Programme and Abstract Book

International Conference on Quantum, Atomic, Molecular and Plasma Physics

4–7 September 2017
Hilton Glasgow Grosvenor Hotel, Glasgow, UK

Organised by the Institute of Physics Quantum Optics, Quantum Information and Quantum Control Group, Quantum Electronics and Photonics Group, Plasma Physics Group, Atomic and Molecular Interactions Group, Molecular Physics Group and Computational Physics Group

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Sponsors

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University of Glasgow

Conference committee:

Professor Stephen M Barnett
University of Glasgow, UK

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University of Strathclyde, UK

Dr Jonathan Pritchard
University of Strathclyde, UK

Dr Neal Radwell
University of Glasgow, UK

Dr Alison Yao
University of Strathclyde, UK

Welcome

On behalf of the conference organisers we welcome you to QuAMP 2017!

Against all odds (and a few evens too) our conference is just about to start. We're happy and a wee bit proud to bring QuAMP for the first time to **Scotland**, more specifically to Glasgow's West End.

We are grateful for your positive response; many of our invited speakers confirmed their attendance within the first days, sometimes minutes of our request; we have received over 130 submissions for oral and poster presentations, with only 16 slots for contributed talks available. Therefore, we can almost guarantee you a series of high quality oral presentations as well as a packed poster session with plenty of opportunity for scientific discussion, networking, and socialising.

Congratulations to James Millen who will present the Bates Prize lecture.

We would also like to thank our industrial exhibitors and sponsors for their generous support. Please make use of the opportunity to visit the exhibition space, located in the foyer of the Hilton, the same space that will be used for the poster session as well as the lunch/coffee breaks. We thank Glasgow City Council for sponsoring the drinks reception at the City Chambers, the international Max Planck Partnership (IMPP) for their financial support for our local helpers, QQQ/QEP for providing the Alan Gibson poster prize and Springer for generous book vouchers for two further student prizes, and all involved IoP groups for co-sponsoring the event.

We hope you will enjoy your time here,

Sonja Franke-Arnold
Sarah Croke
Steve Barnett
Jonathan Pritchard

Monday 4 September

11:00 Conference registration

12:20 Lunch

14:00 Welcome

Session Chair: Sonja Franke-Arnold

14:10 (invited) **Magneto-optical trapping and sub-Doppler cooling of molecules**
Ed A Hinds, Imperial College London, UK

14:50 (invited) **Polyatomic Molecules: Cool and Cooled**
Gerd Rempe, Max Planck Institute of Quantum Optics, Germany

15:30 **Cavity-enhanced frequency up-conversion in rubidium vapour**
Rachel Offer, University of Strathclyde, UK

15:50 Refreshments

Session Chair: Jonathan Pritchard

16:20 (invited) **Laser systems for the commercialisation of quantum technologies**
Graeme Malcolm, M2 Lasers, UK

17:00 (invited) **Continuous-time quantum computing**
Viv Kendon, Durham University, UK

17:40 Conference close – Day 1

18:00 Depart for reception

18:30 Reception at City Chambers (Sponsored by Glasgow City Life)

19:30 Reception concludes

Tuesday 5 September

08:30 Registration

Session Chair: Gordon Robb

09:00 (invited) **Gigahertz quantum signatures compatible with telecommunication technologies**
Natalia Korolkova, University of St. Andrews, UK

09:40 (invited) **Dressed atom wave-guides, shells and lattices for quantum technology applications**
Barry M Garraway, University of Sussex, UK

10:20 **Transport of spatial quantum correlations through an optical waveguide**
Plamin Petrov, University of Birmingham, UK

10:40 Refreshments

Session Chair: Sarah Croke

11:00 (invited) **Ion microtraps for atomic quantum technologies**
Alastair Sinclair, National Physical Laboratory, UK

11:40 **Optical nanofibres as probes for cold atomic ensembles**
Sile Nic Chormaic, OIST Graduate University, Japan

12:00 **Cavity-induced anti-correlated photon emission rates of a single ion**
Ezra Kassa, University of Sussex, UK

12:20 Lunch with posters and exhibition session

Session Chair: Alison Yao

14:40 (invited) **Quantising the electromagnetic field near semi-transparent mirrors**
Almut Beige, University of Leeds, UK

15:20 (invited) **Paths towards a universal fault tolerant quantum computer**
Dan Browne, University College London, UK

16:00 Refreshments

Session Chair: John Jeffers

16:20 (invited) **Ion acceleration with high power lasers: recent developments and perspectives**
Marco Borghesi, Queen's University of Belfast, UK

17:00 (invited) **Probing the extreme: x-ray spectroscopy from inertial fusion plasmas to brown dwarfs**
Nigel Woolsey, University of York, UK

17:40 **MHz band surface fluctuation in supersonic molecular beam injection in Heliotron-J plasma**
Masaru Irie, Waseda University, Japan

18:00 Poster session

20:00 Poster session concludes

20:00 Delegates free time

Wednesday 6 September

08:30 Registration

Session Chair: Alastair Sinclair

09:00 (invited) **Quantum cavity optomechanics with levitated nanoscale oscillators**
Peter F Barker, University College London, UK

09:40 (invited) **Big Ideas for Giant Atoms: Applying Rydberg atoms to ion beams and terahertz sensing**
Kevin J Weatherill, Durham University, UK

10:20 **Chiral Rotational Spectroscopy**
Rob P Cameron, University of Glasgow, UK

10:40 Refreshments

Session Chair: Paul Griffin

11:00 (invited) **Photonic quantum technologies: Metrology, Spins and Photons**
John Rarity, University of Bristol, UK

11:40 **Photonic realization of an anomalous topological insulator in a slowly driven lattice**
Sebabrata Mukherjee, Heriot-Watt University, UK

12:00 **Analytic few photon scattering in waveguide QED for entanglement generation**
David Hurst, University of Sheffield, UK

12:20 Lunch

Session Chair: Aidan Arnold

14:00 (invited) **Cold atomic gravity sensing for field applications**
Michael Holynski, University of Birmingham, UK

14:40 **The spin resonance clock transition of the endohedral fullerene $^{15}N@C_{60}$**
Edward Laird, University of Oxford, UK

15:00 **Spontaneous magnetic ordering induced by light in cold atomic gases**
Gordon Robb, University of Strathclyde, UK

15:20 **Making the most of interference: speckle metrology and its application to cold atoms**
Graham Bruce, University of St Andrews, UK

15:40 Refreshments

Session Chair: Nigel Badnell

16:00 (invited) **Pursuing precision spectroscopy with antimatter: the 1S – 2S transition in trapped antihydrogen**
William Bertsche, University of Manchester, UK

16:40 (invited) **Quantum effects in biomolecules**
Alexandra Olaya-Castro, University College London, UK

17:20 **Photoexcitation spectroscopy of cold molecules in the Cryogenic Storage Ring CSR**
Preeti Manjari Mishra, Max Planck Institute for Nuclear Physics, Germany

17:40 **Coherent Control and Optical Trapping of Ultracold Polar $^{87}Rb^{133}Cs$ Molecules**
Philip Gregory, Durham University, UK

18:00 Conference close – Day 3

19:00 Conference Dinner at Oran Mor

23:00 Conference Dinner concludes

Thursday 7 September

08:30 Registration

Session Chair: Kevin Weatherill

09:00 (invited) **Buckling transitions and clock order of two-dimensional coulomb crystals**
Giovanna Morigi, Saarland University, Germany

09:40 (Bates Prize winner) **Optical control and cooling of levitated nanoparticles**
James Millen, University of Vienna, Austria

10:20 Refreshments

Session Chair: Stephen M Barnett

10:50 (invited) **Entanglement swapping of multiple orbital angular momentum states of light**
Jonathan Leach, Heriot-Watt University, UK

11:30 **Observing a quantum Maxwell demon at work**
Janet Anders, University of Exeter, UK

11:50 **Tunable-range, photon-mediated interactions between atoms using a multimode cavity**
Kyle Ballantine, University of St Andrews, UK

12:10 **Atomic disciplined charge-qubit clock**
Deshui Yu, National University of Singapore, Singapore

12:30 Closing of the conference

12:40 Lunch

14:00 Opportunity for lab tours at Glasgow/Strathclyde

16:00 Lab tours conclude

Posters

P1. Relativistic calculations of K-shell photoionization cross-sections for $^{32}_{16}S$ at 59.6 keV excitation energy
Sahnoune Yassine, Mohamed El Bachir El Ibrahimi University, Algeria

P2. 3D control of atomic populations from structured light and darkness
Adam Selyem, University of Glasgow, UK

P3. Light Scattering from Chiral Molecules
Neel Mackinnon, University of Glasgow, UK

P4. Atom-light interaction in thermal Rubidium vapours confinedto a volume less than λ3
William Hamlyn, Durham University, UK

P5. Excitation of positronium: from the ground state to Rydberg levels
Ben Marshall, Swansea University, UK

P6. A compact inertial sensor using atom interferometry
Indranil Dutta, Imperial College London, UK

P7. Vacuum friction and other surprises emerging from the Roentgen interaction term
Matthias Sonnleitner, University of Glasgow, UK

P8. Creating a superfluid by kinetically driving an insulator
Charles Creffield, Universidad Complutense, Spain

P9. Towards high resolution spectroscopy of N_2^+
Amy Gardner, University of Sussex, UK

P10. Conditional quasi-exact solvability of the quantum planar pendulum and of its anti-isospectral hyperbolic counterpart
Marjansadat Mirahmadi, Freie Universität Berlin/Technische Universität Berlin, Germany

P11. Fresnel holography for atomic waveguides
Victoria Henderson, University of Strathclyde, UK

P12. Progress towards a trapped atom clock guided interferometer
Hector Mas, University of Crete/IESL FORTH, Greece

P13. Towards a BEC-ONF Quantum Interface
Alexandros C Alampounti, Swansea University, UK

P14. Spatially dependent Electromagnetically Induced Transparency
Francesco Castellucci, University of Glasgow, UK

P15. Interferometry with ultra-cold atoms in a BEC using optical waveguides
Richard Moore, University of Liverpool, UK

P16. Dynamics of a quantum system driven by multiple harmonic fields
German Sinuco, University of Sussex, UK

P17. Ultracold atoms as a quantum transport simulator subject to classical noise fields
Christopher Gill, University of Birmingham, UK

P18. A Gravity Gradiometer based on an NPL Rb Atomic Fountain
Jonathan Tinsley, University of Liverpool, UK

P19. Design and construction of an Atom Interferometer at the University of Liverpool
Andrew Carroll, University of Liverpool, UK

P20. Potential landscaping for ultracold atoms using Holographic Optical Traps
Graham Bruce, University of St Andrews, UK

P21. An ultracold mixture of Cs and Yb: Towards quantum simulation with ultracold 2Σ molecules
Alex Guttridge, Durham University, UK

P22. Towards coherent splitting and recombination of bright solitary matter waves
Oliver Wales, Durham University, UK

P23. A quantum-gas microscope for fermionic potassium-40
Bruno Peaudecerf, University of Strathclyde, UK

P24. Efficient loading and characterisation of laser-cooled Rubidium Atoms within Hollow-Core Photonic-Crystal Fibre
Philip Light, University of Adelaide, Australia

P25. An ε-pseudoclassical model for quantum resonances in a cold dilute atomic gasperiodically driven by finite-duration standing-wave laser pulses
Benjamin Beswick, Durham University, UK

P26. Compact cold-atoms interferometer for gravimetry
Clemens Rammeloo, University of Birmingham, UK

P27. Laser cooling a molecular beam of YbF for measurement of the electron electric dipole moment
Jongseok Lim, Imperial College London, UK

P28. Stark-tuned Förster resonances in collisions of NH_3 with He Rydberg atoms
Stephen Hogan, University College London, UK

P29. Relativistic Electron Vortices
Steve Barnett, University of Glasgow, UK

P30. Proposed optical realization of a two photon, four-qubit entangled χ state
Atirach Ritboon, University of Glasgow, UK

P31. Unusual Electromagnetic Disturbances
Robert Cameron, University of Glasgow, UK

P32. Thermal Rydberg Vapours for terahertz sensing and imaging
Lucy Downes, Durham University, UK

P33. Time-reversal symmetric work distributions for closed quantum dynamics in the histories framework
Harry Miller, University of Exeter, UK

P34. Propagation of laser light through glass capillaries for ultraviolet microbeams
Mitsuyoshi Matsubara, Toho University, Japan

P35. Accurate mass measurement of an optically levitated nanoparticle
Christopher Dawson, Swansea University, UK

P36. Efficient tracking, imaging and recognition of faces with a single-pixel camera
John Jeffers, University of Strathclyde, UK

P37. Particle statistics and lossy dynamics of ultracold atoms in optical lattices
Jorge Yago Malo, University of Strathclyde, UK

P38. Nonuniform currents and spins of relativistic electron vortices in a magnetic field
Jorg B Goette, Max Planck Institute for the Physics of Complex Systems, Germany

P39. High energy and efficiency proton acceleration via an enhanced hybrid laser-ion acceleration mechanism
Adam Higginson, University of Strathclyde, UK

P40. Deriving a correlation between the emission intensities of molecular nitrogen species and the metastables of argon and helium using optical spectroscopy
Laurence Scally, Dublin Institute of Technology, Ireland

P41. Effect of target thickness on the absorption of laser energy and escaping electrons in the interaction between ultra-intense laser pulses and overdense plasma targets
Samuel Williamson, University of Strathclyde, UK

P42. Theoretical study of the splitting of electromagnetically induced transparency window of Rb vapor in an external magnetic field
Paramjit Kaur, Guru Nanak Dev University, India

P43. Can boson sampling tell us anything about the difficulty of simulating XY spin Hamiltonians?
Thomas Brougham, University of Glasgow, UK

P44. Entanglement enhancement for continuous-variable measurement-based quantum information processing through multi-rail noise reduction
Shin-Tza Wu, National Chung Cheng University, Taiwan

P45. From retrodiction to bayesian quantum imaging
Fiona Speirits, University of Glasgow, UK

P46. Holographic quantum imaging
Gergely Ferenczi, University of Glasgow, UK

P47. Axiomatic approach to sequential measurements
Kieran Flatt, University of Glasgow, UK

P48. How fast are photons that carry orbital angular momentum?
Thomas Roger, Heriot-Watt University, UK

P49. Novel ion trap design with an integrated optical fibre cavity and a tunable ion-cavity coupling
Costas Christoforou, University of Sussex, UK

P50. Achromatic vector vortex beams generated from Fresnel cones
Neal Radwell, University of Glasgow, UK

P51. Minimum-error discrimination of single-qubit mixed states
Graeme Weir, University of Glasgow, UK

P52. Attosecond Hong-Ou-Mandel Interferometry
Ashley Lyons, Heriot-Watt Univeristy, UK

P53. Single atom imaging with a sCMOS camera
Craig Picken, University of Strathclyde, UK

P54. The roles of coarse-graining in the properties of Markovian master equations
James Cresser, University of Glasgow, UK

P55. Quasi-device-independent witnessing of genuine multilevel quantum coherence
Marco Piani, University of Strathclyde, UK

P56. Quantum feedback control of levitated nano-particles
Liam Walker, University of Strathclyde, UK

P57. Almost tight bounds for 1-out-of-2 oblivious transfer
Ryan Amiri, Heriot Watt University, UK

P58. EPR steering, bell non-locality and entanglement in systems of identical bosons
Bryan Dalton, Swinburne University, Australia

P59. Long-distance continuous-variable quantum cryptography by using quantum scissors
Masoud Ghalaii, University of Leeds, UK

P60. Influence of quantized atomic motion on cooperative spontaneous emissions of light
Francois Damanet, University of Strathclyde, UK

P61. Quantum computation with mechanical cluster states
Darren Moore, Queen's University Belfast, UK

P62. Quantitative modelling of coherent atom-light interactions in 2, 3 and 4-level systems in the hyperfine Paschen-Back (HPB) regime
Renju Mathew, Durham University, UK

P63. In search of multipath interference using large molecules
Joseph Cotter, Imperial College London, UK

P64. Control of polarisation rotation and fragmentation of vector vortex beams in nonlinear media
Christopher Gibson, University of Strathclyde, UK

P65. Quantum state comparison amplifier with feedforward state correction
Luca Mazzarella, University of Strathclyde, UK

P66. Single-shot, phase-insensitive readout of an atom interferometer
Andrew MacKellar, University of Strathclyde, UK

P67. Benchmarking probabilistic quantum amplifiers
Erika Andersson, Heriot-Watt University, UK

P68. Single organic molecule coupling to a hybrid plasmonic waveguide
Alex Clark, Imperial College London, UK

P69. Tightly confined cold atomic media for contactless non-linear optics mediated by long-range Rydberg interactions
Nicholas Spong, Durham University, UK

P70. A framework for measures of non-Gaussian operations
Jennifer Radtke, University of Strathclyde, UK

P71. Ellipsoidal plasma mirror focusing of high power laser pulses to ultra-high intensities
Robbie Wilson, University of Strathclyde, UK

P72. Microplasmas for selective surface cleaning in microfabricated ion-traps
Mariam Akhtar, NPL, UK

P73. Interfacing dipole-trapped single atoms with individual photons in fiber-tip cavities
Naomi Holland, University of Oxford, UK

P74. A cold atom gravity gradiometer for field applications
Ben Stray, University of Birmingham, UK

P75. A Rydberg-dressed magneto-optical trap
Niamh Keegan, Durham University, UK

P76. Towards a space compatible atom gravity gradiometer
Heleri Ramler, University of Aberdeen, UK

P77. Quantal and classical mobility calculations of open-shell ions in cooled helium gas
Lamia Aissaoui, University of Batna, Algeria

P78. Quantum digital signatures based on measurement-device-independent framework
Professor Erika Andersson, Heriot-Watt University, UK

(invited) **Magneto-optical trapping and sub-Doppler cooling of molecules**

S Truppe, H J Williams, M Hambach, L Caldwell, N J Fitch, M A Trigatzis, J Lim, J R Almond, E A Hinds, B E Sauer and M R Tarbutt

Imperial College London, UK

Atomic physics has been revolutionised by the introduction of laser techniques to cool atoms far below the Doppler limit. Now, it has become possible to laser cool molecules, to collect them in a magneto-optical trap, to cool them below the Doppler limit [1] and to trap them with modest magnetic fields. These ultracold molecules open up a wide vista of future applications. To give a few examples, they can be optically or magnetically trapped to form arrays for quantum simulation, they can make a molecular fountain for testing fundamental physics at unprecedented levels of sensitivity, and they open a new energy range for the study of ultracold collisions and ultracold chemistry. I will review the current status of this field.

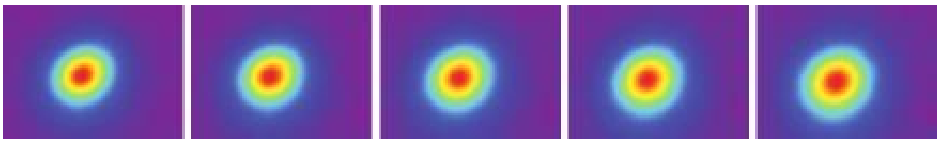

Fig. 1 Images of a CaF cloud expanding freely after cooling to 52(2) μK [1].

[1] S. Truppe *et al.* arXiv:1703.00580v1

(invited) **Polyatomic Molecules: Cool and Cooled**

G Rempe

Max Planck Institute of Quantum Optics, Germany

Molecules are quantum objects with properties like permanent electric dipole moments that do not exist for atoms. This renders molecules an ideal resource for a plethora of basic investigations and applications in the emerging fields of cold chemistry and quantum simulation. The generic pathway towards the envisioned collision experiments is to prepare molecular samples that are simultaneously cold and dense for high phase-space density as well as slow for trapping.

The talk presents a novel experimental toolbox that has recently been developed to achieve all three goals in one experimental setting. This includes electrostatic guiding of molecules over meters, minute-long electrostatic trapping, cryogenic buffer-gas cooling to temperatures of a few kelvin, centrifuge deceleration to standstill, translational Sisyphus cooling into the microkelvin regime, and rotational cooling to a high degree of purity. The realization of all these control methods constitutes a challenging journey through both physics and technology, and has recently led us to a new research territory where dipolar interactions between small polyatomic molecules – an experimentally simple and conceptually important species – start to play a dominant role. This achievement represents an important step towards cold chemistry and quantum simulation.

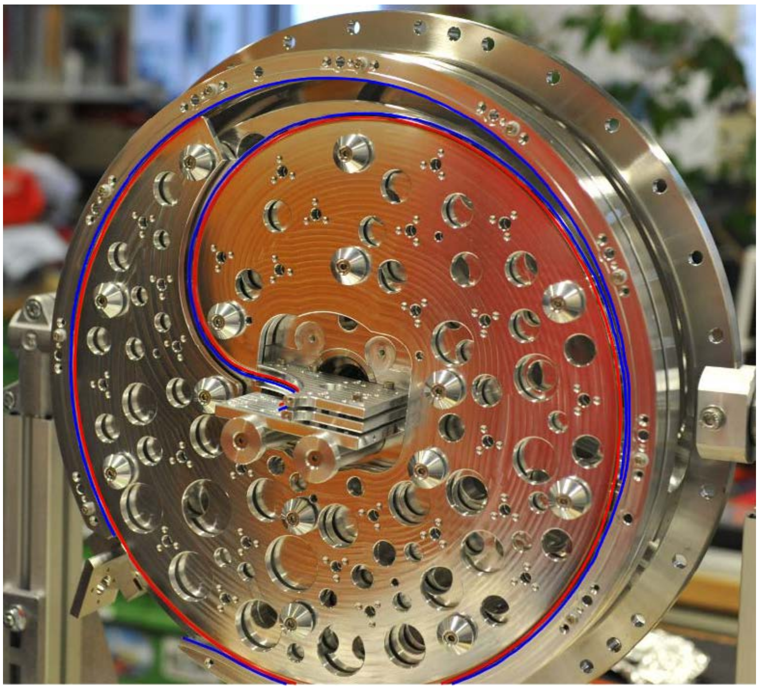

Fig. 1. Photograph of a centrifuge capable to decelerate polar molecules from thermal velocities to standstill. The molecules are injected onto a spinning disk at the periphery, are electrically guided along a spiral trajectory to the center of the disk (electrodes indicated in red and blue), and removed from the disk along the rotation axis (reproduced from Chervenkov et al., Phys. Rev. Lett. 112, 013001 (2014)). While guided to the center, molecules climb a centrifugal barrier and are slowed down.

Cavity-enhanced frequency up-conversion in rubidium vapour

R F Offer[1], J W C Conway[1], E Riis[1], S Franke-Arnold[2] and A Arnold[1]

[1]University of Strathclyde, UK, [2]University of Glasgow, UK

Atomic coherence can be used to enhance the efficiency of nonlinear frequency conversion processes. In particular, we investigate a quasi-resonant four wave mixing (FWM) system within rubidium vapour, which allows efficient frequency up-conversion of near-IR light (780 nm and 776 nm) to blue light (420 nm) [1-4]. With only low power, continuous wave pump lasers, 1 mW of coherent 420 nm emission can be generated [4].

We have recently demonstrated the first use of a ring cavity to both increase the output power and narrow the linewidth of the blue light generated in this FWM process (fig. 1 a) and b)) [5]. We find that for single pass FWM the 420 nm emission has a relatively broad linewidth of 33 MHz, which is consistent with power broadening of the 420 nm transition. Adding a low finesse ring cavity, singly resonant with the generated blue light, narrows this linewidth to <1 MHz. The ring cavity thus allows high output power and narrow linewidth to be achieved concurrently.

For single pass FWM, it has been demonstrated that transverse phase structure, for example orbital angular momentum, can be transferred from the near-IR pump beams to the 420 nm light [6]. Using a spatial light modulator, we shape the pump light into a variety of different modes [7], and study the transverse mode of the resulting 420 nm emission (fig. 1 c)). This technique allows both intensity and phase information to be transferred from near-IR wavelengths to 420 nm. The results are also relevant for schemes involving inscription and storage of phase information, or images, in atomic gases.

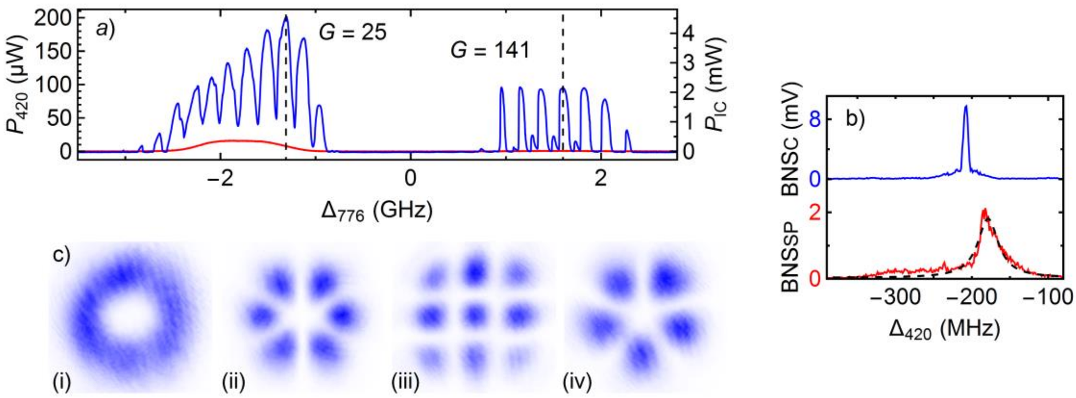

Fig. 1 (a) 420 nm output power and (b) linewidth for single pass (red) and cavity-enhanced (blue) FWM. (c) Intensity profile of the 420 nm emission when the 776 nm pump is shaped into the following modes: (i, ii) $LG_{l=3,p=0}$, (iii) $HG_{m=2,n=2}$ and (iv) $LG_{l=3,p=0} + LG_{l=2,p=0}$. The 780 nm pump is left as a Gaussian. (ii) Shows the interference pattern formed when the mode in (i) is interfered with its mirror image.

[1] □ A. S. Zibrov, M. D. Lukin, L. Hollberg, and M. O. Scully, Phys. Rev. A 65, 051801 (2002)
[2] A. M. Akulshin, R. J. McLean, A. I. Sidorov, and P. Hannaford, Opt. Express 17, 22861 (2009)
[3] T. Meijer, J. D. White, B. Smeets, M. Jeppesen, and R. E. Scholten, Opt. Lett. 31, 1002 (2006)
[4] A. Vernier, S. Franke-Arnold, E. Riis, and A. S. Arnold, Opt. Express 18, 17020 (2010)
[5] R. F. Offer, J. W. C. Conway, E. Riis, S. Franke-Arnold, A. S. Arnold, Opt. Lett 41, 2177 (2016)
[6] G. Walker, A. S. Arnold, and S. Franke-Arnold, Phys. Rev. Lett. 108, 243601 (2012)
[7] T. W. Clark, R. F. Offer, S. Franke-Arnold, A. S. Arnold, and N. Radwell, Opt. Express 24, 6249 (2016)

(invited) **Laser systems for the commercialisation of quantum technologies**

G Malcolm

M2 Lasers, UK

Carefully tuned interactions between cold atoms and laser fields are central to emerging technologies such as quantum sensors, quantum computers and optical atomic clocks. Such devices, broadly classified as quantum technologies (QT), are expected to revolutionise many aspects of society in areas as diverse as navigation, underground detection, security, finance and healthcare. As these novel applications of QT advance towards technological maturity, the increasingly stringent demands of the required laser systems and associated 'quantum hardware' must be met in terms of performance, reliability and usability. This talk will describe how M2 Lasers is achieving this goal.

QT can be realised with a range of atomic species, with each implementation requiring unique wavelengths for laser cooling, trapping, and quantum state manipulation. Due to its high power, exceptionally low noise and broad spectral coverage, M2 Lasers' SolsTiS platform is often the tool of choice for these demanding applications. This is evidenced by the presence of M2 systems in leading quantum laboratories worldwide, each of which is designed to meet the exacting requirements of a particular application. Recent examples include a system with two phase locked SolsTiS lasers, producing a high power signal for driving beam splitter and combiner pulses in an atom interferometer. Using an experimental control module (Ice-Bloc DCS) and a phase-lock servo module (Ice-Bloc PL), both developed specifically for QT applications, the system delivers sequences of optical pulses with the low phase noise required for precise measurements of acceleration and rotation. A further phase locked system has been developed to implement quantum logic operations with trapped ions, with sufficiently low phase noise as to achieve a gate error rate that is compatible with practical quantum computation.

M2 Lasers is also developing complete quantum sensor systems devices in house. A quantum gravimeter is being advanced towards commercial deployment, with applications envisaged in oil and gas prospecting, civil infrastructure monitoring and threat detection. Atom interferometry has already been demonstrated in the portable setup, and measurements of gravitational acceleration are currently underway. We are also constructing the building blocks of an optical clock based on a lattice of Strontium atoms.

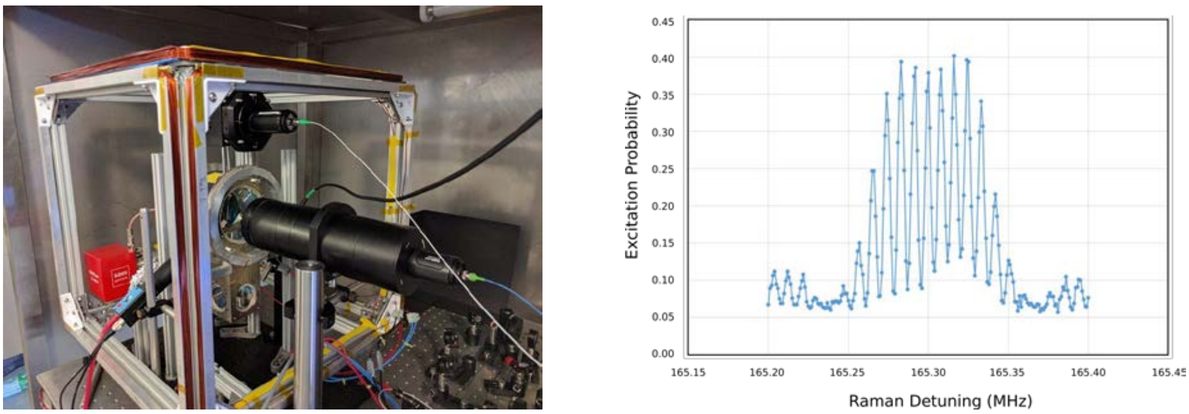

Fig. 1. (a) Quantum gravimeter being developed at M2 Lasers. (b) Interference fringes produced in the atom interferometer.

(invited) **Continuous-time quantum computing**

V Kendon

Durham University, UK

Continuous-time quantum computing is a generalisation and unifying view of quantum computation with continuous-time quantum walks, adiabatic quantum computing, quantum annealing, and a range of special purpose quantum simulators. It uses a register of qudits (qubits as special case) to which Hamiltonian time evolution is applied. The Hamiltonian can be varied continuously in time, and the register can also be coupled to an engineered bath environment, providing controllable open quantum system effects in addition to unitary evolution. This contrasts with the circuit model, in which discrete unitary quantum gates are applied to the register, with error correction to ensure the computation remains coherent throughout. Continuous-time quantum computing is complementary to the circuit model, and it provides a paradigm for quantum computing in which techniques can be adopted across what were previously seen as separate approaches. In particular, it suggests that hardware platforms suitable for one should be suitable for all, providing a focus for hardware design and development of continuous-time quantum computers alongside digital quantum computers. As further motivation, and to provide examples of the benefits of viewing continuous-time quantum computing in this way, I will present examples where hybrid quantum algorithms are the best approach. Incorporating elements of both adiabatic and quantum walk strategies provides robustness under unwanted environmental noise and errors in specifying the problem, while maintaining the computational speed up.

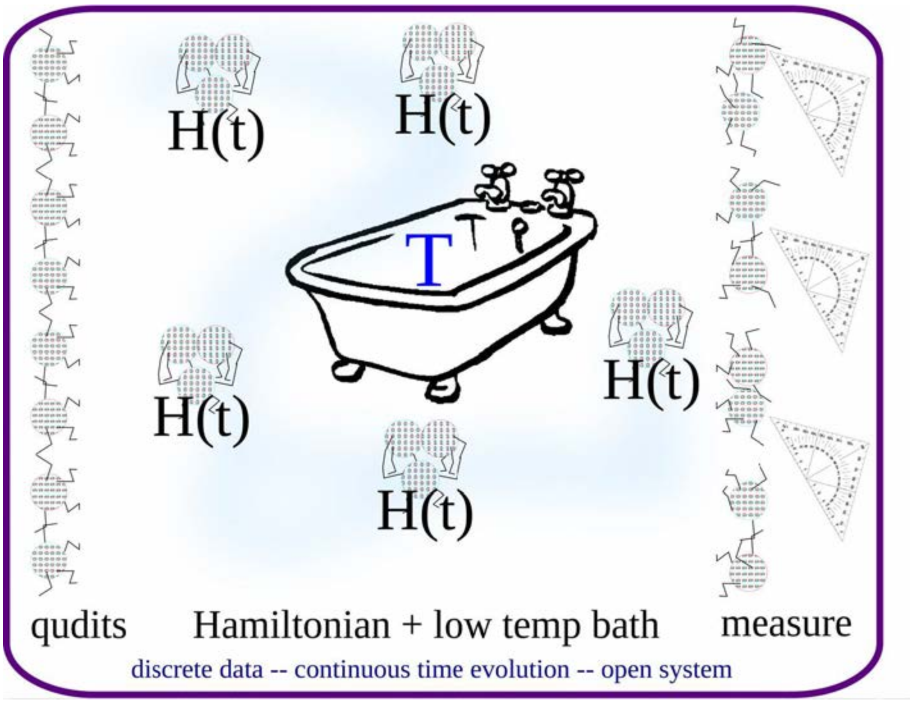

Diagram depicting the elements of continuous-time quantum computing.

(invited) **Gigahertz quantum signatures compatible with telecommunication technologies**

M Thornton[1], C Croal[1], I Khan[2,3], C Marquardt[2,3], G Leuchs[2,3] and N Korolkova[1]

[1]University of St. Andrews, UK, [2]Max Planck Institute for the Science of Light, Germany, [3]University of Erlangen-Nuremberg, Germany

Digital Signatures are a widely used cryptographic primitive, found in e-mail, e-commerce and digital banking. A signature σ_m appended to a classical message m ensures the authenticity and transferability of the message, whilst preventing forgery and repudiation. By employing quantum mechanics to distribute the σ_m between recipients, un-conditionally secure signature schemes can be constructed [1]. To this end, we present a continuous-variable quantum digital signature (QDS) scheme with an emphasis on compatibility with existing telecommunication technologies. Our scheme is information-theoretically secure against passive repudiation attacks and collective forging attacks, and can be implemented even when some QKD-based signature protocols fail. This is the first continous-variable QDS scheme which does not require secure quantum channels between the parties (discrete-variable protocols exist [2]). In the simplest scenario, QDS schemes involve three parties: Alice, who wishes to sign m, and two recipients, Bob and Charlie. In a Distribution stage, Alice forms sequences of quantum states, ρ_{B}^{m} and ρ_{C}^{m}, and sends them to Bob and Charlie, who measure the states and record their outcomes. The quantum states can be thought of as Alice's "public key". Her corresponding "private key", containing information about which states she sent, is used as the signature σ_m. Crucially, since QDS relies on quantum measurement, recipients gain only partial information about σ_m. Later, in an entirely "classical" Messaging stage Alice sends $(m; \sigma_m)$. Bob and Charlie compare σ_m to their measurement results, and accept or reject m accordingly. We have implemented our scheme by distributing an alphabet of phase-modulated coherent states over a 20 km optical fiber, and have devised the corresponding security proof. In particular, we prove that a dishonest forger who interacts with the quantum states cannot then declare some σ'_m which will be accepted by honest recipients, except with negligible probability (security against forging). The probability of successful forgery is related to the smooth- min entropy, which quantifies the uncertainty that an eavesdropper has about an honest participant's measurement outcomes [3]. By estimating a lower bound for the smooth min-entropy we prove security of our protocol, taking into account the finite-size effects intrinsic to signatures. As tighter bounds are developed these can readily be incorporated. Furthermore, Bob's and Charlie's measurement outcomes are symmetrised with respect to Alice to guarantee the security against repudiation. Our system is built from telecom components running at a wavelength of 1553.33 nm and is completely fiber-integrated. The coherent states are distributed by Alice at a rate of 10 GHz and are measured using heterodyne detection at Bob/Charlie. For security against passive eavesdropping attacks and any party dishonesty, we derive signature lengths on the order of 10^6 to sign m with a percent chance of failure, meaning a 1 bit message can be signed in 0.1 ms. This opens up the possibility of efficiently distributing quantum signatures on a large scale with minimal installation cost, and makes our scheme competitive in a landscape where both practicality and security are important.

