantization of the free radiation field. Although new, the approach is entirely based on the well-known multipole technique that has broad application in physics and, especially, in classical electrodynamics [4]. In contrast to the plane-wave expansion of the conventional quantization, the multipole expansion takes into account more detailed spatial dependences of the Maxwell’s equations [4]. In brief, the comparison between the two methods is summarized as follows. In the conventional approach to the energy quantization, the plane wave expansion solves the three-dimensional integration of the classical energy by means of Dirac delta functions [3]. In this work, instead, we use the electric field that solves the Helmholtz equation resulting from the Maxwell’s equations [5]. Thus, the two classical energies are

\[ \mathcal{E}_{\text{plane wave}} = 2\varepsilon_0 \sum_{k,s} \left| A_{k,s}^{(0)} \right|^2 \]
\[ \mathcal{E}_{\text{this work}} = \varepsilon_0 \sum_{k,s} \int d^3r \left| E_{k,s}(r,t) \right|^2 \]

As usual, \( V \) is the quantization volume, \( A_{k,s}^{(0)} \) is the Fourier amplitude of the vector potential of wave vector \( k \) and polarisation \( s \), the summation runs over the field modes \( (k,s) \), whereas \( E_{k,s}(r,t) \) is the electric field component that solves the associated Helmholtz equation. The spatial dependences of \( E_{k,s}(r,t) \) are separable on the three-dimensional sphere and the angular part contains the so-called spherical harmonics that are countable [4]. Their number \( n \) quantizes the field and the energy in a manner that is equivalent to the Fock state of quantum optics and, thanks to this demonstration, it appears that the vacuum field and the zero-point energy emerge in classical electrodynamics [5]. Furthermore, analogies with photon distributions of probability can be established for chaotic and coherent light. In the end, it seems that the Maxwell’s theory of light is a complete theory that is successful in capturing the quantum nature of the free radiation field. Indeed, the theory has the potential of explaining the basics of quantum optics and, what is more, it seems to guarantee quantization without recourse to creation and destruction operators that are necessary for the conventional correspondence between \( E_{\text{plane wave}} \) and the energy of quantum harmonic oscillators.
P05. Solitary waves in plasma with pressure variations in both electrons and ions

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In this plasma with ions and electrons subject to pressure variations of both the components and stationary dusts, both compressive and rarefactive KdV solitons of interesting characters are established. Based on high dust charge, characteristics of soliton growths are amplified for various pairs of values of ion’s and electron’s streaming speeds. It is noteworthy to mention that for some pairs of values of ion’s and electron’s initial streaming, only compressive KdV solitons with either decreasing or increasing growth are found to exist. Contrary to this, for some other pairs of ion’s and electron’s streamings, the amplitudes of both rarefactive and compressive solitons reflect changes from rarefactive growth to compressive soliton growth.

P06. High density sub-Doppler laser cooling of ⁴⁰K using grey molasses on the D₂-Line

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Grey molasses is a powerful tool for laser cooling atoms with poorly-resolved hyperfine structure to below the Doppler limit at high densities. It is commonly implemented on the D₁-line after an initial magneto-optical trapping (MOT) phase on the D₂-line [1–3]. We show, using numerical solutions of the Optical Bloch Equations and experiments with ⁴⁰K, that efficient grey molasses can also be realised on the D₂-line using the same lasers as for the MOT.

For the optical molasses phase, the cooling laser is detuned by −22 MHz from the $F = 9/2 \rightarrow 11/2$ transition, and the repumper laser frequency is brought close to a two-photon Raman resonance. The energies of the dressed states vary with the polarisation of the light, and with the Raman detuning. When the two-photon detuning lowers the energies of the dark states below those of the bright states, the resultant grey molasses cools the atoms to 42 µK at a density of $1.4 \times 10^{10}$ cm$^{-3}$, and provides an efficient method for direct loading of $10^7$ atoms into a 200 W crossed optical dipole trap at 1070 nm.
**FIG. 1. a)** Principle of grey molasses cooling scheme. $^{40}$K atoms propagate through a polarisation gradient induced by counter-propagating laser beams of wavelength $\lambda = 766.7$ nm with orthogonal linear polarisations. Motional coupling transfers hot atoms from the dark $F = 7/2$ states (green) to the bright $F = 9/2$ states (blue), in which they undergo Sisyphus-like cooling.

**b)** By varying the Raman detuning of cooling and repumping laser beams, the temperature of atoms follows a Fano-shaped profile, with a minimum temperature of 42 µK.


**P07. Towards rotation sensing with a Bose-Einstein condensate**

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Superconducting quantum interference devices (SQUIDs) are well-known for their ability to measure extremely small magnetic fields. An analogous device has been constructed using superfluid $^3$He [1], producing two-path quantum interference that is sensitive to rotation of the interferometer. This sensitivity is also a property of ultracold Bose gases trapped in geometries containing Josephson junctions [2].

We present the development of our new experimental apparatus. In our double-chamber vacuum system, a two-dimensional magneto-optical trap (MOT) creates a bright atomic beam, which is used to load a three-dimensional MOT. Evaporative cooling will take place in a hybrid magnetic / optical trap [3] to bring the atoms close to quantum degeneracy, before the atoms are transferred to an optical trap generated using a Spatial Light Modulator. This will allow the implementation of adiabatic and reversible methods of crossing the BEC transition [4], as well as providing the platform to realise our goal of using dynamic, holographic optical ring traps [5, 6] to investigate the sensitivity to rotations of a Bose-Einstein Condensate (BEC) of $^{87}$Rb atoms.

**FIG. 1. a)** Image of our double vacuum chamber setup

**b)** holographic ring trap with Josephson junctions which can be rotated to stir the trapped BEC
Progress towards a molecular fountain for measuring the electron's electric dipole moment

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While the Standard Model of particle physics is enormously successful in describing the fundamental particles and their interactions, it has some shortcomings. It does not account for either dark matter or dark energy, fails to explain the observed asymmetry between matter and antimatter, and is incompatible with General Relativity. These shortcomings have led to many theories that extend the Standard Model. Each makes a prediction about the value of the electron's electric dipole moment (eEDM), and so a measurement of the eEDM can distinguish between the theories.

We use ytterbium fluoride (YbF) molecules to measure the eEDM. We do this by measuring the spin precession of the electron in an applied electric field which is greatly enhanced by the structure of the molecule. The sensitivity of the measurement is limited by the spin precession time, which in turn is limited by the high speed of the molecules as they pass through the apparatus. We are building a new experiment where slow YbF molecules are captured and cooled to low temperature in a magneto-optical trap, and then thrown upwards to produce a molecular fountain. This will greatly extend the spin precession time. I will discuss the preparation of beams of YbF molecules with speeds below 100m/s produced using a two-stage cryogenic buffer gas source, and present measurements of state selection and optical cycling in YbF. I will also address the guiding and velocity selection of the molecules using a permanent magnet guide, forming a beam suitable for loading into a magneto-optical trap.

Many-body localisation in modular systems of quantum spin chains

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Many-body localisation (MBL) is an exciting phase transition that is marked by the failure of an isolated quantum system to adhere to the laws of thermodynamics. That is, the system does not thermalize and thus does not lose its initial information, thereby making MBL states a promising form of quantum memory. Through simulations, we study the antiferromagnetic Heisenberg spin-1/2 chain, imposing quenched randomness to promote MBL. Our investigation extends to modular systems composed of this prototype. This analysis is enhanced by novel measures based on the reduced density matrix, which by nature isolates a subsystem of choice. We see signatures of an MBL transition that are comparable between the modular quantum systems.
P10. Towards a cold gas ring laser with coherent dispersion control
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University of Birmingham, UK

Bi-directional ring lasers are proposed to have a breadth of applications in precision timing and sensing. Strong dispersion is possible with cold atoms. We aim to use electromagnetically induced transparency (EIT) and four-wave mixing in order to control the dispersive properties of the gain medium, leading to the first bi-directional superradiant laser and a superluminal ring laser gyroscope. In the experiment cold potassium atoms in a high finesse ring cavity are investigated. I will present details of the experiment design and progress towards trapping of potassium in the ring cavity.

P11. Quantum simulation of a lattice gauge theory
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In this work we study a spin-boson chain that exhibits a local Z2 symmetry. We have investigated the quantum phase diagram of the model by means of perturbation theory, mean-field theory and the Density Matrix Renormalization Group method. Our calculations show the existence of a 1st order phase transition in the region where the boson quantum dynamics is slow compared to the spin-spin interactions. Our model can be implemented with trapped ion quantum simulators, leading to a realisation of minimal models showing local gauge invariance and 1st order phase transitions.

P12. Magnetic field and density effects on the streaming instability in magnetized electron-positron plasmas
Y D Jung and M J Lee
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The influence of magnetic field and density on the streaming instability for the plasma system composed of magnetized electron-positron plasmas with the moving ion fluid is investigated. The dispersion relation for the electrostatic mode is derived and the analytic expressions of the growth rate and oscillating frequency of the streaming instability are obtained as functions of the cyclotron frequency, electron density, positron density, ion density, streaming velocity, and wave number. The variations of the growth rate and oscillating frequency of streaming instability due to the change of magnetic field and plasma parameters are discussed.

P13. An improved experiment to measure the electron electric dipole moment with ytterbium fluoride
J A Devlin, I Rabey, M R Tarbutt, B E Sauer, J J Hudson and E A Hinds
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The electron is predicted to have a small electric dipole moment (EDM), although so far no one has been able to detect this experimentally. The size of this fundamental property is intimately connected to the breaking of time reversal symmetry (T) in nature. The Standard Model, which contains a small amount of T asymmetry, predicts a very small EDM, |de| \approx 10^{-38} \text{e.cm.} However, many alternatives to the Standard Model contain more T-violation to account for the matter-antimatter imbalance in the universe. With a new upper limit of |de| < 8.7 \times 10^{-38} \text{e.cm with 90% confidence [1]}, experiments are already challenging the EDMs predicted by these theories.
Ramsey spectroscopy on paramagnetic, polar molecules has proved a very effective method for measuring EDMs. Here we describe the improvements made to our machine since our last result [2] which will enable a more sensitive determination of de. We have increased the interaction time and the electric fields used in the experiment, and also improved the contrast of the interferometer. We have also implemented a new scheme of state preparation which allows many more molecules to participate in the experiment. Finally, we have demonstrated an enhanced cycling detection scheme in which twice as many molecules are detected, and each molecule scatters ~10 times more photons. Taking these improvements together, we expect to be able to measure EDMs at the $1 \times 10^{-29}$ e.cm level.


P14. Superfluid in rotating helical pipe

A Okulov

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The quantum fluids and gases are known as macroscopic objects following to laws of quantum mechanics and such a behavior is due to Bose-Einstein condensation [1]. The frictionless flows had been observed experimentally by Allen and Misener [2] and Kapitza [3] yet. The quantum gases trapped by optical potential demonstrate the similar macroscopically observable quantum state with mean-field wavefunction $\psi$ following to Gross-Pitaevskii equation [4]. The main geometries of potential are sigar and pancake traps where trapping forces are produced by anisotropic laser beams superposition [5,6]. We present here the spiraling geometry of trapping [7]. This geometry occurs due to superposition of the optical vortices which carry orbital angular momentum of light [8]. The helical confinement of quantum matter offers a new possibility to study phase transitions [1,5] and it might have applications in quantum metrology [9]. The analytical solutions of the Gross-Pitaevskii equation in the Thomas Fermi approximation gives a new insight in quantum matter dynamics in helical environment. In particular the important macroscopic observables such as momentum and angular momentum of atomic ensemble had been obtained in explicit form as well as the effective field of “classical” velocities and density of atomic cloud [6,10]. To model behavior of degenerate quantum gas in noninertial reference frame the trapping potential might be rotated via angular Doppler effect [11]. The required detuning of two counter-propagating Laguerre-Gaussian beams with vorticity having opposite orbital angular momenta may be produced by rotating Dove prism [12].

P15. Quantum carburettor effect for photon number shifting

J C J Radtke, J Jeffers and D K L Oi
University of Strathclyde, UK

Non-Gaussian operations are useful for continuous variable quantum information processing [1], one example being the Susskind-Glogower photon shift operators $\hat{E}^\pm$ [2]. The use of cavity QED [3] has been proposed to implement these bare raising and lowering operators but here we consider using conditional measurement together with linear quantum optics [4] to approximate $\hat{E}^+$. We utilise a modification of the schemes by [5, 6, 7], mixing an input state and a single photon at a beam splitter and conditioning on the detection of the vacuum in one of the output ports (Fig. 1a). By optimising the reflectivity of the beamsplitter, we can shape the state amplitudes to approximate the action of $\hat{E}^+$ instead of $\hat{a}^+$ as usually considered (Fig.1b). Interestingly, in the limit of large coherent state amplitude and low reflectivity the success probability tends to $1/e \approx 0.368$. This effect is like a “quantum carburettor” where the large flux of photons in the input induces the single photon input to be added to the output beam.

The setup can also be used for different input states, e.g. Fock state $|n\rangle$ with success probability is $(n+1)(1-t)t^n$, optimal value $t = n/(1+n)$ giving the maximum probability of success $(1+1/n)^n$ with limit $1/e$. This is in accordance with [5] which had a similar setup though for different applications. In this case, the actions of $\hat{a}^+$ and $\hat{E}^+$ are identical, only for superpositions of Fock states do they differ.

The experimental ingredients for this implementation have already been demonstrated [8]. The “quantum carburettor” effect is an elegant and experimentally feasible example of the bosonic nature of light but could also be used to characterise a beam splitter with an unknown transmissibility, or reflectivity in a reversed setup (Fig.1c).

Fig. 1 a) Scheme for conditional implementation of $\hat{E}^+$. A coherent state input is sent into port 1 and a single photon state into port 2. For a given value of a, the beamsplitter amplitude transmissivity t is chosen to maximise the fidelity of the output state with the ideal photon shifted state $\hat{E}^+ |\alpha\rangle$ conditional on measuring 0 photons in mode 4. b) Success probability (green, solid) and optimum $t$ (purple, dashed) for coherent state $|\alpha\rangle$ input. For large $|\alpha|$, the success probability tends to the limit $1/e$ and $t \to 1$. c) For fixed $t=0.8$, success probability for $|\alpha\rangle$ (green, solid) and output fidelity (purple, dashed) as a function of input coherent state amplitude showing a peak in the success probability. Scanning the input coherent state amplitude, the peak of the vacuum probability can be used to infer an unknown transmission coefficient $t$. By swapping the output ports 3 and 4, a highly reflective beamsplitter could be characterised by using large coherent states, the photon being “sucked” through the beamsplitter by the high photon flux on the other side.

We describe two exhibits that have been prepared for public engagement activities in occasion of the UNESCO International Year of Light IYL 2015: computer-generated holography with a spatial light modulator, and a magneto-optical trap (MOT) of rubidium atoms.

The holography exhibit elucidates the concept of holographic projection by phase-manipulation of laser light, with particular emphasis on applications to cold atom experiments [1–3]. Participants are introduced to the concept of Fourier transforms, and may calculate their own holograms to view on the device in real time.

The MOT exhibit allows visitors to view and manipulate cold atoms in real time, therefore conveying the underlying science in a very visual way. In order to build a robust and compact apparatus that is easily taken outside the laboratory, our MOT combines several technological advances in a unique setup, in particular a grating MOT [4] and DAVLL spectroscopy [5]. The grating MOT geometry generates all the cooling laser beams out of just one circularly-polarised laser beam impinging on a microfabricated grating, thereby massively simplifying the optics required while maintaining good optical access. The DAVLL spectroscopy provides a simple and robust way to control the frequency of the cooling laser which is robust against common-mode noise such as temperature fluctuations, and allows the detuning of the cooling light to be set using only polarisation optics. Finally, an electro-optical modulator is used to generate the MOT repumper light, eliminating the need for a second laser. We envisage that the combination of these techniques will benefit the development of compact cold atom setups not just for public engagement events, but more broadly also for atom-based quantum technologies.

In recent years, there has been increasing interest in spatially-tailored optical patterns for use in manipulating ultracold neutral atoms. We demonstrate our methods to produce smooth, high-accuracy and multi-wavelength light patterns by engineering the phase of light with a Spatial Light Modulator (SLM).

The calculation of phase-modulating holograms is an inverse problem, and is commonly performed by variants of the Gerchberg-Saxton Iterative Fourier Transform Algorithm. As an alternative to this approach, we have recently developed a new method for the generation of holograms based on the direct minimisation of a cost function by a conjugate gradient local search algorithm [1]. Smoothness of the light pattern (important in cold atom experiments to avoid heating the ensemble) is ensured by regional weightings in the cost function used to determine the accuracy of the resultant light pattern. This algorithm offers a high degree of control, as demonstrated by controlling optical vortex formation, and converges even from random initial conditions.

Light patterns are experimentally realised using a single SLM illuminated by up to three overlapped laser beams at 670nm, 780nm and 1064nm. In order to compensate for experimental aberrations, we have developed a simple and robust feedback-enhanced algorithm [2] to improve the accuracy of the light patterns, which reduces the RMS error to the percent level. The combination of regional calculation and feedback algorithm is further used to generate multi-wavelength holographic light patterns using just a single SLM [3], where the light profile of each wavelength is independently controlled.

FIG. 1. A red-detuned optical trap (colour) comprising two reservoirs connected by a one-dimensional channel with independently controlled blue-detuned barriers (white) [3].

Magnetic levitation is used to obtain clear spatial interference between two Bose-Einstein condensates that are initially axially separated. Fringes with periods of up to 85 µm are observed using non-tomographic resonant absorption imaging, utilising the ‘magnifying’ effect of a weak axial inverted parabolic potential [1]. We report the first observation of the spatial Talbot effect for light interacting with periodic BEC fringes [2]. With 160ms levitation [3], and careful choice of probe detuning, Talbot-enhanced single-shot interference contrast of > 95% is observed - close to the theoretical limit caused by CCD camera pixellation of the sinusoidal fringes. An example of such fringes is shown in figure 1a. Though this effect can lead to undesired effects in precision interferometry, it can be used as a tool to enhance fringe visibility, thus improving system sensitivity.

Phase fluctuations are an inherent property of highly elongated BECs at non-zero temperature [4], which can degrade interferometry. New levels of sensitivity to these fluctuations is made possible by the system’s long time-of-flight, high fringe contrast, our ability to modify the trapping potential during the experimental sequence, and the recent addition of a vertical imaging system (allowing for full 3 dimensional imaging). Within our system, such fluctuations lead to fringed density distributions with striking spatial regularity and reproducibility, as shown in figure 1b.

FIG. 1. Subfigure a shows an absorption image of two BECs initially separated by 40 µm and levitated for 163 ms; the fringes have a period of λ = 51 µm. Subfigure b demonstrates the clear, regular, fringes encountered due to phase fluctuations across a single highly elongated BEC which has been levitated for 58 ms. The inset shows the BEC absorption image. The density distribution (blue dots) has been fitted to a bimodal condensate modulated by sine wave fluctuations. Two possible bimodal fits of two gaussians or a gaussian plus a Thomas-Fermi are shown by the green and red lines respectively.

P19. Creation of ultracold RbCs molecules in the rovibrational ground state
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Ultracold and quantum degenerate mixtures of two or more atomic species open up many new research avenues, including the formation of ultracold heteronuclear ground-state molecules possessing a permanent electric dipole moment [1]. The anisotropic, long range dipole-dipole interactions between such molecules offer many potential applications, including novel schemes for quantum computation [2] and simulation [3]. Here we demonstrate the creation of ultracold $^{87}$Rb$^{133}$Cs molecules in the rovibrational ground state. The molecules are created from a high phase space density mixture of $^{87}$Rb and $^{133}$Cs [4] in a two-step process. First weakly-bound $^{87}$Rb$^{133}$Cs molecules are created using magnetoassociation on an interspecies Feshbach resonance [5]. The molecules are then optically transferred into the rovibrational ground state by stimulated Raman adiabatic passage (STIRAP). We present two-photon spectroscopy of the ground state using a novel well-calibrated narrow-linewidth laser system [7] to measure the splitting between the $|v_l=0, j_l=0\rangle$ and $|v_l=0, j_l=2\rangle$ states as 2940.09(6) MHz. The binding energy of the ground state is measured as 3811.576(1) cm$^{-1}$ at zero field, in good agreement with other studies [6]. We report STIRAP transfer to the rovibrational ground state with a one way efficiency of $\sim 50\%$. Stark shift of the ground state in electric fields as high as 765 V cm$^{-1}$ lead to a precise measurement of the permanent electric dipole moment as 1.225(6) D [8].


P20. A hybrid atom-photon-superconductor quantum interface
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Quantum mechanics offers a revolutionary approach to how information is processed, with unprecedented levels of security through quantum encryption and exponential speed up with quantum computing. A key challenge to exploiting these benefits is the development of the next generation hardware required for creating networks exploiting light at the single photon level. Hybrid quantum computation overcomes this challenge by combining the unique strengths of disparate quantum technologies, enabling realisation of a scalable quantum devices.

We present a new project seeking to use cold atoms trapped above superconducting microwave resonators to enable generation, storage and entanglement of optical photons on-chip. Strong Rydberg atom dipole-dipole interactions provide a mechanism for efficient single photon coupling to atomic ensembles [1], whilst entanglement is mediated via an off-resonant interaction with the superconducting microwave cavity to provide long distance (~mm scale) interaction lengths [2]. As well as providing an exciting test bed to explore fundamental ideas of quantum optics, this represents the first steps to the creation of a quantum analog of a router, an essential building block for quantum networking. Long term this can be integrated with superconducting qubits technologies to exploit fast on-chip processing power [3].

Towards laser spectroscopy of trapped antihydrogen

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Antihydrogen offers a unique way to test matter/antimatter symmetry. Antihydrogen can reproducibly be synthesised and trapped in the laboratory for extended periods of time [1, 2] offering an opportunity to study the properties of antimatter at high precision. New techniques to study antihydrogen have emerged; the ALPHA collaboration at CERN can now interrogate the bound state energy structure with resonant microwaves [3] and determine the gravitational mass to inertial mass ratio [4] and charge neutrality [5]. The results are not yet sensitive enough to draw conclusions on matter/antimatter symmetry but the recent progress shows that experiments with trapped antihydrogen are possible and the collaboration is firmly en-route towards precision measurements. The ALPHA-collaboration has upgraded the trapping apparatus improving access for both laser beams and microwave radiation. The apparatus includes a cryogenic enhancement cavity for two-photon spectroscopy of the 1S – 2S transition in trapped antihydrogen. We present the upgraded apparatus in detail.