[1] D. Gottesman and I. Chuang, arXiv:0105032 [quant-ph]; R. J. Collins et al, Phys. Rev. Lett. 113, 040502 (2014); C. Croal et al, Phys. Rev. Lett. 117, 100503 (2016), arXiv:1604.03708.

[2] R. Amiri, P. Wallden, A. Kent, and E. Andersson, Phys. Rev. A 93, 1 (2016), arXiv:1507.02975v1; I. V. Puthoor, R. Amiri, P. Wallden, M. Curty, and E. Andersson, Phys. Rev. A 94, 1 (2016).

[3] R. K□onig, R. Renner, and C. Schaffner, Information Theory, IEEE 55, 11 (2009), arXiv:0807.1338.

(invited) **Dressed atom wave-guides, shells and lattices for quantum technology applications**

G Sinuco-Leon[1], K Burrows[1], H Perrin[2] and B M Garraway[1]

[1]University of Sussex, UK, [2]Université Paris 13, France

Dressing atoms with radio-frequency and microwave radiation opens up new possibilities for a BEC in new types of trap and in new topologies such as spherical surfaces and in waveguide loops [1,2] as well as in well studied lattices [3,4]. This is because of the flexibility inherent in the vector coupling of a magnetic dipole moment to electromagnetic fields which can be varied in time, frequency, orientation and space. This may in turn result in quantum technology applications to sensing (with ring traps and gyroscopes [5,6]), metrology, interferometry and atomtronics. Both applications and limitations [7] will be discussed.

[1] Topical Review: *Recent developments in trapping and manipulation of atoms with adiabatic potentials*, B.M. Garraway and H. Perrin, J. Phys. B 49, 172001 (2016)
[2] *Trapping atoms with radio-frequency adiabatic potentials*, H. Perrin and B.M. Garraway, in Advances in Atomic, Molecular and Optical Physics, vol 66, Eds E. Arimondo, C.C. Lin and S.F. Yelin (Academic press, 2017), pp. 181-262
[3] *Radio-frequency dressed lattices for ultracold alkali atoms*, G.A. Sinuco-León and B.M. Garraway, New J. Phys. 17, 053037 (2015)
[4] *Addressed qubit manipulation in radio-frequency dressed lattices*, G.A. Sinuco-León and B.M. Garraway, New J. Phys. 18, 035009 (2016)
[5] *Ring trap for ultracold atoms*, O.Morizot, Y.Colombe, V.Lorent, H.Perrin, and B.M.Garraway, Phys. Rev. A 74, 023617 (2006)
[6] *Inductively guided circuits for ultracold dressed atoms*, G. Sinuco-León, K. Burrows, A.S. Arnold, and B.M. Garraway, Nat. Commun. 5, 5289 (2014)
[7] *Non-adiabatic losses from RF-dressed cold atom traps: beyond the Landau-Zener model*, K. Burrows, H. Perrin and B.M. Garraway, arXiv:1706.08063

Transport of spatial quantum correlations through an optical waveguide

P Petrov, J Hordell, D Benedicto-Orenes, A Kowalczyk, G Barontini and V Boyer

University of Birmingham, UK

The success of optical communications has been granted to a large extent by the invention of the optical fibre, which allows for efficient transmission of light-encoded information. The single mode fibres used in serial communication channels have proven to be effective for the transport of quantum information, for example in commercial quantum key distribution systems. In biomedical applications, the developments in the fibre optics technology, has allowed the transmission of images, e.g. in endoscopic devices. A question then arises whether this technology is also suitable for the parallel transport of spatial quantum information such as quantum images [1]. Here, we report the realisation of coherent transport of spatial quantum intensity correlations through a conduit made of the ordered packing of thousands of fibres. Maintaining the spatial character of quantum information opens the way to the use of guided-light technology in the emergent field of quantum imaging as well as parallel quantum communication networks.

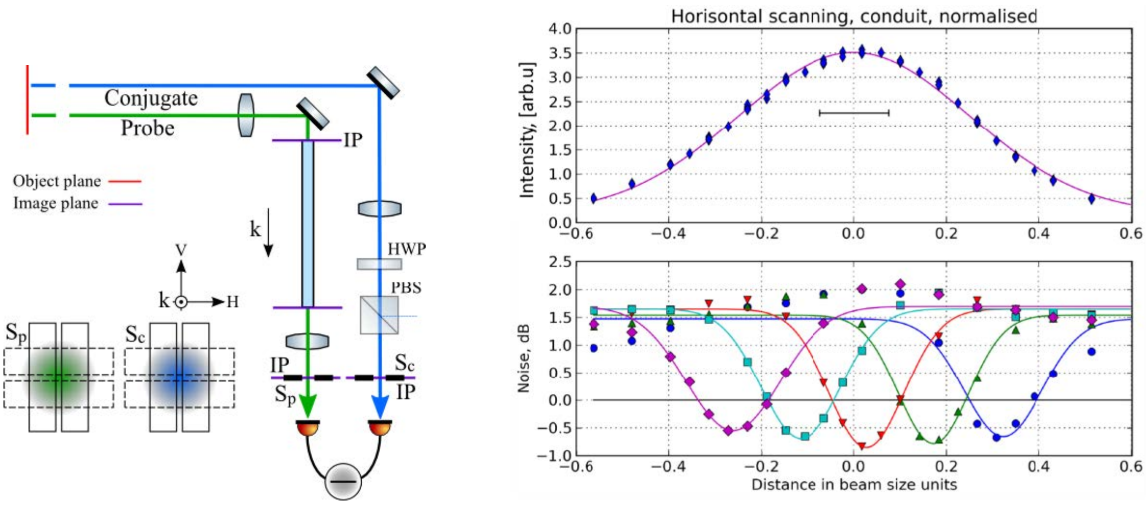

Fig. 1. Experimental setup (Left): Spatial quantum correlations between probe and conjugate beams are generated via four-wave-mixing process in hot atomic vapor. The probe beam is propagating through the conduit (direction vector k). The centre of the cell (shown with red bar), or the near field (NF), is imaged onto the slits Sp and Sc. Additional lenses in the probe path are used to image the NF at the input facet and the output facet at the probe slit Sp. In the image plane, hence in the NF, the local quantum fluctuations are identical in both beams. Additional polarizing-beamsplitter cube (PBS) and a half-wave-plate (HWP) are used to balance the power of the transmitted beams at the balanced detector. Measurements and results (Right): The degree of correlations between probe and conjugate is deduced by the intensity-difference squeezing [2]. The measurement is done by scanning the slit position on the conjugate beam for a fixed slit position on the probe beam. When the slits select correlated regions of the beams the result is a single dip in the detected intensity-difference noise as a function of the distance. The process is repeated for multiple positions along the probe beam, which results in a number of dips. The scanning is done in both horizontal (shown here) and vertical directions (H and V). The top graph on the right is the fitted intensity profile of the conjugate beam. The noise dips are fitted to Gaussians, the black solid line at 0dB represents the shot noise and the bar on the beam profile graph denotes the slit size. The observation of multiple peaks after the conduit is an evidence for the transport of spatial quantum correlations transported through the waveguide.

[1] V. Boyer *et al.* Science, 321, (5888), 544-547, (2008)
[2] C. F. McCormick *et al.*, Opt. Lett. 32, 178-180, (2007)

(invited) **Ion microtraps for atomic quantum technologies**

G Wilpers[1], K Choonee[1,2], M Akhtar[1,2], E Riis[2] and A Sinclair[1]

[1]National Physical Laboratory, UK, [2]University of Strathclyde, UK

Much research has been conducted into the use of trapped atomic ions for quantum information processing, quantum simulation and quantum metrology [1]. During the past two decades, considerable progress has been made in developing scalable microfabricated ion trap devices [2], as well as in reducing infidelities of laser-driven two-qubit gates [3,4]. Motional heating of the trapped ions is detrimental to maintaining quantum coherence, and is often a limit to the fidelity achieved. Combining the scalable properties of a microfabricated device with a low motional heating rate is essential for the development of these technologies.

We have developed monolithic ion microtrap chips which are made using parallel, wafer-scale MEMS fabrication techniques. The devices (Fig. 1) have a near-ideal, three-dimensional electrode geometry, and an ion-electrode distance of 240 µm. Each trap chip contains a remote zone for loading the ions and a linear array of 7 operation segments for precision experiments. Most fabrication is performed at wafer level; the mechanical form of the microstructured chips is fully intact and 90 % of chips are within a few % of geometric design targets. Using an automated process, individual chips are electronically packaged in a ceramic chip carrier, which also serves as a UHV electrical feedthrough. RF tests show surface breakdown voltages ranging up to 600 V amplitude.

A first chip from the most recent batch has undergone trapping tests using a Doppler-cooled $^{88}Sr^{+}$ ion. Coherent optical spectroscopy on the S-D transition shows Lamb-Dicke confinement and initial measurements suggest an ion heating rate of 10 quanta/s; this is at least a 30-fold improvement over our earlier work [5-7]. Notably, this is achieved in a scalable device operating at room temperature, in contrast to scalable microtraps with a 2D electrode geometry requiring cryogenic temperatures to reduce the heating rate. A detailed study of heating rates, measured with sideband-cooled ions, is in progress. Results arising from this, as well as those from coherent spectroscopy of the trapped ion, will be presented. This work demonstrates the feasibility of achieving a low ion heating rate, in a room-temperature device, made using scalable microfabrication techniques.

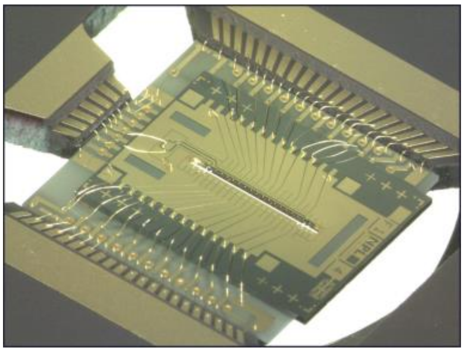

Fig. 1. Monolithic ion microtrap chip with 3D electrode geometry

[1] R. Blatt and D. Wineland, Nature 453, 1008 (2008)
[2] M. D. Hughes, *et al*, Contemporary Physics 52, 505 (2011)
[3] C. J. Ballance, *et al*, Phys. Rev. Lett. 117, 060504 (2016)
[4] J. P. Gaebler, *et al*, Phys. Rev. Lett. 117, 060505 (2016)
[5] G. Wilpers, P. See, P. Gill and A. G. Sinclair, Nature Nanotech., 7, 572 (2012)
[6] P. See, G. Wilpers, P. Gill and A. G. Sinclair, J. Micro Elec. Mech. Syst. 22, 1180 (2013)
[7] G. Wilpers, P. See, P. Gill and A. G. Sinclair, Appl. Phys. B 111, 21 (2013)

Optical nanofibres as probes for cold atomic ensembles

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The integration of nanophotonic devices into cold atomic systems is one of the more recent candidates to emerge for the development of quantum technologies. Optical nanofibres (ONF), see Fig. 1, which are fabricated by tapering standard optical fibre over a heat source to subwavelength diameter [1], are now a popular choice of nanophotonic tool for such atom-photon hybrid quantum systems [2], with the added benefit of providing a means to explore chiral quantum optics for quantum networks [3] and the fact that they don't rely on any large scale fabrication facilities, hence are accessible for many laboratories. In a sub-wavelength diameter ONF a large portion of the guided mode energy is contained within the evanescent field beyond the nanofibre surface. The tight confinement of the light provides a high intensity and field gradient even for very low input powers. The fibre-guided light can probe ensembles of atoms around the nanofibre or the nanofibre can be used to transfer light from one atomic system to another.

In our work, we study the interaction of magneto-optically trapped ^{87}Rb atoms with the evanescent field of an ONF. Atoms near the surface of the nanofibre interact with a resonant evanescent field to exhibit ultralow-power nonlinear effects [4,5]. We present our studies on higher order mode fibre-based atom interactions [6]. The advantage of such a system over fundamental mode trapping includes the ability to use orbital angular momentum carrying trapping or probe beams and the possibility of generating a tractor beam effect [7].

We will also report on progress on the formation and detection of Rydberg atoms near the surface of an optical nanofibre. Rydberg atoms have large dipole moments which can lead to a blockade of simultaneous excitation for nearby atoms. The effect of the van der Waal's force from the surface of the ONF on a single atom and on the collective blockade condition will be discussed.

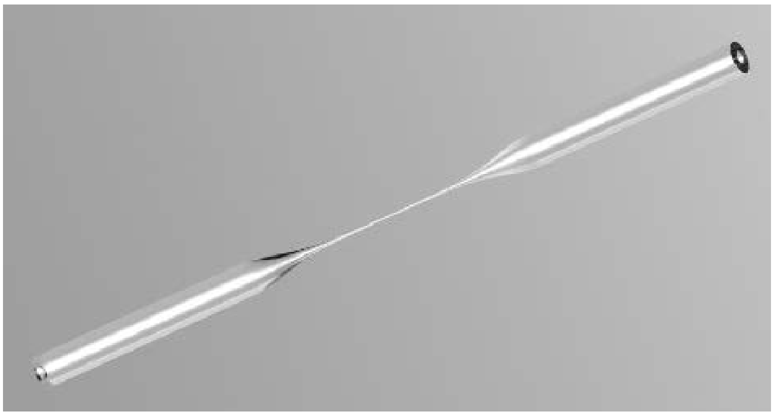


Fig. 1. Schematic representation of a tapered optical fibre. Interactions with the evanescent light field occur at the narrowest region, known as the nanofibre.

[1] J.M. Ward, V.H. Le, A. Maimaiti and S. Nic Chormaic, Rev. Sci. Instr. 85, 111501 (2014)
[2] T. Nieddu, V. Gokhroo and S. Nic Chormaic, J. Opt. 18, 053001 (2016)
[3] P. Lodahl, S. Mahmoodian, S. Stobbe, A. Rauschenbeutel, P. Schneeweiss, J. Volz, H. Pichler and P. Zoller, Nature 541, 473 (2017)
[4] R. Kumar, V. Gokhroo, K. Deasy and S. Nic Chormaic, Phys. Rev. A 91, 053842 (2015)
[5] R. Kumar, V. Gokhroo and S. Nic Chormaic, New J. Phys. 17, 123012 (2015)
[6] F. Le Kien, S.S.S. Hejazi, T. Busch, V.G. Truong and S. Nic Chormaic, arxiv.org/abs/1706.04291
[7] M. Sadgrove, S. Wimberger and S. Nic Chormaic, Sci. Rep. 6, 30131 (2016)

Cavity-induced anti-correlated photon emission rates of a single ion

H Takahashi, E Kassa, C Christoforou and M Keller

University of Sussex, UK

We report on the alteration of photon emission properties of a single trapped ion coupled to a high finesse optical fiber cavity. We show that the vacuum field of the cavity can simultaneously affect the emissions in both the infrared (IR) and ultraviolet (UV) branches of the $\Lambda-$type level system of $^{40}Ca+$ despite the cavity coupling only to the IR transition.

The cavity induces strong emission in the IR transition through the Purcell effect resulting in a simultaneous suppression of the UV fluorescence. The measured suppression of this fluorescence is as large as 66% compared with the case without the cavity. Through analysis of the measurement results, we have obtained an ion-cavity coupling of $\bar{g}_0 = 2\pi \cdot (5:3 \pm 0:1)$ MHz, the largest ever reported so far for a single ion in the IR domain.

(invited) **Quantising the electromagnetic field near semi-transparent mirrors**

A Beige

University of Leeds, UK

The question of how to model the emission of light from atomic systems is older than quantum physics itself. For example, Planck's seminal paper on the spectrum of black body radiation [1] is what eventually led to the discovery of quantum physics. Nowadays, we routinely use quantum optical master equations [2,3] to analyse the dynamics of atomic systems with spontaneous photon emission. In this talk, we use the same notion of photons as in free space [4] to quantise the electromagnetic field near a semi-transparent mirror with finite transmission and reflection rates [5]. Afterwards, we derive the master equation of an atom with spontaneous photon emission in front of such a mirror. Systems like this and related systems are expected to find applications which range from testing the quantum physics of open quantum systems to quantum metrology, quantum sensing and quantum information processing.

[1] M. Planck, *On the law of the energy distribution in the normal spectrum*, Ann. Phys. 4, 553 (1901)

[2] G. S. Agarwal, *Quantum statistical theories of spontaneous emission and their relation to other approaches*, Springer Tracts in Modern Physics; Quantum Optics, Vol. 70 (Springer Verlag Berlin, 1974)

[3] A. Stokes, A. Kurcz, T. P. Spiller and A. Beige, *Extending the validity range of quantum optical master equations*, Phys. Rev. A 85, 053805 (2012)

[4] R. Bennett, T. M. Barlow, and A. Beige, *A physically-motivated quantisation of the electromagnetic field*, Eur. J. Phys. 37, 014001 (2016)

[5] N. Furtak-Wells, L. A. Clark, R. Purdy and A. Beige, *Quantising the electromagnetic field near a semi-transparent mirror*, arXiv:1704.02898 (2017)

(invited) **Paths towards a universal fault tolerant quantum computer**

D Browne

University College London, UK

(invited) **Ion acceleration with high power lasers: recent developments and perspectives**

M Borghesi

Queen's University of Belfast, UK

Ion acceleration driven by high intensity laser pulses is attracting an impressive and steadily increasing research effort. Experiments over the past 10-15 years have demonstrated, over a wide range of laser and target parameters, the generation of multi-MeV proton and ion beams with unique properties such as ultrashort burst emission, high brilliance, and low emittance. The talk will provide an overview of the state of the art in this field by discussing both the established sheath acceleration mechanism (or TNSA), and emerging mechanisms (e.g. Radiation Pressure Acceleration), which hold the promise for acceleration to GeV/nucleon energies with next generation laser facilities. In particular, recent developments obtained in the framework of the A-SAIL (*Advanced Strategies for Accelerating Ions with Lasers*) project will be discussed. This is a UK-wide consortium aimed to the development of ion acceleration towards medical applications, which carries out experimental research at the UK national facilities of the Rutherford Appleton Laboratory employing the PW-class VULCAN and GEMINI lasers.

(invited) **Probing the extreme: x-ray spectroscopy from inertial fusion plasmas to brown dwarfs**

N Woolsey

University of York, UK

High energy and ultra-intense lasers offer the exciting opportunity of creating the conditions for fusion and stellar objects such as brown dwarfs. In the context of inertial confinement fusion multi-beam lasers are used to compress a spherical shell of plastic containing deuterium-tritium fuel. During the implosion, material from the outer shell mixes with the fuel. I discuss how spectral emission from this mixed material encodes information about the fuel hotspot, the deuterium-tritium ice layer, the imploding shell as well as the degree of mix in the fuel. In separate experiments, when interacting with a solid, an ultra-intense laser, short pulse laser generates intense beams of relativistic electrons. These electrons and the associated return currents scatter and generate intense x-ray emission in the solid creating warm-dense matter and radiation-dominated environments. Interpretation of the exotic atomic states that form within these environments, through modelling the emission from hollow ions and the non-thermal excitation of magnetic sub-states, provides information on the microphysics which can occur in astrophysical objects such as brown dwarfs. In this talk I will cover aspects of the experiments, diagnostics, data interpretation and the use of spectroscopic models needed to extract information.

MHz band surface fluctuation in supersonic molecular beam injection in Heliotron-J plasma

M Irie[1] and M Kubo-Irie[2]

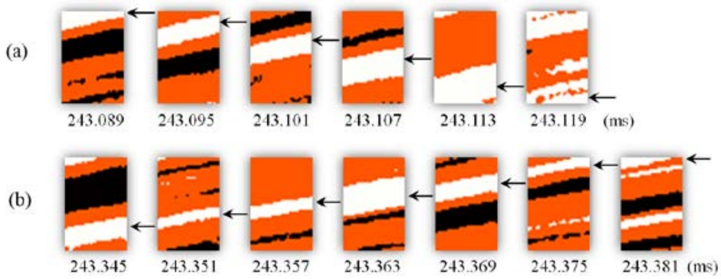
[1]Waseda University, Japan, [2]Open University of Japan, Japan

Thermonuclear plasma confinement scheme are closely dependent on the edge localized mode (ELM) and L-H Transition. In Heliotron - J in Kyoto University, Japan, intense hydrogen radiation were observed in the super-sonic molecular beam injection (SMBI) phase. The qualitative aspects based on the high speed, 160kf/s, movie data are summed up and published in 2013 by L.Zang et.al.[1]

However extraordinary image jump was detected in every consecutive frames just as shown in Figure 1. The shutter duration of 5 micro second is well over the frame separation of 1.5 micro second. This indicates that the plasma surface configuration changes well below the time duration of 1 micro second time scale and the surface fluctuation frequency can be estimated within MHz frequency band. In figure 2 quasi-3D (vertical direction –horizontal direction – time duration) contour image is presented which technique was already published [2]. In this presentation, we would like to propose and demonstrate the new type of movie analysis based on the Digital Imaging technique to resolve sub-frame behavior of the movie diagnostics.

In SMBI phase the Hydrogen-alpha radiation intensity is nearly two orders of magnitude higher than the background plasma radiation and/or inherent noise level. The high speed frame camera data can be used as a space integrated (0D) detector, slit (1D) detector, and frame (2D) detector with the 0th dimension of "Time" dimension. These pictures show time integrated radiation during shutter opening time. The brightness contour closely follows the magnetic field line as expected.

From"1D" slit images, we applied the statistical estimation of the brightest spot moving across the magnetic field lines. The shutter opening time of this experiment was set at 5 μs. In this particular experiment, we are planning to apply conventional 100ns shuttering time camera system to prove our computer interpolation image and find out the filamentary plasma fluctuation on the edge region.



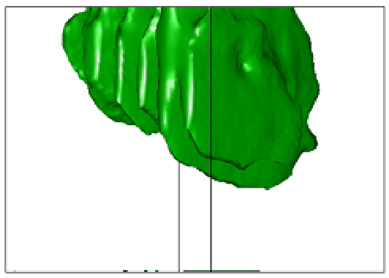


Fig. 1. The sub-contoured image of the surface radiation in Heliotron –J plasma in Supersonic Molecular Beam Injection Phase taken from the published Reference [1] Movement in (a) Ion Diamagnetic direction (b) Electron diamagnetic direction. Fig.2. The reconstructed 3D (x-y-t) contour image taken from the experimental data.

This work is (was) supported by the "Joint Usage/Research Program on Zero - Emission Energy Research, Institute of Advanced Energy, Kyoto University: ZE27B43 and ZE28B-29. This work was also supported by a Waseda University Grant for Special Research Projects (2008 A-042, 2013B-090, 2015 K-159, 2015B-198,2016B-126 and 2017K-183). The authors thank Profs. Tohru Mizuuchi of Kyoto University and Nobuhiro Nishino of Hiroshima University for fruitful discussions over the actual unpublished experimental data.

[1] Linge Zang *et al.,* Plasma Fusion Res. 8, 1402066 (2013)
[2] Miyoko KUBO-IRIE *et al.* Scientific Reports 6, 23819 (2016)

(invited) **Quantum cavity optomechanics with levitated nanoscale oscillators**

P F Barker

University College London, UK

Nanoscale oscillators levitated by optical, electric or magnetic fields in high vacuum offer a completely new arena for studies of foundational science. The drastic suppression of decoherence potentially allows observation of non-classical states of motion, while the creation of long-lived macroscopic quantum states may enable demonstrations of quantum behaviour on very large mass scales. This includes the possibility of creating large macroscopic superpositions, as well as tests of proposed mechanisms of wavefunction collapse at large length scales. Additionally, the exquisite force-sensing capabilities of these systems offer the potential for measuring classical gravity at short length scales and detection of gravitational waves at high frequencies as explored in Reno.

An important enabling requirement for these studies is the development of methods to manipulate and cool the centre-of-mass motion of these oscillators. In addition, the internal temperature must often be maintained at or below 300 K. In this talk I will describe our work which has demonstrated cavity cooling of levitated silica spheres (r = 200 nm) to milliKelvin temperatures in a hybrid electro-optical trap [1-2]. I will also outline more recent work that has shown internal cooling of optically levitated ytterbium-doped yttrium lithium fluoride (Yb^{+3}: YLF) nanocrystals using anti-stokes laser refrigeration from room temperature to 130 K [2]. I will also discuss future foundational experiments which will use these developments.

[1] J. Millen, P. Z. G. Fonseca, T. Mavrogordatos, T. S. Monteiro, and P. F. Barker Phys. Rev. Lett. 114, 123602 (2015)

[2] P. Z. G. Fonseca, E. B. Aranas, J. Millen, T. S. Monteiro, and P. F. Barker, Phys. Rev. Lett. 117, 173602 (2016)

[3] A. T. M. Anishur Rahman, P. F. Barker, arXiv:1703.07155v1 (2017)

(invited) **Big Ideas for Giant Atoms: Applying Rydberg atoms to ion beams and terahertz sensing**

C G Wade, N Šibalić, C S Adams and K J Weatherill

Durham University, UK

When atoms are excited to states with large principle quantum number, n, they exhibit some extreme properties. For example, these so-called Rydberg atoms are very sensitive to electric fields as their polarizability scales as n^7 and they exhibit very strong inter-particle interactions as the van der Waals coefficient scales as n^{11} [1]. The also exhibit a manifold of very strong electric dipole transitions across the microwave and terahertz range. In this talk I will explain how the extreme properties of Rydberg atoms can be used to demonstrate applications is areas as diverse as terahertz science and nanotechnology.

I will discuss how ultracold ion sources based upon laser cooled atoms can be used for focused ion beam applications. I will then present progress in Durham towards using a cold Rydberg gas to produce a fast and deterministic source of single ions [2] for implanting and imaging applications.

I will then present recent experimental results where we demonstrate that Rydberg atoms in a thermal vapour can be used for fast, sensitive and calibrated imaging of terahertz fields [3]. Fig. 1 shows a video rate image of a terahertz standing wave in an atomic vapour. Furthermore, we show how strongly-driven Rydberg vapours undergo a phase transition [4] due to interaction effects and the sharp changes in optical transmission that accompany the transition are sensitive to terahertz frequency fields giving rise to collectively enhanced terahertz detection [5].

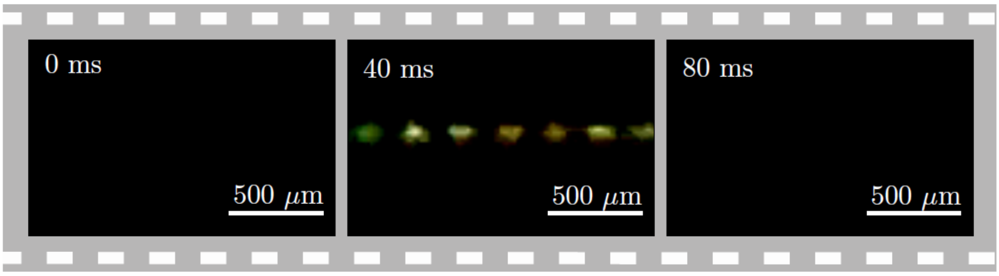


Fig. 1. Real time imaging of terahertz standing wave: Sequence of frames from a 25 frame per second video. The THz field is gated to be on and off in consecutive frames.

[1] N. Šibalić, J. D. Pritchard, C. S. Adams and K. J. Weatherill, Comput. Phys. Commun. (2017) atomcalc.jqc.org.uk

[2] C. Ates, I. Lesanovsky, C. S. Adams and K. J. Weatherill, Phys. Rev. Lett. 110, 213003 (2013)

[3] C. G. Wade, N. Šibalić, N. R. De Melo, J. M. Kondo, C. S. Adams and K. J. Weatherill, Nature Photon. 11, 40 (2017)

[4] C. Carr, R. Ritter, C. S. Adams and K. J. Weatherill, Phys. Rev. Lett. 111, 113901 (2013)

[5] C. G. Wade, E. Levi, M. Marcuzzi, J. M. Kondo, I. Lesanovsky, C. S. Adams and K. J. Weatherill (In preparation)

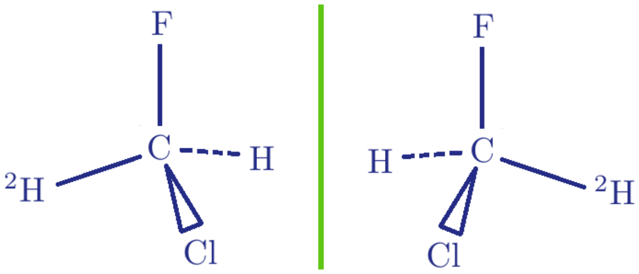
Chiral Rotational Spectroscopy

R P Cameron[1,2], J B Götte[1,3] and S M Barnett[2]

[1]University of Glasgow, UK, [2]Max Planck Institute for the Physics of Complex Systems, Germany, [3]Nanjing University, China

Chirality pervades the natural world and is of particular importance to life, as the molecules that comprise living things are chiral and their chirality is crucial to their biological function. Our ability to probe and harness molecular chirality remains incomplete in many respects, however, and new techniques for chiral molecules are, therefore, highly sought after.

We present a theoretical proposal for such a technique: Chiral Rotational Spectroscopy [1,2,3] promises the ability to determine the orientated optical activity pseudotensor components B_{XX}, B_{YY} and B_{ZZ} of chiral molecules, in a manner that reveals the enantiomeric constitution of a sample and provides an incisive signal even for a racemate. Chiral Rotational Spectroscopy could find particular use in the analysis of molecules that are chiral solely by virtue of their isotopic constitution (see the figure below) and molecules with multiple chiral centres.



Enantiomers of isotopically chiral chlorofluoromethane. These molecules are distinct mirror image versions of each other, differing solely by the placement of a single neutron. Chiral Rotational Spectroscopy should be able to distinguish between them to leading order.

[1] R. P. Cameron, J. B. Götte, S. M. Barnett, Phys. Rev. A 94, 032505 (2016)
[2] R. P. Cameron, J. B. Götte, S. M. Barnett, A. M. Yao, Phil. Trans. R. Soc. A 375, 20150433 (2016)
[3] J. B. Götte, R. P. Cameron, S. M. Barnett, Proc. of SPIE Vol 10120 (2017)

(invited) **Photonic quantum technologies: Metrology, Spins and Photons**

J Rarity

University of Bristol, UK

Photons are well known as carriers of information in quantum secured key distribution but not so close to applications in quantum metrology and information processing. Here I will summarise aspects of our work focusing on measurement achieving sub-shot noise performance in transmission measurements. In an experiment using commercial camera technologies we have demonstrated record 'absolute' noise reductions [1] and have begun scanned imaging experiments using heralded photons [2] and CCD and hope to report latest results at the conference.

For quantum information processing we investigate solid state systems including quantum dots and colour centres in diamond. These atom-like two level systems are promising as deterministic single photon sources [3] particularly when incorporated in microcavities. Here we also aim to exploit their ground state spins that lead to spin dependent transitions and the potential to entangle ground state spin with emitted or reflected photons [4]. Spin-photon entanglers are effectively universal and deterministic quantum gates enabling quantum memories, quantum repeaters [5] and eventually large-scale quantum computation. Our latest work shows that low Q-factor pillar microcavities efficiently couple a dot to a single mode (ie have high β-factor) enabling us to detect large spin dependent phase shift (Faraday rotation). When the dot is on resonance we see 80% of reflected photons receive a pi phase shift sufficient for entangling operation [6]. Our present measurements were performed in a Faraday geometry magnetic field separating spin up and down transitions. In future measurements we intend to investigate low field and Voigt geometry measurements that may allow measurement of spin rotation via photon scattering, the first indication of a spin-photon interface.

Quantum dot spins are hard to control with decoherence times measured in microseconds. In contrast the ground state spin in NV-centres in diamond has spin coherence out to milliseconds at room temperature and the polarisation of spin is simply dome by reading out the spin in fluorescence measurements. Fabrication of cavity structures coupled to NV-centres is still not perfected so single shot measurements of spin are still limited by light collection efficiency. However the long coherence times allow the spins to be used as electric field and/or nuclear magnetic field sensors. In our group we are perfecting strain sensing techniques using the ground state spin hyperfine split by the local nitrogen 14 nucleus. A review of our latest results in NV-centre spin-photon interfaces will be presented.

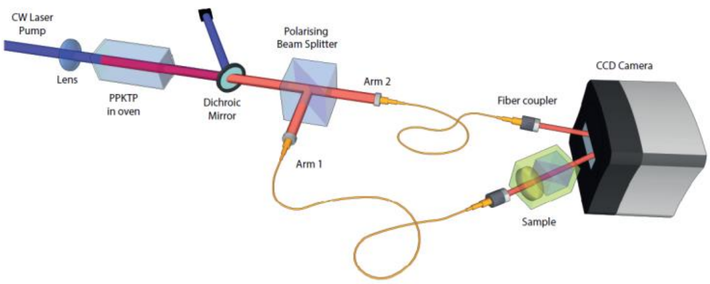


Fig 1. Sub shot noise measurement of transmission. A PPKTP crystal is used to create quantum identical twin light beams. One beam is used to measure transmission and the other as reference. A high efficiency CCD is used to measure the beams and the subtraction of probe from reference gives a sub-shot noise measure of sample transmission

[1] P-A Moreau et al Sci Rep 7, 2017
[2] J. Sabines et al Phys Rev Applied 8, 14016, 2017
[3] S. Maier, et al Opt. Express 22, 8136 (2014)
[4] C. Y. Hu et al Phys. Rev. B 78, 085307 (2008)
[5] C.Y. Hu and J.G. Rarity, Phys Rev B, 83, 115303 (2011)
[6] P. Androvitsaneas et al., Phys. Rev. B 93, 241409(R) (2016)
[7] P. Androvitsaneas et al., arXiv:1609.02851(2016)

Photonic realization of an anomalous topological insulator in a slowly driven lattice

S Mukherjee[1], A Spracklen[1], M Valiente[1], E Andersson[1], P Öhberg[1], N Goldman[2] and R R Thomson[1]

[1]Heriot-Watt University, UK, [2]Université Libre de Bruxelles, Belgium

Topologically protected quantum phenomena can be observed in the presence of a suitable time-periodic driving. In the limit of low-frequency driving (i.e. driving frequency ~ inter-site coupling strength), the standard topological invariants, such as Chern numbers, may become irrelevant to describe the topology of the system. In fact, topological edge modes can exist even if the Chern numbers of all the bulk bands are zero [1, 2]. Here we present the experimental observation of such "anomalous" topological edge modes in a slowly driven two-dimensional photonic lattice, where these propagating edge states are observed to coexist with a quasi-localized bulk [3, 4].

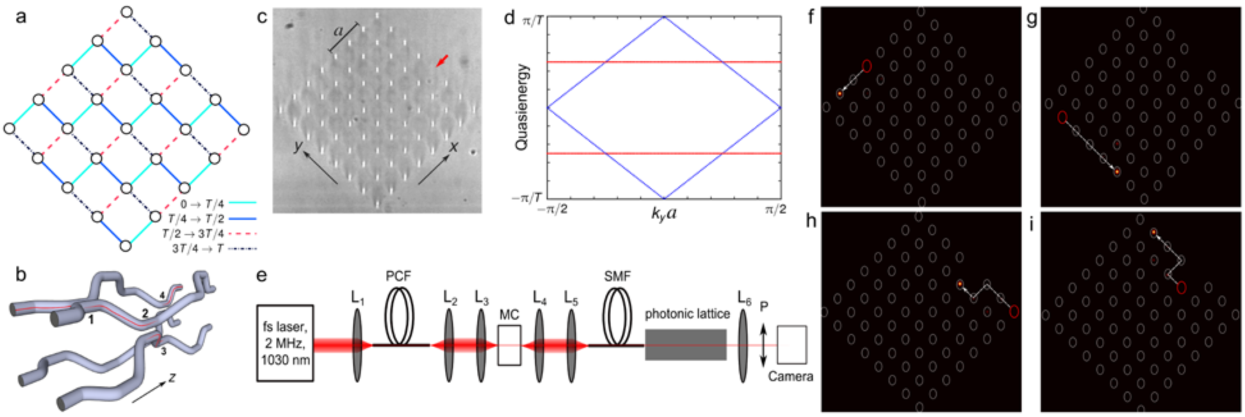


Fig. 1. (a) The driving protocol; the bond strengths are turned on and off in a spatially homogeneous and time-periodic manner. For each quarter of the total driving period, only one type of bonds (indicated by different colors) are turned on. (b) Photonic implementation of the above-mentioned driving protocol. (c) Micrograph of the facet of the laser-fabricated photonic lattice. The red arrow indicates a missing waveguide which acts as a defect. (d) Floquet spectrum of the slowly driven square lattice. (c) Experimental setup to excite different lattice sites with tunable coupling strength. (f-i) Chiral topological edge modes were observed to be robust against defects.

Using ultrafast laser inscription technique, we fabricated a photonic square lattice with nearest-neighbour couplings, which are varied in a spatially homogeneous and time-periodic manner, Fig. 1 (a-c). The total driving period (T) is equally divided into four, and all the bonds are turned off for the first quarter. During the next three quarters of the driving period, the desired bonds are turned on such that a particle can hop to its nearest neighbour site with unit probability. The Floquet quasienergy spectrum for this driving protocol is shown in Fig. 1 (d). The lattice supports two bulk bands with zero Chern number, while the winding numbers associated with both the energy gaps (centered on 0 and π/T) are one. In the experiment, the edge modes are excited with nearly unit efficiency [Fig. 1 (e)], and it was observed that these edge modes propagate one way [Fig. 1 (f, g)] and are not scattered by defects [Fig. 1 (h, i)]. Our work opens an exciting route for the experimental investigation of slowly driven topological systems in the presence of disorder and inter-particle interactions.

[1] T. Kitagawa, E. Berg, M. Rudner, E. Demler, Phys. Rev. B 82, 235114 (2010)
[2] M. S. Rudner, N. H. Lindner, E. Berg, M. Levin, Phys. Rev. X 3, 031005 (2013)
[3] S. Mukherjee, A. Spracklen, M. Valiente, E. Andersson, P. Öhberg, N. Goldman, and R. R. Thomson, Nat. Commun. 8, 13918 (2017)
[4] L. J. Maczewsky, J. M. Zeuner, S. Nolte, A. Szameit, Nat. Commun. 8, 13756 (2017)

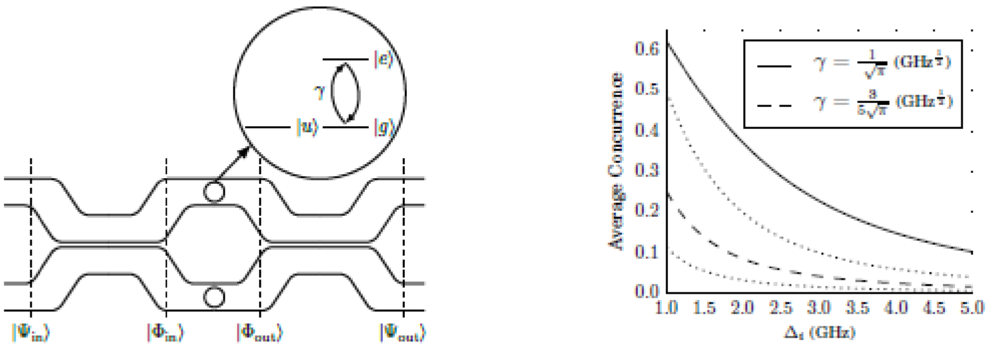
Analytic few photon scattering in waveguide QED for entanglement generation

D Hurst and P Kok

University of Sheffield, UK

Proposals for practical quantum devices such as a measurement-based quantum computer or a Quantum Internet require large entangled states of stationary qubits [1]. Optical photons, with their long coherence times and large velocities, form the ideal carriers of quantum information between these nodes and this means that understanding the light-matter interaction is of great importance. A possible route towards engineering this light-matter interaction involves coupling quantum emitters to the modes of a nanophotonic waveguide and there has been a great deal of recent experimental progress in this field [2].

We develop an approach to light-matter coupling in waveguide QED based upon scattering amplitudes evaluated via Dyson series [3]. Unlike previously reported procedures, our method fully specifies a combined emitter-optical state that permits investigation of matter-matter entanglement generation protocols. We find that for multi-photon input optical states, terms in the Dyson series increase in complexity and we develop a diagrammatic recipe for their evaluation.



(a) Mach-Zehnder interferometer where the optical modes in each arm are coupled at a rate γ to the $|g\rangle \rightarrow |e\rangle$ transition of an emitter with L-type energy level configuration. (b) Average concurrence between emitters for two photon input states at two coupling strengths. Dotted lines represent the equivalent results for single-photon input states.

We use our expressions to study a scheme for entangling spatially separated two-level systems. Figure 1a depicts two quantum emitters coupled to the arms of a Mach-Zehnder interferometer and we calculate the entanglement between these emitters following a scattering event for both single and two photon input states, various coupling strengths and possible optical detection events. We find that an entangled two-photon input state provides a clear advantage over a separable single photon one. At larger photon-emitter detunings this improvement exceeds the factor of two that may have been naively expected.

[1] H. J. Kimble. "The quantum internet". In: Nature 453.7198 (June 2008), pp. 1023{1030. url: http://dx.doi.org/10.1038/nature07127.

[2] P. Lodahl et al. "Chiral quantum optics". In: Nature 541.7638 (Jan. 2017), pp. 473{480. url: http://dx.doi.org/10.1038/nature21037.

[3] D. L. Hurst and P. Kok. "Analytic Few Photon Scattering in Waveguide QED for Entanglement Generation". In: ArXiv e-prints (May 2017). arXiv: 1705.07016 [quant-ph].

(invited) **Cold atomic gravity sensing for field applications**

M Holynski

University of Birmingham, UK

Cold atom interferometry provides an exceptional approach for inertial measurement, allowing sensitive and low drift measurements of rotation and acceleration. Since the early 90's its use in measuring gravity in laboratory based systems has been well demonstrated, reaching sensitivities of significant relevance for fundamental physics such as the search for violations of Einstein's equivalence principle and the future detection of gravitational waves. More recently there has been a growing push towards making devices of relevance for commercial applications, resulting in systems which are operable in non-laboratory environments.

The UK National Quantum Technology Hub in Sensors and Metrology is focused on the next generation of sensors, targeting significant improvements in the technology readiness of cold atom based sensing and demonstrating their potential use within practical applications such as micro-gravity survey. A particular focus is on the development of cold atom gravity gradiometers for field applications, aiming to detect targets such as sub-surface tunnels or pipes. This involves a significant push in improving the system robustness, size, weight and power, while also aiming to achieve high sensitivities.

The spin resonance clock transition of the endohedral fullerene $^{15}N@C_{60}$

E Laird[1], R Harding[1], S Zhou[1], J Zhou[1], T Lindvall[2], W Myers[1], A Ardavan[1], A Briggs[1] and K Porfyrakis[1]

[1]University of Oxford, UK, [2]VTT Technical Research Centre of Finland, Finland

Portable atomic clocks have applications ranging from jam-resistant GPS to undersea seismometers. Existing clocks based on atomic vapours are challenging to miniaturise, but a clock based on spin resonance would allow the entire device to be integrated onto a single chip. We have measured the spin resonance clock transition of the endohedral fullerene $^{15}N@C_{60}$ – nature's atom trap. In this material, a carbon cage encloses and protects a central nitrogen radical, leading to outstanding spin resonance lifetime at room temperature. Moreover, at the clock field, the electron and nuclear spins conspire to make the resonance frequency independent of magnetic field, and therefore resistant to field noise. This is the first molecular spin resonance clock transition discovered at room temperature.

We characterize the entire low-field spin resonance spectrum of this molecule in parallel and perpendicular magnetic field. We infer an upper bound to the clock transition linewidth of 100 kHz. Using experimental data, we are able to place a bound on the clock's projected frequency stability, and we discuss ways to improve the stability to be competitive with existing miniature clocks.

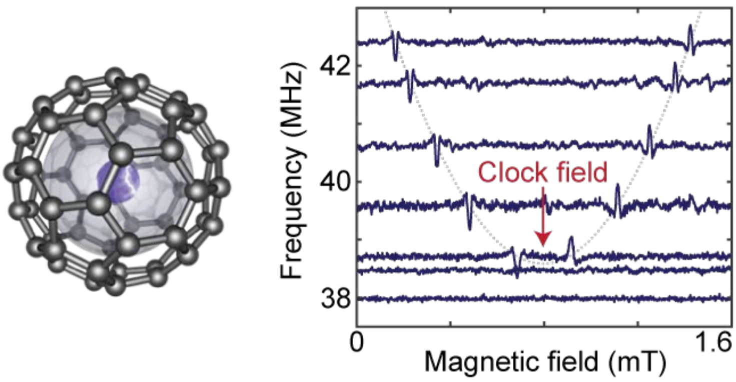


Figure 2 Left: the endohedral fullerene molecule $N@C_{60}$. Right: The clock transition detected in electron spin resonance.

Spontaneous magnetic ordering induced by light in cold atomic gases

I Kresic[1], T Ackemann[1], G R M Robb[1], G-L Oppo[1], P M Gomes[1], P Griffin[1], R Kaiser[3] and G Labeyrie[2]

[1]University of Strathclyde, UK, [2]Universite Cote d'Azur, CNRS, France

An improved understanding of magnetic interactions is of paramount importance due to the challenges associated with understanding exotic magnetic phenomena such as high-Tc superconductivity, and the widespread use of magnetic materials in current technology.

Recent efforts have been made to develop "quantum simulators" of magnetic interactions using ultracold atoms loaded in optical lattices [1], and to create magnetic coupling between atoms via artificial gauge fields [2]. We present an alternative approach based on a single-mirror feedback scheme [3] (see Fig. 1) where a cloud of laser-cooled Rb atoms is illuminated by an optical beam which is then reflected by a mirror (M) behind the atomic cloud.

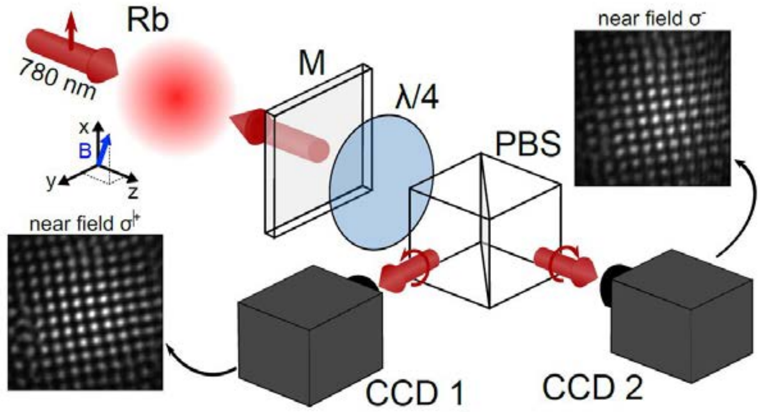


Figure 1 : Schematic diagram of single mirror feedback setup for the observation of optical spin/magnetic pattern formation in the presence of a magnetic field B.

The nonlinear interaction between the cold atoms and the optical fields leads to the spontaneous formation of optical structures (spontaneous 2D lattices) in the plane transverse to the direction of pump propagation. Experiments and simulations of the atom-light interaction show that the observed optical structures co-exist with magnetic patterns in the atomic cloud, which involve magnetic dipole and magnetic quadrupole contributions. These magnetic patterns originate due to non-local spin-spin interactions mediated by light, where the non-local nature of the interaction is due to optical diffraction. As the optical dynamics is much faster than the atomic dynamics, this amounts effectively to magnetic interactions within the atomic sample. Transitions between different magnetic phases e.g. anti-ferromagnetic and ferrimagnetic, can be induced by an external magnetic field. Analogies and differences with ‘quantum magnetism’ observed in Fermi gases [1] will be presented.

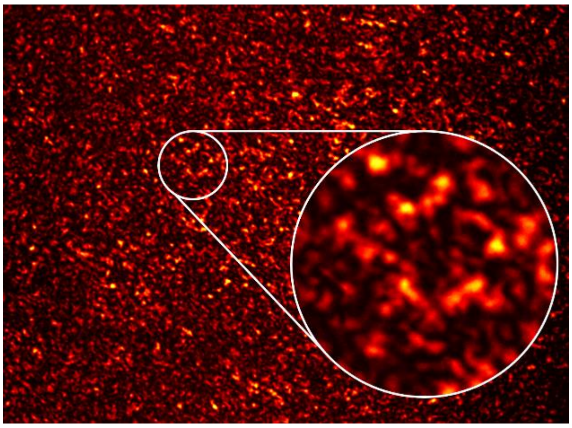
[1] D. Greif, T. Uehlinger, G. Jotzu, L. Tarruell, T. Esslinger, Science 340, 1307 (2013)
[2] J. Dalibard, F. Gerbier, G. Juzeliūnas, and P. Öhberg, Rev. Mod. Phys. 83, 1523 (2011)
[3] W.J. Firth, J. Mod. Opt. 37, 151 (1990)

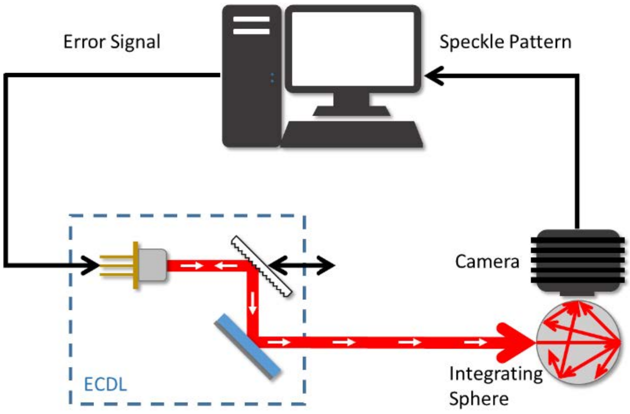
Making the most of interference: speckle metrology and its application to cold atoms

G D Bruce[1], N K Metzger[1], R Spesyvtsev[1], B Miller[2], G T Maker[2], G Malcolm[2], M Mazilu[1] and K Dholakia[1]

[1]University of St Andrews, UK, [2]M Squared Lasers Ltd, UK

Speckle patterns result from the interference of multiple reflections in disordered media. This is regarded as a randomization process which destroys information contained within the initial light beam and is deleterious to many optical systems. Indeed, many engineers study speckle to remove its effect. Intriguingly however, the processes that produce the speckle are entirely linear, and there is growing recognition that this complex pattern is rich in useful information on both the incident laser source and the environment, with startling potential uses. We will demonstrate our recent results [1], which show that the speckle pattern produced by light propagation in an integrating sphere can be used as a sensitive wavemeter, with a resolution below 1fm. Moreover, this can be used to stabilize the wavelength of a laser on a timescale and to a stability applicable for laser cooling of cold atoms.





(left) An example of a speckle pattern produced in the integrating sphere (right) Experimental configuration for laser-locking using speckle.

[1] N. K. Metzger, et al., "Harnessing speckle for a sub-femtometre resolved broadband wavemeter and laser stabilization", Nature Communications 8, 15610 (2017)

(invited) **Pursuing precision spectroscopy with antimatter: the 1S – 2S transition in trapped antihydrogen**

W Bertsche *on behalf of the ALPHA Collaboration*

University of Manchester, UK

The ALPHA Collaboration has made the first measurements of optical transitions in trapped antihydrogen atoms and recently published the first observation of the 1S – 2S transition in a fully antimatter atom. Spectroscopic measurements of this kind remain one of the most promising routes towards precision tests of CPT invariance and physics beyond the Standard Model. The work presented finds the transition consistent with CPT invariance at a level of approximately 2×10^{-10} [1]. This talk will review the details of this pioneering experiment and discuss the progress of existing spectroscopy studies and other fundamental measurements with the ALPHA apparatus at CERN.

This work had been graciously funded in part by EPSRC and STFC in the UK.

[1] M. Ahmadi, et al (ALPHA Collaboration), "Observation of the 1S–2S transition in trapped antihydrogen" *Nature* 541, 506–510 (2017)

(invited) **Quantum effects in biomolecules**

A Olaya-Castro

University College London, UK

Quantum science has achieved a remarkable theoretical, experimental and technological success that currently allows us predicting, probing and quantifying “quantumness” with an unprecedented level of precision and in a variety of scenarios ranging from single photons to isolated atoms and molecules. At the same time, technological advances have enabled us to zoom into the biological world, down to the molecular scale to investigate what life looks like at the nanoscale. The dialog, at times full of skepticism, between quantum science and biology at the molecular scale has given rise to the emerging field of quantum biology. The bilateral exchange of concepts and methods between these fields promises to bring changes to the way we think about processes supporting life on Earth as well as to deepen our understanding of the quantum phenomena that can be observed in systems operating at the interface between the quantum and the classical world. Achieving this fruitful dialog requires the scientific community to gain clarity in one key question: what processes at the biomolecular scale can only be satisfactory described within a quantum theoretical framework and what is the place of such phenomena within biology? In this talk I will discuss answers that are emerging to these questions. In particular, I will illustrate how careful inspection of the dynamics and fluctuations of quantum-scale molecular motions during photo-activated energy transport processes in photosynthetic complexes could benchmark a common principle for non-trivial quantum effects in biomolecules [1].

[1] E.J. O’Reilly and A. Olaya-Castro, “Non-classicality of the molecular vibrations assisting exciton energy transfer at room temperature”, Nature Communications 5, 3012 (2014)

Photoexcitation spectroscopy of cold molecules in the Cryogenic Storage Ring CSR

P M Mishra and the CSR team

Max Planck Institute for Nuclear Physics, Germany

The Cryogenic Storage Ring (CSR) [1] located at Max-Planck-Institut für Kernphysik in Heidelberg is an ideal experimental setup to perform collision studies of photons and cold electrons as well neutrals with stored molecular ions of kinetic energies between 20-300 keV. The circumference of the ring is 35 m and being fully electrostatic it has no mass limit for stored ions. The cryogenic temperature of about 6 K offers unique storage capabilities in extremely high vacuum conditions of below 140 rest-gas particles per cm^3 and almost vanishing blackbody radiation. An electron cooler (ecool) is installed in one straight section of the CSR which uses a photocathode to produce cold electrons. These cold electrons can further reduce the momentum spread of the stored ion beam upon interaction. A tunable optical parametric oscillator (OPO) laser system in the same section allows photon interaction studies from the ultraviolet (225 nm) to the infrared (2600 nm) regime. The CSR is equipped with two independent ion source platforms, which can deliver ions up to an energy of 60 and 300 keV per charge state, respectively. The low energy platform can be used to produce neutral beams by photo-detachment of the negative ions. Whereas the 300 kV platform presently contains a metal ion sputter source, a Penning source and an electron cyclotron resonance source; extension by a laser vaporization and an electrospray ionization ion source is in progress. The entire facility enables to perform photodissociation, electron-ion recombination, and ion-atom interaction studies with ro-vibrationally cooled stored positive and negative ions as well as clusters and highly charged ions. Further experiments aim to study decay rates of metastable ions and radiative lifetimes. The first experimental results, machine characteristics as well as future experimental possibilities of this unique infrastructure will be discussed [2, 3].

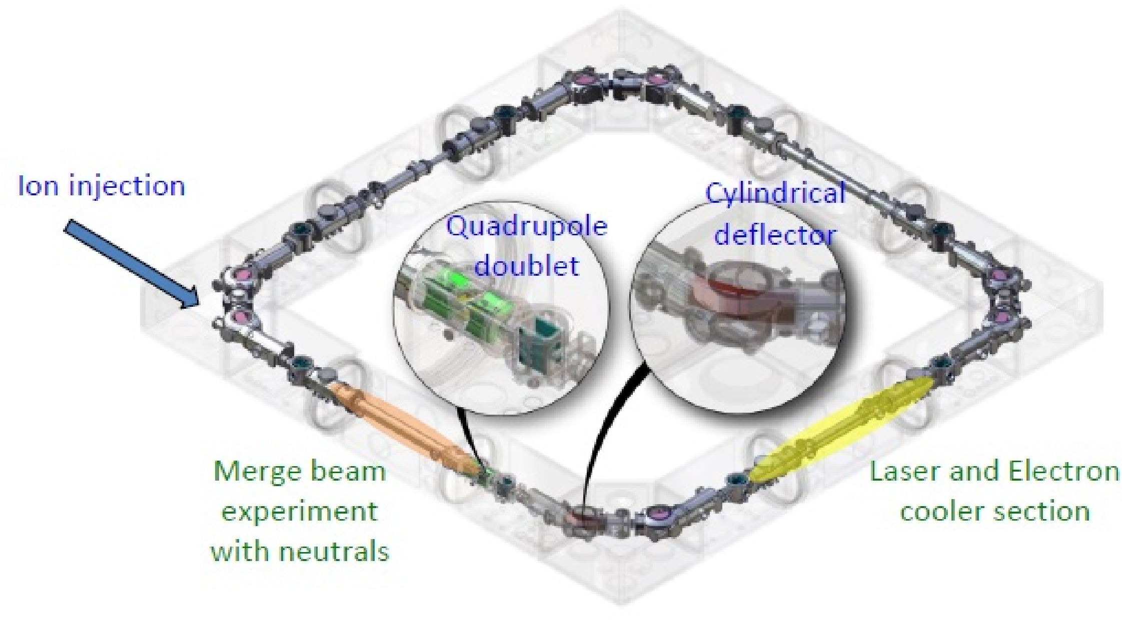


Fig. 1. The layout of CSR showing ion optical elements and experimental probes.

[1] R. von Hahn, *et al.*, Rev. Sci. Instrum. 87, 063115 (2016)
[2] A. O' Connor, *et al.*, Phys. Rev. Lett. 116, 113002 (2016)
[3] C. Meyer, *et al.*, Phys. Rev. Lett. accepted (2017)

Coherent Control and Optical Trapping of Ultracold Polar ^{87}Rb^{133}Cs Molecules

P D Gregory[1], J A Blackmore[1], E M Bridge[1], J Aldegunde[2], J M Hutson[1] and S L Cornish[1]

[1]Durham University, UK, [2]Universidad de Salamanca, Spain

The formation of ultracold heteronuclear molecules opens many exciting areas of research, spanning precision measurement, quantum computation, quantum simulation, ultracold chemistry, and fundamental studies of quantum matter. The large electric dipole moments of such molecules allow long-range interactions tunable over length scales similar to the spacing between sites in an optical lattice.

In this work, a sample of up to 4000 ^{87}Rb^{133}Cs molecules in their electronic, vibrational, rotational, and hyperfine ground state are created at ultracold temperatures by magnetoassociation on a Feshbach resonance [1] followed by transfer to their rovibronic and hyperfine ground state by stimulated Raman adiabatic passage (STIRAP) [2]. We demonstrate coherent control of the rotational and hyperfine state using external microwave fields (see Fig. 1). Spectroscopy of the hyperfine structure of the first excited rotational state N = 1 allows us to determine accurate values of rotational and hyperfine coupling constants that agree well with previous calculations. We find significant mixing between hyperfine states principally due to the scalar spin-spin coupling in N = 0, and nuclear quadrupole coupling in N = 1 [3].

We investigate the interaction between the far-off-resonant light of our optical trap on the molecules. Through high-resolution microwave spectroscopy, we measure the AC Stark shift of the hyperfine states of the ground and first excited rotational states. We demonstrate that the trapping light can couple neighbouring hyperfine states, yielding rich and complex structure with many avoided crossings [4]. This leads to our conclusion where we will be looking towards our future work, where we hope to investigate collisions between our bosonic molecules confined in a 3D optical trap.

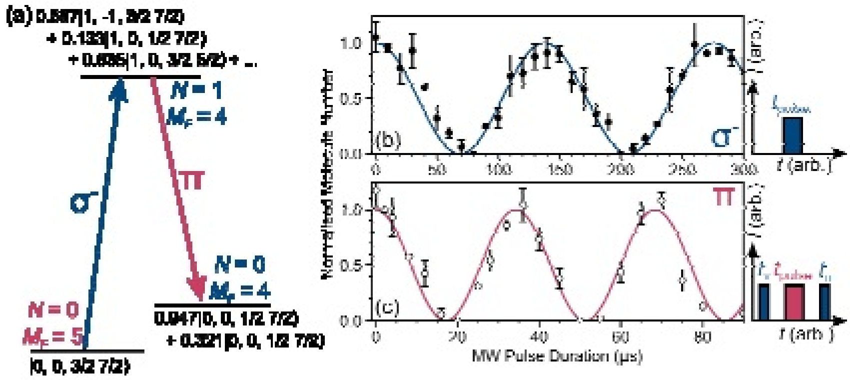


Fig. 1 Coherent Population transfer between specific hyperfine states in rotational levels $N = 0$ and $N = 1$. (a) Transfer scheme followed, where molecules begin in the lowest hyperfine state $M_F = 5$ of $N = 0$. States are described in the coupled basis set N, M_N, m_I^{Rb}, m_I^{Cs}. (b) Rabi oscillations in one-photon transfer. (c) Rabi oscillations in two-photon transfer.

[1] M. P. Köppinger *et al.* Phys. Rev. A 89, 033604 (2014)
[2] P. K. Molony *et al.* Phys. Rev. Lett. 113, 225301 (2014)
[3] P. D. Gregory *et al.* Phys. Rev. A 94, 041403(R) (2016)
[4] P. D. Gregory *et al.* Phys. Rev. A (Accepted, 2017)

(invited) **Buckling transitions and clock order of two-dimensional coulomb crystals**

G Morigi[1], D Podolsky[2], S Fishman[2] and E Shimshoni[3]

[1]Saarland University, Germany, [2]Technion, Israel, [3]Bar-Ilan University, Israel

Crystals of repulsively interacting ions in planar traps form hexagonal lattices, which undergo a buckling instability towards a multilayer structure as the transverse trap frequency is reduced. Numerical and experimental results indicate that the new structure is composed of three planes, whose separation increases continuously from zero. We study the effects of thermal and quantum fluctuations by mapping this structural instability to the six-state clock model. A prominent implication of this mapping is that at finite temperature, fluctuations split the buckling instability into two thermal transitions, accompanied by the appearance of an intermediate critical phase. This phase is characterized by quasi-long-range order in the spatial tripartite pattern. It is manifested by broadened Bragg peaks at new wave vectors, whose line shape provides a direct measurement of the temperature-dependent exponent $\eta(T)$ characteristic of the power-law correlations in the critical phase. A quantum phase transition is found at the largest value of the critical transverse frequency: Here, the critical intermediate phase shrinks to zero. Moreover, within the ordered phase, we predict a crossover from classical to quantum behavior, signifying the emergence of an additional characteristic scale for clock order. We discuss experimental realizations with trapped ions and polarized dipolar gases, and propose that within accessible technology, such experiments can provide a direct probe of the rich phase diagram of the quantum clock model, not easily observable in condensed matter analogues. Therefore, this work highlights the potential for ionic and dipolar systems to serve as simulators for complex models in statistical mechanics and condensed matter physics [1].

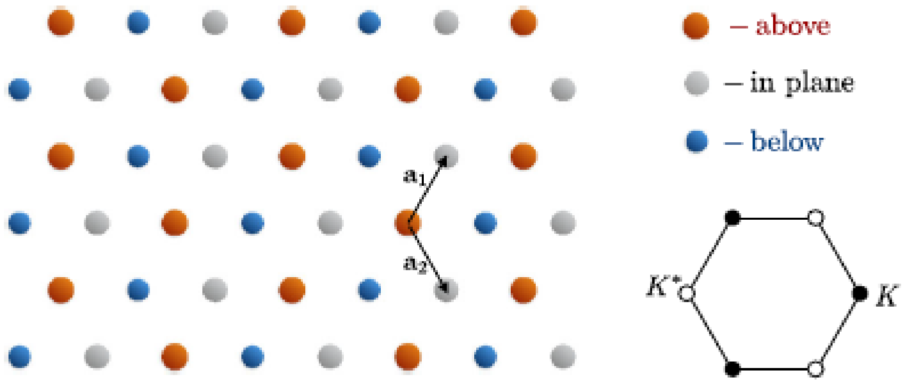


Fig. 1. Ions in a planar trap form a hexagonal lattice, which undergoes a mechanical instability as a function of the temperature and/or the transverse frequency. Left panel: Height pattern in the ordered phase. The hexagonal lattice is split into three sublattices, one of which stays in the z =0 plane (gray circles),one is raised above it (red), and one is lowered below it (blue). There are six inequivalent configurations, corresponding to the 3! possible height assignments to the sublattices. Right panel: The first Brillouin zone of the undistorted hexagonal lattice is shown.

[1] D. Podolsky, *et al.,* Phys. Rev. X 6, 031025 (2016).

(Bates Prize winner) **Optical control and cooling of levitated nanoparticles**

J Millen

University of Vienna, Austria

Levitated systems are a fascinating addition to the world of optically-controlled mechanical resonators. It is predicted that nanoparticles can be cooled to their c.o.m. ground state via the interaction with an optical cavity. By freeing the oscillator from clamping forces dissipation and decoherence is greatly reduced, leading to the potential to produce long-lived, macroscopically spread, mechanical quantum states, allowing tests of collapse models and any mass limit of quantum physics.

Reaching the low pressures required to cavity-cool to the ground state has proved challenging. In this talk I will discuss methods to manipulate nanoparticles in vacuum, and progress towards ultra-high mass interferometry using fabricated microcavities. I will also present our work on controlling the rotation of nanoparticles, which has led to the production of both the fastest spinning and the most frequency stable man-made object.

(invited) **Entanglement swapping of multiple orbital angular momentum states of light**

M Agnew [1], Y Zhang [2], T Roger [1], F S Roux [3], T Konrad [4], D Faccio [1], A Forbes [2, 3] and J Leach[1]

[1]Heriot-Watt University, UK, [2]CSIR National Laser Centre, South Africa, [3]University of Witwatersrand, South Africa, [4]University of KwaZulu-Natal, South Africa

Entanglement swapping generates remote quantum correlations between particles that have not interacted and is the cornerstone of long-distance quantum communication, quantum networks, and fundamental tests of quantum science. The remote creation of high-dimensional entanglement provides an avenue to increase the bandwidth of quantum communications and provides more stringent limits for tests of quantum foundations. I will report on the simultaneous swapping of the entanglement of multiple orbital angular momentum states of light. The system is based on a new quantum protocol using a degenerate filter that cannot distinguish between different anti-symmetric states, and thus entanglement swapping occurs for several thousand pairs of spatial light modes simultaneously. I will also discuss a mechanism that allows high-dimensional entanglement swapping with only four photons, removing the need for scaling photon numbers with dimensions.

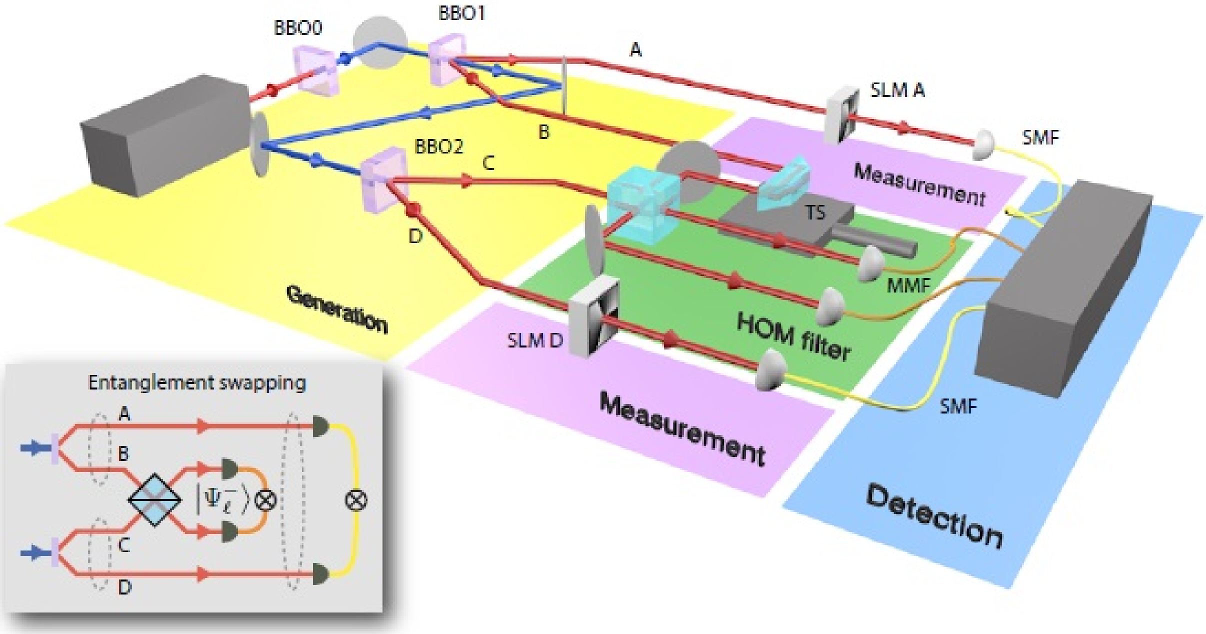


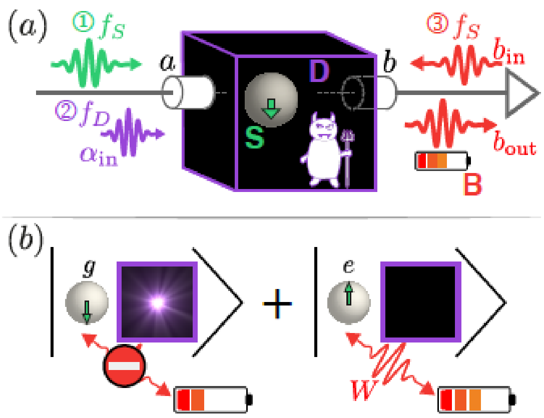
Fig. 1. A simplified version of the experimental setup. BBO 0 is pumped by a Ti:Sapphire laser to produce UV light via upconversion. BBO 1 produces a downconverted pair A and B; BBO2 produces a downconverted pair C and D. The path length of B is adjusted using a translation stage (TS) such that B and C interfere on a beamsplitter; they are projected onto the antisymmetric state when detected in coincidence in the multi-mode fibres (MMFs). At this point, photons at A and D become entangled, which we measure using spatial light modulators (SLMs) in combination with single-mode fibres (SMFs). Inset: A conceptual diagram of entanglement swapping. Entanglement between A and B is transferred to A and D via interference at a beamsplitter and detection in coincidence.