Quantum properties of light and matter in quantum optical lattices for ultracold atoms

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In this work we consider the effect of quantum light fields coupled with ultracold matter in optical lattices in a cavity [1]. In the ultimate quantum regime, system induces effective long range many-body interactions that change the landscape of the phase diagram of the typical Bose-Hubbard model and the properties of the light. Therefore, the system can support nontrivial strongly correlated phases, i.e. multi-component supersolids and self-organised matter fields (bond) ordered phases [2]. Their emergence can be designed depending on the choice of the wavelength and pattern of the light with respect to the classical optical lattice potential. We find that by carefully choosing the system parameters one can investigate diverse strongly correlated physics with the same set-up. In addition, due to the quantum potential, the system can have genuine multi-partite entanglement and non-trivial dynamics due to measurement back-action [3]. Beyond weak atomic dynamics and weak on-site many-body interaction the system presents the opportunity to maximise the effect of processes in between the classical optical lattice minima [4]. This allows for additional control, measurement and maximisation of quantum effects. Specifically, quantum fluctuations become relevant and the system has access to novel correlated phases. In addition, beyond well known two component models of interacting bosons, the choice upon the structure of the quantum light allows for a plethora of different emergent phases competing and/or co-existing, i.e. the system manifests spontaneously additional density waves with supersolid order and gapped superfluids. We support our findings by using ab-initio calculations of the Wannier functions beyond the gaussian approximation, exact diagonalisation and mean-field theory of the many-body effective quantum Hamiltonians. We show how the structure of the light-matter states gets modified and explicitly show how the information regarding the matter many-body states components (i.e. correlation functions) gets imprinted in the light field amplitude and its quantum fluctuations. Moreover, the interplay between light waves and quantum matter leads to additional energy scales due to local processes that can modify the landscape of correlated matter even further beyond the limit when light is in a stationary state. We find the structure of the quantum many-body light-matter states that can be generated by...
either an effective classical light potential or even driven by quantum fluctuations of light and matter, going beyond the typical considerations in classical optical lattices.


**P23. An AC MOT for atoms and molecules with complex level structures**

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Magneto-optical trapping is a vital technique for producing cold, confined atomic ensembles. Most magneto-optical traps (MOTs) operate on a transition from a lower state with total angular momentum quantum number $F_l$ to one with $F_r = F_l + 1$, where optical cycling allows high scattering rates and hence strong confinement. MOTs in which the trapping transition has $F_r \leq F_l$ can be produced, but these tend to produce weaker confining forces.

It is now becoming clear that the powerful technique of laser cooling can be applied to molecules as well as atoms. The molecular species so far cooled (SrF, YO, CaF) use cooling transitions in which $F_r = F_l + 1$. This scheme produces a closed rotation system for cooling, but can produce MOTs with very weak restoring forces. The molecules can be quickly pumped into a ground state hyperfine magnetic sub level that is dark to the restoring radiation, but not the anti-restoring radiation. This problem can be circumvented by rapidly and synchronously switching the magnetic field direction and polarisation of all cooling beams. In this way the molecules can be non-adiabatically switched to a different Zeeman sub-state in which the atom interacts with the confining radiation. This method will allow us to greatly enhance the restoring forces for magneto-optical trapping of molecules, as well as atoms with a level structure different from the norm.

We are currently building an AC MOT of Rb, with which we will study how to optimise the trapping process for transitions containing magnetic sub-levels dark to the confining beams in the traditional MOT scheme. We shall discuss our progress, in particular the ac coils that will allow us to produce a magnetic field suitable for trapping that can be switched at around 5 MHz, and the offset lock that will be used to tune the cooling lasers to any desired transition.

**P24. Ultracold collisions of highly magnetic Erbium isotopes: How much chaotic are they?**

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Recent experiments with ultracold samples of highly-magnetic erbium [1] and dysprosium [2,3] atoms reveal an unusually large number of resonant features. A first study of the spacing distribution between these resonances in the Er case pointed to the system being in a chaotic regime [1] (see also [4]).

We perform an extended analysis of the spectral statistics of the collisional resonances in 166Er and 168Er reported in Ref. [1] with the aim of determining the chaoticity of this system. We calculate different independent statistical properties to check their degree of agreement with Random Matrix Theory (RMT), and analyse if they are consistent with the possibility of having missing resonances [5,6]. The short- and long-range fluctuations of the resonance positions at high magnetic fields are in agreement with RMT predictions, with an estimated 20-25% fraction of missing levels. On the other hand, an independent chaoticity test based on the distribution of resonance widths provides no definite answer, even with the assumption of missing resonances, a fact that we attribute to the
limited experimental magnetic field resolution. We conclude that further measurements with increased resolution will be necessary to give a final answer to the problem of missing resonances and the agreement with RMT.


P25. Measurement of K-shell X-ray production cross-sections in Ti due to 0.3 – 0.7 MeV/u $^{28}$Si and $^{63}$Cu incident ions

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An accurate and reliable basic ion beam-matter interaction database is crucial for the development and implementation of heavy ion beam materials analysis techniques. The development of theoretical models to describe various interaction phenomena is strongly dependent on the availability of experimental data to test these models. Secondary Ion Mass Spectrometry using heavy ion beams in the MeV energy regime (MeV-SIMS) promises to be an effective technique in molecular imaging studies. If used simultaneously with heavy ion Particle Induced X-ray Spectrometry (PIXE), the two techniques may lead to a much more complete description of analysed samples. An inhibiting factor in the implementation of heavy ion PIXE is that heavy ion X-ray production cross sections, among other important variables, are not well known for many materials. This contribution reports on work carried out at iThemba LABS to measure X-ray production cross-sections in Ti and TiO$_2$ films irradiated with $^{28}$Si and $^{63}$Cu ions within the 0.3 – 0.7 MeV/u energy range. Experimental data is compared to predictions by the PWBA and ECPSSR theories using the ISICSoo [1] code. The effect of chemical bonding on the cross sections is also discussed, in view of potential application in molecular imaging.


P26. Toward a charged-wire storage ring for high-field-seeking Rydberg atoms

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The methods that have been developed to date for controlling the translational motion, and trapping Rydberg atoms and molecules using inhomogeneous electric fields have centered upon low-field-seeking Rydberg-Stark states with positive Stark energy shifts [1–3]. However, there are several areas in which efficient methods for guiding and manipulating samples in high-field-seeking states, with negative Stark energy shifts, are desirable. These include (i) collision and spectroscopic studies involving molecules in low-angular-momentum Rydberg states in which the Rydberg electron couples strongly to the ion core, (ii) the confinement and manipulation of antihydrogen atoms, which are produced simultaneously in low- and high-field-seeking Rydberg-Stark states [4], (iii) approaches to hybrid cavity-quantum electrodynamics involving atoms in high-angular-momentum circular Rydberg states [5, 6], and (iv) tests of quantum mechanics in non-commutative space [7].
With applications in these areas in mind, we present the results of experiments in which beams of helium atoms in high-field-seeking Rydberg-Stark states have been guided and decelerated. The electrostatic guide used in these experiments was based on a charged wire suspended along the axis of a grounded cylindrical metallic tube [8]. In this device, the guided atoms followed helical trajectories in the $1/r$ electric field close to the wire [9]. The operation of this electrostatic wire-guide was investigated using dc and pulsed electric potentials applied to the wire while the guided atoms were detected by spatially resolved, pulsed electric field ionisation. With the aim of storing Rydberg atoms at a fixed longitudinal position as they orbit about the wire, we have now implemented a miniature multistage decelerator for these samples. The output of this decelerator is designed to be coupled to the storage ring so that slow, velocity-controlled samples can be injected into stable orbits. The design and results of the first deceleration experiments with this device will be presented.


P27. Single-shot, phase-insensitive readout of an atom interferometer
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Atom interferometry is a next-generation precision measurement technique, mapping information encoded in the phase of atoms to an easily measureable output. The sensitivity of atoms to fields such as electromagnetism and gravity allows atom interferometry to examine physics which conventional photon interferometers cannot.

We have constructed an atom interferometer, with atom optics generated by the off-resonant Kapitza-Dirac scattering of a rubidium Bose-Einstein condensate from a time-varied optical lattice. The phase-sensitivity of this scattering mechanism allows for the design of high-fidelity ‘beam splitter’ and reflection operations at multiple scattering orders, without altering atomic internal state. This enables the creation of atom interferometers with various geometries and common mode rejection of typical phase-noise sources such as stray DC magnetic fields, without destroying sensitivity to gradient fields or non-inertial motion.

Here we present preliminary measurements of a phase-contrast interferometry signal. This technique maps the evolving interferometer phase to the fringe contrast of an atomic hologram. By probing this hologram, the entire interferometry signal can be read out in a single shot, removing the need for long temporal stability.

P28. Towards the production of a quantum gas near a tapered optical nanofibre
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In recent years novel techniques have been developed to create an ultracold atomic quantum degenerate gas each with their own advantage: speed, large atom number, simplicity to name a few. Quantum degenerate gases (QDG) have a large application well, ranging from solid state research by imposing state-of-the-art optical lattice techniques [1], or to create high control quantum processors via the light-matter frontier [2, 3]. Such applications
can further our understanding and insight into fundamental quantum physics and developing a new generation of
technological advancements.

At present we are working towards the production of a light-QDG interface with single atom sensitivity through the
medium of optical tapered nanofibres (TNFs). As the presence of TNFs does not impose severe restrictions on laser
cooling techniques [4], we can probe macroscopic quantum systems by placing a TNF at the vicinity of our atoms.
Such a setup would enable the observation of atomic fluorescence into the TNF or inversely, atomic interaction via
resonant nanofibre photons. The scheme can also be extended to simultaneously detect atoms in different internal
states.

We have a laser cooling system designed to trap Rb and K. We routinely magnetically trap $^{87}$Rb atoms with a field
gradient of 1.0T/m (maximum of 2.2T/m) at 140 µK. Currently we are incorporating a hybrid “dimple” trap
technique for a Bose-Einstein condensate production ($^{85}$Rb BEC). We have incorporated an optical dipole trap laser
and calculations give values for the trap depth of our system throughout the adiabatic transfer from the dimple trap
to a pure optical trap to be $U_0 = 49$ µK and the temperature of the atom cloud at completion of the transfer to the
pure optical trap to be 4.9 µK if we assume the relation of $T_f = 0.1U_0 /k_b$ as shown in [5]. The final step involves
evacative cooling in the pure optical trap resulting in quantum degeneracy.

The system also includes provision for independent detection of atoms via a high resolution single photon sensitive
optical system. We are currently working on a four component fluorescence collection lens inspired by [2, 6, 7].

Here we present an overview of our work to date.


P29. Towards ultracold CsYb molecules for quantum simulation

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1Durham University, UK, 2Imperial College London, UK

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][4].

We present the development of our two-species apparatus, as well as some theoretical background to the project.
We demonstrate the capability of the two-species apparatus to produce cesium and ytterbium MOTs with atom
numbers in excess of 108 and temperatures below 20 µK and also the results of evaporative cooling of the atoms in
an optical dipole trap. Finally we outline our progress towards characterising the ultracold Cs-Yb mixture, using
photoassociation spectroscopy to determine the interspecies scattering length.

Correlations between photons in two beams of light allow an image of an object to be obtained using photons which have never directly interacted with the object. This procedure is called ghost imaging [1]. If correct information about the object implies a strategic decision, an intruder may try to change the image by jamming the imaging procedure. This issue is of importance in RADAR- or LIDAR-type systems. In general ghost imaging cannot be made completely secure. However, for a large class of the intrusion strategies based on intercepting and resending photons we can detect the intrusion and in many cases we can recover the correct image. This kind of jamming and appropriate protection based on quantum protocols have been recently studied in context of military applications [2] using the BB84 or an entanglement-based protocol in a LIDAR-type imaging arrangement. Here we provide a general description of intruder detection and correct image recovery and show its application to ghost imaging protocols.

FIG. 1: Ghost imaging with intrusion and a security setup. Regions within dotted lines denote zones controlled by legitimate parties.

The investigated situation is shown in Fig. 1. Intruder $E$ intercepts part of a signal emitted by source $S$ to investigate an object $\Lambda$. $E$ re-sends pairs of photons produced by source $S_E$ fully controlled by $E$. These photons carry information about a false object $T$ to both right- and left-hand detectors. Analysers $P_i$ in different configurations provide the detection and recovery setup.