Observing a quantum Maxwell demon at work

J Anders[1], N Cottet[2], S Jezouin[2], L Bretheau[2], P Campagne-Ibarcq[2], Q Ficheux[2], A Auffèves[3], R Azouit[4], P Rouchon[4] and B Huard[2,5]

[1]University of Exeter, UK, [2]Université Paris Diderot, France, [3]Institut Néel, France, [4]Mines ParisTech, France, [5]Ecole Normale Supérieure de Lyon, France

In apparent contradiction to the laws of thermodynamics, Maxwell's demon is able to cyclically extract work from a system in contact with a thermal bath exploiting the information about its microstate. The resolution of this paradox required the insight that an intimate relationship exists between information and thermodynamics. We report on a realisation of a Maxwell demon that tracks the state of each constituent both in the classical and quantum regimes [1]. The demon is a microwave cavity that encodes quantum information about a superconducting qubit and converts information into work by powering up a propagating microwave pulse with stimulated emission. Thanks to the high level of control of superconducting circuits, we directly measure the extracted work and quantify the entropy remaining in the demon's memory. This experiment provides an enlightening illustration of the interplay of thermodynamics with quantum information.



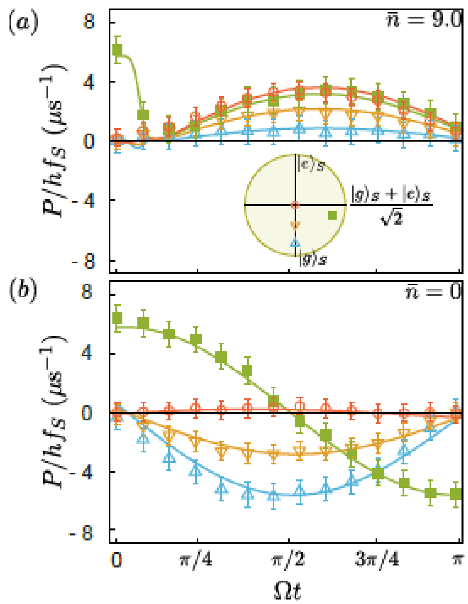


FIG. 1. Sketch of quantum Maxwell demon experiment. (a) After preparation 1 in a thermal (or quantum) state the system S (superconducting qubit) state is recorded 2 into the demon's quantum memory D (microwave cavity). This information is used to extract work W 3, which charges a battery B (a microwave pulse at frequency f_S on port b) with one extra photon.

FIG. 2. Measured extracted power. Measured extracted power for step 3 as a function of time. Blue, orange and red symbols and error bars correspond to an initial system at temperatures T = 0.17, 0.40 K and above 8K (see inset for initial Bloch vectors). Green symbols correspond to an initial quantum superposition. (a) The demon distinguishes the state of the qubit well (memory state $\bar{n}$ = 9). (b) Same figure for a demon who cannot distinguish the qubit states ($\bar{n}$ = 0).

In the experiment [1] the system S is a transmon superconducting qubit with ground $|g\rangle$ and excited $|e\rangle$ states. It is embedded in a microwave cavity which plays the role of the demon's memory D. By driving the cavity through one of the two microwave ports a and b (Fig. 1) coupling between the cavity and the qubit is realised. Work is drawn from the qubit to a microwave pulse B in a completely autonomous manner, with the power varying depending on the initial state of the qubit and the ability of the demon to distinguish the two qubit states (Fig. 2). Finally the state of the demon's memory is read out with quantum tomographic techniques, revealing the information stored by the demon illustrating the resolution of the demonic paradox for the first time.

[1] Cottet et al. PNAS 114 7561 (2017)

Tunable-range, photon-mediated interactions between atoms using a multimode cavity

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Controllable interactions between particles are a key component of quantum simulation and of exploring quantum many-body physics. We demonstrate that, by using a nearly confocal optical resonator [1,2], one may engineer tunable-range interactions between condensates of ultra-cold atoms. We show that the experimental data matches the theoretically expected form of the interaction, giving a clear understanding of the range and form of this interaction. Near confocality, we derive a closed form for the effective interaction potential which decays exponentially at small distances. The length scale of this decay depends on the detuning of the pump beam and the cavity mode spacing, both easily controllable. Together with previous advances in quantum simulation in multimode cavity QED, this flexible interaction opens the way to studying emergent many-body phenomena beyond mean-field theory in a confocal cavity.

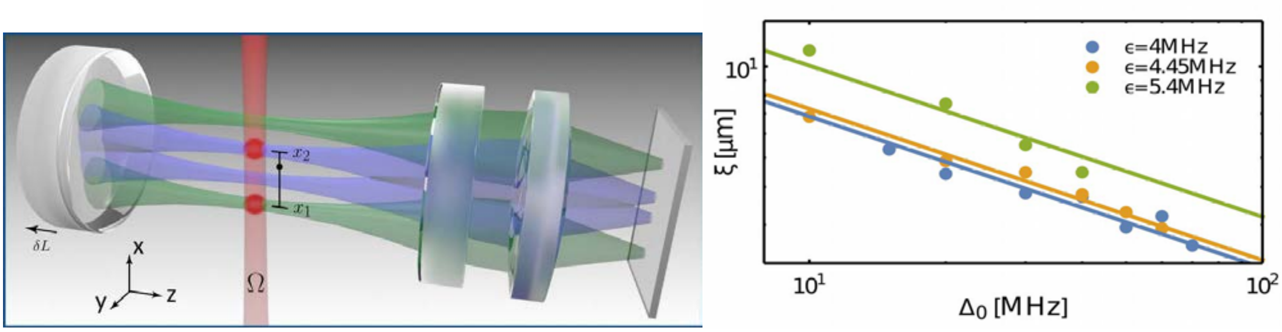

Fig. 1. (a) Schematic of experimental setup with multimode cavity photons mediating interaction between two atomic condensates. (b) Effective atom-atom interaction length as function of detuning from TEM_{00} mode (Δ_0) and mode spacing (ε). Dots are extracted from experiment and dashed lines are a fit to theory.

[1] A. J. Kollar *et al.*, N. J. Phys. 17, 043012 (2015)
[2] A. J. Kollar *et al.*, Nat. Commun. 8, 14386 (2017)

Atomic disciplined charge-qubit clock

D Yu[1], L Chuan Kwek[1], L Amico[1] and R Dumke[1,2]

[1]National University of Singapore, Singapore, [2]Nanyang Technological University, Singapore

Macroscopic superconducting circuits based on Josephson junctions are one of the most promising candidates for implementing quantum computation. Nonetheless, the inevitable relaxation and dephasing, caused by the 1/f fluctuations of the background charge and flux, restrict the further application of these solid devices. A hybrid structure, where the superconducting circuits interact with a microscopic quantum system, such as atoms and ions, may lead to a rapid processor and a long-term memory [1]. However, the weak inter-subsystem coupling strength challenges the practical implementation [2,3,4]. Feedback-control method, which has been widely applied in atomic clocks, may dramatically suppress the noise spectrum of an oscillator and maintain its stability.

We consider a voltage-biased Cooper-pair box as an example. The single excess Cooper pair periodically tunneling between the island and reservoir forms a Rabi oscillator. The environmental fluctuation is mapped onto the voltage source and disturbs the Rabi oscillation. An ensemble of atoms, composed of a ground and Rydberg states, fly through the gate capacitor. The intracapacitor electric field, proportional to the gate-voltage bias, shifts the energy level of Rydberg state while hardly affects the ground state. Combining the Ramsey measurement and shelving detection, the Rabi oscillation is stabilized via feedback controlling the voltage source.

The dynamics of the feedback-controlled Rabi oscillator is numerically performed in a long term. The Allan deviation, which measures the stability of oscillator, is strongly enhanced in comparison with that of the open loop. The ultimate stability is limited by the quantum projection noise and the photon shot noise. To further improve the Rabi oscillator, a larger number of atoms inside the capacitor and a faster decay channel for the shelving detection are required.

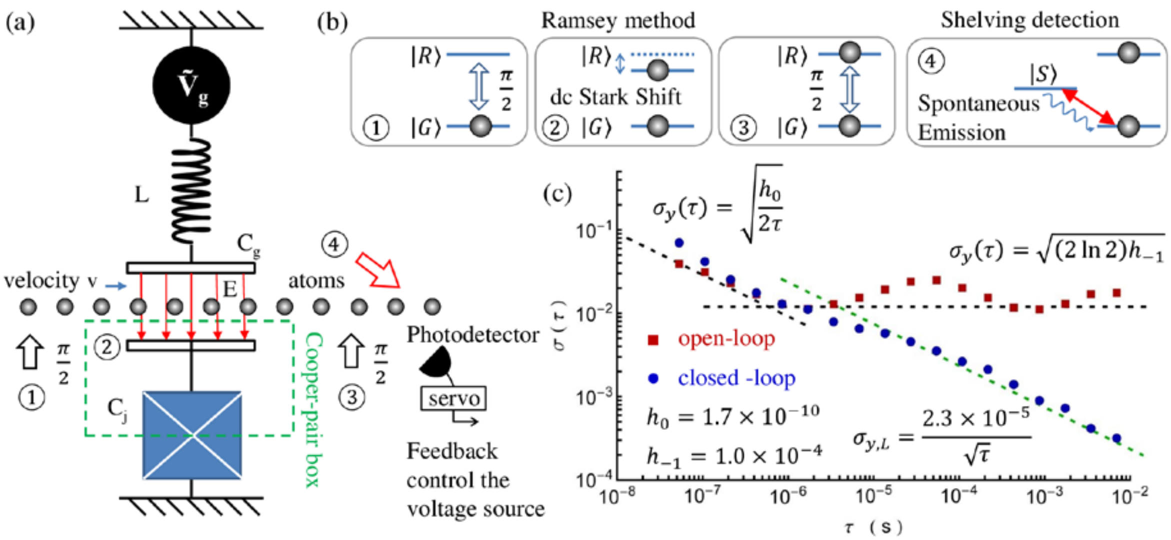

Fig. 1. (a) A superconducting charge quit interacting with an ensemble of atoms composed of a ground and Rydberg states; (b) Ramsey-like measurement and shelving detection; (c) Allan deviation of Rabi oscillation.

[1] D. Yu, *et al.*, Sci. Rep. 6, 38356 (2016)
[2] D. Yu, *et al.*, Phys. Rev. A 93, 042329 (2016)
[3] D. Yu, *et al.*, Phys. Rev. A 94, 062301 (2016)
[4] D. Yu, *et al.*, Phys. Rev. A 95, 053811 (2017)

Posters

P1. Relativistic calculations of K-shell photoionization cross-sections for $^{32}_{16}S$ at 59.6 keV excitation energy

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[1]Mohamed El Bachir El Ibrahimi University, Algeria, [2]L'école Normale Superieure Vieux-Kouba, Algeria, [3]University of Bejaia, Algeria, [4]University of Mohamed Boudiaf, Algeria, [5]LIP-Laboratório de Instrumentação e Física Experimental de Partículas, Portugal, [6]BioISI – Biosystems & Integrative Sciences Institute, Portugal, [7]Iskenderun Technical University, Turkey

In this work we calculate photoionization X-ray cross-sections of K-shell vacancies in S at incident photon energy of 59.6 keV using the Dirac-Fock method and the MCDFGME (Multi Configuration Dirac Fock and General Matrix Element) code [1-3]. Calculations are performed in single configuration approach with the Breit interaction. Higher-order retardation corrections and QED effects were also included as perturbations. Fluorescence yield necessary to derive the X-ray production cross section (XPCS) were obtained in a previous work using the exact same approach. The obtained results are compared to existing theoretical results.

[1] J.P. Desclaux, Comput. Phys. Commun. 9, 31 (1975)
[2] P. Indelicato, J.P. Desclaux, Phys. Rev. A 42, 5139 (1990)
[3] P. Indelicato, O. Gorveix, J.P. Desclaux, J. Phys. B 20, 651 (1987)

P2. 3D control of atomic populations from structured light and darkness

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We demonstrate the use of a room temperature atomic vapour to visualise 3D light structures, and in turn use the 3D light structures to imprint their shape onto the local atomic population distributions. Structured light is often analysed in terms of its 2D beam profile, however on propagation interesting 3D structures can be realised, including optical vortex knots, bottle beams and 3D lattices.

We have previously developed a method to reconstruct the full 3D structure by measuring light scattered from an atomic vapour [1]. The structured light in [1], however, also affects the electronic levels of the atoms in the vapour. Atoms are pumped between electronic levels at rates dependent on the local light intensity, generating 3D population structures. In the room temperature cell atoms continually leave and enter the beam volume. Collisions between cell walls and the atoms redistribute the populations outside the beam. We use a structured laser, shaped by a spatial light modulator and tuned to the D2 transition in rubidium 85, to deplete the $5^2S_{1/2}$ F=3 level within the beam. We pump atoms out of the upper, F=3 ground state via excitation of the short-lived $5^2P_{1/2}$ excited state and subsequent spontaneous decay into the lower F=2 ground state. In dark regions of the beam, atoms remain in the upper ground state and we can probe this remaining population with an unshaped laser driving the D1 transition to the $5^2P_{3/2}$ F=4 stretched state. We then tomographically reconstruct the 3D population pattern from the fluorescence of this probe laser [2]. Bright regions of the structured light beam coincide with suppressed fluorescence from the probe laser. The structured light also produces fluorescence, separated in wavelength from the probe light. The retrieved 3D fluorescence patterns from the two lasers are therefore complementary to each other as shown in Fig. 1.

Here we demonstrate the 3D structuring of atomic populations by measurement of 3D fluorescence distributions. We establish a link between fluorescence rates and populations using a spatially resolved rate equation model.

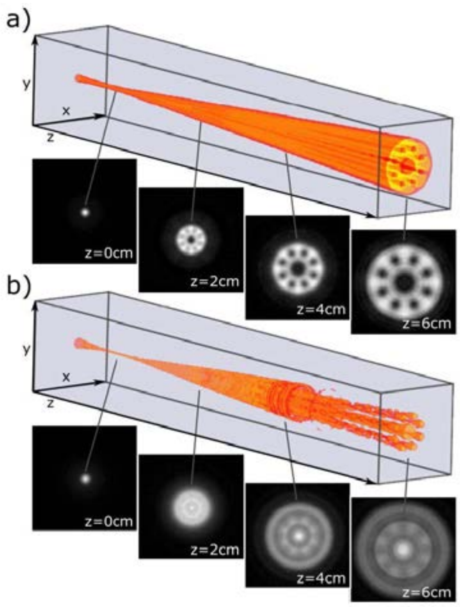

Fig. 1. 3D reconstructions of fluorescence from a) a focused structured light field with an 'optical ferris wheel[3]' profile and b) the corresponding focused (but otherwise unshaped) probe laser. The boxes correspond to a physical volume of approximately 1x1x7 cm3. The insets show the reconstructed cross-sections at various propagation distances from the focus.

[1] N. Radwell, M.A. Boukhet, S. Franke-Arnold, Optics Express, 21, 22215-22220, 2013
[2] A. Selyem, T.W. Clark, N. Radwell and S. Franke-Arnold, in preparation
[3] S. Franke-Arnold, *et al.,* Optics Express, 15, 8619-8625, 2007

P3. Light Scattering from Chiral Molecules

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University of Glasgow, UK

The scattering of light from molecules is often described by a semi-classical treatment, which considers the radiation emitted by the oscillating multipole moments that are induced in the target molecule by the input light [1]. Chirally sensitive optical techniques – such as optical rotation and Rayleigh/Raman optical activity, as well as other effects involving structured light [2] – are fundamentally scattering processes, which can be understood in the above terms through the differing response of the enantiomers to left- and right-handed circularly polarised light

In order to describe these effects, contributions to the scattered intensity up to products of the molecule's electric dipole and magnetic dipole polarisability tensors must be retained. This work presents the contributions made at the next order – involving, among other terms, the squares of the magnetic dipole and electric quadrupole polarisability tensors – and examines their dependence on input polarisation and scattering angle.

[1] Barron L. D., 2004 *Molecular Light Scattering and Optical Activity* 2nd ed. (Cambridge University Press: Cambridge)

[2] Cameron R. P, Barnett S. M., 2014 Optical Activity in the Scattering of Structured Light *Physical Chemistry Chemical Physics* 16 (47) 25819-25829

P4. Atom-light interaction in thermal Rubidium vapours confined to a volume less than λ^3

W J Hamlyn[1], J Keaveney[1], I G Hughes[1],V Sandoghdar[2] and C S Adams[1]

[1]Joint Quntum Centre (JQC) Durham-Newcastle, Durham University, UK, [2]Max Planck Institute for the Science of Light (MPL), Germany

Atom-Light interactions in the quantum regime show promise for applications in quantum information processing e.g. computing. Here, we study the fundamentals of the interaction itself using thermal vapours of Rubidium confined to sub-wavelength scale cavities. We achieve this with bespoke 'Nanocells' made in-house via ion-etching and optical contact bonding. Using a variety of detection methods we achieve high signal-to-noise spectroscopic and photon statistic measurements that indicate the rich effects of the extreme geometry on the atom-light interaction. Ultimately, through use of high numercal aperture lensing, we hope to resolve a single atom in a volume less than λ^3.

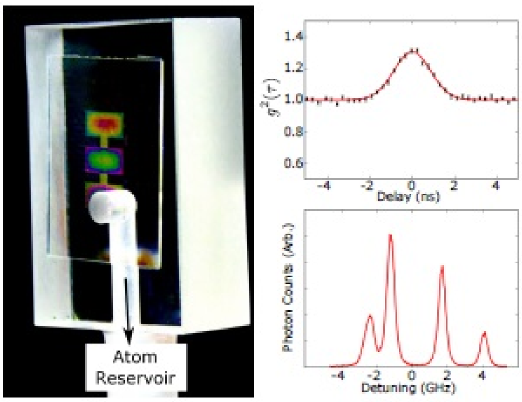

FIG. 1. A photograph of a nano-layer vapour cell (left), photon bunching observed via Hanbury Brown and Twiss [1] method (upper-right), and Total Internal Reflection Fluoresence (TIRF) spectroscopy (lower-right) of the D2 ($5^2S_{1/2} \rightarrow 5^2P_{3/2}$) manifold in Rubidium.

[1] R. Hanbury Brown and R. Q. Twiss, Nature 178 1046-1048 (1956)

P5. Excitation of positronium: from the ground state to Rydberg levels

C J Baker, D Edwards, C A Isaac, H H Telle, D P van der Werf, M Charlton and B C Marshall

Swansea University, UK

Ortho-positronium (o-Ps) was produced with 27-28% efficiency following the bombardment of a mesoporous silica sample by positrons ejected from a two-stage buffer gas trap. This ensemble was emitted into vacuum with a density close to 10^{11} m^{-3}. Excitation of the o-Ps Lyman-α transition, followed by subsequent excitation and, if desired, ionisation to vacuum was enabled by a tunable solid state laser system with a wide wavelength range (230-1500 nm). Irradiation of o-Ps has resulted in excitation into the 2P state and furthermore to higher principle quantum number (n_{Ps}) states, resolvable in the range $3 \leq n_{Ps} \leq 18$ with efficiencies $\varepsilon^{nPs} \geq 80\%$, whilst the excitation efficiency of ground state o-Ps to the 2P state of $\varepsilon^2 \sim 13\%$ is currently limited by the Doppler broadening of the 1S-2P transition and the 225 GHz laser bandwidth at 243 nm.

P6. A compact inertial sensor using atom interferometry

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Imperial College London, UK

Inertial navigation systems (INS) rely on accelerometers and gyroscopes to track the position of an object over time. The accuracy and stability of these devices are limited primarily by their electronic and mechanical bias drift. Cold-atom interferometers, which uses atom-light interactions, can provide a good solution as they can be used as absolute inertial sensors [1]. They benefit from the long-term stability of atoms and can achieve higher inertial sensitivity than conventional sensors. To be used as an INS, the cycling time of these systems also have to be high such that the loss of information introduced by the dead-time is negligible [2, 3].

Here, we present our work towards a 3-axis cold atom accelerometer using Rubidium-87 atoms. Our cold atoms are prepared in a 3D-MOT, fast-loaded by a 2D-MOT, under ultra-high vacuum. We achieve consistent 10^7 atoms prepared at ~10 μK in few Hz of experimental cycling time. This provides enough atomic signal to perform a three-pulse Mach-Zehnder (π/2-π-π/2) interferometer, using momentum-sensitive Raman transitions, to measure the acceleration with high sensitivity. A large dynamic operation range can be achieved by hybridizing the atom interferometer with that of a conventional MEMS accelerometer [4]. This MEMS accelerometer has been mounted in-vacuum. Our inertial sensor is designed as a sensor head of no more than 10 litre of volume and connected to the experimental hardware which is designed as transportable rack-mounted systems. An in-vacuum optical system collimates the laser light used for the momentum-sensitive atom-light interaction with very low wavefront distortion to maintain high sensitivity to linear accelerations when the atoms fall under gravity.

We aim to achieve a repetition rate of 10 Hz to reduce the dead-time while maintaining a good signal-to-noise ratio. Currently, we are testing the system as a one-axis acceleration sensor to measure horizontal acceleration with a sensitivity of 100 ng/√Hz and a dynamic range of +/- 0.3g.

P7. Vacuum friction and other surprises emerging from the Roentgen interaction term

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[1]University of Glasgow, UK, [2]Technische Universität Darmstadt, Germany

We show how a simple calculation on textbook level leads to the surprising result, that an excited two-level atom moving through vacuum sees a (tiny) friction force in first order v/c.

At first sight this seems to be in obvious contradiction to other calculations showing that the interaction with the vacuum does not change the velocity of an atom. Even worse, it appears to be in contradiction to the principle of relativity. It is thus even more surprising that this change in the atom's momentum turns out to be a necessary result of energy and momentum conservation in special relativity [1].

To solve this puzzle we have to include the Roentgen term, an often neglected contribution to the usual atomlight Hamiltonian, which is known to affect calculations on the spontaneous decay rate of moving atoms [2,3].

But it is less known that this term can also lead to intricate forces on atoms in laser fields, in addition to the usual dipole force and radiation pressure. We will thus also discuss some surprising features of this interaction, including forces acting perpendicular to the propagation axis of a plane-wave laser field [4].

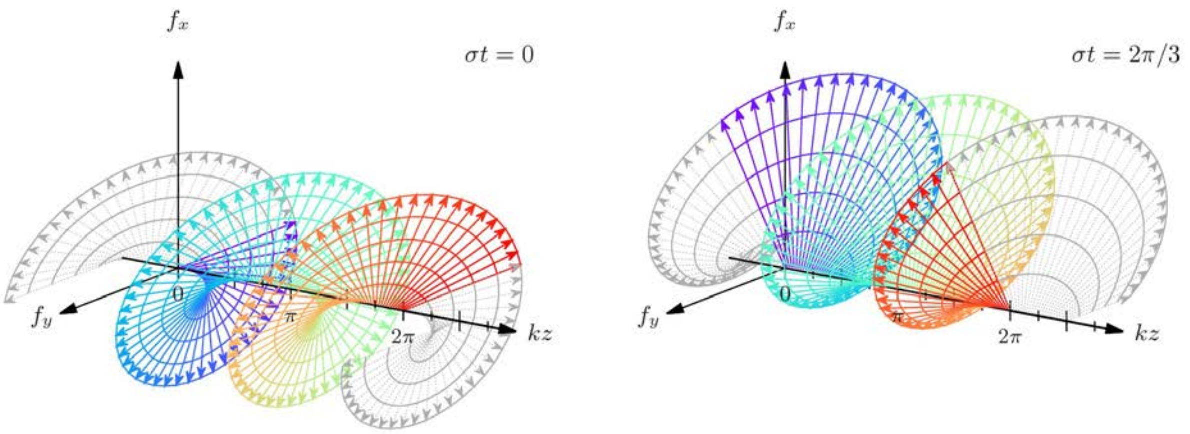

Fig. 1: Using an atom in which ground ans excited states are each respectively degenerate, a static magnetic field and two counter-propagating plane-wave laser beams in a σ+ – σ- configuration, one can generate time-dependent radiation forces, acting perpendicular to the beam-propagation axis. The relative detuning between the light beams determines the time-scale σt.

[1] M. Sonnleitner, N. Trautmann and S.M. Barnett, Phys. Rev. Lett 118, 053601 (2017)
[2] M. Wilkens, Phys. Rev. A 49, 570 (1994)
[3] J. D. Cresser and S. M Barnett, J. Phys. B: At. Mol. Opt. Phys. 36, 1755 (2003)
[4] M. Sonnleitner and S.M. Barnett, arXiv:1704.01835 (2017)

P8. Creating a superfluid by kinetically driving an insulator

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We study the effect of time-periodically varying the hopping amplitude (which we term “kinetic driving”) in a one-dimensional Bose-Hubbard model, such that the time-averaged value of the hopping is zero. By making a Floquet analysis, we derive a static effective Hamiltonian for the system, which has the unusual feature that the nearest-neighbor single-particle hopping processes are suppressed, but all even higher-order processes are allowed, and can be arbitrarily long-ranged. Unusual many-body features arise from the combined effect of non-local interactions and correlated tunneling. At a critical value of the driving, the system passes from a Mott insulator to a superfluid formed by two condensates with opposite non-zero momenta. The onset of this phase transition can be understood in terms of bound doublon-hole pairs coexisting with the Mott insulator state to form a Luttinger liquid, and evaluating the Luttinger liquid parameters allows the point of this phase transition to be precisely located. This work shows how driving of the kinetic energy can be used as a novel form of Floquet engineering, which enables exotic Hamiltonians and unusual states of matter to be produced and controlled.

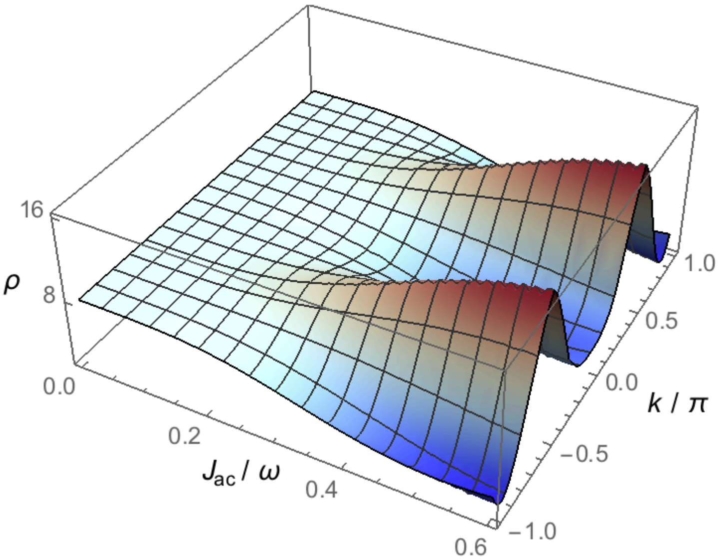

Fig. 1. Momentum density over the first Brillouin zone, for an 8-site system, as the amplitude of the driving J_{ac} is varied. In the absence of driving the momentum density is flat, corresponding to the Mott state. As J_{ac} is increased, peaks appear at $\pm\pi/2$, indicating the formation of a fragmented condensate at these momenta.

[1] G. Pieplow, F. Sols, and C.E. Creffield, arXiv:1706.04864

P9. Towards high resolution spectroscopy of N_2^+

A Gardner and M Keller

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High resolution spectroscopy of molecular nitrogen is a prime candidate for measurement of a potential variation in the electron-to-proton mass ratio μ [1]. Prerequisites are preparation and non-destructive state detection of the internal states of N_2^+.

Ion traps provide a highly isolated and stable environment, as well as enabling the high degree of localisation that is vital for high resolution spectroscopy. Additionally multiple species can be confined in the same potential, allowing for techniques such as sympathetic cooling [2] and non-destructive state detection [3,4] which take advantage of the shared motional modes for internal state readout to be employed. This allows for the translational cooling and spectroscopy of complex species such as molecular ions, which has been demonstrated for molecules such as $^{24}MgH^+$ [5] and $^{40}CaH^+$ [6].

In this experiment an ion trap and molecular beamline system have been set up. The fluorescence from laser-cooled ^{40}Ca-ions will be used for the state-readout of the co-trapped N_2^+. The non-destructive state detection scheme relies on a weak state-dependent dipole force that is used to resonantly excite the motion of the $^{40}Ca^+$- N_2^+ Coulomb crystal. In order to make this excitation detectable, a separate pulse scheme has been devised to amplify the motion and extend the period of oscillation, using a rapid change in radiation pressure of the $^{40}Ca^+$ cooling laser to simulate the dipole force [7]. The frequency of the secular motion can then be detected via Doppler velocimetry.

A separate ionisation spectroscopy experiment has been used to investigate the $a^1\Pi_g$ (v=10) $\leftarrow$ $X^1\Sigma_g^+$ (v=0) band in N_2 for state preparation via a same-colour 2+1 resonance enhanced multi-photon ionisation (REMPI) process. By employing an additional laser, a new 2+1' REMPI scheme can be used for fully state-selective ion preparation, by use of the $a^1\Pi_g$ (v=6) $\leftarrow$ $X^1\Sigma_g^+$ (v=0) band in N_2.

[1] M. Kajita et al., Physical Review A 89, 032509 (2014)
[2] J. B. Wübbena et al., Physical Review A 85, 043412 (2012)
[3] D. B. Hume et al., Physical Review Letters 107, 243902 (2011)
[4] P. O. Schmidt et al., Science 309, 5735 (2005)
[5] F. Wolf et al., Nature 530, 457 (2016)
[6] C. Chou et al., arXiv:1612.03926v2 (2017)
[7] K. Sheridan et al., European Physical Journal D 66, 289 (2012)

P10. Conditional quasi-exact solvability of the quantum planar pendulum and of its anti-isospectral hyperbolic counterpart

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[1]Freie Universität Berlin, Germany, [2]Fritz-Haber-Institut der Max-Planck-Gesellschaft, Germany

We, in [1], have subjected the planar pendulum eigenproblem to a symmetry analysis with the goal of explaining the relationship between its conditional quasi-exact solvability (C-QES) and the topology of its eigenenergy surfaces, established in our earlier work [2]. The present analysis revealed that this relationship can be traced to the structure of the tridiagonal matrices representing the symmetry-adapted pendular Hamiltonian, as well as enabled us to identify many more -- forty in total to be exact -- analytic solutions. Furthermore, an analogous analysis of the hyperbolic counterpart of the planar pendulum, the Razavy problem, which was shown to be also C-QES [3], confirmed that it is anti-isospectral with the pendular eigenproblem. Of key importance for both eigenproblems proved to be the topological index $\boldsymbol{\kappa}$, as it determines the loci of the intersections (genuine and avoided) of the eigenenergy surfaces spanned by the dimensionless interaction parameters $\boldsymbol{\eta}$ and $\boldsymbol{\zeta}$ It also encapsulates the conditions under which analytic solutions to the two eigenproblems obtain and provides the number of analytic solutions. At a given $\boldsymbol{\kappa}$, the anti-isospectrality occurs for single states only (i.e., not for doublets), like C-QES holds solely for integer values of $\boldsymbol{\kappa}$, and only occurs for the lowest eigenvalues of the pendular and Razavy Hamiltonians, with the order of the eigenvalues reversed for the latter. For all other states, the pendular and Razavy spectra become in fact qualitatively different, as higher pendular states appear as doublets whereas all higher Razavy states are singlets.

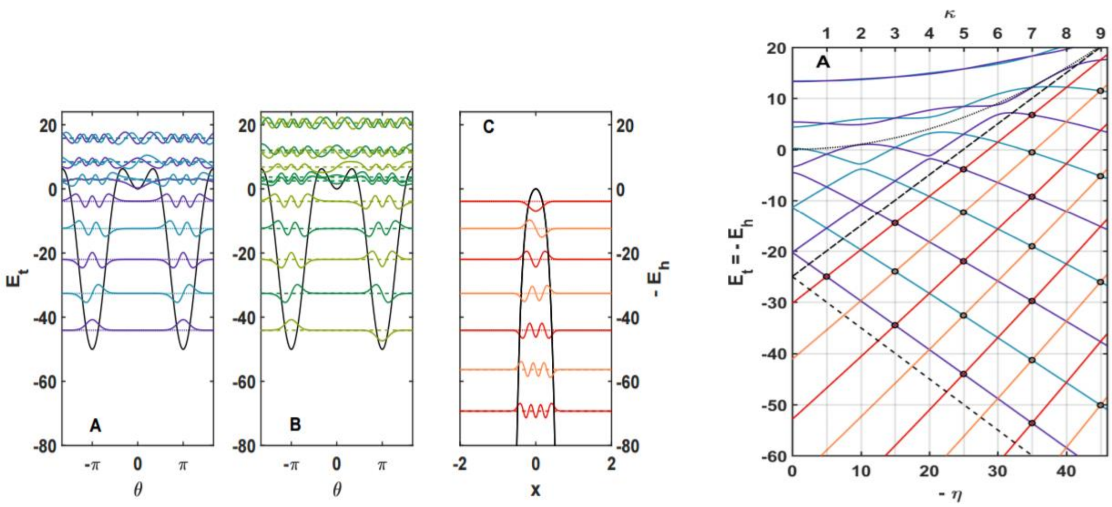

Fig. 1. (Left) Trigonometric (A, B) and inverted hyperbolic (C) potentials for $\boldsymbol{\kappa}$ = 5; (right) numeric and analytic energies of planar pendulum (with periodic boundary condition) and inverted energies of the Razavy system for different $\boldsymbol{\kappa}$ values.

[1] Becker, S. and Mirahmadi, M. and Schmidt, B. and Schatz, K. and Friedrich, B., Eur. J. Phys. D, 71 (6). p. 149. (2017)
[2] B. Schmidt, B. Friedrich, Front. Phys. Phys. Chem. Chem. Phys. 2, 1 (2014)
[3] M. Razavy, Am. J. Phys. 48, 285 (1980)

P11. Fresnel holography for atomic waveguides

V A Henderson, M Y H Johnson, Y B Kale, P F Griffin, E Riis and A S Arnold

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The progress and practicality of quantum technologies, such as rotation sensing, are contingent on the portability of existing ultracold atom technologies [1] and the exploration of new alternative techniques. In response to this, we integrate existing knowledge with new Fresnel Zone Plate (FZP) hologram chips (Fig. 1a, b [2]) to develop a compact Bose-Einstein condensate interferometry device. Due to high precision microfabrication, FZPs are exciting candidates for the production of static trapping potentials useful to atomtronics, interferometry, and fundamental physics. They are particularly useful for quantum technologies due to their low cost and simplicity.

The suitability of FZPs has been demonstrated with computational simulations comparing FZPs to spatial light modulators [2]. Experimental imaging of a range of manufactured ring patterns gives an average RMS error in the brightest 10% of at most 10% with respect to trap depth. A typical ring (of RMS error 3%) is shown in Fig. 1c, d, with this limited by the imaging system, beam shape and alignment. The patterns will be further characterised using ultra-cold atoms.

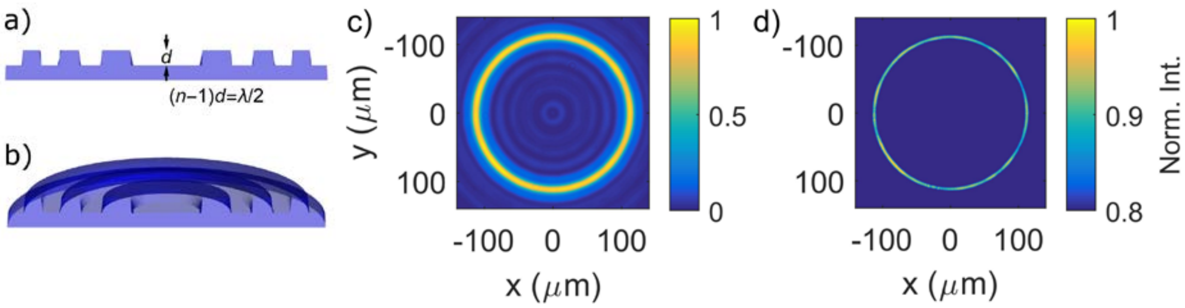

FIG. 1: A binary phase pattern is used to produce a transmission hologram as shown in (a) and (b). In these holograms, a phase pattern is etched in refractive index n material, with half-wavelength steps in optical depth $(n-1)d$. (c) and (d) show 0-100% and 80-100% respectively, of the normalised experimental intensity in the focal plane of a ring of radius 112μm.

[1] J. P. McGilligan, P. F. Griffin, R. Elvin, S. J. Ingleby, E. Riis, A. S. Arnold, Sci. Rep. 7, 384 (2017)

[2] V.A. Henderson, P.F. Griffin, E. Riis and A.S. Arnold, New J. Phys. 18, 025007 (2016)

P12. Progress towards a trapped atom clock guided interferometer

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[1]Institute of electronic structure and laser (IESL), Foundation for research and technology Hellas (FORTH), Greece,
[2]University of Crete, Crete

We present recent advances towards the realisation of a trapped state-dependent guided Sagnac clocktype atom interferometer. In our proposal [1], the clock states of Rubidium87, $|2{,}1\rangle$ and $|1,-1\rangle$, would be guided independently and simultaneously in a ring TAAP waveguide [2] along two opposite paths.

Two Ramsey sequences before and after a full turn over the waveguide would create a population imbalance proportional to the phase accumulation between the two paths [3] Therefore, since in our system the time an atom cloud takes to complete a full rotation in the waveguide without spreading is of the order of 1s, the stability of the atom clock needs to be of the order of $\sim$1Hz. Matching the traps of the two states at the magic field, where differential Zeeman shifts are suppressed [4], is a fundamental challenge.

As a first approach to the realisation of an atom clock in the rf dressed potential, we have implemented a bi-chromatic radio-frequency trapping configuration that yields two state dependent shell traps [5], for $|2{,}1\rangle$ and $|1,-1\rangle$, respectively. These are independently tuneable in position and curvature, therefore providing lower dephasing rates at the matching conditions. In parallel, we have developed several techniques for the loading, adiabatic manipulation and acceleration of a BEC in a ring potential.

Fig 1. Slow BEC oscillations in a tilted Time Averaged Adiabatic ring potential. Each picture is an absorption image separated by 50ms. The leftmost picture corresponds to $\sim$100ms after the release of the BEC in the tilted ring trap.

[1] P. Navez, S. Pandey, H. Mas et al., New J. Phys. 18 075014 (2016)
[2] I. Lesanovsky and W. von Klitzing Phys. Rev. Lett. 99, 083001 (2007)
[3] R. Stevenson, et al. Phys. Rev. Lett. 115 (16) 163001 (2015)
[4] Szmuk et al., Phys. Rerv. A 92, 012106 (2015)
[5] O. Zobay and B. M. Garraway, Phys. Rev. Lett. 86, 1195 (2001)

P13. Towards a BEC-ONF Quantum Interface

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We report on the successful implementation of a single-mode tapered optical nanofibre (ONF) [1] into our experimental setup. Preliminary results show that the photon count rate in one pigtail increases when Rb-87 atoms are present in a MOT formed in the vicinity of the ONF, indicating that the atoms can be detected by the fibre. The result is similar to previously reported experiments with Cs atoms [2], but more data is needed to accurately quantify the increase. More recently we have achieved a pure magnetic trap in the vicinity of the ONF with no visible deleterious effects on the trap. We have additionally shown that we have control over the internal state of the atoms by means of optical pumping which could be of great interest when exploring atom-ONF interactions.

Confirmation of an atom-ONF-photon interface allows us to progress to the final stage of our plan to create a Bose-Einstein condensate (BEC)-ONF interface. Before installing the fibre we have routinely trapped Rb-87 atom magnetically and we have recently incorporated the 'dimple trap' [3] in our experimental setup. In addition to this, our setup has provision for combining the ONF and a high-resolution optical microscope.
Optical nanofibres are excellent imaging tools with single atom sensitivity [4]. Such a tool could be used to reconstruct the correlation function of atoms [5] to explore the existence of exotic phase transitions in quantum degenerate gases [6]. ONFs also show promise in applications relating to quantum information processing [7]–[9].

[1] F. Warken, E. Vetsch, D. Meschede, M. Sokolowski, and A. Rauschenbeutel, "Ultra-sensitive surface absorption spectroscopy using sub-wavelength diameter optical fibers.," Opt. Express, vol. 15, no. 19, pp. 11952–11958, 2007

[2] K. P. Nayak, P. N. Melentiev, M. Morinaga, F. Le Kien, V. I. Balykin, and K. Hakuta, "Optical nanofiber as an efficient tool for manipulating and probing atomic Fluorescence.," Opt. Express, vol. 15, no. 9, pp. 5431–5438, 2007

[3] Y.-J. Lin, A. R. Perry, R. L. Compton, I. B. Spielman, and J. V. Porto, "Rapid production of R 87 b Bose-Einstein condensates in a combined magnetic and optical potential," Phys. Rev. A, vol. 79, no. 6, p. 63631, Jun. 2009

[4] K. P. Nayak and K. Hakuta, "Single atoms on an optical nanofibre," New J. Phys., vol. 10, no. 5, p. 53003, May 2008

[5] J. A. Grover, P. Solano, L. A. Orozco, and S. L. Rolston, "Photon-correlation measurements of atomic-cloud temperature using an optical nanofiber," Phys. Rev. A - At. Mol. Opt. Phys., vol. 92, no. 1, p. 13850, Jul. 2015

[6] Á. Rapp, G. Zaránd, C. Honerkamp, and W. Hofstetter, "Color Superfluidity and 'Baryon' Formation in Ultracold Fermions," Phys. Rev. Lett., vol. 98, no. 16, p. 160405, Apr. 2007

[7] R. Kumar, V. Gokhroo, and S. N. Chormaic, "Multi-level cascaded electromagnetically induced transparency in cold atoms using an optical nanofibre interface," New J. Phys., vol. 17, no. 12, p. 123012, Dec. 2015

[8] C. Sayrin, C. Clausen, B. Albrecht, P. Schneeweiss, and A. Rauschenbeutel, "Storage of fiber-guided light in a nanofiber-trapped ensemble of cold atoms," Optica, vol. 2, no. 4, p. 353, Apr. 2015

[9] P. Lodahl, S. Mahmoodian, S. Stobbe, A. Rauschenbeutel, P. Schneeweiss, J. Volz, H. Pichler, and P. Zoller, "Chiral quantum optics," Nature, vol. 541, no. 3, 2017

P14. Spatially dependent Electromagnetically Induced Transparency

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[1]University of Glasgow, UK, [2]Università di Napoli Federico II, Italy

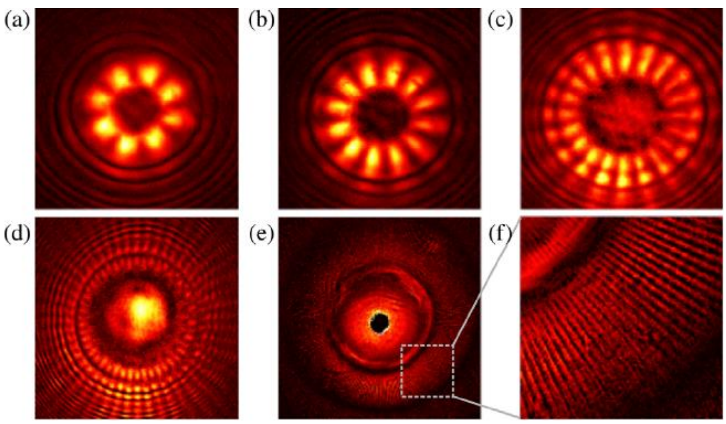
We demonstrate the rise of Spatially dependent Electromagnetically Induced Transparency (SEIT) in a sample of cold atoms, where light beams with Orbital Angular Momentum (OAM) are used to locally modify the atoms' absorption, and therefore their transparency [1].

In a typical EIT configuration, two lower atomic states are coupled to a common upper state with two near-resonant laser beams. EIT is often characterised by scanning a laser beam across the atomic transition, with transparency occurring for two-photon resonance. Here, on the other hand, we show that EIT also depends on the relative phase between the two driving laser beams, so that a beam with locally varying phase structure results in spatially varying dark states, and hence spatially varying EIT. Typical EIT is not phase dependent. In our case, however, the two lower states are coupled by a residual transverse magnetic field, resulting in a closed atomic system which displays phase dependence.

To achieve SEIT in our lab we prepare a Rb^{87} atomic sample with $2*10^{11}$ cm^{-3} density in the lower F=1 ground state. A magnetic field of about 0.1 G is directed mainly along the propagation direction of the beam, with only a fraction in the transverse plane. This transverse component gives rise to a Hanle-type coupling of the lower levels. We structure the phase of our EIT beams by use of *q*-plates [2], which for a charge of $q=l/2$, and linearly polarized input light generate a field with opposite OAM in the right and left handed polarization component $\sigma + e^{-i2q\phi} + \sigma\_e^{+i2q\phi}$. So that from linearly polarized light passing through the q-plate comes out a beam with correlations between polarization and azimuthal angle of the probe laser, which also results in the generated beams containing OAM.

The interaction between this shaped light beam and the atoms is analysed from the absorption imaging, of which the Figures (a) to (f) are examples. The number of lobes in each picture is $2l$, where l is the OAM value of the beam.

We have shown theoretically that the absorption pattern changes as a function of both the intensity and the direction of the magnetic field, so that the system should be suitable as a high resolution magnetic field rotation detector.



Absorption patterns for different q values, each showing a 4q-fold symmetry, for q= 2 (a), q = 3 (b), q = 5 (c), q = 12 (d), and q = 100 (e), with a zoom of the marked section in (f). All absorption patterns arise from single shot images.

[1] N. Radwell, T.W. Clark, B. Piccirillo, S. M. Barnett, and S. Franke-Arnold1 PRL 114, 123603 (2015)
[2] L. Marrucci, C. Manzo, and D. Paparo, PRL 96, 163905 (2006)

P15. Interferometry with ultra-cold atoms in a BEC using optical waveguides

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[1]University of Liverpool, UK, [2]National Physical Laboratory, UK, [3]University of Birmingham, UK

An atom interferometer based upon a novel distributed quasi-Bragg splitter for cold atoms propagating in optical waveguides is under development at the National Physical Laboratory. Atoms are guided by horizontal red-detuned laser beams which cross with a variable angle θ. A lattice is formed from the interference between the two waveguides and is used as a quasi-Bragg splitter to coherently split the atomic wavepacket between the two waveguides. Among other applications, this appears promising for the realization of coherent matter wave circuits with enclosed areas to operate as gyroscopes for potential uses in inertial navigation.

P16. Dynamics of a quantum system driven by multiple harmonic fields

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Applying harmonic perturbations to quantum systems, it is possible to access at least three applications: (1) investigate the system's properties (e.g. via spectroscopy); (2) prepare quantum states (e.g. qubit rotations); (3) modify or prepare the system response to external fields (e.g. electromagnetically induced transparency). Nowadays, in a number of quantum platforms (e.g. cold atoms, trapped ions, NV centres and superconducting circuits) it is possible to use two or more harmonic fields to simultaneously produce a combination of these functions. This is accomplished by tuning each harmonic drive to affect a specific degree of freedom (e.g. atomic motional and internal states). In many of these experimental implementations, it is possible to reach the regime of strong driving, for which an accurate description requires going beyond standard simplifications (e.g. rotating wave approximation and resonant two-level system).

In this work, we describe a multimode Floquet formalism to study the dynamics of quantum systems subject to several harmonic fields, without a limitation in the coupling strength. We provide a recipe to construct a numerically accurate time-evolution operator and time-averaged transition probabilities in an arbitrary basis. Both of these applications are required to study atomic and condensed matter systems driven by strong electromagnetic radiation. As a concrete example, we consider the dynamics of 87Rb, driven simultaneously by radiofrequency and microwave radiation. This configuration is commonly used to perform interferometric sequences of spatially traped atomic ensembles [1]. We will present results on the response of radio-frequency 'dressed' atoms to a microwave field and describe applications for atomic interferometry [2] and quantum information processing [3].

[1] G. A. Sinuco-Leon and B.M. Garraway, NJP 17, 053037 (2015)
[2] G.A. Sinuco-Leon, K. Burrows, B.M Garraway and A. Arnold. Nat. Comm. 5, 5289 (2014)
[3] G. A. Sinuco-Leon and B.M. Garraway, NJP 18, 035009 (2016)

P17. Ultracold atoms as a quantum transport simulator subject to classical noise fields

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Recent measurements on key biological exciton transport structures in photosynthesis complexes have demonstrated that quantum behavior may play a key role in such structures [1]. Especially of interest is the interaction of the systems with a surrounding environment. (see eg. [2,3,4]). Typical theoretical treatments model the structures as quantum networks operating in noisy environments.

We present a cold atoms system used to simulate and probe simple models of quantum networks subjected to classical noise fields, which mimic external coupling to an environment. A linear chain of states is coupled off-resonantly with radiofrequency fields and a classical noise field applied to the state energy levels. We demonstrate coherent enhancement of the state transfer for single-frequency “noise” and statistically averaged enhancement for broadband noise drawn from stochastic processes. We observe in the broadband results the presence of a maximum transport enhancement for a particular strength of the external noise field.

We also present future steps towards a more complex network topology as well as a potential implementation of irreversible transfer out of the network, or a so called ‘sink’ state.

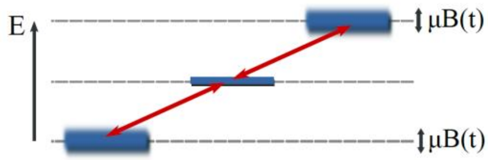

Fig. 1. The three magnetic projection sublevels subjected to a magnetic bias field, to control their relative energies, and coupled using a radiofrequency magnetic field. Arbitrary modulation in time of the bias field provides an external stimulus on the system, simulating a noise process. This process can increase coupling when the radiofrequency coupling is off-resonant.

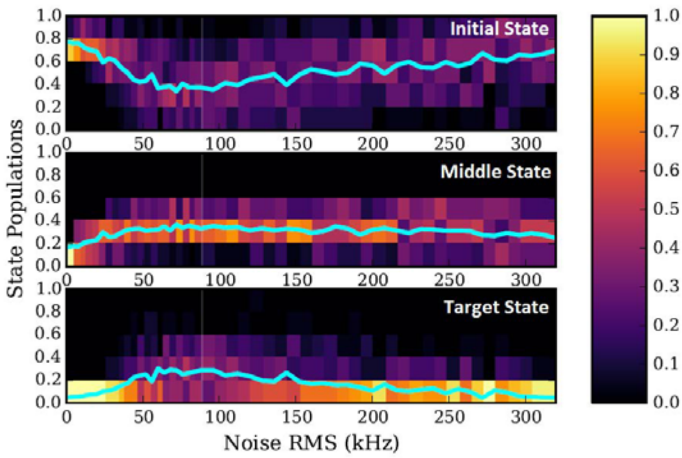

Fig. 2. Two-dimensional histogram binning and mean (cyan lines) of the populations of the magnetic sublevels after a fixed time for multiple trajectories of a random white-noise process applied to the noise field. A clear maximum of transfer to the target state is visible when varying the strength of the noise field.

[1] G. S. Engel, *et al.*, Nature 446, 782-786 (2007).
[2] F. Caruso, *et al.*, The Journal of Chemical Physics 131, 105106 (2009).
[3] D.P. S. McCutcheon, A. Nazir, The Journal of Chemical Physics 114501 (2011).
[4] N. Lambert, *et al.*, Nature Physics 9, 10-18 (2013)

P18. A Gravity Gradiometer based on an NPL Rb Atomic Fountain

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[1]National Physical Laboratory, UK, [2]University of Liverpool, UK

A gravimeter and gravity gradiometer package based on an atomic interferometer is being developed by leveraging a frequency fountain system from NPL in collaboration with the University of Liverpool atomic interferometry research group. In addition to many potential industrial applications, the device also allows for an opportunity to test many novel concepts in interferometry and provides opportunities in fundamental physics, whilst concurrently building on the long-term stability and robustness of the NPL fountain program. Work towards the full experimental realisation of the device is ongoing, with fast loading and juggling capability demonstrated. A pair of phase-locked telecommunication lasers (1560 nm output) are to be frequency-doubled to form the basis of the Raman beam system, which is currently in the process of being tested.

P19. Design and construction of an Atom Interferometer at the University of Liverpool

A Carroll, J Coleman, G Elertas, C Metelko, D Morris and J Tinsley

University of Liverpool, UK

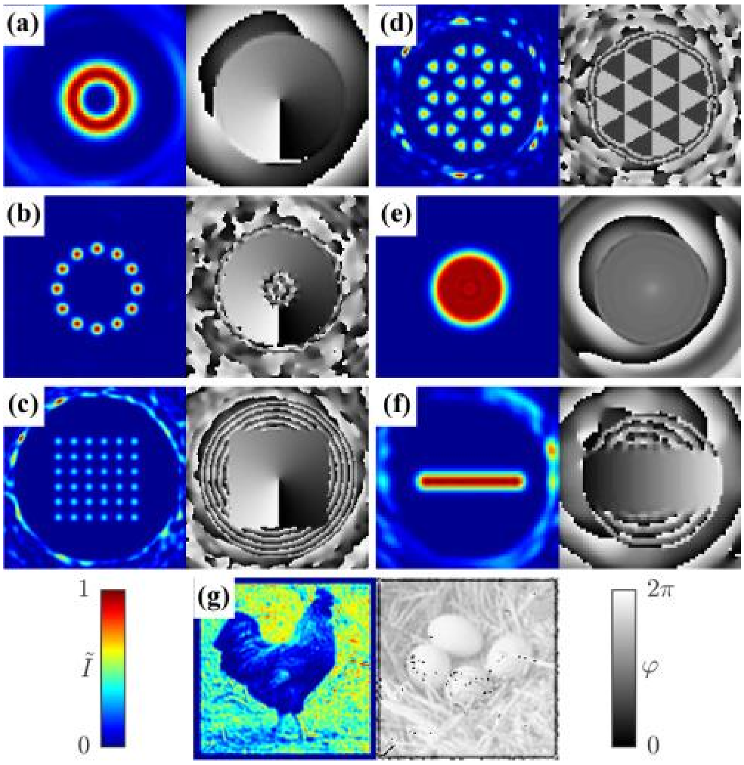
An atom interferometer at the University of Liverpool has been developed at low-cost by employing common-off-the-shelf components with minor modifications, using 85Rb as the atomic medium and a simplified two-laser optical system for state manipulation. This device is intended for dark content of the vacuum searches, as well as a test stand for inertial sensing applications. We can report the recent observation of Rabi oscillations and Ramsey fringes in the apparatus. Upgrades are currently underway towards realisation of the experiment’s long term goals.

P20. Potential landscaping for ultracold atoms using holographic optical traps

D Bowman[1], T Harte[2], P Ireland[1], D Cassettari[1] and G D Bruce[1]

[1]University of St Andrews, UK, [2]University of Oxford, UK

The development of new laser beam shaping methods is important in a variety of fields within optics, atomic physics and biophotonics. Spatial light modulators offer a highly versatile method of time-dependent beam shaping, based on imprinting a phase profile onto an incident laser beam that determines the intensity in the trapping plane laser field. The calculation of the required phase is a well-known inverse problem, which can be tackled with different approaches. Our method based on conjugate gradient minimisation [1] not only allows the calculation of smooth and accurate intensity profiles suitable for trapping cold atoms, but can also be used to generate multi-wavelength traps [2] and for simultaneous control over both the intensity and the phase of the light [3], with exceptionally high reconstruction fidelity.



Simultaneous control over the amplitude (colour) and phase (gray) of holographic optical traps [3]

[1] T Harte, et al., "Conjugate gradient minimisation approach to generating holographic traps for ultracold atoms" Opt. Express 22, 26548 (2014)

[2] D Bowman, et al., "Multi-wavelength holography with a single spatial light modulator for ultracold atom experiments" Opt. Express 23, 8365 (2015)

[3] D Bowman, et al., "High-fidelity phase and amplitude control of phase-only computer generated holograms using conjugate gradient minimisation" Opt. Express 25, 11692 (2017)

P21. An ultracold mixture of Cs and Yb: Towards quantum simulation with ultracold $^2\Sigma$ molecules

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[1]Durham University, UK, [2]University of Western Australia, Australia

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

I will present the development of our two-species apparatus [4–6] for the production of ultracold $^2\Sigma$ molecules. I will then demonstrate the capability of the two-species apparatus in producing cesium BECs containing 4×10^4 atoms and large ytterbium BECs containing in excess of 4×10^5 atoms. I will also discuss our recent experiment [7] where we have measured the interspecies thermalisation cross sections of Cs – ^{170}Yb and Cs – ^{174}Yb systems; the comparison of these measurements to quantum scattering calculations allows us to predict the scattering lengths of all isotopic combinations of Cs and Yb. Finally, I will present our ongoing measurements of the CsYb* molecular potential via 1-photon photoassociation spectroscopy.

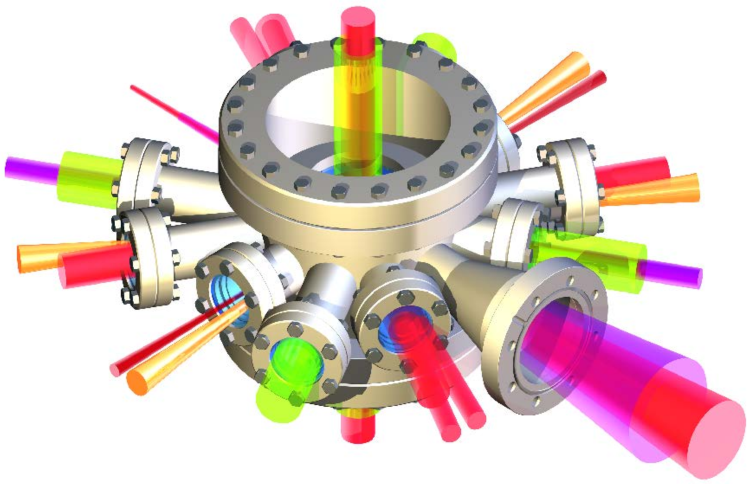

Figure 1: Optical layout of the CsYb apparatus

[1] P. S. Zuchowski, J. Aldegunde, J. M. Hutson, Phys. Rev. Lett.105, 153201 (2010)
[2] K. Bergmann, H. Theuer and B. W. Shore, Rev. Mod. Phys. 70, 1003 (1998)
[3] A. Micheli, G. K. Brennen and P. Zoller, Nature Physics 2, 341 (2006)
[4] S. L. Kemp et al., Rev. Sci. Instrum. 87, 023105 (2016)
[5] S. A. Hopkins et al., Rev. Sci. Instrum. 87, 043109 (2016)
[6] A. Guttridge et al., J. Phys. B: At. Mol. Opt. Phys. 49, 145006 (2016)
[7] A. Guttridge et al., Phys. Rev. A (to be published)

P22. Towards coherent splitting and recombination of bright solitary matter waves

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[1]Durham University, UK, [2]Newcastle University, UK, [3]University of Otago, New Zealand

We report on the controlled creation and apparent velocity-selective splitting of bright solitary matter waves formed from Bose-Einstein condensates of 85Rb atoms. These solitons propagate over macroscopic distances without visible dispersion and are found to be long-lived; observable for more than 20 seconds. Following our previous work on classical reflection of solitons from a broad repulsive barrier [1] and quantum reflection from a narrow attractive well [2], we extend our investigations to solitons incident on a narrow repulsive gaussian barrier [3]. When the centre of mass kinetic energy of the soliton is comparable to the amplitude of the potential provided by the narrow repulsive barrier we observe splitting of the soliton into two daughter solitons. The splitting proportion between the two daughter solitons is tunable depending on incident soliton velocity and barrier height, in good agreement with 1D and 3D Gross-Pitaevskii simulations.

We allow the daughter solitons to oscillate in a weak harmonic potential and observe that the transmitted daughter soliton has a larger centre of mass kinetic energy after splitting than the reflected daughter soliton, indicating that velocity filtering of the atoms is present in the splitting process. Future experiments with a narrower barrier should allow us to reach a coherent splitting regime where we expect the velocity filtering effect to be suppressed, enabling us to achieve coherent recombination of the daughter solitons. We will utilise such a scheme for soliton-based interferometry in a variety of configurations [4]. Of particular interest is a ring geometry for Sagnac interferometry [5], which we will implement using a 2D painted ring potential. We also aim to undertake further experimental studies of bright solitary matter wave dynamics that can be used to elucidate the wealth of theoretical work in the field, as well as to realise Schrödinger cat states [6, 7] and to study short-range atom-surface potentials [8].

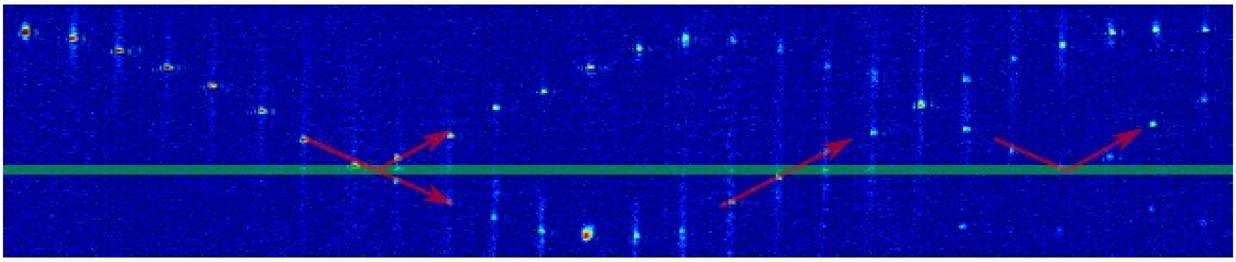

Fig. 1: A series of destructive absorption images at 30 ms time intervals showing splitting of a soliton into two equal-sized daughter solitons by a narrow repulsive gaussian barrier, along with the subsequent interactions of the daughter solitons with the barrier. This is a clear demonstration that velocity filtering is present in the splitting process.

[1] A. L. Marchant, T. P. Billam, T. P. Wiles, M. M. H. Yu, S. A Gardiner and S. L. Cornish, Nat. Commun. 4, 1865 (2013)
[2] A. L. Marchant, T. P. Billam, M. M. H. Yu, A. Rakonjac, J. L. Helm, J. Polo, C. Weiss, S. A. Gardiner and S. L. Cornish, Phys. Rev. A 93, 021604(R) (2016)
[3] J. L. Helm, T. P. Billam and S. A. Gardiner, Phys. Rev. A 85, 053621 (2012)
[4] A. D. Cronin, J. Schmiedmayer and D. E. Pritchard, Rev. Mod. Phys. 81, 1051 (2009)
[5] J. L. Helm, S. L. Cornish and S. A. Gardiner, Phys. Rev. Lett. 114, 134101 (2015)
[6] C. Weiss and Y. Castin, Phys. Rev. Lett. 102, 010403 (2009)
[7] A. I. Streltsov, O. E. Alon and L. S. Cederbaum, Phys. Rev. A 80, 043616 (2009)
[8] S. L. Cornish, N. G Parker, A. M. Martin, T. E. Judd, R. G. Scott, T. M. Fromhold and C. S. Adams, Physica D 238, 1299 (2009)

P23. A quantum-gas microscope for fermionic potassium-40

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University of Strathclyde, UK

Single-atom-resolved detection in optical lattices using quantum-gas microscopes [1,2] has enabled a new generation of experiments in the field of quantum simulation. We achieve single-site-resolved imaging of individual atoms in an optical lattice with high fluorescence yield while maintaining a negligible particle loss rate, by simultaneously laser cooling the atoms to sub-Doppler temperatures while detecting the fluorescence photons emitted during this process. However, cooling of fermionic alkaline atoms in optical lattices is challenging, as their low mass and small excited-state hyperfine splitting make it more difficult to obtain low temperatures using the standard technique of polarization-gradient cooling.

We present how we achieved single-atom-resolved fluorescence imaging of 40K using electromagnetically-induced-transparency (EIT) cooling [3]. This technique relies on the existence of a spectrally narrow, Fano-like line profile and dark resonances arising from quantum interference in a 3-level system. In confining potentials with quantized vibrational levels, as is the case in our optical lattice, the narrow absorption line can selectively excite red-sideband transitions that cool the atomic motion by removing one vibrational quantum, while carrier and blue-sideband excitations are suppressed. In our setup, we detected on average 1000 fluorescence photons from a single atom within 1.5s, while keeping it close to the vibrational ground state of the optical lattice.

We also demonstrate a new Raman grey-molasses cooling scheme which operates on the D2-line [4] using red-detuned lasers, in contrast to other schemes which operate on the D1-line. With this scheme we reached sub-Doppler temperatures of 48(2) μK, which enables direct loading of $9.2(3)\times10^6$ atoms from a magneto-optical trap into an optical dipole trap.

Our fermionic quantum-gas microscope will provide new possibilities to probe strongly correlated fermionic many-body systems at the single-atom level. It will allow the direct observation of spin-spin correlations, or, for example, the study of out-of-equilibrium dynamics and thermalisation of fermionic quantum systems.

[1] W. Bakr et al., Nature 462, 74 (2009); J. Sherson et al., Nature 467, 68 (2010).
[2] S. Kuhr, Natl. Sci. Rev. 3, 170 (2016)
[3] E. Haller et al., Nature Physics 11, 738 (2015)
[4] G. Bruce et al., J. Phys. B: At. Mol. Opt. Phys. 50, 095002 (2017)

P24. Efficient Loading and Characterisation of Laser-cooled Rubidium Atoms within Hollow-Core Photonic-Crystal Fibre

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University of Adelaide, Australia

The use of laser cooled atoms for precise spectroscopic measurements is of great interest in applications such as quantum information processing, as well as for inertial sensors such as gyroscopes [1]. Recently, hollow-core photonic crystal fibre has been explored as a host for laser-cooled atoms, where cold atoms have been transferred from a free-space trap into a trap just inside the core of such a fibre [2], and red-detuned guidance of cold-atoms in a hollow fibre has also been demonstrated [3, 4].

Cold-atom loaded HC-PCF combines the best qualities of optical fibre such mechanical flexibility, high optical intensities at low power, and long interaction lengths, with the long coherence times and high optical densities of cold atom clouds. This fusion of technologies offers an excellent platform for experiments in the fields of quantum optics and matter-wave optics.

A challenge remaining in the full exploitation of cold atoms is the ability to flexibly guide and transport the atoms while minimizing parasitic heating. We are using optical dipole guide beams coupled into a 45μm kagome-lattice hollow-core photonic crystal fibre to produce a diverging optical funnel, which guides atoms released from a magneto-optical trap and falling under gravity, into the core of the fibre. The guide beam also serves to prevent rubidium atoms within the fibre from colliding with the core wall, avoiding loss of coherence that would occur through rethermalizing collisions with the silica wall. We use both red-detuned Guassian beam and blue-detuned hollow Laguerre-Gaussian guide beams and will present the advantages and disadvantages offered by each option.

3D semi-classical Monte-Carlo simulations [5] show that for the coldest atoms, i.e with least transverse energy, the higher light scattering rate of a red-detuned guide makes a hollow blue-detuned guide preferable for use.

We present theoretical and experimental exploration of the fibre-loading process (see fig. 1), and of the properties of the rubidium atoms loaded within the fibre, with a view towards implementation of gradient echo memory [6] within such a fibre for use as a quantum repeater.

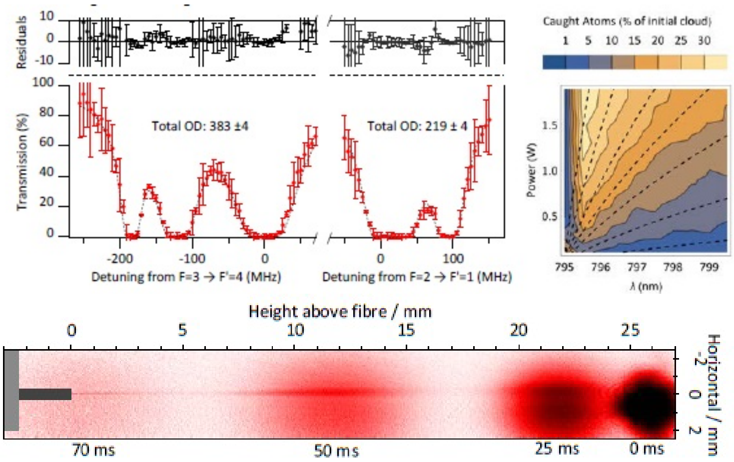

Fig. 1. (a) Measured optical depth of Rb atoms loaded into hollow-core fibre; (b) Theoretical atom-capture efficiency from magneto-optical trap as a function of dipole guide power and wavelength; (c) Composite shadow image of Rb atoms falling under gravity into a hollow-core fibre using red-detuned guide beam.

[1] S. Bize, P. Laurent, M. Abgrall et al., J. Phys. B: At. Mol. Opt. Phys. 38 (2005) S448-S468
[2] C. A. Christensen, S. Will, M. Saba et al., Phys. Rev. A 78 (2008) 033429
[3] M. Bajcsy et al. Phys. Rev. A 83 (2011) 063830
[4] H. Katori et al. Nature Comms 5 (2014) 4096
[5] J. Poulin, P. S. Light, R. Kashyap and A. N. Luiten, Phys. Rev. A 84 (2011) 053812
[6] Sparkes, B. M. et al., New J. Phys. 15 (2013) 085027

P25. An ε-pseudoclassical model for quantum resonances in a cold dilute atomic gasperiodically driven by finite-duration standing-wave laser pulses

B T Beswick[1], S A Gardiner[1], I G Hughes[1], H P A G Astier[2], M F Andersen[3] and B Daszuta[3]

[1]Durham University, UK, [2]Cambridge University, UK, [3]University of Otago, New Zealand

Atom interferometers are a useful tool for precision measurements of fundamental physical phenomena, ranging from local gravitational field strength to the atomic fine structure constant [1]. In such experiments, it is desirable to implement a high momentum transfer "beam-splitter," which may be achieved by inducing quantum resonance in a finite-temperature laser-driven atomic gas [2]. We use Monte Carlo simulations to investigate these quantum resonances in the regime where the gas receives laser pulses of finite duration, and derive an e-classical model for the dynamics of the gas atoms, conceptually similar to that introduced to describe quantum accelerator modes by Fishman, Guarneri and Rebbuzzini [3].