<table>
<thead>
<tr>
<th>Attack</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
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<tbody>
<tr>
<td>Protection</td>
<td>Quantum</td>
<td>Classical</td>
<td>Dual</td>
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<tr>
<td>Classical</td>
<td>Quantum</td>
<td>Dual</td>
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TABLE I: Intrusion recognition. Quantum, classical and partial refer to maximally entangled, maximally mixed polarising states and their mixture respectively.

Our detection and recovery protocol uses polarisation. A set of polarisation analysers in different configurations allows us to see intensity changes in observed images depending on states produced by our source. Because of the symmetry in Fig. 1 if the intruder's source $S_E$ is identical to the trusted source $S$ the changes in intensity of the correct and false images $\Lambda$ and $T$ are identical and we cannot decide if the observed object is $\Lambda$, $T$ or their overlap. Occasionally, however, legitimate parties can change the type of state, removing the symmetry between the correct and false images.

We consider the particular case of two types of photonic states: quantum - maximally entangled states in polarisation degrees of freedom and classical - maximally mixed photonic states. This choice is motivated by the fact that these states are indistinguishable by local measurement by the intruder, who cannot recognise changes in the trusted source. Intrusion detection depends on the intruder's strategy as shown in table I.
The possibility of image recovery depends on the fraction of photons intercepted by the intruder. Fig. 2 shows the recognition of a type of attack based on the dependence of the images on the legitimate parties' choice of states and analysers. Finally we propose a general recovery scheme that is not restricted to ghost imaging. Its application is shown in Fig. 3.

**FIG. 2:** Recognition of type of attack. Index i denotes configuration of analysers. Index j the state chosen by legitimate parties.

**FIG. 3:** Image recovery process simulation. Upper left image: the unprocessed mixture of the correct and false images received by the detectors. Upper right: false image extracted from analysis with security setup. Lower left: the recovered image. For comparison lower right image shows the object.


**P31. Cavity cooling a single charged levitated nanosphere**

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The cooling of the centre-of-mass motion of a levitated macroscopic particle is seen as an important step towards the creation of long-lived macroscopic quantum states and the study of quantum mechanics and nonclassicality at large mass scales \cite{1}. Levitation in vacuum minimises coupling to the environment, while the lack of clamping leads to extremely high mechanical quality factors of the oscillating particle \cite{2}. The ability to rapidly turn off the levitation coupled with cooling, offers the prospect of interferometry in the absence of any perturbations other than gravity \cite{3}. However, like cold atoms trapped in vacuum, levitated nanoparticles are sensitive to parametric noise and internal heating via even a small absorption of the levitating light field \cite{4}. To date this has limited the lower pressure at which particles can be stably trapped and cavity cooled. We overcome this problem by levitating a naturally charged silica nanosphere in a hybrid electro-optical trap by combining a Paul trap with an optical dipole.
trap formed from a single mode optical cavity (figure 1). We show that the hybrid nature of the trap introduces an unexpected synergy where the Paul trap plays an important role in the cavity cooling dynamics by introducing a cyclic displacement of the equilibrium point of the mechanical oscillations in the optical field [5]. This eliminates the need for a second, dedicated cooling optical mode of the cavity [6] and importantly allows us to cool the trapped particle in vacuum to mK temperatures.

![Figure 1: A schematic diagram of the hybrid trap consisting of a Paul trap and standing wave optical cavity potential.](image)


P32. The Zeeman-Sisyphus decelerator: A new time-independent slowing method for molecules

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The ability to slow down molecular beams is highly advantageous for the field of cold molecules, in particular for realising a molecular magneto-optical trap (MOT) [1]. Standard techniques, such as Stark and Zeeman deceleration, are best suited for short (∼ 10 – 100 µs) molecular pulses as produced in supersonic expansions.

With the recent development of buffer gas sources, which produce molecules over extended periods of time [2], a new deceleration technique is required.

Here, we present a new design for a Zeeman-Sisyphus decelerator, where the molecular beam is decelerated using an array of permanent magnets and 2 pump lasers. This approach is an extension of the trap loading method demonstrated in [2]. In our decelerator, the Zeeman shift in the magnetic field produces potential hills or valleys, depending on the internal state of the molecule (see FIG. 1). The two lasers switch the molecule between the strong- and weak field seeking states as they come in resonance near the potential energy hilltops. In this way the molecule constantly gains potential energy and is decelerated. This process depends on position but not on time and should be applicable to both continuous and pulsed beams of large temporal extent. Since current molecular MOT experiments start with these type of sources, this new decelerator will be an ideal tool for loading molecular MOTs.
P33. Developing a next generation ultrafast electron microscope

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Since its conception, the field of electron microscopy has allowed for investigations into atomic length scales via continuous emission and more recently into atomic timescales, due to the advent of femtosecond or ultrafast laser systems [1]. Ultrafast electron microscopy and diffraction ultimately aims to observe atomic dynamics on the timescales at which they occur. The work to be presented in Sussex seeks to highlight the advances we have made towards this goal.

Our next generation electron microscope will allow imaging under both the point projection [2] and diffractive regimes on ultrafast timescales. The electron source utilised in our work is an electro-chemically etched tungsten nano-wire [3]. Time-resolved Point Projection Microscopy (PPM) has been demonstrated through the investigation of femtosecond laser pulse induced charge mobility in such a tungsten nanotip with sub-picosecond resolution, and allowed us to view the reaction of the very emission process which underpins the whole experiment.

Complimentary simulations of the probing electron pulses allowed for the fine tuning of experimental parameters to create electron packets with the smallest temporal profile within our configuration. These particle tracing simulations provide a lower bound on the pulse length upon arrival at the target and give an indication of the resolution of our system.

Future work includes adapting the instrument to accommodate coherent diffractive imaging (CDI). This means existing components of the experiment need to be suitably adapted or new components added, including an adaption to the sample mount and configuring the geometry of the additional collimating electron lens. A complete analysis of the PPM experiment detailed above involving charge motion will be conducted, as will investigations into untraditional targets, including aqueous samples [4] and nano-scale metallic rods and wires.

**P34. Rydberg spectroscopy and dressing in strontium with a high power, narrow linewidth UV laser**

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Rydberg atoms with high principal quantum number \( n \) have large atomic polarisabilities, and hence exhibit strong long-range interactions. Using an off-resonant laser to couple these Rydberg states to a ground state is known as “Rydberg dressing” [1], and introduces switchable, tunable, soft-core interactions between the ground state atoms. The first demonstration of Rydberg dressing has very recently been achieved in caesium atoms [2], but is yet to be demonstrated in other systems.

The near-isotropically repulsive interactions provided by the \( 5sns^3S_1 \) Rydberg states in strontium [3], along with the possibility of low-decoherence two-photon excitation via the narrow intercombination lines, makes strontium an ideal system for investigating Rydberg dressing. The interactions between Rydberg-dressed strontium atoms can be used to generate a high degree of spin-squeezing in optical lattice clocks, which could have application in reducing the instability of the frequency measurement below that imposed by the quantum projection noise limit [4].

To study Rydberg dressing in strontium we have developed a high power, widely tunable, narrow linewidth UV laser system at 318 nm. We are able to produce over 200 mW of UV light with a linewidth and long-term drift of <100 kHz, and a tunability of > 4 THz. We use an atomic-referenced optical cavity to narrow and stabilise the frequency of this laser, and a GPS-referenced optical frequency comb to measure its frequency stability and make absolute frequency measurements of the atomic transitions.


**P35. Laser cooling of CaF molecules**

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Laser cooling is a powerful tool that underpins many experiments with cold matter. It enables the production of ultracold samples of a range of atomic species. The technique requires a closed system of energy levels that can scatter many thousands of photons. Typically, this condition is not easily met by molecules, whose rich internal structure makes it hard to find a closed system. A particular problem is caused by decays to different vibrational manifolds, which can require many repump lasers. However, recently a number of molecules have been found to be good candidates for laser cooling.

We report on the laser cooling of CaF molecules. The A-X transition in this molecule has a highly diagonal Frank-Condon matrix, and cooling can be achieved with only two vibrational repump lasers. We recently cooled CaF molecules from a 600 m/s supersonic beam, reducing their forward speed by about 20 m/s and cooling the translational temperature to around 300 mK. More recently, we have built a new cryogenic source which produces CaF pulses with a mean speed of 150 m/s. We aim to slow these molecules to rest and capture them in a magneto-optical trap. We will present our latest results from this experiment.
P36. Sensitivity improvements to the YbF electron electric dipole moment experiment
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We present a series of technical improvements to the preparation and detection stages of the YbF electron electric dipole moment (EDM) experiment [1]. The magnitude of the electron dipole, \( d_e \), is intimately connected to the amount of time-reversal asymmetry present in the universe. Current measurements of the electrons EDM tightly constrain physics beyond the Standard Model, and future measurements [2] could provide evidence for theories such as super symmetry.

We can increase the statistical sensitivity of our measurement by increasing the number of YbF molecules that participate in the experiment and by increasing their detection probability. We demonstrate several hardware developments that combine laser, microwave and rf fields which, when applied to YbF, can pump six times more population into the initial measurement state. In the detection region we have used techniques developed for molecular laser cooling, including resonant polarisation modulation, to dramatically increase the number of scattered photons by a factor of 10. Combining all improvements, the statistical uncertainty of our measurement is expected to be reduced by a factor of ninety, enabling us to search for an EDM below the recent upper limit of \( 8.7 \times 10^{-29} \) e.cm [3].


P37. Transporting and storing Rydberg atoms above electrical transmission-lines
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With the goal of realising a chip-based laboratory for manipulating, and studying interactions involving, Rydberg atoms and molecules we have recently developed a set of electrical transmission-line guides, decelerators and traps for these samples [1, 2]. These devices exploit the very large electric dipole moments associated with high Rydberg states, which for states with principal quantum number \( n \geq 52 \) exceed 10000 D. These dipole moments permit the translational motion of such samples to be efficiently controlled using inhomogeneous electric fields [3, 4]. In contrast to previous chip-based Rydberg-Stark decelerators [5, 6], the transmission-line based design permits strong confinement in all three spatial dimensions during transporting, deceleration and trapping, is compatible with the introduction of curvatures in the plane of the transmission-line surface, and is suited to coupling to microwave circuits [7]. The results of deceleration experiments performed with these devices using pulsed supersonic beams of metastable helium will be presented. The role of atom-atom interactions in the travelling traps of the decelerator, highlighted by comparison of the experimental data with the results of numerical calculations of Rydberg atom trajectories, will be discussed. As will recent experimental tests of a chip-based Rydberg-atom storage-ring. The cold, velocity-controlled samples that can be generated in these transmission-line decelerators are of importance for (i) applications of Rydberg atoms in hybrid approaches to quantum information processing [8, 9], (ii) investigations of atom/molecule-surface interactions [7], and (iii) experiments with antihydrogen and positronium [10].

P38. Adiabatic elimination of a qubit transducer from stochastic quantum dynamics. Quantum jumps monitoring in optomechanical system

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There is a growing number of physical systems which provide access to a continuous monitoring of quantum dynamics in order to engineer nontrivial quantum states and to observe and stabilise quantum trajectories. Such control allows for plenty of applications in metrology and quantum information processing. In many experimental realisations the system of interest is monitored by means of an ancillary device, whose sole purpose is to transduce the signal from the system to the measurement apparatus. Here we extend the method of adiabatic elimination for stochastic dynamics proposed in [1] to a transducer which consists of a qubit linearly coupled to the system and the monitored light mode. The obtained stochastic master equation (SME) for the system with adiabatically eliminated transducer leads to a dramatic increase in the numerical performance for the simulation of the system dynamics. It is interesting that in general the effect of the qubit transducer on the system dynamics cannot be represented by an effective Markovian stochastic terms.

The transducer can be implemented in a number of systems such as quantum dots, superconducting qubits, NV centres in diamonds etc. We propose an optomechanical scheme with embedded emitters as an effective qubit transducer which allows for observation of phonon jumps of the nano-mechanical oscillator. The derived adiabatically eliminated SME helps to optimise the system parameters and the measurement strategy.


P39. Rydberg atoms in time-varying electric fields: sensing electrical noise and monitoring many-body interactions

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The excited electron in a Rydberg atom (atom in a state of high principle quantum number n) spends most of its time away from the ion core where it experiences a weaker Coulomb potential making it very sensitive to the presence of external electric fields. The addition of a dc external electric field breaks the symmetry of the spherically symmetric Coulomb potential and splits the field-free energy eigenstates into a manifold of Rydberg-Stark states each of which has a mixed l-character. It is this l-mixing which causes some of the states in the Rydberg-Stark manifold to acquire a very large electric dipole moment (of the order of 10000 D for n >51).
Here we present experiments in which helium atoms produced in a supersonic source are excited to Rydberg-Stark states in the vicinity of \(n=52\). In the electric fields used in the experiment the states excited have linear Stark shifts and electric dipole moments of \(\sim 7900\) D. Because of the high particle number densities in the supersonic beam \(\sim 10^9\) cm\(^{-3}\)), such huge electric dipole moments can be exploited to study dipole-dipole interactions in the ensemble of Rydberg atoms. These classical dipole-dipole interactions are fundamentally different from those traditionally explored in ultracold ensembles of Rydberg atoms, i.e. (i) the resonant dipole-dipole interactions arising from large transition moments [1], and (ii) the second-order van der Waals interactions exploited in Rydberg excitation blockade experiments [2].

The states with large electric dipole moments employed in the current experiments are very sensitive to low-frequency (1-100 MHz) non-resonant electric fields. Such fields, even of small amplitude, significantly modify the energy level structure of the Rydberg atoms. This modification, which can be described theoretically using Floquet methods [3], opens up the possibility of using the atoms as sensitive probes for broadband electrical noise. We show that the modified spectral intensity distributions associated with the transitions to the Rydberg-Stark states with linear Stark shifts in the presence of applied low rf field can also be used to directly identify coherent many-body interactions without the need to count individual atoms. The experimental results are in excellent agreement with calculations of the Rydberg energy level structure carried out using Floquet methods, and indicate that the coherent excitations are shared by up to 4 atoms [4].

**P41. First principles study of the electronic and magnetic structure of RESn3 intermetallic compounds**

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First-principles investigation has been carried out in order to analyse structural, electronic and magnetic properties of RESn3 compounds thereby exploiting specific properties for better understanding of their magnetic structure. The generalised gradient approximation +U formalism has been used to account for the strong on-site Coulomb repulsion among the localised RE 4f electrons. By varying the Hubbard U parameter from 0 eV to 8 eV, a detailed study of magnetism of these compounds via the density of states DOS and charge densities, is presented.

**P42. Holography-based device for the study of the topological Kondo effect in cold atom systems**

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The topological Kondo model has been proposed in solid-state devices as a way to realise in a controllable setting the non-Fermi behaviours expected at the critical point of multichannel Kondo systems. This proposal is based on the interaction of Majorana edge modes at the boundaries of one-dimensional wires merging in a star-like geometry. In the present work, we show that a Y-junction of Tonks-Girardeau gases provides a physical realisation of the topological Kondo model in the realm of cold atom systems. An explicit computation is presented by considering the XX model on the star lattice (obtained by discretising the Hamiltonian of the system or, physically, by superimposing optical lattices on it) and then performing the continuous limit. The topological Kondo effect presents clear signatures in the thermodynamic properties, whose detection is discussed for cold atom systems.

We also experimentally realise a Y-shaped light pattern using a computer-generated hologram, showing that it is possible to have controllable and independent tunnelling coefficients between different arms of the junction. The size of the junction is of the order of a few m, showing the complete proof-of-principle of a holography-based device exhibiting the topological Kondo effect.

![FIG. 1. Holographically generated Y-shaped light pattern](image)
**P43. A co-trapped barium and ytterbium ion trap experiment for remote entanglement and hybrid quantum networks**

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Trapped ions remain a leading candidate for the implementation scalable quantum networks. Promising schemes include quantum information processing using deterministic local ion entanglement with ion chains and heralded remote entanglement using photonic links between separate nodes in a quantum network, ideally at high rates [1]. For long-haul transmission, trapped barium ions emit, with relatively high probability, single photons in the visible spectrum making it a promising candidate as a photonic link. We plan to establish one node of a network using co-trapped barium and ytterbium ions, with ytterbium serving as a memory qubit, due to its long qubit lifetime, and barium serving as a photonic link [2]. We are currently building a segmented four-blade trap [3], which allows trapping of both single ions and chains of ions with a large unobstructed solid angle of collection of emitted photons and, therefore, can increase remote entanglement rates. Local entangling gates between barium and ytterbium ions will transfer quantum information between memory qubits and photonic link qubits. We will then implement frequency conversion on photons emitted from the barium ion to demonstrate compatibility with remote entanglement protocols over large distances and to create a hybrid quantum network.


**P44. Observation of localised multi-spatial-mode quadrature squeezing in four wave mixing**

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When using classical light, optical measurements and light-based sensing methods are limited by the unavoidable quantum fluctuations in phase and amplitude, also known as shot noise. We investigate methods of manipulating the quantum noise locally across the transverse profile of a beam, hereby reducing the “quantum roughness” inherent in the output of even the quietest lasers. This presentation aims to introduce our technique through an explanation of the experimental set-up and differentiate between the different types of spatial squeezing already achieved, before showing how we are planning to use this quantum light to improve the spatial resolution of certain imaging techniques.

**P45. Observation of chiral edge states with neutral fermions in synthetic hall ribbons**


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Chiral edge states are a hallmark of quantum Hall physics. In electronic systems, they appear as a macroscopic consequence of the cyclotron orbits induced by a magnetic field, which are naturally truncated at the physical boundary of the sample. Here we report on the experimental realisation of chiral edge states in a ribbon geometry with an ultracold gas of neutral fermions subjected to an artificial gauge field. By imaging individual sites along a synthetic dimension, we detect the existence of the edge states, investigate the onset of chirality as a function of the bulk-edge coupling, and observe the edge-cyclotron orbits induced during a quench dynamics. The realisation of
fermionic chiral edge states is a fundamental achievement, which opens the door towards experiments including edge state interferometry and the study of non-Abelian anyons in atomic systems.

P46. Towards a molecular MOT of YbF

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The magneto-optical trap has been a powerful tool for producing ultracold atoms for a huge variety of applications. Magneto-optical trapping of molecules is new and is important for many applications including precision measurement, quantum simulation, quantum information processing and ultracold chemistry. Recently, such a molecular MOT has been demonstrated [1].

The molecular species, ytterbium fluoride (YbF) has been used to measure the electron's electric dipole moment (eEDM) [2]. Laser cooling of YbF is feasible by addressing the set of transitions illustrated in Fig. 2 [3]. We are building an experiment where YbF molecules will be captured and cooled to low temperatures in a MOT, and then launched into a fountain [4], as illustrated in Fig. 1. This fountain apparatus will greatly lengthen the transit time of the molecules through the eEDM experiment, which will allow us to make a new eEDM measurement with increased precision over the best previous measurement [5].

We will present our scheme for the YbF MOT, our work towards building the laser system and first results towards laser cooling this molecule.

Figure 1: Schematic of the experimental design. YbF molecules are produced in a thermal beam from a cryogenic buffer gas source; the molecules are cooled by collisions with helium at 4 K. The YbF is deflected out of the beam and is brought to rest in a MOT. Trapped molecules are then launched upward to form a fountain in which the eEDM is measured.
Figure 2: The molecular transitions we use for laser cooling and the required wavelengths of the cooling lasers. $v''$ and $v'$ are the vibrational quantum numbers of the ground and excited states respectively. Franck-Condon factors are given as percentages. The linewidth of the $v' = 0$ state is 5.7 MHz.


P47. Quantum simulation of the two dimensional compass model with periodic driving fields

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In this work, we show how the quantum compass model on a rectangular lattice can be simulated by the use of the photon-assisted tunneling induced by periodic drivings. The 2D-version of this model on a $n \times m$ lattice is defined by the following spin Hamiltonian ($S = 1/2$),

$$H_C = -J_x \sum_j \sigma_j^x \sigma_{j+e_x}^x - J_y \sum_j \sigma_j^y \sigma_{j+e_y}^y,$$

where $\sigma_j^{x,y}$ are the usual Pauli matrices and $j$ runs over the lattice sites. This model belongs to a broad type of lattice Hamiltonians in which the couplings between sites depend on the orientation of the bonds in the lattice. The physical implementation in experimental setups is therefore generally a challenge as the interactions are usually spatially independent. The remarkable symmetry of this model was applied to implement protected qubits in the context of Josephson junction arrays, motivated by the fact that a high degree of symmetry of the system may prevent local physical noise from destroying the degeneracy at least in the lowest orders in the strength of the noises. We describe a way to adiabatically prepare one of the doubly-degenerate ground states of this model by means of a transverse magnetic field, with surprising differences depending on the parity of the lattice size. Exact diagonalisations confirm the validity of this approach for small lattices. A specific implementation of this scheme is given in the context of ultracold atoms in optical lattices in the Mott-insulator regime.
P48. Observing the average trajectories of particles in a double slit interferometer

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The 1988 work on weak measurements by Aharonov et al. showed the weak value as a new kind value of quantum variable [1]. This created new perspectives when it came to the limits of quantum uncertainty. More recently, Kocsis et al [2] had used weak measurements experimentally, claiming to have measured the average trajectories of photons that had passed out of a double slit interferometer. This was done without destroying the interference pattern, an act apparently forbidden by standard quantum mechanics. We aim to replicate Kocsis experiment by dropping ultra-cold, metastable, argon atoms from a magneto-optical trap, over a pair of nano fabricated slits. Here we present our intended method of measuring the atoms trajectories as they fall below the slits, while maintaining the interference pattern.

Figure 1: Atom interferometer Schematic


P49. Dielectric anomaly in H₂O Ice near 20 K; Evidence of macroscopic quantum phenomena

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Water ice is arguably the most studied substance; though yet, not much is known about its ground state. Herein, an anomaly in the form of a minimum is identified in the imaginary part of the dielectric constant as a function of temperature near 20 K; in contrast, the real part remains monotonic. Isothermal dispersion and absorption measurements reveal consistent results. In the case of heavy ice (D₂O), no minimum was identified confirming an apparent isotope effect. Correlated quantum tunneling of protons is believed to be the underlying cause behind the observed anomaly. Our findings suggest that the H₂O system also exhibits macroscopic quantum phenomena of which seldom occur in nature.
Dense and cold atomic beam delivered by a 2DMOT repumped and channelled by a Laguerre-Gaussian laser beam

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Nowadays, 2DMOTs are atomic sources currently used for trap loading, 3DMOTs for example. Indeed, they deliver slow and cold atom beams: typically for rubidium, the transverse temperature is 0.4 mK and the longitudinal velocity in the 10-50 m/s range. Nevertheless, the divergence of the output beam being about 40 mrad leads to a rapid decrease of the atomic density as the beam propagates. It is the reason why the 3DMOTs are installed close to the 2DMOT exit and require cooling-laser beams with a large diameter and a large power. The divergence can be reduced with an additional far-blue-detuned Laguerre-Gaussian (LG) mode set on the 2DMOT axis, which operates as a 2D-dipole trap on exiting atoms [1].