This model is attractive due to its mathematical simplicity and the minimal computational complexity of the numerics. We show that the e-classical model is capable of reproducing quantum resonant behaviour for both zero-temperature and finite-temperature non-interacting gases, see Fig. 1. We show that this model agrees well with the fully quantum treatment of the system over a time-scale set by the choice of experimental parameters. We also show that this model is capable of correctly treating the time-reversal mechanism necessary for implementing an interferometer with this physical configuration, and that it explains an unexpected universality in the dynamics [4].

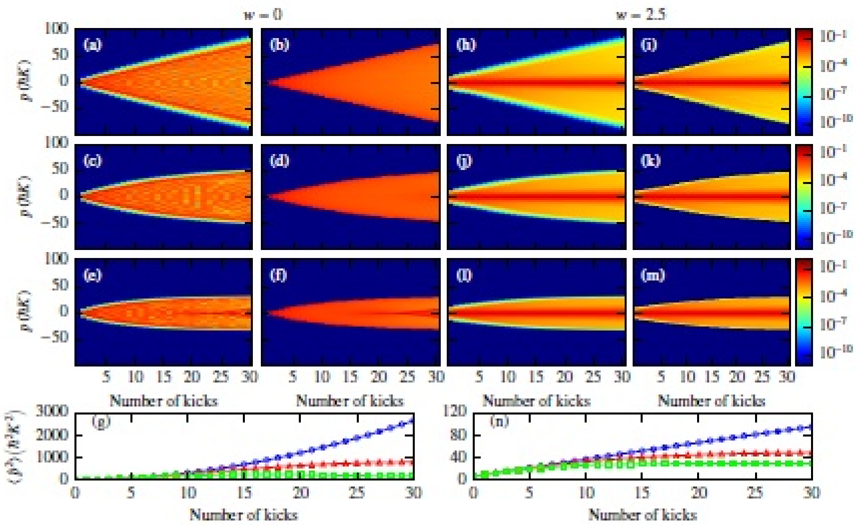

Fig. 1: Comparison between the dynamics of the momentum distributions of the gas population, computed by the fully quantum and pseudoclassical models, for differing values of the scaled pulse duration ε. The first and second columns show momentum distributions for a zero temperature gas (w = 0) as computed by the quantum [(a), (c), (e)] and pseudoclassical models [(b), (d), (f)] respectively. Columns 3 and 4 show the same calculation for a finite temperature, w = 2:5. In each row, the distribution dynamics are computed for a different value of ε: row 1 [(a), (b), (h), (i)] has ε = 0:02, row 2 [(c), (d), (j), (k)] has ε = 0:11, and row 3 [(e), (f), (l), (m)] has e = 0:2.The corresponding time-evolution of $\langle \hat{p}^2 \rangle$ [in units of h^2K^2] is given in (g), for w = 0 and (n) for w = 2:5; solid lines represent results of quantum calculations, and symbols those of the effective classical model (squares correspond to ε = 0:2, triangles to ε = 0:11, and circles to ε = 0:02).

[1] A. Miffre, M. Jacquey, M. büchner, G. Trénec and J. Vigué, arXiv:quant-ph/0605055v1 (2006)
[2] B. Daszuta and M. Andersen, Physical Review A 86, 043604 (2012)
[3] Shmuel Fishman, Italo Guarneri and Laura Rebuzzini, Phys. Rev. Lett. 89, 084101 (2002)
[4] B. T. Beswick et al, Phys. Rev. A 94, 063604 (2016)

P26. Compact cold-atoms interferometer for gravimetry

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The presented work focusses on the development of a transportable atom-interferometry experiment and a compact fibre laser system towards precision measurements of gravitational acceleration. Interference fringes are shown with clouds of cold ^{87}Rb atoms using co-propagating laser beams to drive stimulated Raman transitions. This is demonstrated both in and outside of laboratory environments for which an integrated and transportable experiment is constructed. Further improvements lead to the generation of clouds containing $1.7 \cdot 10^8$ atoms at a rate of 2.5 Hz and having a temperature of (9 ± 1) μK. A large part of this is due to the development of a compact laser system based on all-fibre coupled components. It is shown that the laser system designed here can achieve fast frequency sweeps over 1.8 GHz within 2 ms, making it widely applicable in compact atom-interferometry experiments with rubidium atoms. This is demonstrated by creating a Mach–Zehnder type interferometer with counter-propagating Raman beams, thus enabling the experiment to perform measurements of gravitational acceleration. Since the laser system uses only two lasers and one fibre amplifier, a significant reduction in size is achieved, as well as a decrease in the total power consumption of the overall experiment by a third to (162 ± 7) W.

P27. Laser cooling a molecular beam of YbF for measurement of the electron electric dipole moment

J Lim, J R Almond, M A Trigatzis, N J Fitch, B E Sauer, M R Tarbutt and E A Hinds

Imperial College London, UK

YbF molecules have been used to measure the electron's electric dipole moment (eEDM) [1]. The precision of this eEDM experiment can be improved by using more molecules and increasing the time they spend in the experiment. This can be achieved by slowing the molecules down or increasing the length of the experiment, and then using transverse laser cooling to reduce the divergence of the molecular beam. In this study, we demonstrate one-dimensional laser cooling of a molecular beam of YbF.

Figure 1 (a) shows a schematic of the experimental apparatus. A cryogenic beam of YbF is produced by a buffer gas source in a 250-μs-long pulse with forward speed v_z=160 m/s (Δv_z=100 m/s). YbF molecules enter the 20-cm-long laser cooling region where intensity or polarization gradient is produced across the cooling axis by two counter-propagating laser beams. Each laser beam forms a multi-pass configuration [2]. The laser light contains the four wavelengths to address the vibrational states in the electronic ground state up to v''=3 [3], each with the rf sidebands in order to address all ground-state hyperfine and spin-rotation sub levels. Population leak from rotational branching is eliminated by driving an N=1⟶N'=0 transition. This gives a nearly-closed laser cooling transition. The spatial distribution of YbF molecules is recorded at two distances. Figure 1 (b) shows the molecular beam spatial distribution at the upper CCD for two different detunings of the cooling laser, Δ=±1.5 Γ, when the two counter-propagating laser beams has the parallel linear polarization. For a blue detuning of Δ=+1.5 Γ, we observe strong cooling which results in a squeezed distribution of molecules at the centre of the beam with small transverse velocity. The comparison of the central peak at the two CCDs sets the upper limit of the temperature to be 65±55 μK, which is lower than the Doppler limit. We will present laser cooling of a beam of YbF focused on the sub-Doppler force arising from various polarization configurations, and discuss how this beam will be used to improve the measurement of the eEDM.

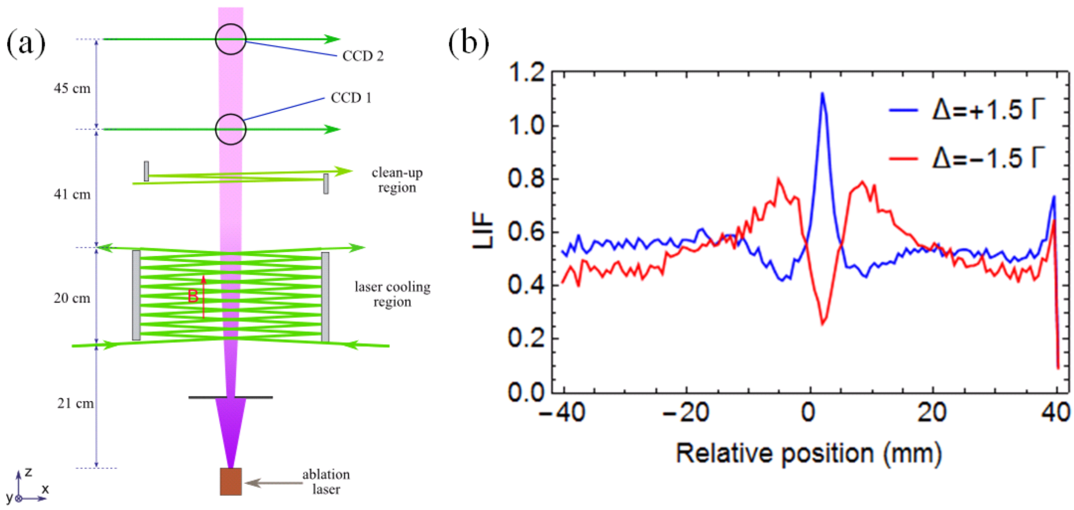


Fig. 1. (a) Schematic of the experimental apparatus; (b) Integrated molecular beam distributions for two different detunings of the cooling laser, Δ=±1.5 Γ, measured at the upper CCD in (a).

[1] J. J. Hudson *et al.*, Nature 473, 493 (2011)
[2] E. Shuman, J. Barry and D. DeMille, Nature 467, 820 (2010)
[3] M. R. Tarbutt, B. E. Sauer, J. J. Hudson, and E. A. Hinds, New J. Phys. 15, 053034 (2013)

P28. Stark-tuned Förster resonances in collisions of NH_3 with He Rydberg atoms

V Zhelyazkova, A Morgan and S D Hogan

University College London, UK

Rydberg states of atoms and molecules can possess very large electric-dipole transition moments [1]. They can therefore be exploited as model systems with which to study resonant energy transfer in collisions with polar ground-state molecules. The results of experiments in which such electric dipole-dipole interactions have been studied, and controlled using electric fields, in collisions of He atoms in triplet Rydberg states with NH_3 in the X $^1A_1$ ground electronic state will be presented [2].

In the triplet Rydberg states in He with principal quantum numbers, n, between 36 and 41, electric-dipole transitions between the states that evolve adiabatically to the 1sns $^3S_1$ and 1snp ^3P_J levels in zero electric field can be tuned through resonance with the ground-state inversion transitions in NH_3 using electric fields on the order of 10 V/cm. Förster resonance energy transfer between these systems has been studied in a crossed beam apparatus. In these experiments the energy transfer rates were controlled using weak electric fields. The electric-field dependences of these transfer rates are in good agreement with the results of calculations in which the resonant electric dipole-dipole coupling between the collision partners is accounted for.

These results open the way for studies of chemical dynamics at low temperatures in which long-range dipolar interactions can be exploited to regulate access to short-range Penning ionization processes. It has also been suggested that such interactions between Rydberg atoms and ground state polar molecules could be exploited to cool [3,4], or non-destructively detect [5] trapped samples of molecules.

This work is supported by the Engineering and Physical Sciences Research Council UK under Grant No. EP/L019620/1, and the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement No 683341).

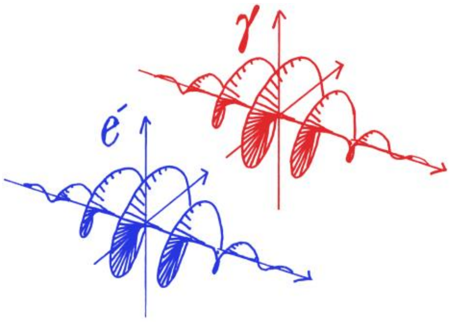
[1] T. F. Gallagher and P. Pillet, Adv. At. Mol. Opt. Phys. 56, 161 (2008)
[2] V. Zhelyazkova and S. D. Hogan, Phys. Rev. A 95, 042710 (2017)
[3] S. D. Huber and H. P. Büchler, Phys. Rev. Lett. 108, 193006 (2012)
[4] B. Zhao, A. W. Glaetzle, G. Pupillo, and P. Zoller, Phys. Rev. Lett. 108, 193007 (2012)
[5] M. Zeppenfeld, Euro. Phys. Lett. 118, 13002 (2017)

P29. Relativistic electron vortices

S M Barnett and F C Speirits

University of Glasgow, UK

Recent developments have demonstrated, beyond reasonable doubt, the existence of propagating electrons with an on-axis vortex, corresponding to a phase singularity in the wavefunction of the form $e^{il\varphi}$ where φ is the azimuthal coordinate [1,2]. This feature is strongly analogous to the corresponding optical vortices with their characteristic orbital angular momentum [3].



The desire to push electron experiments on electron vortices to higher energies has led to some theoretical difficulties. In particular the simple and very successful picture of phase vortices of vortex charge l associated with $l\hbar$ units of orbital angular momentum per electron has been challenged by the facts that: (i) the spin and orbital angular momentum are not separately conserved for a Dirac electron, which suggests that the existence of a spin-orbit coupling will complicate matters (which echoes the intricacies surrounding the spin and orbital components of optical vortices [4]) and (ii) that the velocity of a Dirac electron is not simply the gradient of a phase as it is in the Schrödinger theory suggesting that, perhaps, electron vortices might not exist at a fundamental level [5].

We resolve these difficulties by showing that electron vortices do indeed exist in the relativistic theory and show that the charge of such a vortex is simply related to a conserved orbital part of the total angular momentum, closely related to the familiar situation for the orbital angular momentum of a photon [6]. The link is made yet stronger by writing Maxwell's equations in the form of a Dirac equation [7].

[1] M. Uchida and A. Tonomura, Nature 464, 737 (2010)
[2] J. Verbeeck, H. Tian and P. Schattschneider, Nature 467, 301 (2010)
[3] A. M. Yao and M. J. Padgett, Adv. Opt. Photonics, 3, 161 (2011)
[4] S. M. Barnett, L. Allen, R. P. Cameron, C. R. Gilson, M. J. Padgett, F. C. Speirits and A. M. Yao, J. Opt. 18, 064004 (2016)
[5] I. Bialynicki-Birula and Z. Bialynicka-Birula, Phys. Rev. Lett. 118, 114801 (2017).
[6] S. M. Barnett, Phys. Rev. Lett. 118, 114802 (2017)
[7] S. M. Barnett, New J. Phys. 16, 09308 (2014)

P30. Proposed optical realization of a two photon, four-qubit entangled χ state

A Ritboon, S Croke and S M Barnett

University of Glasgow, UK

The four-qubit states $|\chi^{ij}\rangle$, exhibiting genuinely multi-partite entanglement have been shown to have many interesting properties and have been suggested for novel applications in quantum information processing. In this work we propose a simple quantum circuit and its corresponding optical embodiment with which to prepare photon pairs in the $|\chi^{ij}\rangle$ states.

Our approach uses hyper-entangled photon pairs, produced by the type-I spontaneous parametric down-conversion (SPDC) process in two contiguous nonlinear crystals [1], together with a set of simple linear-optical transformations which is illustrated in the figure 2. Our photon pairs are maximally hyperentangled in both their polarisation and orbital angular momentum (OAM). After one of these daughter photons passes through our optical setup, we obtain photon pairs in the hyper-entangled state $|\chi^{00}\rangle$, and the $|\chi^{ij}\rangle$ states can be achieved by further simple transformations. A more complete account of this work may be found at [2].

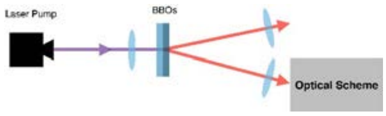


Figure 1: The optical alignment to create hyper-entangled photon pair by coherent sequential spontaneous parametric down-conversion. The crystals are aligned such that their optical axes are perpendicular to each other.

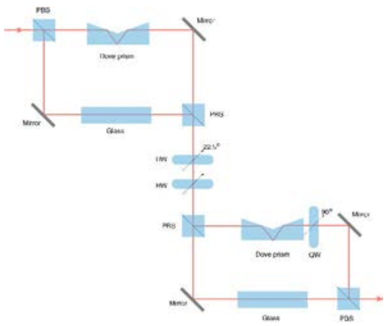


Figure 2: This figure shows our proposed optical system which is the detailed version of the grey box named optical scheme in the figure 1.

[1] Barreiro J T, Langford N K, Peters N A and Kwiat P G 2005 Generation of hyperentangled photon pairs *Phys. Rev. Lett.* 95 260501

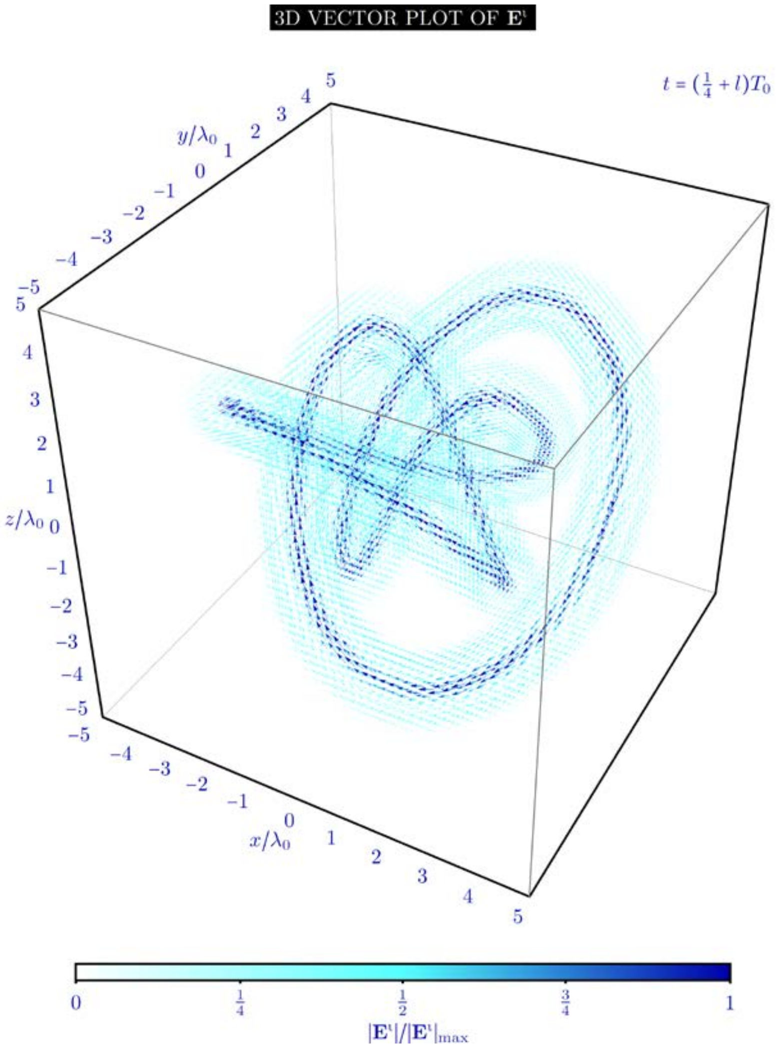
[2] Ritboon A, Croke S and Barnett S M 2017 Proposed optical realization of a two photon, four-qubit entangled χ state *J. Opt.* 19 075201

P31. Unusual Electromagnetic Disturbances

R Cameron

University of Glasgow, UK

Depicted in the figure below is the electric field of an exact solution to Maxwell's equations in free space [1].



The electric field of an electric figure-of-eight knot: each blue arrow represents an electric field vector at an instant of time.

I will present a collection of such unusual electromagnetic disturbances, explain how I have constructed them, describe their properties and highlight some possible directions for future research.

[1] R. P. Cameron, *Monochromatic knots and other unusual electromagnetic disturbances* (in preparation) (2017)

P32. Thermal Rydberg Vapours for Terahertz Sensing and Imaging

L Downes, K Weatherill and C Adams

Durham University, UK

Terahertz (THz) radiation lies on the electromagnetic spectrum between the infrared and microwave regions, commonly defined as spanning the frequency range 0.1-10 THz. It has promising applications in many areas; from materials identification in security [1] to non-destructive sub-surface imaging in medicine [2]. However a lack of easily available THz sources providing power greater than 1 mW and convenient detection methods mean there is far less technological exploitation of radiation in this region than elsewhere on the EM spectrum, referred to as the THz Gap [3].

Rydberg atoms have been used to perform electrometry of microwave and radio frequency fields [4], and the technique is well understood. Their well-defined properties eliminates the need for calibration using a known field and allows the measurements to be related directly to SI units, something which other detectors are unable to do. Alkali Rydberg atoms have atomic transitions spanning the THz gap hence making them promising THz sensors for both electrometry and imaging applications.

We show that a thermal Caesium Rydberg vapour can be used to perform THz electrometry at more than one frequency and relate the field strength directly to SI units. This method is now of considerable interest in academia and industry as a possible new quantum technology [5]. By imaging the fluorescence from the vapour we are able to image the THz field in real-time and by setting up an interference pattern we make wavelength measurements of the THz radiation. We also explore progress towards a full 2D THz imaging system.

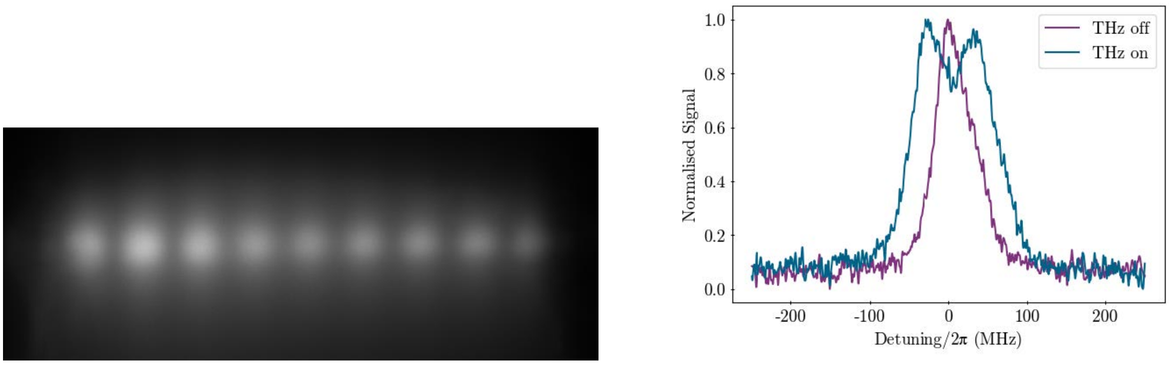


Fig. 1. (a) Imaging a THz field using Rydberg fluorescence; (b) Autler-Townes splitting of the Rydberg lineshape due to the THz field

[1] H.-B. Liu, H. Zhong, N. Karpowicz, Y. Chen, and X.-C. Zhang, "Terahertz Spectroscopy and Imaging for Defense and Security Applications," *Proc. IEEE*, vol. 95, no. 8, pp. 1514–1527, 2007

[2] F. Wahaia *et al.*, "Detection of colon cancer by terahertz techniques," *J. Mol. Struct.*, vol. 1006, no. 1–3, pp. 77–82, 2011

[3] C. Sirtori, "Applied physics: Bridge for the terahertz gap," *Nature*, vol. 417, no. 6885, pp. 132–133, 2002

[4] C. L. Holloway *et al.*, "Broadband Rydberg atom-based electric-field probe for SI-traceable, self-calibrated measurements," *IEEE Trans. Antennas Propag.*, vol. 62, no. 12, 2014

[5] "New winners announced at Quantum Technologies Showcase - EPSRC Website," *EPSRC Website*, 2016. [Online]. Available: https://www.epsrc.ac.uk/newsevents/news/qtshowcase/. [Accessed: 16-Jun-2017]

P33. Time-reversal symmetric work distributions for closed quantum dynamics in the histories framework

H J D Miller and J Anders

University of Exeter, UK

A central topic in the emerging field of quantum thermodynamics is the definition of thermodynamic work in the quantum regime. One widely used solution is to define work for a closed system undergoing non-equilibrium dynamics according to the two-point energy measurement scheme. However, due to the invasive nature of measurement the two-point quantum work probability distribution cannot describe the statistics of energy change from the perspective of the system alone. We here introduce the quantum histories framework as a method to characterise the thermodynamic properties of the unmeasured, closed dynamics. Constructing continuous power operator trajectories allows us to derive an alternative quantum work distribution for closed quantum dynamics that fulfils energy conservation and is time- reversal symmetric. This opens the possibility to compare the measured work with the unmeasured work, contrasting with the classical situation where measurement does not affect the work statistics. We find that the work distribution of the unmeasured dynamics leads to deviations from the classical Jarzynski equality and can have negative values highlighting distinctly non-classical features of quantum work.

[1] H. J. D. Miller and J. Anders, N. J. Phys 19, 062001 (2017)

P34. Propagation of laser light through glass capillaries for ultraviolet microbeams

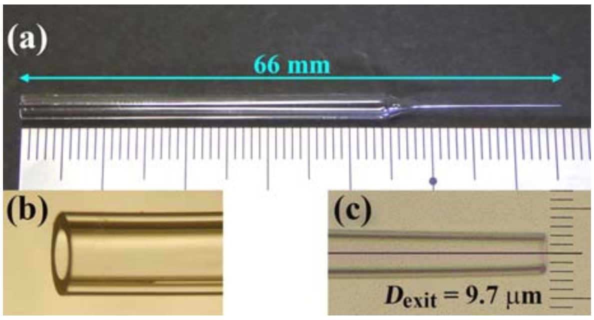
M Matsubara[1], T Masuyama[1], T Ikeda[1,2], T Minowa[1] and W-G Jin[1]

[1]Toho University, Japan, [2]RIKEN Nishina Center for Accelerator-Based Science, Japan

Glass capillary optics with an outlet diameter in the order of micron has been utilized for producing MeV energy ion and light microbeams. The advantages of the method are low cost, easily positioning on a target and preferable sizes of beams. Such a kind of light microbeam has many potential applications not only in physics but in biology. For example, in micro-surgery of single living cell, light microbeam, especially shorter wavelength, provides a pin-point damaging to a part of cell nucleus in a microscope view keeping the neighboring cells safe. A challenging combination of ion and ultraviolet (UV) microbeams at the same system is also possible. Moreover, the development of the UV microbeam through the capillary optics will provide a way to access to an X-ray microbeam.

The light transmission and propagation through a capillary itself are also interesting in terms of light-matter interaction. The experimental data of light transmittances through capillaries provide a critical check of the theoretical calculation employing a realistic capillary shape data which will enable us to estimate light transmission and optimize the best shape of the capillary. Our primary studies for visible light have been reported [1], taking into account the capillary shape, the polarization components of the traveling light, the beam profile, the index of the glass material and so on.

We have started the same investigation in the UV region to open the micro-surgery with UV microbeams. In this presentation, we report transmittances of laser beam with a UV wavelength of 375nm as well as the visible light through tapered glass capillaries as shown in Fig.1. Figure 2 shows experimental and calculated transmittances of laser beam for wavelengths λ=375, 488 and 633 nm through the capillaries as a function of outlet diameter. The transmittance was extracted from the ratio between the output power and input power through the capillary. It can be seen from Fig. 2 that the experimental values are well reproduced by the theoretical calculation. Experimental details together with the theoretical calculation will be presented. Further, transmission and propagation of laser beam through capillaries are discussed.



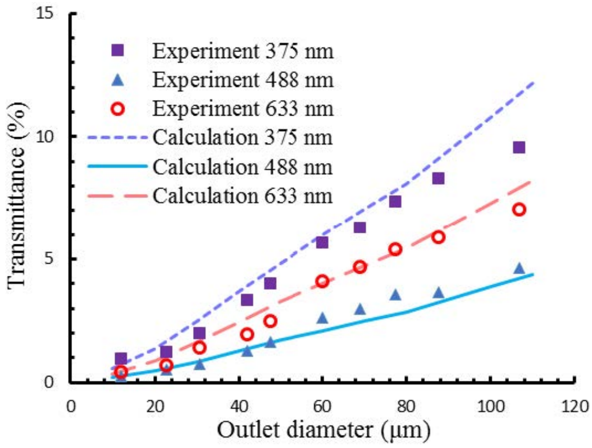


Fig. 1. Photographs of a typical glass capillary optics: (a) Capillary length ranges from 50 to 70 mm according to the outlet diameter. (b) Beam inlet part with a diameter of 1.8 mm. (c) An example of the outlet part with a diameter of 9.7 μm. Fig. 2. Experimental and calculated transmittances of laser beam for λ =375, 488 and 633 nm through the capillary as a function of outlet diameter.

[1] W-G. Jin, *et al.*, J. Phys. Soc. Jpn. 84, 114301 (2015)

P35. Accurate mass measurement of an optically levitated nanoparticle

C Dawson and J Bateman

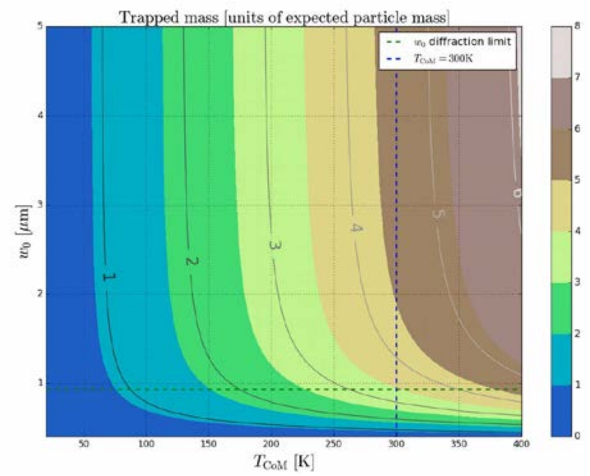
Swansea University, UK

In levitated optomechanics, it is vital to have good information about the mass and radius of nanoparticles being trapped, in order to make full use of this promising experimental platform.

These systems hold promise for testing high mass superpositions, in which claims of ultracold temperatures are often predicated on accurate mass measurement. As ground state cooling is approached it is becoming vital to develop such measurement techniques.

We propose a novel method for obtaining particle mass by fitting a theoretical function to an entire spectrum in excellent agreement, in order to determine the spatial exploration extent, and then to obtain a mass by equipartition argument.

We find an RMS spatial exploration of 103.9 nm ± 1.6 nm, in close agreement with the values in the literature. We also find a centre-of-mass temperature to mass ration of 57.9 ± 1.8 K/fg. Power spectral density peak asymmetry in previous related work is discussed and explained as an increase in laser intensity increasing the harmonic oscillator frequency in a way that correlates with an increase in the received signal amplitude, and a decrease in position variance. Future improvements for removing these undesirable spectral distortions are also presented.



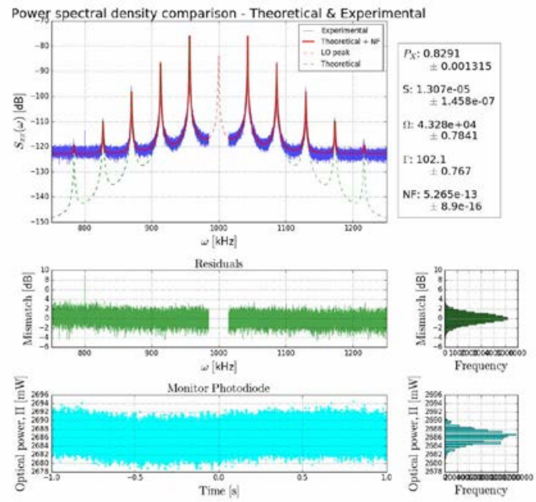


Fig. 1. – Heterodyne power spectral density fitting and residuals. Fig. 2) – Parameter space of trapped mass as a function of centre of mass temperature and beam waist.

[1] J. Gieseler, et al, Phys. Rev. Lett. 109, 103603 (2012)

[2] J. Vovrosh, et al., arXiv. 1603.02917v2 (2016)

P36. Efficient tracking, imaging and recognition of faces with a single-pixel camera

W Roga and J Jeffers

University of Strathclyde, UK

Face recognition is a problem with many practical applications that has been recently intensively investigated. Modern image analysis methods covering object tracking, feature extraction, classification or verification that explore advanced techniques of machine learning and compressive sensing have been used for this purpose. Many of these methods, which are usually applicable in image post-processing, are adaptable to fast intelligent viewing by a single pixel camera [1].

Here we study the single pixel camera for face recognition with limited information. We seek for the optimal basis of patterns for the camera and resolve practical issues related to face localisation and alignment. We compare the Hadamard and eigenface pattern bases for imaging and verification of faces. For this latter task we develop a simple algorithm based on compressive sensing [2].

Our methods allow us to find a high quality image of a 32 × 32 pixel face within the field of view of the camera of dimensions 64 × 64 pixels. A standard single-pixel camera needs view the 4096 pixel scene using a number of patterns of the same order. Our simple position- and alignment-finding schemes allow us to image an arbitrary face with only about 500 patterns, including only 6 patterns that find one of 80 possible face positions in the field of view and one of 180 orientation angles. Furthermore, face verification and discrimination with the compressive sensing methods allow us to recognise a particular face from a list with high probability using only about 25 measurements of random patterns, an order of magnitude better than previously. We observe that the eigenface patterns perform better than the Hadamard patterns, which are independent of the analysed subject.

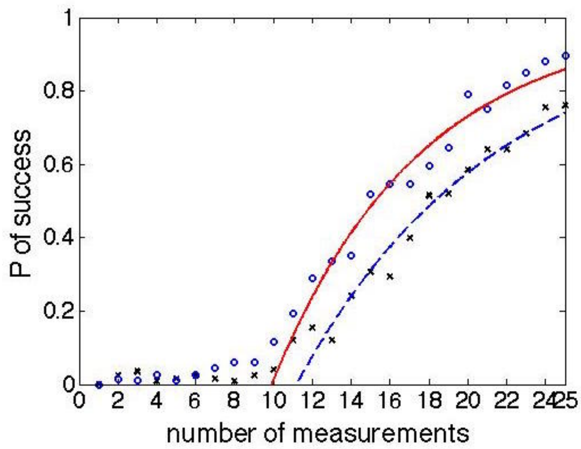


Fig. 1. Probability of success in face discrimination as a function of the number of spc measurements using random eigenpatterns (dots) and random Hadamard patterns (crosses), with no detector noise. The curves (28) are best fits to a typical compressed sensing curve form. The fitting parameters (with 95% confidence bounds) are: red solid line for eigenface patterns, blue dashed line for Hadamard patterns .

[1] M. P. Edgar, G. M. Gibson, R. W. Bowman, B. Sun, N. Radwell, K. J. Mitchell, S. S. Welsh, and M. J. Padgett, *Simultaneous real-time visible and infrared video with single-pixel detectors*, Sci Rep. 5 10669 (2015)

[2] Q. Shi, A. Eriksson, A. Hengel, C. Shen, *Is face recognition really a compressive sensing problem*, in: Proceedings of the International Conference on Computer Vision and Pattern Recognition, 2011, pp. 553560

P37. Particle statistics and lossy dynamics of ultracold atoms in optical lattices

J Yago Malo[1], E P L. van Nieuwenburg[2, 3], M H Fischer[2] and A J Daley[1]

[1]University of Strathclyde, UK, [2]ETH Zurich, Switzerland, [3]Institute for Quantum Information and Matter, Caltech, USA

Experimental control over ultra-cold quantum gases has made it possible to investigate low-dimensional systems of both bosonic and fermionic atoms. In 1D there are a lot of similarities in the dynamics of local quantities for fermions and strongly interacting "hard-core" bosons.

At the same time, there has been a huge development in the characterization and control of dissipative dynamics in optical lattices. And in fact, the presence of dissipation can lead to relevant differences in the dynamics of the two even in local quantities. In this study, we analyse the differences for fermions and bosons on a lattice in the presence of particle loss and other dissipation sources, such as incoherent light scattering; both of which are present naturally in many of the current experiments [1].

We identify signatures of these dynamics – governed by a different particle exchange symmetry for both species – in terms of local particle density, which could be measured using quantum gas microscopes [2]. We analyse the regimes over which these differences are preserved even with losses at random times and positions. We also study the impact of dissipation in aspects of the closed system dynamics as many-body localisation [3].

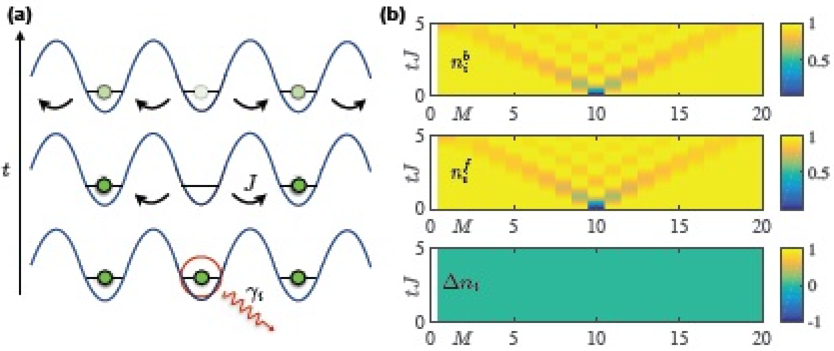


FIG. 1: (a) Scheme of a loss event in the optical lattice. The hole created will propagate through tunneling processes; (b) Evolution of the particle density for bosons n_i^b, fermions n_i^f and its weighted difference $\Delta n_i = \frac{n_i^b - n_i^f}{n_i^b + n_i^f}$ after a loss even occured. In the case of a product state, the local densities are identical after the loss.

[1] M. Schreiber et al., Science 349, 842 (2015)
[2] E. Haller et al., Nature Physics 11, 738742 (2015)
[3] E.P.L. van Nieuwenburg, J. Yago Malo, A.J. Daley and M.H. Fischer, arXiv:1706.00788

P38. Nonuniform currents and spins of relativistic electron vortices in a magnetic field

K van Kruining[1], A G Hayrapetyan[1] and J B Götte[2,3]

[1]Max Planck Institute for the Physics of Complex Systems, Germany, [2]University of Glasgow, UK, [3]Nanjing University, China

We present a relativistic solution for the problem of electron vortex beams propagating in a coaxial magnetic field. Accounting for the effects of spin consistently reveals that these beams have a complicated azimuthal current structure, containing small rings of counterrotating current between rings of stronger corotating current, which differs from the case when the electrons spin is neglected or when the beams are not confined by the presence of the magnetic field.

Interestingly, there exists a set of vortex beams with exactly zero spin-orbit mixing in the highly relativistic and nonparaxial regime, which is contrary to many other problems in relativistic quantum mechanics, and is typical for confined solutions. The phase structure of these particular beams is analogous to simpler scalar vortex beams, owing to the protection by the Zeeman effect. For the states that do show spin-orbit mixing, the spin polarization across the beam is nonuniform rendering the spin and orbital degrees of freedom inherently inseparable.

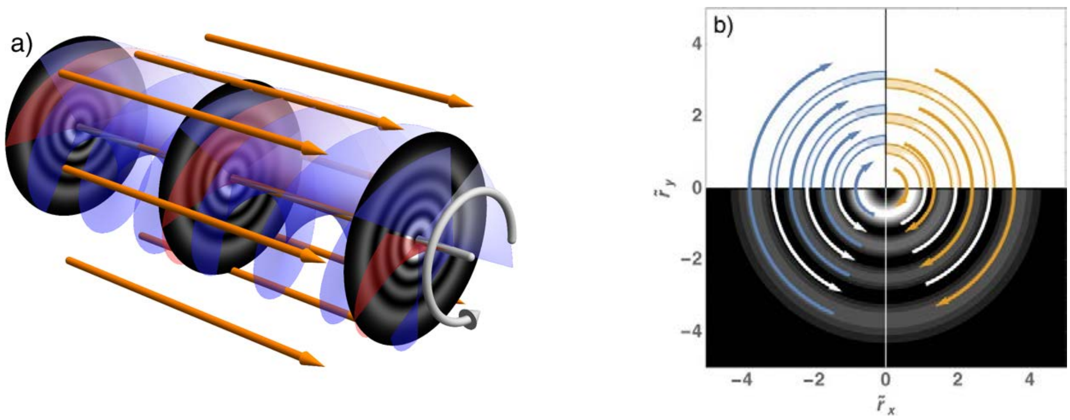


Fig. 1. (a) Schematic of electron vortex beams confined by coaxial magnetic field. The figures shows concentric rings for the structure of the probability density and intertwined helices in red and blue to indicate the different azimuthal phases present in the bispinor components; (b) Comparison between the probability density and current structure for positive (left) and negative spin (right). The orbital angular momentum is positive with $\ell = 2$.

The interaction with the magnetic field confines the beam and gives rise to a set of discrete energy levels (Landau levels) [1,2] and in addition, positive and negative spin states are shifted relative to each other by the Zeeman effect. The quantized Landau and Zeeman contributions to the energy determine which states undergo spin-orbit mixing with each other and completely forbid spin-orbit mixing for some of them [3].

Our results and conclusions are not only applicable to electrons propagating in beams, but also for electrons confined in Penning traps.

[1] L. D. Landau and J. M. Lifshitz, Quantum Mechanics (Non-Relativistic Theory) Course of Theoretical Physics, Vol. 3, 3rd ed. (Butterworth-Heineman, London, 1991)
[2] K. Y. Bliokh, P. Schattschneider, J. Verbeeck, F. Nori, Phys. Rev. X 2, 041011 (2012)
[3] K. van Kruining, A. G. Hayrapetyan, J. B. Götte, Phys. Rev. Lett. 119, 030410 (2017)

P39. High energy and efficiency proton acceleration via an enhanced hybrid laser-ion acceleration mechanism

A Higginson[1], R Gray[1], M King[1], R Dance[1], S Williamson[1], N Butler[1], S Kar[2], M Borghesi[2], X Yuan[3], D Neely[1,4] and P McKenna[1]

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The study of ion acceleration driven by relativistically intense ($>10^{18}$ Wcm^{-2}) laser-solid interactions has received considerable interest over the past 15 years, motivated by the possibility to produce compact particle sources, with potential applications in medicine, industry and security [1,2]. Here, we present an investigation of ion acceleration from ultra-thin (<100 nm) target materials – which become relativistically transparent to the laser pulse during the interaction. Using the Vulcan laser system at the Rutherford Appleton Laboratory, delivering a peak intensity on target of 5×10^{20} Wcm^{-2}, we demonstrate that for targets with an optimal thickness for transparency-enhanced acceleration, it is possible to accelerate proton beams with maximum energies in excess of 95 MeV, and laser-to-proton energy conversion efficiencies of the order of 11%.

The dependence of maximum proton energy and energy conversion efficiency on foil target thickness will be presented. In addition, data from aluminium and plastic targets are compared. Experimental results are supported by 2D particle-in-cell simulations using the fully-relativistic EPOCH code [3]. These simulations are used to explore the transparency enhanced acceleration regime and demonstrate that the acceleration is dominated by a dual-peaked electrostatic field, producing a proton bunch that is accelerated in a hybrid ion acceleration scenario. By controlling the onset of transparency [4], we demonstrate that it is possible to not only enhance the maximum proton energy, but also to manipulate the directional properties of the proton beam.

[1] H. Daido, M. Nishiuchi and A. S. Pirozhkov, Rep. Prog. Phys. 75, 056401 (2012)
[2] A. Macchi, M. Borghesi and M. Passoni, Rev. Mod. Phys. 85, 751 (2013)
[3] T. D. Arber et al., Plasma Phys. Control. Fusion 57, 113001 (2015)
[4] H. W. Powell et al., New J. Phys. 17, 103033 (2015)

P40. Deriving a correlation between the emission intensities of molecular nitrogen species and the metastables of argon and helium using optical spectroscopy

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Plasma discharge in open air has charged species, energetic photons, active radicals, and a low degree of ionization gas. Interaction of such plasma with samples has been a subject of intense study for many decades. Many treatments of samples utilise nitrogen (N2) as a working gas. Some of these include: (i) ammonia generation for fertiliser (ii) and using the inert nature of N2 to use it as a blanket gas to protect certain chemicals, surfaces, and stored foods from degradation through contact with atmospheric oxygen and moisture. In this work helium (He) and argon (Ar) were used individually and as mixtures to study the interaction of their metastable states and the generation of N2.

In this study an atmospheric plasma system, which operates with noble gas and ambient air chemistry, was employed. The system operates at a frequency of 51 kHz and makes use of a cylindrical dielectric barrier discharge geometry with a helically inclined dielectric barrier. At the frequency used, the oscillation of electrons is much higher than that of the ions. This is due to the ions not being able to change momentum fast enough to compensate for the disturbance, whereas the much lighter electrons can change with the shifting of electric fields.

Optical emission spectroscopy (OES) was used to draw a correlation between the changes in emission intensities that finished at He and Ar metastables energy levels and the emission intensities of N2. The correlation has been obtained by comparing the changes in intensity with respect to voltage, time, ratio of gas mixes, and the flow rate of the gases. By determining a correlation between the emissions of these species, it can be shown that OES peak intensities can be used as an indicator to benchmark the most efficient manner to generate the excited nitrogen species for sample treatment.

This work was funded by SFI under the PlasmaGrain project.

P41. Effect of target thickness on the absorption of laser energy and escaping electrons in the interaction between ultra-intense laser pulses and overdense plasma targets

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Compact sources of laser generated high energy particles have several potential applications from proton oncology to energy production via inertially confined plasmas undergoing nuclear fusion [1]. The field of laser-plasma interaction is a broad one. However, there are still some crucial challenges to be met to improve our understanding and control of the products of these interactions. The processes of absorption of laser light during the interaction and subsequent dynamics of electrons that carry away this energy are both yet to be fully understood. Among the many reasons for this is the dependence of the interactions on a myriad of laser and target parameters.

Here we present total absorption measurements from the interaction of ultra-thin targets on the nanometre to micron scale using a novel combination of experimental diagnostics. Using the PHELIX laser system at GSI, Darmstadt in Germany, where incident laser intensities of $1x10^{20}$ Wcm^{-2} were achieved, a range of target thicknesses were irradiated to investigate the effect of changing this parameter. Previous studies have shown a change from surface to volume dominated interaction in a similar range of target thickness in this study [2].

To characterise the total absorption of the dense plasma an integrating Ulbricht sphere was placed around the target and interaction point. This allowed for full characterisation of the amount of light not scattered or back-reflected and thus absorbed by the plasma created during the interaction. Changes to the angular and energy distributions of the electron beam that escapes the target are measured, using FUJIFILM image plate sensitive to ionising radiation, to characterise the laser-plasma interaction dynamics [3].

[1] M. Tabak *et al.*, Phys. Plasmas 1, 1626 (1994)
[2] B. Gonzalez-Izquierdo *et al.*, High Power Laser Science and Engineering. 4, e33 (2016)
[3] R. J. Gray *et al.*, Appl. Phys. Lett. 99, 171502 (2011)

P42. Theoretical study of the splitting of electromagnetically induced transparency window of Rb vapor in an external magnetic field

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In this work, we study the phenomenon of electromagnetically induced transparency (EIT) in Rb vapor at the room temperature with external magnetic fields. It has already been studied that the overall transparency window for a three-level Λ or Ξ-system gets narrowed after carrying out the thermal averaging of all velocities at the room temperature vapor [1,2] and it has been verified experimentally.

We propose a theoretical analysis, using density matrix approach [3], to study the influence of external magnetic field as well as closely spaced multiple excited states on the optical properties of Λ- type EIT system using the D2 line in ^{85}Rb and ^{87}Rb atoms. The presence of magnetic field also plays important role in reducing the linewidth of EIT window. The degeneracy of the involved hyperfine levels will be broken due to the applied external magnetic field. So, in a system several subsystems will be formed as each magnetic sublevel is shifted by different amounts of energies. We calculate the probe absorption and dispersion spectra in different cases with or without a magnetic field. We present the absorption and dispersion profiles for stationary as well as moving atoms by performing thermal averaging at the room temperature (297 K). The presence of closely spaced multiple excited states causes asymmetry in the absorption and dispersion profiles. We observe a wide EIT window with a positive slope at the line center for a stationary atom. While for a moving atom, the linewidth of EIT window reduces and positive dispersion becomes steeper. When magnetic field is applied, our calculations show multiple EIT subwindows that are significantly narrower and shallow than single EIT window as shown in fig. 1 (c). The numbers of EIT subwindows depend on the orientation of the magnetic field. We also obtain multiple positive dispersive regions for subluminal propagation in the medium as shown in fig.1 (d). The anomalous dispersion exists in between two subwindows showing the superluminal light propagation. Our theoretical analyses explain the experiments performed by Wei et al. [4] and Iftiquar et al. [5].

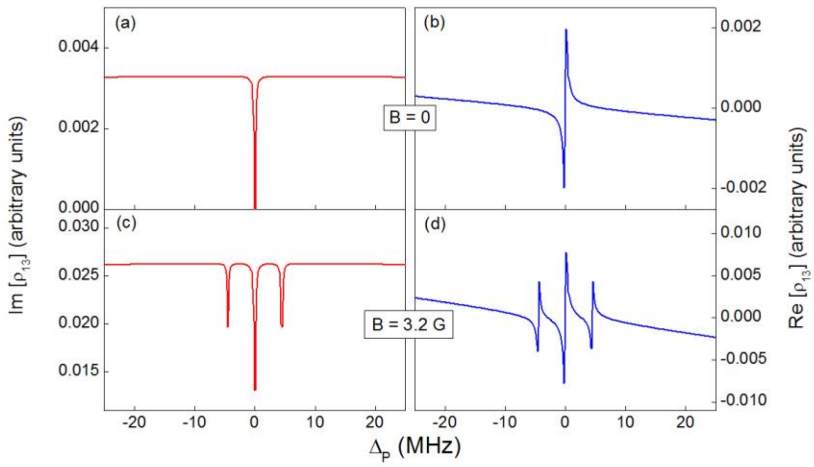

Fig. 1. The probe absorption $[\rho_{13}]$ and dispersion coefficients Re $[\rho_{13}]$ of ^{87}Rb as a function of probe detuning $[\Delta_\rho]$ for moving atom with (i) B = 0 fig. (a-b) (ii) B = 3.2G fig. (c-d). Parameters used in calculations are $\Omega_c = 10MHz$ and $[\Delta_\rho] = 0$ in the weak probe regime.

[1] S.M. Iftiquar, G. R. Karve, V. Natarajan, Phys. Rev. A. 77, 063807 (2008)
[2] V. Bharti, A. Wasan, J. Phys. B 45, 185501 (2012)
[3] M. Auzinsh, D. Budker and S. M. Rochester, Optically Polarized Atoms, Oxford University press, UK, 2010
[4] X.-G. Wei et al., Phys. Rev. A 72, 023806 (2005)
[5] S.M. Iftiquar, V. Natarajan, Phys. Rev. A 79, 013808 (2009)

P43. Can boson sampling tell us anything about the difficulty of simulating XY spin Hamiltonians?

T Brougham

University of Glasgow, UK

The weirdness of quantum mechanics is now realized to be a powerful resource for computation. Quantum computers, for instance, would be able to efficiently solve problems that are in effect intractable, using classical resources. Experimentally demonstrating the power of quantum systems is however, rather challenging. This is why the problem of boson sampling has attracted a great deal of interest. In practice, a boson sampler consists of a linear optical network, where the inputs are either single photons or the vacuum. Surprisingly, it has been shown that it is very difficult to classically simulate this setup [1]. A large scale experimental implementation of boson sampling would thus demonstrate the computational supremacy of quantum systems over classical.

One can also use boson sampling as a primitive to study whether other quantum systems, which are too simple to form a universal quantum computer, could also exhibit similar behavior. This would open up new avenues for experimental demonstrations of quantum supremacy. It could also help shed light on the ultimate computational power of quantum systems.

Recently, it has been shown that one can map boson sampling onto a sampling problem with a set of spin-1/2 particles that interact via an XY Hamiltonian [2]. The network of spins had several restrictions: for example, the spins where decomposed into two sets, where interactions where only allowed between spins in different sets (i.e. the network was a bi-graph).

We will investigate an alternative connection between XY Hamiltonians and boson sampling. Our approach uses similar Hamiltonians to that considered earlier [2], but where there are no limitations on which spins are coupled. The approach thus applies to networks described by a general undirected graph. The key idea is to re-express the dynamics of the spins under the XY Hamiltonian, so that they resemble a linear optical network. One can then define a sampling problem by direct analogy with boson sampling. Given the general nature of the XY Hamiltonians that our results apply to, it is believed that the results will be of importance for study of quantum information applications, such as quantum state transfer [3], which use such Hamiltonians.

[1] S. Aaronson and A. Arkhipov, Theory Comput. 9, 143 (2013)
[2] B. Peropadre, A. Aspuru-Guzik and J. J. Garcia-Ripoll, Phys. Rev. A 95, 032327 (2017)
[3] *Quantum State Transfer and Network Engineering*, Ed. G. M. Nikolopoulos and I. Jex, Berlin, Springer-Verlag (2004)

P44. Entanglement enhancement for continuous-variable measurement-based quantum information processing through multi-rail noise reduction

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National Chung-Cheng University, Taiwan

We provide theoretical study for the teleportation of controlled-phase (CZ) gate through measurement-based quantum information processing for continuous-variable systems. We examine the degree of entanglement in the output modes of the teleported CZ-gate for two classes of resource states: the canonical cluster states that are constructed via direct implementations of two-mode squeezing operations, and the linear-optical version of cluster states which are built from linear-optical networks of beam splitters and phase shifters. In order to reduce the excess noise arising from finite-squeezed resource states, we consider teleportation through resource states with different multi-rail designs and analyze the enhancement of entanglement in the teleported CZ-gates. For multi-rail cluster with an arbitrary number of rails, we obtain analytical expressions for the entanglement in the output modes and compare the results for both classes of resource states in detail. To facilitate the analysis, we develop a trick with manipulations of quadrature operators that can reveal rather efficiently the measurement sequence and corrective operations needed for the measurement-based gate teleportation.

P45. From retrodiction to bayesian quantum imaging

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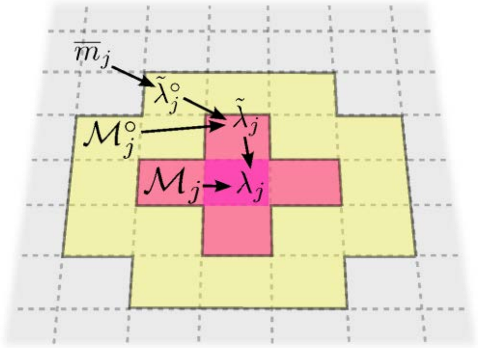
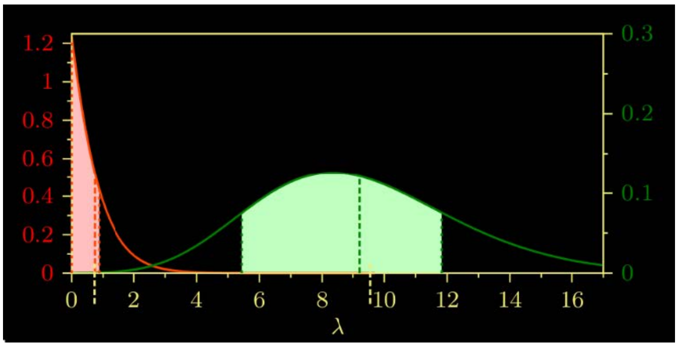
University of Glasgow, UK

We employ quantum retrodiction to develop a robust Bayesian algorithm for reconstructing the intensity values λ_j of an image from sparse photocount data, while also accounting for detector noise in the form of dark counts. This method yields not only a reconstructed image but also provides the full probability distribution function for the intensity at each pixel [1].

We use simulated as well as real data [2] to illustrate both the applications of the algorithm and the analysis options that are only available when the full probability distribution functions are known. These include calculating Bayesian credible regions for each pixel intensity, allowing an objective assessment of the reliability of the reconstructed image intensity values.





[1] M. Sonnleitner, J. Jeffers & S.M. Barnett, *Image retrodiction at low light levels*, Optica, 2(11):950-957 (2015)

[2] P.A. Morris et al., *Imaging with a small number of photons*, Nature Communications, 6:5913, (2015)

P46. Holographic quantum imaging

G Ferenczi[1], N Trautmann[2], S Croke[1] and S Barnett[1]

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We present an improvement [1] to a two-particle interference based approach to quantum tomography of the transverse spatial profile of a particle [2].

Hong-Ou-Mandel interference [3] is an intrinsically quantum phenomenon whereby two photons, identical in every respect except for which input port of the beam splitter they enter, always emerge together in one of the output ports of said beam splitter. The corresponding experiment for electrons sees them always emerge in distinct output ports [4].

If the particles have only a single degree of freedom (port mode number) then the symmetry under the exchange of these quantum numbers reflects the symmetry under particle exchange of the particle pair and thus HOM interference for bosons and fermions contrast the behaviour of a particle pair that is symmetric or antisymmetric (respectively) under the exchange of port mode labels.

When extended to particles with two degrees of freedom (we append the port mode numbers with a transverse spatial profile) it is the simultaneous exchange of both quantum numbers that corresponds to particle exchange and under the exchange of only the port mode labels an arbitrary phase can be picked up meaning that arbitrary statistics can be achieved by either type of particle pair at the output of a beam splitter [5,6,7].

This principle has been used to collect tomographic information about the real part of the density matrix from coincidence count rates [2]. Our extension of this method either by introducing losses or introducing a third degree of freedom (this latter approach is detailed in the poster) allows access to the imaginary part of the density matrix as well [1].

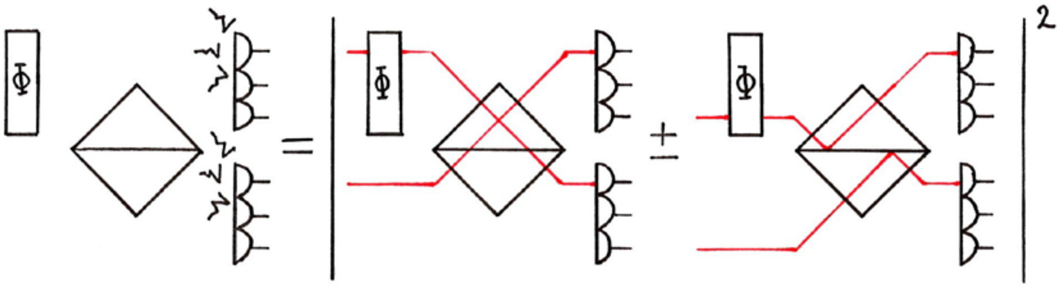

Fig. 1 The two interfering alternatives that contribute to the probability of a click at a given pair of detectors at different transverse positions in distinct output ports. Φ represents the transverse spatial profile that one of the pair of identical particles is imprinted with to be determined from difference in count rates of detection occurring in the same port (not shown) or in distinct ports. (illustrated above).

[1] N. Trautmann, G. Ferenczi, S. Croke, S. M. Barnett, Holographic quantum imaging: reconstructing spatial properties via two-particle interference J. Opt. 19 054005 (2017)

[2] R. Chrapkiewicz, M. Jachura, K. Banaszek and W. Wasilewski, Hologram of a single photon Nat. Photon. 10 576–9 (2016)

[3] C. Hong, Z.-Y. Ou and L. Mandel, Measurement of subpicosecond time intervals between two photons by interference Phys. Rev. Lett. 59 2044–6 (1987)

[4] R. C. Liu, B. Odom, Y. Yamamoto and S. Tarucha, Quantum interference in electron collision Nature 391 263-265 (1998)

[5] A. Zeilinger, Quantum entanglement: A fundamental concept finding its applications Phys. Scripta T76 203-209 (1998)

[6] G. Ferenczi, V. Potoček and S. M. Barnett, Two-particle multi-mode interference J. Opt. 161057102 (2014)

[7] Y. Zhang, F. S. Roux, T. Konrad, M. Agnew, J. Leach and A. Forbes, Engineering two-photon highdimensional states through quantum interference Sci. Adv. 2 e1501165 (2016)

P47. Axiomatic approach to sequential measurements

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Sequential quantum measurements impact upon many areas of quantum information including communication and cryptography. Quantum mechanics is active, so that performing a measurement also changes the state of the system and hence sequential measurements in particular play a central role in applications as well as more foundational issues. Sets of Kraus operators, alternately known as effects, are the mathematical objects used to handle the state update [1]. In recent work, we have taken an axiomatic approach to understanding the logical structure which underpins this theory. From a small number of physically motivated first principles, we derive the conditional probability rule as unique. This is an extension of theorems due to Gleason [2] and Busch [3] who provided related theorems for the case of single measurements.

This can also be thought of as work in the lineage of Hardy [4] and others who seek an axiomatization of quantum theory. Importantly, that work exploits the links between probabilities and inner products, an approach adapted in our work. With this connection in mind we show that single measurement probabilities can be calculated using one type of complex vector space (Liouville space) and conditional measurement probabilities another (super-Liouville space). Following this the problem becomes to limit the relevant vectors in such a way that inner products are positive numbers, consistent with our familiar understanding of probabilities. This is what leads to the Kraus formalism.

Quantum cryptography is one application which has been investigated. The security of key distribution routines is based on the fact that an eavesdropper will disturb the transmitted signal, such that legitimate parties become aware of their presence [5]. We claim that our work provides further confidence for the security of such systems by demonstrating precisely the axioms upon which the security relies.

[1] K. Kraus. 1983 *States, Effects and Operations* (Springer-Verlag)
[2] A. M. Gleason. 1957 *J. Math. Mech.* 6 885
[3] P. Busch. 2003 *Phys. Rev. Lett.* 91 120403
[4] L. Hardy. 2001. (available from arXiv: quant-ph/0101012)
[5] C.H. Bennett and G. Brassard. 1984. *Proceedings of IEEE…* . 175.

P48. How fast are photons that carry orbital angular momentum?

T Roger[1], A Lyons[1], C Maitland[1], S Vezzoli[1], N Westerberg[1], J Leach[1], M Padgett[2] and D Faccio[1]

[1]Heriot-Watt University, UK, [2]University of Glasgow, UK

The velocity of light in vacuum is known according to relativity to be a constant. However, recent studies have shown that spatial structuring of single photons can lead to a deviation from this constant. For instance, a photon in a Bessel mode, which has a non-zero transverse wavevector, will have a longer transit time over a fixed distance with respect to a non-structured (plane-wave) photon [1]. For more complex structuring of the beam phase, for instance adding an azimuthal phase gradient inducing orbital angular momentum (OAM), a slowdown of the propagation speed of light was reported [2]. We will show that the true effect of adding OAM to a photon can lead to an acceleration of the photon and depends specifically on the transverse mode distribution of the photon.

We provide a simple ray-tracing description of how orbital angular momentum affects the propagation delay of photons. This simple theoretical model clearly indicates that, in the case of a focused beam, adding OAM while fixing the transverse mode distribution will reduce the photon delay i.e. speed the photon up. The reduction in delay (speed up of the photon) due to OAM can be understood within the proposed framework of ray optics and is related to the fact that the longest path for a ray is given by paths that invert an image through a telescope. Beams with OAM will rotate an image by a certain angle that is always less than 180 deg [3] and hence, light rays will propagate along shorter paths. We present a series of measurements based on a Hong-Ou-Mandel interferometer with which we verify our predictions and measure the OAM-induced speed-up of single photons.

We note that in previous studies, the intensity profile of the beam was not fixed, i.e. the spatial profile was allowed to vary in radius as OAM was added to the beam, thus leading to the opposite conclusion [4]. The aim of this study is to investigate the intrinsic OAM delay, rather than the overall effect of adding an OAM phase, which can lead to a dominant contribution due to spatial reshaping of the beam as in [4].

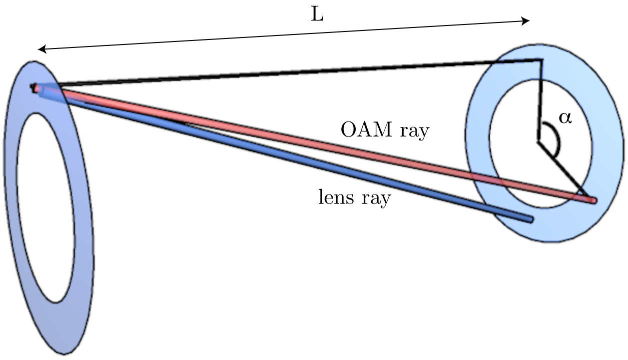

Fig. 1. (a). Ray tracing for beams carrying orbital angular momentum compared to a focused plane wave.

[1] D. Giovanni, J. Romero, V. Potocek, G. Ferenczi, F. Speirits, S. M. Barnett, D. Faccio, M. J. Padgett, Science, E20, 857-860 (2015)
[2] F. Bouchard, J. Harris, H. Mand, R. Boyd, and E. Karimi, Optica 3, 351-354 (2016)
[3] N. D. Bareza, and N. Hermosa, Sci. Rep. 6, 26842, doi: 10.1038/srep26842 (2016)
[4] J. Arlt, Journal of Modern Optics, 50, 10, 1573-1580 (2003)

P49. Novel ion trap design with an integrated optical fibre cavity and a tunable ion-cavity coupling

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We report a novel miniature Paul ion trap design with an integrated optical fibre cavity which can serve as a building block for a fibre-linked quantum network. In this design, the ion remains unperturbed by the presence of the dielectric mirrors and stays stably trapped for an unprecedented duration. The trap features additional electrodes for the application of radio frequency signals to shift the ions position and probe the cavity field mode. With the capacity to tune the ion-cavity coupling, this system can also be used to study atom-light dynamics in different coupling regimes.

P50. Achromatic vector vortex beams generated from Fresnel cones

N Radwell, R D Hawley and S Franke-Arnold

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We present a new method to generate broadband vector vortex beams. This method, based on Fresnel cone technology (shown in figure 1) produces beams with both structured polarisation and orbital angular momentum (OAM) and the associated spin-orbit coupling has been suggested as a classical analogue to quantum entanglement.

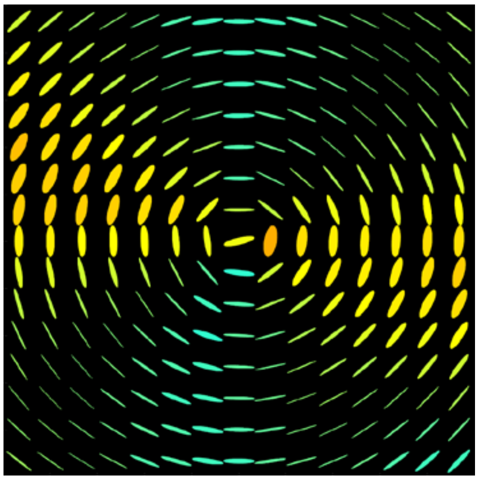

Figure 1: Photograph of a Fresnel cone with 10mm diameter. Figure 2: Azimuthal polarization structure generated from a Fresnel Cone.

Vector vortex beams can be generated using a number of methods: Interferometric techniques based on SLMs or DMDs are highly flexible, but typically optically complex and restricted to operation at a single wavelength. More specific beams may be generated by fixed optical components such as q-plates as well as achromatic OAM generators. Here we discuss recent progress on vector vortex beam generation using our Fresnel cones. We demonstrate generation of broadband vector vortex beams with close to 100% efficiency, including white light radially and azimuthally polarised (see figure 2) beams.

Structured polarisation beams have also been shown to produce focal spots below the conventional diffraction limit and here we present our investigations into the focal properties of beams generated by Fresnel cones. Such beams are subtly different to conventional vector vortex beams and we present several advantages including smaller spot sizes and a pure-transverse field component in the focal plane.

P51. Minimum-error discrimination of single-qubit mixed states

G Weir, S M Barnett and S Croke

University of Glasgow, UK

Quantum state discrimination between single qubits is a central and fundamental problem in the field of quantum information; it has relevance in quantum key distribution and quantum metrology [1], and it also provides insights into problems in the multiple-qubit regime [2].

We consider the problem of minimum-error quantum state discrimination for single-qubit mixed states. We find a way to use the Helstrom conditions constructively for such states, thereby solving the problem analytically for any number of arbitrary single-qubit signal states with arbitrary prior probabilities. This method also reveals that when the number of signal states is smaller than five, the solution given - and hence the optimal measurement strategy – is unique, with a caveat.

[1] J. Bae, L. Kwek, Journal of Physics A, 48, 8 (2015)
[2] S. Croke, S. M. Barnett, G. Weir In Preparation, (2016)

P52. Attosecond Hong-Ou-Mandel Interferometry

A Lyons[1], G Knee[2], E Bolduc[1], T Roger[1], J Leach[1], E Gauger[1] and D Faccio[1]

[1]Heriot-Watt University, UK, [2]University of Warwick, UK

Quantum interference forces two indistinguishable input photons to depart a beamsplitter in the same (of two possible) spatial output modes; this is known as the Hong-Ou-Mandel (HOM) effect. It provides a quantitative way of measuring the distinguishability between two photons and is commonly utilised to determine their relative temporal delays [1,2]. HOM interferometry offers numerous advantages over its classical counterpart, most importantly it lacks any dependence on the phase of the photons and therefore can potentially provide reliable measurements in environments where the phase is unstable. Additionally, it offers a much greater dynamic range when compared to phase dependent interferometeric techniques which are limited to distances on the order of a wavelength.

In the presented work, the Fisher information of the characteristic HOM dip is analysed to devise a measurement protocol that maximises the amount of information acquired for a fixed integration time or, equivalently, per photon. The point of maximum Fisher information identifies the optimal compromise between the number of coincident photons observed at two detectors and the gradient as a function of temporal delay (see Figure). It is at this point that measurements with the highest precision can take place by evaluating any small change in the number of photon counts versus changes in delay/path length.

We implement such a metrological protocol with a non-collinear design of HOM interferometer by introducing a known temporal delay to one of the photons with a piezo actuator. This method is shown to perform with a precision exceeding 6 as (1.7 nm) exhibiting an improvement on previous comparable experiments by approximately two orders of magnitude [3,4]. The proposed scheme boasts a wide scope of applications ranging from thickness measurements of optically transparent media to high precision measurements of the refractive index and topological measurements with attosecond precision.

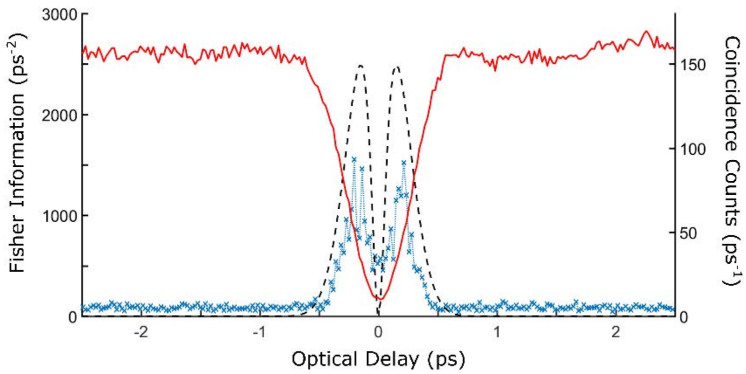

Fig 1. (Red) Measured Hong-Ou-Mandel dip. (Blue) The Fisher information calculated from the measured data. (Black) Fisher information theoretically predicted from the extracted parameters of the HOM dip.