In the present version the LG mode, frequency-locked to the $^{87}$Rb $5s_{1/2} F=1 \rightarrow 5p_{3/2} F'=2$ transition, is set along the main axis of a vapor-cell 2D-magneto-optical trap (2DMOT) and, realises both functions, namely repumping atoms inside the 2DMOT and channelling atoms exiting the cell. It avoids any other repumping light. The output atomic beam properties (flux, density) depend on the LG power (enough to repump and to channel) and order (large enough for minimise atom losses due to residual heating), as shown in the figure. We show that with about 50-100 mW the density gain exceeds 100. As preliminary result we will present a LG2DMOT-loaded 3DMOT realised with millimeter-sized cooling laser beams.

Figure 1: Density gain of the LG2DMOT observed at 300 mm, versus the LG power, for orders equal to 4, 6 and 8.


Trapped atomic ions are ideal systems for emergent technologies such as quantum information processing (QIP) [1], optical atomic clocks [2] and quantum-enhanced sensors [3]. High-fidelity coherent control of the ion’s electronic and motional states is of paramount importance for these applications. This control is frequently performed via laser pulses tuned to the qubit transition frequency, both for optical qubits [4] and for hyperfine qubits through Raman transitions [5]. Variations in the strength of the ion-laser interaction can make a significant contribution to infidelities in the coherent processes required for quantum gate operations. These are caused by fluctuations in laser frequency and the precise intensity of the optical pulses experienced by the ion. To address this, we have developed a qubit laser system which targets long-term stability of the ion-laser interaction at the level required for fault-tolerant QIP. Crucially, this stabilisation does not compromise agility in phase, frequency, and temporal pulse shaping [6].

This work is centred on the 674 nm optical qubit transition in $^{88}$Sr+. To extend the system coherence time towards the limit imposed by the qubit lifetime (391 ms [7]), the frequency stability of an ultra-stable source [8] is transferred to the qubit laser via a phase-noise cancellation system and an injection lock. Optical pulses are generated with a power stable to $<10^{-3}$ of the programmed value, at a set-point in a range covering about 5 orders of magnitude (~10 nW to 1 mW); this is achieved by monitoring the pulses with a series of cascaded avalanche photodiodes and providing feedback to optical modulators. To transfer this power stability to the intensity experienced by the ion, the position of the beam in the trap region is stabilised to an adjustable set-point using a quadrant photodiode and feedback to an actuated mirror. By measuring the coupling strength as the beam is scanned spatially, the precise beam position for the maximum ion-laser interaction can be determined.

With the combined stability levels, we expect to implement quantum gate operations where infidelities due to the addressing laser are at the $10^{-4}$ level, a current benchmark for fault-tolerant QIP [9]. The system described here is being used, in conjunction with our microfabricated trap [10], to implement the Mølmer-Sørensen entangling gate [11,12] with a fidelity approaching this target. Our approach is widely applicable to experiments requiring high-fidelity atom-laser interactions, covering matter-wave interferometry, high precision spectroscopy and other quantum gate operations.

P52. Four wave mixing in CMOS compatible high order ring resonators

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All-optical integrated devices for wavelength conversion via Four Wave Mixing (FWM) have been widely explored for future ultrafast optical networks. All optical conversion in CMOS compatible devices has been demonstrated in silicon [1] and in nonlinear glasses such as chalcogenides [2]. Silica glass and silicon nitride based platforms offer a suitable alternative, overcoming limitations from nonlinear losses in comparison to other materials, while maintaining high effective nonlinearities as well as CMOS compatibility [3]. Resonant devices, such as microring resonators, allow for frequency conversion at very low powers, e.g. at milliwatt levels, thanks to their ability to dramatically enhance the optical field, but at the same time they also place significant limitations in terms of bandwidth. One approach to overcoming these limitations is through the use of higher order resonator structures that exploit coupled microring resonators, and indeed travelling wave FMW has been demonstrated in coupled silicon micro-ring (CROW) devices[4]. In this work, we demonstrate wavelength conversion of signals in a high index silica glass (Hydex) 5th order ring resonator at milliwatt power levels. The pictures below show the frequency conversion of a pump centered at 1560nm with power PP=20mW and a signal at 1555nm with power PS=15mW (Fig. 1(a)). Remarkably, by varying the pump frequency we obtain almost flat frequency conversion over a bandwidth of about 7GHz. Figure 1 (b) shows the power drop in the signal (top) and the converted power of the idler centered around 1565nm (bottom) are as a function of the pump wavelength. Cascaded FWM conversion, producing additional frequency products at 1570nm is observed for a pump wavelength at 1560.35 nm with a corresponding drop in idler power visible in Fig. (b). Preliminary numerical simulations are shown in Fig. 1 (c) showing good agreement with experiment. Further details will be presented.

![Fig.1 (a) Power Spectral Density](image)

![Fig.1 (b) Signal power (top) and idler power (bottom) at variance of the pump wavelength](image)

![Fig.1 (c) Simulations, as in (b)](image)


The proposed protocol is capable to transmit more classical information using a single photon, compared with half of a bit in of a classical QKD protocol. It offer better capabilities to detect receive-retransmit attacks, and it can be implemented more easily.

The terminal Tx on the QCC transmit the bits $q_i$ (i=1,2,..) encoded in photons and each bit is encoded in a randomly chosen base $b_i$. The photons are emitted at the random time moments $t_i$, precisely measured. The receiving terminal Rx measures all the photons in randomly selected bases $b_j$ and also precisely measure the time moments $t_j$ when these have been detected (in the measurement setup).

The time $t_i$ traveled by the photons, on the QCC, between a transmitter Tx and a receiver Rx have been measured and it is known by Tx and Rx.

Because the photons are emitted at random time moments $t_i$, this value of $t_i$ is used as an one time pad (OTP) encryption key. In the case when, the same photon emitted by Tx has been measured at the time moment $t_j$ by Rx, then it knows the encryption key because $t_i = t_j - t_r$. The keys $[t_i, t_j - t_r]$ are naturally distributed between Tx and Rx in all the cases when the same photons emitted by Tx have been detected by Rx. In this cases Tx or Rx can encrypt a secret message $s$ with the key $t_i$ or $t_j - t_r$ and send it on a classical communication channel (CCC) to the other.

The QKD will be established using the secret information $s_i=[q_i,b_i]$ which is both the value of the bits $q_i$ and the base $b_i$ in which the photons have been encoded. This secret information $s_i$ is encrypted with the key $t_i$ and transmitted by Tx to Rx on the CCC. The encrypted messages $m_k=K(t_i,s_i)$ are transmitted in a random order, between $k$ and $i$ is a two-way function.

Then Rx decrypt the messages $m_k$ with the key $t_j - t_r$ and then compare the decrypted messages $s_k$ with what it has measured/received on the QCC $[q_j,b_j]$. All the messages for which $s_k=[q_k,b_k]$ are retained and Rx transmit to Tx only the index numbers $k_1, k_2, ...$. In this way, both Tx and Rx have been identified the same set of secret information. These retained secret messages $s_{k_1}, s_{k_2}, s_{k_3}, ...$ is the brute key and then in the next step the error correction will follow.

**P54. Burst-mode operation of a 655GHz mode locked laser based on an 11th order microring resonator**

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Future generation telecommunication networks will need practical, high performance sources that can provide extremely stable optical clocks at ultrahigh pulse repetition rates - larger than 100GHz. Passively modelocked fibre lasers, free of any speed limitations imposed by electronics, have attracted considerable interest for this and many other applications [1].

Recently [2], we reported the first stable mode-locked laser achieved by introducing a variation of dissipative FWM that we termed Filter-Driven Four Wave Mixing (FD-FWM), where we combined a linear filter with a nonlinear element via an integrated nonlinear monolithic high Q (quality) factor micro-ring resonator. The high efficiency of the nonlinear wave mixing in the ring resonator eliminates the need for the long external cavities required in earlier approaches. Our scheme relies on optical nonlinearities only within the micro-resonator, and so allows for much
shorter main cavity lengths, resulting in much wider main cavity mode frequency spacings. This in turn restricts the number of oscillating main cavity modes within a single nonlinear micro ring resonance to at most very few - potentially even a single mode - and thus removes the inherent source of instability – so-called “supermode” instability. Using this approach we achieved extremely stable operation at high repetition rates while maintaining very narrow linewdths, thus leading to a very high quality pulsed emission. The FD-FWM scheme is also capable of achieving stable operation where two main cavity modes within each microresonator linewidth are allowed to oscillate, yielding an extremely high fidelity RF tone [3].

Here, we demonstrate a new and qualitatively very different stable operating regime for modelocked lasers that results from the interplay of intercavity and intracavity modes, allowed by the high nonlinearity of the intracavity filter. By employing a nonlinear cavity comprised of an 11th order filter (Fig. 1), we achieve low-frequency mode-locking between the main cavity modes that oscillate within each resonance of the filter. The high order of the filter, combined with the relatively low Q factor of the individual microring resonators, results in an extremely wide and flat resonance with a bandwidth of 22GHz and an FSR of 655GHz. We present experimental results and compare them with numerical simulations.

Fig. 1 Schematic of the passively mode locking optical fibre laser using a feedback ring configuration, including an EDFA, a tunable filter, a polarisation controller, a 11-order micro-ring resonator and a 99:1 ratio coupler.

Fig. 2 Mode-locking within four resonator lines. (a) Pulse train as collected with a fast optical oscilloscope. (b) Optical spectrum collected with an OSA. (c) The autocorrelation measurement showing a high frequency modulation due to the phase locking between the 6 lines that are spaced at 655GHz. The FFT of the autocorrelation (d) showing a beat note at 655 GHz suggesting the coherent interaction of the 6 mode-locked pulse trains.
P55. Towards strong coupling of single ions to an optical cavity

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In our aim to pave the way towards cavity-QED based quantum network interfaces with trapped ions, we have developed a miniature endcap trap with a tightly integrated fibre cavity [1]. This allowed us to bring the cavity length to below 300 µm. We have produced fibre cavities with finesse of up to 60,000 by CO2 laser machining [2]. We have successfully trapped single Ca+ ions in close vicinity of fibre ends and will couple them to the optical fibre cavity to implement a coherent ion-photon interface through strongly coupled cavity-QED.

[2] Takahashi et. al, Novel laser machining of optical fibers for long cavities with low birefringence, accepted by Optics Express

P56. Non-destructive state detection and identification of molecular ions

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The nature of ion traps allow for extremely well localised atomic and sympathetically cooled molecular species; leading to a variety of applications - most notably cold chemistry, testing fundamental theories, searching for changes in fundamental constants and, potentially, the development of methods for quantum computing. Prerequisite for these applications is the cooling of the molecule’s motion and its non-invasive identification. Furthermore, the internal quantum state of the molecule needs to be prepared and, at readout, non-destructively detected.

While blackbody assisted laser cooling was recently demonstrated, the non-destructive state detection of trapped molecules is still beyond current experiments. Employing state selective laser induced dipole forces we aim to detect the internal state of molecular ions by mapping the state information onto the ions motion.

We can also identify different ionic species within a coulomb crystal by measuring the average charge-to-mass ratio of trapped ions with high precision. This is a tool that can be used to investigate chemical reactions between neutral molecules/atoms and trapped molecular ions. The same means can also be achieved by using only laser forces.

P57. Terahertz waves for ancient manuscripts conservation

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Paper has been widely used as convenient vehicle for the acquisition, storage and dissemination of human knowledge. For centuries, a growing number of cellulose-based manuscript and printed book have been
accumulating in archives, libraries and museums. The progressive transformation leading to an increased fragility
and yellowing -commonly observed in the ancient paper-based artefacts- have been connected to the
fragmentation of cellulose polymers (depolymerisation) and their oxidation [1,2]. The establishment and
improvements of models of preservation for often-irreplaceable items is in many ways connected to the
development of techniques (possibly in-situ and standoff, in light of the practical constraints in moving and
handling some of those items), to assess in non-destructive ways the state of degradation of cellulose compounds
[3]. Our investigation demonstrates that microscopy techniques based on Terahertz-Time Domain Spectroscopy
(TDS) [4] are competitive with state-of-the-art solutions and have the potential to outperform them. Resonances in
the THz region are dominated by collective atomic vibrational modes (Fig. 1). These modes are directly correlated to
cellulose crystallinity and can give information on the state of the depolymerisation of cellulose polymers. In
addition TDS provides access to the average optical density spectrum, information in general not available in other
frequency ranges. The investigation approach undertaken here highlights specific spectral markers of degradation
with remarkably high contrast for practical sample thicknesses.

Our investigation approach on the degradation of ancient manuscript samples and a consistent benchmarking
against different probing technologies, such as X-RAY, UV/Vis and IR spectroscopy, will be presented in detail.

Fig. 1 THz experimental spectra of paper samples acquired compared with ab-initio theoretical computational
simulations. In the inset atomic displacement vectors of cellulose polymer for 1.9 THz mode are represented.

"Optical response of strongly absorbing inhomogeneous materials: Application to paper degradation,"
Morandotti, "Exact reconstruction of THz sub-lambda source features in knife-edge measurements.," IEEE
P58. Ion trap cavity QED - probabilistic ion entanglement for cluster state generation

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A single calcium ion, trapped in a radio frequency quadrupole trap and placed between the mirrors of a high-finesse optical cavity, is an ideal system to control the interaction between an atom and a single photon. We employ this system to generate single photons on demand or to map the quantum state of a trapped ion onto the polarisation of a single photon. With more than one ion coupled to the cavity, multi-ion entanglement may be generated. Of particular practical interest is the pair-wise entanglement of several ions in a string as the basis for the production of cluster states for quantum computation.

We use a laser pulse to drive the ion from the ground state to a meta-stable qubit state in a cavity-assisted Raman transition. This results in the emission of a single photon in the cavity mode.

With two ions equally coupled to the same cavity mode and simultaneously driven by the laser, coincident detection of orthogonal polarisation states in the cavity emission heralds entanglement between the ions.

The trap design accommodates strings of tens of ions, enabling the generation of 2-D cluster states through pair-wise entanglement.

P59. Scalable cryogenic and microwave systems for the creation of high fidelity quantum gates

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To create a quantum computer we need to be able to apply high-fidelity quantum logic gates to large numbers of trapped ions. Here we present the basic elements of quantum information applied to small numbers of ions in a macroscopic trap, and our work towards being able to apply such gates to large numbers of ions. Our gates are implemented using long wavelength radiation in the form of microwaves rather than lasers. We use a magnetic gradient to allow the microwaves to couple between the internal and motional states. Microwaves are preferred because they are controllable, easy to generate and are a proven scalable technology. To allow us to create a truly scalable quantum computer we also need to create surface ion traps that can be scaled, in number, to perform quantum calculations. To this end, here at Sussex, we are developing quantum technologies, using ytterbium ions, in a variety of trap geometries to create a scalable quantum computer. Part of this work involves developing new microfabrication techniques, microwave control schemes and novel vacuum systems to operate ion traps with high trap fidelities.

One of the key technologies we are working on is the use of a cryogenic set-up capable of sustaining an ion trap at cryogenic temperatures with a low vibrational interface. In creating a cryogenic environment we should be able to vastly reduce heating rates, by several orders of magnitude [1], which is the dominating source of decoherence in our 2-qubit gate. We show how our microfabricated chip is mounted within the cryogenic system, that allows for laser access and view ports for trap imaging. We present the results from an on-chip superconducting microwave cavity resonator showing a Q of $\approx 10000$ at 12.6GHz. We show a current carrying wire chip design that would be cooled within a cryogenic system, that allows for the controllable localised magnetic gradients which is required for our gate technology.

Another key technology is the creation of scalable microwave systems designed for multiple ion traps. We show two systems that are being tested, one utilising on chip microwave waveguides and another using suspended microwave balanced lines that create the required microwave field. We also show our stabilised microwave system using diode power feedback and variable delay lines in a phased power combining system. This new system is capable of 100W with both amplitude and phase stabilisation and is designed for an external horn antenna setup. A corporate system
allows us to have greater control over amplitude stability and extends the limited power density of single GaN technology transistors.


P60. Design of a micro-sized ion trap for cavity-QED

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Precise control over internal states of atomic ions in ion traps has been possible for many years enabling high precision spectroscopy of atomic transitions. Trapped ions are suitable candidates for quantum information processing due to their long storage times, low decoherence rates and high readout efficiency. Recent advances in hybrid fiber optic based ion traps allows one to realise strong coupling between ion and cavity mode by reducing the mode volume. Our trapped ion cavity system utilises $^{40}$Ca$^+$ ions with $\Gamma$ (HWHM) = 11MHz coupled to an optical fiber cavity with typical lengths of 300um. Standard finesse values of around 50,000 are routinely obtained for the cavity in a Fabry-Perot configuration. The cavity linewidth (HWHM), $\kappa$ = 10MHz and ion-cavity coupling factor, $g$ = 20MHz puts the ion-cavity system in the strong coupling regime ($g^2/(\kappa\Gamma) >> 1$).

For strong ion-cavity coupling, deterministic transfer of quantum states between ions and photons is possible. Each basis state of the ion is linked with one polarisation mode of the cavity. Through a partially transparent cavity mirror, a freely propagating photon is generated which can be used to distribute quantum information, for example to entangle distant ions in a network of multiple quantum nodes. For moderate coupling, quantum entanglement may be generated probabilistically. Ions coupled to two orthogonally polarised cavity modes are projected to an entangled state upon detection of photons emitted from the cavity with different polarisation.

We have designed a 'miniaturised' linear Paul trap with an integrated optical cavity collinear to the trap axis, motivated towards coupling multiple ions to the cavity mode, while increasing coupling due to cooperativity between ions. The rf-electrode separation is 50um, while the endcap separation is 400um. The endcap electrodes are narrow tubes of inner diameter 300um allowing optical fibers through the tubes to form the cavity. Future goals of the experiment explore the possibility of coherent manipulation of internal atomic states for quantum information processing protocols.

P61. Route to ultracold NaK groundstate molecules via the spin-orbit coupled d/D complex

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Ultra cold quantum gases with long-range dipolar interaction promise exciting new possibilities for quantum simulation of strongly interacting many-body systems. One way of realising this is to create an ultra cold sample of ground state polar molecules.

A crucial step is the stimulated Raman adiabatic passage (STIRAP), a two-photon process involving a resonant intermediate state. We identified promising candidates for this intermediate level in the molecular potentials of the sodium D-line asymptote. We observe a series of deeply bound vibrational levels, resolving fine and hyperfine structure, by photoassociation spectroscopy on a nearly degenerate mixture of 23Na and 40K. By applying external fields, we observe Zeeman and Stark sub structure.
The binding energy of the rovibrational ground state of NaK is determined by coherent two-photon resonant measurement. In addition, I will present our recent effort on STIRAP process.

**P62. Dressed potentials for ultracold alkali atoms: Theory and applications**

G A Sinuco-Leon and B M Garraway  
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The potential landscape experienced by ultracold alkali atoms can be tailored by microwave and radio-frequency radiation that address the atomic ground state manifold [1]. Here, we describe dressing mechanisms for creating smooth closed tracks [2] and periodic potential landscapes [3], and study their feasibility for realisation with standard atom-chip technology. We also discuss one application of each device: the closed track can be employed to create an atom Sagnac interferometer [2] and, for the periodic potential, we present a protocol for single-site addressing for performing local Rabi oscillations without cross-talking between neighbouring sites.


**P63. Tests of quantum Darwinism with the pseudomode method**

G Pleasance and B M Garraway  
University of Sussex, UK

How we observe ‘everyday life’ on a macroscopic scale is in conflict with predictions made within a fully quantum model of the Universe. Decoherence explains how information about a system is passed into the environment through correlations between the two: effectively the environment measures the system leading to the breaking of the unitary evolution (quantum jumps) of system states and apparent wavefunction collapse to stable pointer states. This has been fundamental to understanding the measurement problem, but originally focused on the environment purely as an information sink. Quantum Darwinism looks at the capacity of the environment to store useful information about the system through the spreading of correlations about pointer observables [1, 2]. Selected states have the ability to proliferate multiple copies into the environment, thus exhibiting high levels of redundancy, meaning many independent observers can obtain the same classical information without perturbing the environment. This effect is realised through the emergence of a ‘classical plateau’ in the mutual information between the system and the fragment, measured in terms of a fraction f of the total environment. We test this paradigm using solutions obtained from models of open quantum systems, where our analysis utilises results obtained from the pseudomode method [3].

In this context we consider the fraction to be defined as a sum over the environmental modes in the fragment, weighted by the frequency-dependent coupling of each mode to the system, such that f can be expressed in terms of a normalized structure function, D(ω). From this we address filtering of mutual information by monitoring of the fraction with a detector system. We present results for spectra of particular interest, including a Lorentzian and photonic band-gap resonances.

P64. Modifying the potential landscape of a Penning trap

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We present the result of calculations detailing the manipulation of the potential landscape of an electron in a Penning trap through electromagnetic field control where we do not change the electrode structure. The proposed method is the well-established technique of mode coupling [1], and aims to modify the trapping potential in such a way as to retain the coherence properties of the electron. Specifically, the Sussex Coplanar Waveguide (CPW) trap is considered [2], as the unique design of the electrode chip mounted onto a microwave transmission line allows for immediate application of these ideas. Discussion and interpretation of these results for controllable parameters will be presented.

Such ability to coherently alter the trapping configuration of the electron, or indeed multiple electrons, would offer new possibilities for quantum information processing, and allow for testing of fundamental quantum mechanical properties.


P65. Realisation of the geonium chip – a planar Penning trap

J Pinder, A Cridland, J Lacy and José Verdú
University of Sussex, UK

At Sussex, we are developing a chip-based Penning trap for the trapping and detection of a single electron - a potentially scalable ion trap technology [1]. This poster discusses the experimental progress towards developing a first generation 'Geonium chip', focussing on the precision planar electric and magnetic field sources, the in-house manufactured vacuum housing, and the associated electrical detection systems for measuring the axial and cyclotron frequencies of a trapped electron [2]. Early tests on the chip, which was micro-manufactured using conventional metal-on-silicon techniques, indicate the possibility for direct coupling of a trapped electron to near-field Ku-band coplanar waveguides. This potentially allows for the direct detection of a single electron through the electron's cyclotron motion. Other novel features of the Sussex device include an on-chip cryogenic vacuum chamber, and a High Temperature Superconducting planar magnetic field source cut from commercially available YBCO tape, which will be driven by magnetic flux pumping [3].

P66. Future applications of the geonium chip

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University of Sussex, UK

The Sussex ‘Geonium Chip’ aims to vastly improve scalability and portability of existing Penning trap technology, allowing Penning traps to become truly compact and mobile devices, ready for incorporation into other devices and systems [1]. The superimposing of static fields to drastically prolong the lifetimes of ions has come a long way since its original discovery as a curious artefact in a pressure gauge, and now the Penning trap is a very versatile tool for fundamental physics [2]. Penning traps have successfully been used to trap a wide range of charged particles and antiparticles [3], and have provided the most stringent tests of Quantum Electrodynamics to date. This versatility opens up future applications in fields including portable mass spectrometry, single microwave detection, quantum radar applications, ultra-high-precision magnetometry to list a few.


P67. Quantum information processing using long-wavelength radiation

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Two-qubit entanglement gates in trapped ions are typically realised with optical frequency radiation due to the resulting strong coupling between the ions’ internal spin states and their collective motional states that mediate spin-spin interactions. When scaling to larger qubit numbers, the use of optical radiation will become more challenging due to the complex engineering that might be required to control multiple highly stable laser systems. The use of long-wavelength radiation in the microwave and radio frequency (RF) regime, combined with static magnetic field gradients, provides an architecture capable of significantly simplifying the construction of a large scale quantum computer. Instead of aligning thousands of pairs of Raman laser beams into designated entanglement zones, the use of a long-wavelength radiation source outside the vacuum system is sufficient.

I will report on the demonstration of a two-qubit logic gate using long-wavelength radiation. We have built a simple experimental setup consisting of a macroscopic linear Paul trap incorporating strong permanent magnets to create a large magnetic field gradient over the ion string, which creates the required coupling between the ions’ spin and motional states. The coupling is only present when qubit states with different magnetic moments are used; however these states are also vulnerable to decoherence due to magnetic field noise. To suppress the effects of decoherence, we engineer an effective clock qubit using microwave dressed states, and demonstrate high fidelity single qubit rotations in our engineered qubit. We can then use two of these well protected qubits to implement a Sørensen-Mølmer type entangling gate, reaching a Bell state fidelity of ~95%. We predict that with only minor adjustments to our setup, fault-tolerant fidelities would be achievable. I will also report the demonstration of ground state cooling using long wavelength radiation, which provides an additional tool for microwave quantum logic with trapped ions.

I will present a blueprint for an ion trap scalable quantum computer module based on microwave quantum logic which makes it possible to create an arbitrarily large quantum computer architecture. This quantum computer module controls all operations as a stand-alone unit, is constructed using silicon microfabrication techniques and
within reach of current technology. Our two-qubit gate can be incorporated into this architecture, making it an integral part of such a large-scale quantum computer.


**P68. Microfabricated ion traps for scalable quantum computation and simulation**

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To build a practical quantum computer extremely large amounts of ions have to be trapped and used to perform many quantum gates in parallel. The most common quantum gates demonstrated so far were implemented using lasers. However, these requires a vast amount of individually controlled and precisely aligned lasers beams which makes them technically extremely challenging. We propose to make use of magnetic field gradients in conjunction with global microwave fields to perform multi-qubits gates and individual addressing of all ions in the system in parallel instead. To realise an architecture based on this approach, scalable units featuring versatile X-junction geometries with the required features to perform such gates have to be fabricated utilising advanced microfabrication technology.

We will report on the design and fabrication of an X-junction trap with current carrying wire structures which produce large static magnetic field gradient. This design can be used to perform microwave based quantum gates and to perform digital quantum simulations. Optimisation and design of X-junction geometries for minimal RF barrier of the junction centre and with loading and detection slots will be presented. We will report the fabrication process and test result of current carrying wires fabricated on diamond substrate with large currents up to 10A applied. We also report on experiments conducted using our previous generation of traps such as a 2 dimensional ion array and a ring trap.

In addition we will discuss future ion trap designs including through silicon vertical interconnections and multi-wafer structures. These technologies are required to create fully scalable ion trap based quantum computer modules that can be aligned with neighbouring modules to create a large quantum computer architecture. They also have to provide efficient thermal paths to remove the heat generated by current carrying wires, which separates our approach from currently used technologies.

Along with our new chip designs, which feature many control electrodes for ion shuttling and separation, we will also report on our new versatile chip carrier system with 90 control connections and multiple microwave connections.
Towards portable ion trap magnetometers

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Highly sensitive magnetometers can be used for applications as varied as detecting the position/motion of magnetic objects or measuring the tiny currents that are produced in biological systems. Some of these applications include measuring heart signals, optical nerves, muscular impulses or even brain activity. Amongst these applications quantum magnetometers can also be used for numerous industrial applications, for example, the characterisation of physical systems like coils, transmission lines or even changes in the earth's magnetic fields to a very precise level.

Single trapped ytterbium ions have already successfully been used to sense magnetic fields with sensitivities of $4 \text{pTHz}^{-1/2}$ for AC magnetic fields near 14MHz [1]. The goal of our project is to make a portable, highly sensitive device based on said method. For quantum sensing of magnetic fields with trapped ions, the number of trapped ions and coherence time are the main contributing factors to improved sensitivity as the sensitivity of the device scales as $\frac{1}{\sqrt{N\tau}}$ [2]. Here we discuss the optimisation of the trap design to increase the number of trapped ions and the dressed state setup that will be used to improve the coherence time.

A micro ion-trap chip has been designed as a surface Paul trap with four trapping rails where each rail is capable of trapping four separate strings of ions along its axial direction. This design has many benefits over a typical 2D array ion trap chip as it produces approx. 30% deeper trap depths, can contain a higher density of trapped ions and can have its geometry manipulated to successfully rotate the principle axis of the trapped ions to allow for effective Doppler cooling. Experiments using our dressed state setup have already demonstrated coherence times for the $|D\rangle$ state of over 500ms [3] and are currently at almost 1s on our current setups. We will go over the theory behind using trapped ions as a magnetometer and the sensing protocol we will be using.

The device being developed will be a portable system. We will describe the miniaturisation of all of the necessary components required to use trapped ions that will be used as a magnetometer. This includes the vacuum system, lasers, camera, optics, rf, dc and microwave sources. Miniaturized lasers for cooling the trapped ions have been sought, a miniaturised UHV system is being designed and a compact imaging setup is under development. This integrated and miniaturised system will allow the entire trapped ion based quantum sensor devices volume to be reduced considerably lower than that of current lab based experimental setups.


Theory for electrostatic rogue waves in multi-ion plasmas

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Plasmas incorporating negative ions, positive ions and electrons exist in the laboratory [1, 2] and also in Space environments [3, 4, 5]. Such multicomponent plasmas support a variety of interesting phenomena associated with, e.g., nonlinear ion acoustic waves [6, 7]. The propagation of ion acoustic waves in multicomponent plasmas with negative ions was studied theoretically within a nonlinear Schrödinger equation (NLSE) framework by Saito et al [8], who have derived an NLS equation and discussed the modulational instability criteria and the occurrence of envelope modes for such a system. From first principles, that work was based on the modified Korteweg-de Vries…
(mKdV) equation, and was thus limited to the weak-amplitude superacoustic region. The problem was later investigated experimentally by Bailung and coworkers [9, 10].

We have made use of a multiscale perturbation technique to derive a nonlinear Schrödinger equation for modulated ion-acoustic wavepackets. Different types of localised electrostatic excitations (envelope modes) are shown to exist, and modulational instability criteria are extended to an arbitrarily short wavelength (large wavenumber). Explicit conditions and instability thresholds for envelope soliton formation and modulational instability are determined, in terms of the negative-to-positive density and mass ratio(s). The stability of the solutions obtained has been investigated numerically via a Crank-Nicolson method.

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P71. Non-adiabatic losses from radio frequency dressed cold atom traps
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Radio frequency (RF) dressed atom traps are a useful tool for coherently manipulating atoms. With a high degree of flexibility in trap potentials and the possibility for miniaturization by use of atom chips, RF dressed atom traps show promise to become standard devices for applications in metrology, high precision sensing and atomic interferometry. We examine the limits to RF dressed atom traps by investigating non-adiabatic losses. We use time dependent perturbation theory to determine decay rates due to spin flip transitions out of the trap. These decay rates enable us to predict how non-adiabatic losses affect the trapped atom population. We compare our predictions to the semi-classical Landau-Zener model, to determine the level of accuracy of this standard approximation.

P72. A carbon nanotube mechanical oscillator coupled to a radio-frequency electrical resonator
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Suspended carbon nanotubes have outstanding nanomechanical properties for the study of quantum motion; they have high resonance frequencies and good quality factors, and their low masses give them exceptionally large zero-point amplitude. Previous experiments on nanotube devices relied on electrical transport to probe the motion, which is a source of dephasing. We have fabricated a device in which the motion can be read out instead via the device’s capacitance. By using a gate voltage to tune the mechanical oscillator into resonance with a radio-frequency resonator at 300 MHz, the mechanical signal is transduced efficiently to an electrical signal.
We detect the ring-down of the driven nanotube, measure the quality factor for different driving power, and show beating between mechanical and electrical decay signals. We evaluate the suitability of this readout scheme for monitoring mechanical motion near the ground state.

P73. The weak measurement process and the weak value of spin for metastable helium

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We are preforming an experiment to observe the two-stage weak measurement process, and measure the weak value of spin for non-zero mass particles that obey Schrödinger’s equation. The principle of the weak measurement was first proposed by Aharonov, Albert and Vaidman [Phys. Rev. Lett. 60, 1351 (1988)]. The experimental method is thoroughly discussed in Duck, Stevenson and Sudarshan [Phys. Rev. D 40, 2112 (1989)]. The experiment will use a pulsed supersonic beam of spin-1 metastable Helium atoms in the 23S1 triplet state. During its flight the atomic beam will travel through two magnets (weak and strong) which both comprise the weak measurement process. Finally the atoms will be detected on a micro-channel plate detector coupled to a phosphorus screen and CCD camera. We will report on the method and its experimental realisation.

P74. NPL & University of Liverpool Interferometer

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A transportable gravimeter and gravity gradiometer package based on an atomic interferometer, is being developed combining a frequency fountain system from NPL with the University of Liverpool interferometer. The device also provides opportunities in fundamental physics for the measurement of the influence of gravity on quantum systems, and as a test bed for a full-tensor gravity gradiometer applications. It allows for an opportunity to test many novel concepts in interferometry at the same time building on the long term stability and robustness of NPL fountain program. The device is currently in the design and development stage.

P75. Thermodynamic properties of NLTE hydrogen plasma: Role of pressure derivative of partition function

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The thermodynamic properties of NLTE hydrogen thermal plasma have been studied by deriving expressions analytically in the temperature range 6000K-60000K and over wide range of pressures. The expressions involve total differential of degree of ionisation in which both temperature and pressure derivative of partition function are included. The results of compressibility coefficient and specific heat at constant volume for the plasma have been compared with and without taking pressure derivative of partition function. The relative deviation in and by considering and neglecting the pressure derivative increase with increase of pressure and non equilibrium parameter.

Alkali vapour cells are among the best sensors for electromagnetic fields, with applications in physics, medicine, and defence. We have developed techniques for imaging dc [1] and microwave [2,3] magnetic fields using vapour cells, detecting the respective fields through Ramsey and Rabi oscillations on atomic hyperfine transitions. The parallel nature of our dc imaging technique could be advantageous in measurements requiring high spatial and time resolution, such as in microfluidics in chemistry and biology. For microwave fields, there are currently no established imaging techniques. Microwave devices form an essential part of modern technology, finding applications in telecommunications, defence, and scientific instrumentation. Our technique could prove transformative in the design, characterisation, and debugging of such devices, and is already being employed in the characterisation and debugging of high-performance vapour cell atomic clocks [1,4].

We present results from a new imaging system providing spatial resolutions below 100 µm, an order of magnitude improvement from previous experiments [2]. More importantly, our vapour cell allows imaging of fields as close as 150 µm above structures of interest, through the use of extremely thin external cell walls. This is crucial in allowing us to take practical advantage of the high spatial resolution, as feature sizes in near-fields are on the order of the distance from their source. We demonstrate our system through the imaging of dc and microwave fields above a selection of devices.

Our spatial resolution, sensitivity, and approach distance are now sufficient for characterising a range of real world devices at fixed frequencies. However, the development of a broadband microwave imaging technique is essential for wider applications. We also present progress on a frequency-tunable setup, where we use a 0.8 T solenoid to Zeeman shift the hyperfine ground state levels, allowing us to image microwaves at any frequency, from sub-GHz to 10s of GHz.

Figure 1: Experimentally obtained images of the microwave magnetic field at several positions above a microwave circuit. The central signal line of the circuit is shown in red, and the ground planes are in orange.