[1] C. K. Hong, Z. Y. Ou, and L. Mandel, "Measurement of subpicosecond time intervals between two photons by interference," Phys. Rev. Lett. 59, 2044 (1987)

[2] D. Giovanni, J. Romero, V. Potoček, G. Ferenczi, F. Speirits, S. M. Barnett, D. Faccio, and M. J. Padgett, " Spatially structured photons that travel in free space slower than the speed of light," Science, 347, 857 (2015)

[3] E. Dauler, G. Jaeger, A. Muller, and A. Midgall, " Tests of a Two-Photon Technique for Measuring Polarization Mode Dispersion With Subfemtosecond Precision," J. Res. Natl. Inst. Stand. Technol. 104, 1 (2000)

[4] D. Branning, A. L. Midgall, and A. V. Sergienko, "Simultaneous measurement of group and phase delay between two photons," Phys. Rev. A. 62, 63808 (2000)

P53. Single atom imaging with a sCMOS camera

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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 realization of a scalable quantum devices. Cold Rydberg atoms trapped above a superconducting microwave resonator offer such a potential [1, 2].

We present the first steps towards such an experiment with the demonstration of addressable single atom quibit sites imaged with an alternative cost effective technology . Resolving single atoms signals requires the ability to distinguish between the weak photon events due to the atom and the collective background signal. Until now this has required the use of costly EMCCD cameras, PMT's or single photon counting modules. Our results show the first resolved single atom signal performed with a sCMOS camera and demonstrate the ability to utilise this device for high fidelity readout. A key step forward for the experiment as we seek to exploit the strong dipole-dipole interactions between Rydberg atoms to achieve our intermediate goal of efficient single photon coupling to atomic ensembles [3].

This work was supported by the EPSRC.

[1] D. Petrosyan and M. Fleischhauer, Phys. Rev. Lett. 100, 170501 (2008)
[2] J. D. Pritchard et al., Phys. Rev. A 89, 010301(R) (2014)
[3] L. H. Pedersen and K. M_lmer, Phys. Rev. A 79, 012320 (2009)

P54. The roles of coarse-graining in the properties of Markovian master equations

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Markovian master equations have long been an essential tool in describing the dynamics of quantum systems interacting with their surrounding environment, where the environment is typically modelled as a thermal reservoir. The derivation of this master equation usually requires implementing the Born-Markov-secular approximations which result in a master equation that is of the required Lindblad form [1]. Implicit in this derivation is coarse-graining over the very short time scales inherent in the dynamics. An alternative derivation, less frequently employed, makes this coarse-graining explicit, as detailed in the text book by Cohen-Tannoudji *et al* [2]. Here the coarse-graining time scale Δt enters as a parameter chosen to achieve the required smoothing of the dynamics.

This approach has been made use of recently in different contexts, e.g., Δt is chosen to give a bestapproximation master equation, see e.g., [3], or else to include terms due to quantum interference in the decay channels [4], or to guarantee that the steady state is the expected Gibbs distribution for thermal equilibrium. But coarse-graining can also be given a direct physical interpretation as implying a temporal resolution of measurements made on the environment, in the quantum trajectory theory sense of measurement induced quantum jumps, and hence different choices of Δt can lead to different master equations.

This work presents a refinement of the original derivation of [2], and explores applications of the formalism to examples involving coupled systems where the coupling of strength Ω between the systems introduces a further intermediate time scale $1/\Omega$ into the evolution. The choice of $\Delta t \gg$ or $\ll 1/\Omega$ gives rise to master equations that differ either in the sense of best-approximation, or in the sense of measurement interpretation. Possible consequences for modelling of associated quantum thermodynamic processes are also considered.

[1] H.-P. Breuer and F. Petruccione, *The Theory of Open Quantum Systems*, Oxford University Press, Oxford, 2002
[2] Claude Cohen-Tannoudji, Jacques Dupont-Roc, Gilbert Grynberg *Atom-photon interactions: basic processes and applications*, Wiley-VCH Verlag GmbH & Co., 2004
[3] G. Schaller and T. Brandes, Phys. Rev. A 78, 022106 (2008)
[4] A. A. Buchheit and G. Morigi, Phys. Rev. A 94, 042111 (2016)

P55. Quasi-device-independent witnessing of genuine multilevel quantum coherence

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Quantum coherence has long been understood as a crucial feature of quantum mechanics. It manifests whenever a quantum system exists in a superposition of a set of classically distinguishable states given by an orthonormal basis of the Hilbert space [1]. The reference set of classical states is typically fixed to correspond to the eigenstates of a physically relevant observable like the Hamiltonian of the system. The system displays quantum coherence whenever its state is not given by a density matrix that is diagonal with respect to the classical basis. Yet, despite its simple description and central role, and beyond seminal studies on coherence of quantum optical fields, quantum coherence has only recently been characterised formally [2,3]. Coherence is now recognized as a fully-fledged resource in the general framework of quantum resource theories. Beyond the basic task of identifying states that possess quantum coherence over those that do not, one can investigate the number of classical states in a given superposition. This leads to the concept of multilevel quantum coherence as an indicator of the level of nonclassicality in the system [4]. Multilevel quantum coherence is important in many areas of physics, such as transfer phenomena in many-body systems [4]. Measuring the amount of genuine multilevel coherence is essential to provide a concrete gauge of nonclassicality, and to explore its quantitative role in determining the performance of quantum technologies. Here, we address this need by introducing the robustness of multilevel coherence, a measure which is shown to be both efficient to compute numerically and accessible experimentally. We demonstrate that the robustness of multilevel coherence can be witnessed in a quasi-device-independent way through the performance of a phase discrimination task, which is implemented experimentally using a photonic setup. Our results contribute to understanding the operational relevance of quantum resources by identifying genuine multilevel coherence as the key necessary ingredient for enhanced phase discrimination, and suggest ways to reliably and effectively test the quantum behaviour of physical systems.

[1] A. Streltsov, G. Adesso, and M. B. Plenio, arXiv preprint arXiv:1609.02439 (2016)
[2] J. Aberg, J. Quantifying superposition. arXiv preprint quantph/0612146 (2006)
[3] T. Baumgratz, M. Cramer, and M. B. Plenio, Phys. Rev. Lett. 113, 140401 (2014)
[4] F. Levi and F. Mintert, New Journal of Physics 16, 033007 (2014)

P56. Quantum feedback control of levitated nanoparticles

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Cooled mechanical resonators have a wide range of potential applications towards future quantum-limited metrology and sensing of small forces (e.g., gravitation), as well as improving our understanding of decoherence in quantum mechanical systems. Various experiments involving cooling trapped microscopic particles are moving towards or have reached the quantum limit. We are developing theoretical models that attempt to describe the dynamics of current experiments which involve measuring and applying feedback damping to diamagnetically levitated nanospheres [1]. Our aim is to understand at what point we reach the fundamental quantum limits of this process and to create a basis for preparing and manipulating quantum states of motion in these experiments.

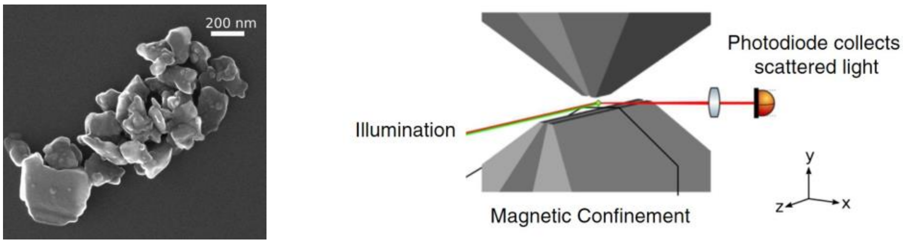

Fig. 1. (a) Scanning electron microscope image of nanodiamond cluster; (b) Magneto-gravitational trap designed for cooling nanoparticles.

[1] Hsu, J. et al. *Scientific Reports* 6, 1–10 (2016)

P57. Almost tight lower bounds for 1-out-of-2 quantum oblivious transfer

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Oblivious transfer (OT) is one of the most important and fundamental primitives in modern classical cryptography, with a variety of applications including secure multiparty computation, oblivious sampling, e-voting, signatures and many more. Its prominence stems from the fact that it can be used as the foundation for all secure two-party computations; with OT, all secure two-party computations are possible. Perfectly secure OT is impossible to achieve in the information-theoretic setting, but imperfect variants, in which the participants' ability to cheat is limited, are possible using quantum means despite remaining classically impossible. Precisely what security parameters are attainable in these imperfect variants remains unknown. For OT, as well as for many other cryptographic primitives, it has been an interesting and productive open question to determine the optimal achievable security parameters.

In this paper we consider stand-alone quantum protocols for 1-2 OT, and are concerned only with information-theoretic security. Intuitively, 1-2 OT is a two-party protocol in which Alice inputs two bits, x_0 and x_1, and Bob inputs a single bit, *b*. The protocol outputs x_b to Bob with the guarantees that Alice does not know b, and that Bob does not know x_b. A cheating Alice aims to find the value of b, and her probability of doing so is denoted by A_{OT}. A cheating Bob aims to correctly guess both x_0 and x_1, and his probability of doing so is denoted by B_{OT}. The cheating probability of the protocol is defined as pC = max{A_{OT} ;B_{OT} }.

As stated above, perfect 1-2 OT is impossible to achieve with information-theoretic security, meaning that all protocols attempting 1-2 OT in the information-theoretic setting must have pC > 1/2. It is not known exactly how much larger than 1/2 the cheating probability must be. In fact, the best known protocol has pC = A_{OT} = B_{OT} = 0:75.

Prior to our work, the best lower bound on pC for 1-2 OT was found by Chailloux, Gutoski and Sikora [1] to be

$$pc = max\{A_{OT}, B_{OT}\} \geq 2/3$$

Clearly, there is still a gap between the known lower bound on pC and the cheating probabilities attained by known protocols; our paper aims to close this gap. In other words, we address the theoretical question: how close to ideal can unconditionally secure 1-2 OT protocols be? Our paper contains three main contributions:

1. We introduce the concept of Semi-random OT and prove an equivalence between cheating in 1-2 OT and Semi-random OT. We further describe a general framework for Semi-random OT.
2. We use this framework to study Semi-random OT and, by extension, 1-2 OT protocols in the information-theoretic setting. We are able to increase the lower bound on pC for 1-2 OT protocols by constructing specific cheating strategies that are always available to Alice and Bob and which are always undetectable. Our construction parametrises Alice's and Bob's ability to cheat in terms of a single quantity and suggests how to construct schemes when guarding against one of either sender or receiver dishonesty is prioritised, as well as allowing us to derive bounds these settings. Unbalanced scenarios can arise, for example, in the context of quantum signature schemes [2], and the derived bounds prove useful for understanding the potential application of imperfect OT to signatures.
3. We illustrate our construction by describing a new OT protocol relying on unambiguous state elimination (USE) measurements. The protocol improves on all previous protocols in the sense that it decreases the average cheating probabilities of the participants. The security parameters achieved are almost tight with the bounds proved in this paper.

[1] A. Chailloux, G. Gutoski, and J. Sikora, arXiv preprint arXiv:1310.3262 (2013)
[2] R. Amiri, P. Wallden, A. Kent, and E. Andersson, Physical Review A 93, no. 3 (2016): 032325

P58. EPR steering, bell non-locality and entanglement in systems of identical bosons

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In previous work [1] quantum entanglement was treated for identical particle bipartite systems based on requiring the density operator to comply with the symmetrisation principle (SP) and with superselection rules (SSR) prohibiting states with coherences between differing total particle numbers. The subsystems are distinguishable modes, the subsystem density operators for separable states also satisfying the SP and SSR for subsystem particle numbers. New sufficiency tests for two mode *entanglement* with massive bosons were found. Spin squeezing in any spin component, two mode quadrature squeezing and a weak correlation test show that the state is entangled. An older entanglement test involving the sum of Sx, Sy spin variances being less than half the mean boson number N [2] also applied.

However, although quantum states for composite systems are categorised as either separable or entangled, they can also be categorised differently as Bell local or Bell non-local states based on local hidden variable theory (LHVT) [3]. All separable states are Bell local, but some Bell local states are entangled [4]. For Bell local states three cases occur for bipartite systems depending on whether both, one of or neither of the LHVT subsystem probabilities are also given by a quantum probability involving sub-system density operators. Cases where one or both are given by a quantum probability involve so-called local hidden states (LHS), and such states are *not* EPR steerable [3].

Recently [5] we found new tests for *EPR steering*. Spin squeezing in any spin component, two mode quadrature squeezing and a weak correlation test show that the LHS model fails (including for the entangled Bell local case) - hence the quantum state is EPR steerable. A new spin variance test for EPR steering was also found involving the sum of Sx, Sy spin variances being less than a quarter of the mean boson number N minus one half the mean of Sz.

In addition [5] we found a new test for *Bell non-locality* that applies when the measured quantities A, B have outcomes other than +1,-1 – such as for spin components.

[1] B J Dalton, L Heaney, J Goold, B M Garraway and Th Busch, New J Phys 16, 013026 (2014); B J Dalton, J Goold , B M Garraway and M D Reid, Phys. Scr. 92, 023004 (2017); Phys. Scr. 92, 023005 (2017)
[2] M Hillery and M S Zubairy, Phys Rev Letts 96, 050503 (2006)
[3] H M Wiseman, S J Jones and A C Doherty, Phys Rev Letts 98, 140402 (2007), Phys Rev A 76, 052116 (2007); E G Cavalcanti, S J Jones, H M Wiseman and M D Reid, Phys Rev A 80, 032112 (2009)
[4] R F Werner, Phys Rev A 40, 4277 (1989)
[5] B J Dalton and M D Reid, (2017) ArXiv 1611.09101 (in preparation)

P59. Long-distance continuous-variable quantum cryptography by using quantum scissors

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The recent progress in continuous-variable quantum key distribution (CV-QKD) systems has placed them in a competitive position with their conventional discrete-variable counterparts [1]. In particular, CV-QKD might be a better choice over short distances. When it comes to long distances, however, the story is different. One of the proposed solutions to improve the rate versus-distance performance of CV systems is to use noiseless linear amplifiers (NLAs) [2]. A realistic analysis that accounts for non-idealities of existing NLAs is, however, missing. One of the most well-known NLAs is based on quantum scissors (QSs) [3], whose ideal operation relies on the assumption that an input coherent state would be mapped, probabilistically, to an amplified coherent state. This would preserve the Gaussianity of the channel. In this study, we calculate the secret key rate of the GG02 protocol [4] enhanced by a single QS, see Fig. 1(a), by properly modeling the QS operation. We remove the Gaussian assumption in the QS modeling and find regimes of operation where QS-assisted GG02 offers advantages over the conventional GG02 system. We show that the rate enhancement is achieved after a certain cross-over distances. Remarkably, our rate is able to nearly reach the ultimate repeater-less bound for QKD, known as the PLOB bound [5], by a proper setting of the QS parameters.

Our QS-amplified GG02 system is described as follows. Alice, the sender, sends Gaussian modulated coherent states with variance V_A to Bob, the receiver, through a quantum channel of length L. Bob first amplifies the states using a QS and then measures randomly either of the quadratures using a homodyne detector (HOM); Fig. 1(a). The QS is assumed successful if only one of its detectors clicks. We find the exact output state of the QS—using characteristic-function relationships—which makes us able to estimate the effective gain and the excess noise that the QS produces; thus, being able to give an accurate estimate of the key rate.

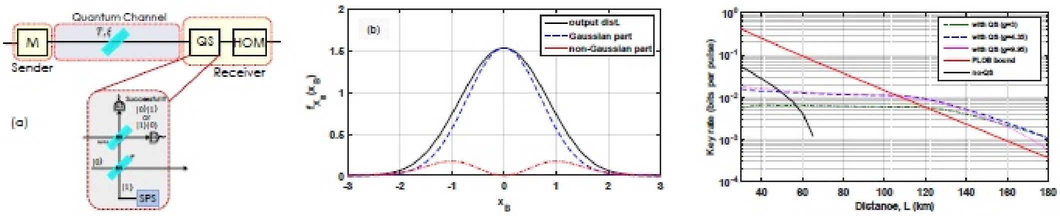

Fig. 1. (a) A CV-QKD link with an additional QS at the receiver. (b) Output distribution at the receiver side, which comprises Gaussian (dashed blue) and non-Gaussian (dot-dashed red) parts. The plots are for μ = 0:2 and V_A = 0:05. (c) The secret key rate for no-QS and QS-based systems, at different gain values $g = \sqrt{(1-\mu)/\mu}$, as compared to the PLOB bound.

Note that because of removing the Gaussian assumption, the output state is no longer a coherent state; thus, the QS operation cannot be noiseless and the generated noise will be detrimental to the performance of the GG02 protocol. Moreover, the output distribution becomes non-Gaussian, see Fig. 1(b), which makes the conventional methods for evaluation of the key rate insufficient. In order to find a lower bound on the key rate we have to calculate the relevant Holevo and mutual information functions in a non-Gaussian setup. In our case, we find the exact values for the mutual information between Alice and Bob, and use a Gaussian approximation approach to come close to the upper bound of the Holevo information term in the key rate. Figure 1(c) shows that, after a certain distance, the QS-based system outperforms the no-QS one and its rate approaches the fundamental rate-loss scaling given by PLOB bound in long distances. There also seems to be an optimum gain for each given distance. We note that the single-photon source in our analysis is assumed to be ideal. Nevertheless, with recent progress in quantum-dot sources, it is expected that the QS-based system can offer enhancement in realistic setups as well. Our study would be highly relevant in analyzing the performance of recently proposed CV quantum repeaters [6], which rely on a similar building block.

This study is partly funded by the White Rose Research Studentship and the UK Quantum Communications Hub EPSRC Grant EP/M013472/1.

[1] P. Jouguet, et al., Nature Photonics 7, 378 (2013)
[2] R. Blandino, et al., Phys. Rev. A 86, 012327 (2012)
[3] T. C. Ralph and A. P. Lund, arXiv:0809.0326
[4] F. Grosshans, et al., Nature 421, 238 (2003)
[5] S. Pirandola, et al., Nature Communications 8, 15043 (2017)
[6] J. Dias and T. C. Ralph, arXiv:1505.03626

P60. Influence of quantized atomic motion on cooperative spontaneous emissions of light

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Spontaneous emission of light is one of the corner stone of our understanding of the light-matter interaction. It is known to depend on different factors depicted in Fig 1: the electromagnetic environment, which can be engineered by placing an atom inside a cavity; the presence of other atoms, which can transform spontaneous emission into a cooperative effect; and the atomic motion, leading to shifts and broadenings of the spectral lines.

In this work, we study the influence of the *quantized* center-of-mass motion of an ensemble of two-level atoms on their interaction with the electromagnetic field in vacuum. For this purpose, we derive a Markovian master equation for their internal dynamics including all effects related to their quantized motion [1]. Our equation provides a unifying picture of the consequences of the recoil and of the statistical nature (bosonic or fermionic) of the atoms on both their dissipative and conservative dynamics, even beyond the Lamb-Dicke regime. From the solutions of the master equation, we investigate in details the cooperative emission processes (superradiance and subradiance) and find that they can be strongly modified through the external state of motion [2]. Our results suggest the possibility to quantum program the internal dynamics of atoms through motional state engineering.

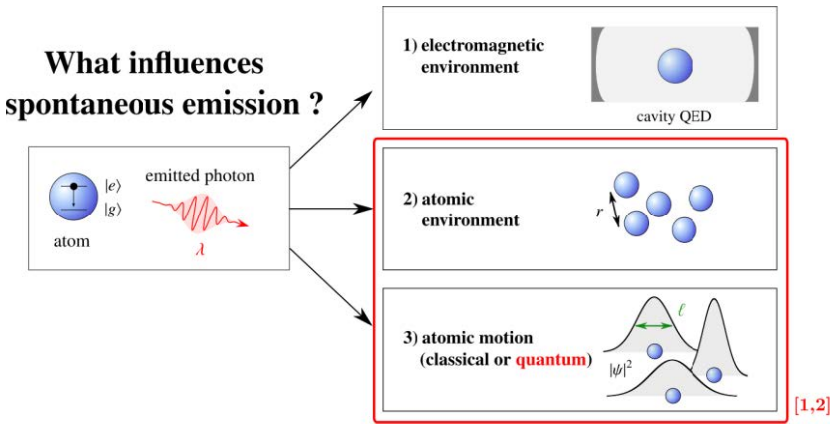

Fig. 1. What influences spontaneous emission of light?

[1] FD, D. Braun, and J. Martin, Phys. Rev. A 93, 022124 (2016)
[2] FD, D. Braun, and J. Martin, Phys. Rev. A 94, 033838 (2016)

P61. Quantum computation with mechanical cluster states

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Gaussian approximations to cluster states may be generated by suspending an array of resonators in a cavity field and driving their respective sidebands in a multi-step process [1]. Three further steps towards the full toolbox for measurement based quantum computation are developed here: verification of the cluster state [2], multimode Gaussian transformations [3] and the inclusion of a non-Gaussian resource.

We develop a method for state reconstruction via measuring the cavity field after interaction with a tuned interaction profile. The system can be described by the cavity field interacting with the center of mass motion of each resonator: $H_1 = \mathrm{g}(t)X\ \sum_j \mathrm{g}_j\left(b_j\ + b_j^\dagger\right)$ where b_j are the mechanical modes, g(t) is a time dependent coupling, g_j is the single photon coupling to the oscillator *j* and $X = \frac{a+a^\dagger}{\sqrt{2}}$ is the optical mode's position quadrature. The dynamics are solved by $U\ =\ e^{i\Psi^\dagger}D(X\beta)$, where $\Psi = \sum_j \psi_j, \beta\ =\ (\beta_1\beta_2\ \ldots.\beta_N)^\intercal$ and $\beta_j\ =\ -i\mathrm{g}_j^*\int_0^t \mathrm{g}(s)e^{i\Omega_j s}ds\ ;\ \psi\ =\ -\int_0^t \mathrm{Im}\left(\beta_j\beta_j^*\right)ds$ with the number of oscillators *N* and mechanical frequencies Ω_j. Under this evolution, statistics of the operator $P = \frac{i(\alpha^\dagger-\alpha)}{\sqrt{2}}$ are directly related to the mechanical mode quadratures, $Q_{\theta_j}\ =\ b_j\ e^{-i\theta_j}\ +\ b_j^\dagger e^{i\theta_j}$ [where $\theta_j = \arg\left(\beta_j\right) + \frac{\pi}{2}$]. The system is assumed to be initialised in the separable state $\rho\ =\ |0\rangle\ \langle 0|\ \otimes\rho_0$ with $0\rangle$ the optical vacuum and ρ_0 an arbitrary state of the network, and is allowed to evolve for a fixed time under an interaction profile *g*(*t*) determined by the quadrature being reconstructed. The measurement of *P* forces us to design the interaction profile such that $\Psi = 0$. The relation between statistical moments is given by

$$\langle P^n\rangle = \sum_{k_0+k_1+\ \ldots k_N=n} \binom{n}{k_0, k_1, \ldots k_N} \langle P^{k_0}\rangle_0$$
$$\langle \prod_{1\leq j\leq N} \left(-\sqrt{2}\left|\beta_j\right|Q_{\theta_j}\right)^{k_j}\rangle$$

where $\langle\cdot\rangle_0$ indicates that the expectation value is taken over the vacuum $|0\rangle$. While reconstruction can be applied to arbitrary states, the procedure is particularly suite to reconstruction of Gaussian states, defined by their first and second moments. Computation proceeds through measurements on the nodes of the cluster. For continuous variable clusters, universality is achieved with multimode Gaussian transformations and one non-Gaussian transformation. The inaccessible mechanical modes are continuously monitored through measurements on the cavity field. Modulating the linearised optomechanical interaction at the mechanical frequency produces a time averaged QND interaction of the cavity position quadrature with a mechanical quadrature defined by the phase of the interaction[4] and produces a Hamiltonian $H\ =\ \alpha(\alpha + \alpha^\dagger)X_\varphi$.

Continuous measurements carried out on the $\alpha + \alpha^\dagger$ quadrature of the cavity field allows the mechanical system to be described by conditional Gaussian dynamics [5] and drives the resonator towards a state highly squeezed in X_φ. This is sufficient to apply multimode Gaussian operations to the cluster. Continuous monitoring suffices to manipulate the cluster as if direct projective measurements were being performed. We provide a thorough numerical analysis demonstrating the performance of monitoring under a collection of relevant experimental parameters.

The non-Gaussian transformation can be realised by including a non-Gaussian resource built directly into the cluster. We demonstrate that by taking advantage of the optomechanical interaction to second order (quadratic in mechanical position) the cubic phase state $e^{\ iq^3}|0\rangle_p$, where q is the mechanical position and $|0\rangle_p$ denotes a zero-momentum eigenstate of momentum, may be dissipatively engineered and incorporated into a cluster state.

[1] Oussama Houhou, Habib Aissaoui, and Alessandro Ferraro. *Phys. Rev. A*, 92:063843, Dec 2015
[2] Darren W. Moore, Tommaso Tufarelli, Mauro Paternostro, and Alessandro Ferraro. *Phys. Rev. A*, 94:053811, Nov 2016
[3] Darren W. Moore, O Houhou, and Alessandro Ferraro. *arXiv:1705.11183*, 2017
[4] A A Clerk, F Marquardt, and K Jacobs. *New Journal of Physics*, 10(9):095010, 2008
[5] Marco G. Genoni, Ludovico Lami, and Alessio Serafini. *Contemporary Physics*, 0(0):1–19, 0

P62. Quantitative modelling of coherent atom-light interactions in 2, 3 and 4-level systems in the hyperfine Paschen-Back (HPB) regime

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The propagation of light through thermal atomic vapours subject to external magnetic fields continues to be a flourishing area of research interest [1]. At Durham we have spent 15 years studying the quantitative spectroscopy of alkali-metal vapours, culminating in the publication of our electric susceptibility code ElecSus [2]. Our investigations include nondegenerate three-level ladder and four-level diamond schemes. Application of a sufficiently large magnetic field gives us access to the hyperfine Paschen-Back (HPB) regime [3] [4], where the Zeeman splittings exceed the Doppler width. We have demonstrated that it is possible to realise electromagnetically induced transparency (EIT) [5] and absorption (EIA) [6] in nondegenerate three-level systems. We have also realised textbook four-wave mixing (4WM) signals that agree quantitatively with a simple 4-level model [12].

Applications of the quantitative understanding of atom-light interactions in the presence of a magnetic field range from devices (a compact optical isolator [7], narrow-line filters [8] [13], a Faraday laser [9]) to fundamental physics (single-photon interference due to motion in an atomic collective excitation [10], characterisation of and modelling of the 4WM process [12]).

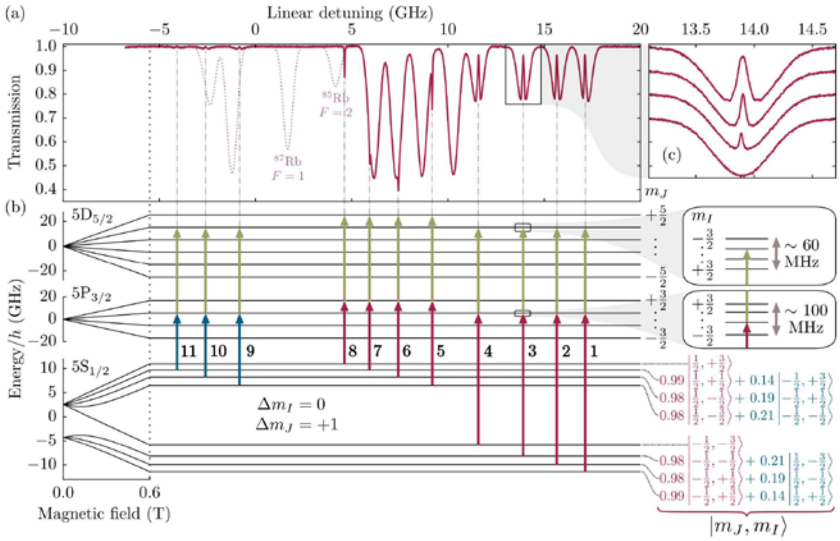

Fig. 1: EIT in isolated three-level systems in the hyperfine Paschen-Back regime. (a) shows a typical weakprobe transmission spectrum (red) and (b) a diagram of the transitions associated with the spectral features in (a). The eigenstates of the system in the jmJ ;mI i basis are shown to the right of the diagram for a magnetic field strength B = 0.6 T, where a significant admixture of states with opposite spin (blue text) in the 5S1=2 manifold remain; these result in the weak transitions indicated by the blue arrows. (c) shows an expanded view of one of the EIT resonances as a function of control-beam power. Zero detuning is the weighted D2 line centre of naturally abundant rubidium in zero-magnetic field [11].

[1] D. Budker et al., Reviews of Modern Physics 74, 1153 (2002)
[2] M. A. Zentile et al., Computer Physics Communications 189, 162–174 (2015)
[3] A Sargsyan et al., Optics Letters 37, 1379–1381 (2012)
[4] A Sargsyan et al., Journal of the Optical Society of America B 31, 1046–1053 (2014)
[5] D. J. Whiting et al., Physical Review A 93, 043854 (2016)
[6] D. J. Whiting et al., Optics Letters 40, 4289–4292 (2015)
[7] L. Weller et al., Optics Letters 37, 3405–3407 (2012)
[8] M. A. Zentile et al., Optics Letters 40, 2000-03 (2015)
[9] J. Keaveney et al., Review of Scientific Instruments 87, 095111 (2016)
[10] D. J. Whiting et al., Physics Review Letters 118(25), 253601 (2017)
[11] P. Siddons et al., Journal of Physics B: Atomic, Molecular and Optical Physics 41 155004 (2008)
[12] D. J. Whiting et al., arXiv preprint arXiv:1705.01855 (2017)
[13] M. A. Zentile et al., Journal of Physics B: Atomic, Molecular and Optical Physics, 48(18), 185001 (2015)

P63. In search of multipath interference using large molecules

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The superposition principle is fundamental to the quantum description of both light and matter. Recently, a number of experiments have sought to directly test this principle using coherent light[1], single photons[1,2], and nuclear spin states[3]. We extend these experiments to massive particles for the first time using a molecular interferometer[4]. Fig. 1 shows an illustration of our experiment. A beam of Pthalocyanine (PcH2) molecules with a mass of 515 amu is desorbed from a surface using a tightly focused laser to produce a beam. Molecules pass through a series of single, double, and triple-slit masks nanofabricated into a thin, amorphous carbon mask where they diffract. Further downstream the molecules land on a quartz screen where they stick. The resulting molecular interference patterns are then imaged through their fluorescence. By comparing these interference patterns we can place bounds on any high-order, or multipath, contributions. We observe an upper bound of less than one particle in a hundred deviating from the expectations of quantum mechanics over a broad range of transverse momenta and de Broglie wavelength.

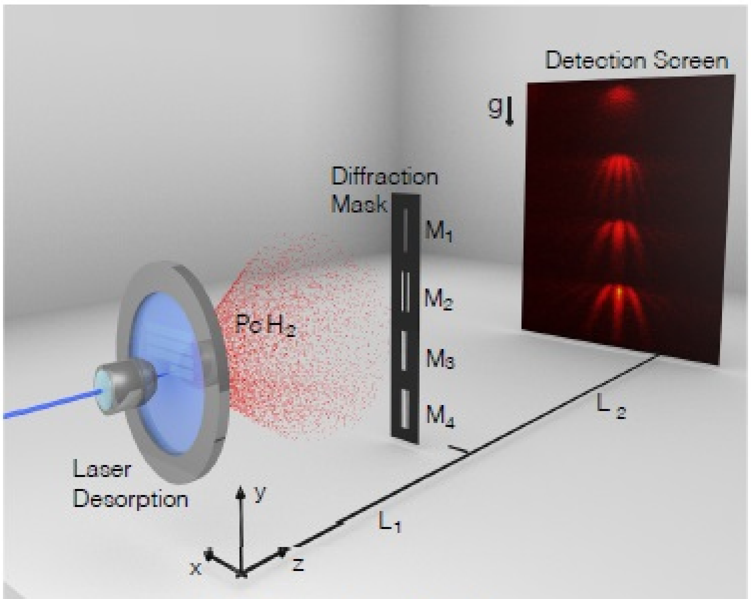

Fig 1: Experimental setup up.

[1] U. Sinha et. al., Science, 329, 418-421 (2010)
[2] O. S. Magnana-Loaiza et al., Nat. Comms, 7, 13987 (2016)
[3] D. K. Park et. al., New J. Phys., 14, 113025 (2012)
[4] Cotter et al., Sci. Adv. 2017;3:e1602478 (2017)

P64. Control of polarisation rotation and fragmentation of vector vortex beams in nonlinear media

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Fully-structured light – light with non-uniform intensity, phase *and* polarisation – lies at the heart of an emerging and extremely promising field of research, with applications in high-resolution imaging, optical trapping and manipulation of nanoparticles, plasmonic lithography, and optical communication. We show that the interplay of polarisation structure and nonlinearity can be used as a means of controlling both the polarisation distribution and the fragmentation of such beams as they propagate in a self-focusing nonlinear medium.

Fully structured light beams are constructed from two spatial, Laguerre-Gauss (LG), modes with orthogonal polarisations:

$$\vec{E} = \cos(\gamma) LG_L \vec{e_l} + e^{i\beta} \sin(\gamma) LG_R \vec{e_r}$$

where γ and β give the relative amplitude and phase, respectively, of the two modes and $\vec{e_l}$ and $\vec{e_r}$ are unit vectors corresponding to left- and right-hand circular polarisation, respectively. They can be characterised by their net orbital angular momentum (OAM) and their spatial polarisation distribution [1].

We show analytically that for *linear* propagation the polarisation rotation depends only on the difference in Gouy phase between the modes. We numerically model *nonlinear* propagation using a coupled nonlinear Schrödinger equation previously shown to have excellent agreement with experimental results [2]. We show that the nonlinearity not only changes the amount of polarisation rotation for beams with a net OAM, but can also induce a rotation in beams with zero net OAM if there is an amplitude difference between the two modes, FIG.1.

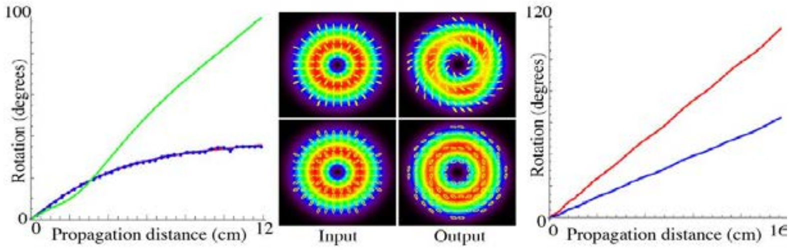

FIG.1 (Left) Polarisation rotation for a beam with a net OAM of 1: linear propagation, red (analytical) and blue (numerical), nonlinear propagation, green. (Centre) Initial and final polarisation distributions for beams with zero net OAM and an intensity bias of $\sqrt{2}$: 1 (top row) and 2: 1 (bottom row). (Right) Corresponding polarisation rotations for $\sqrt{2}$: 1 (blue line) and 2: 1 (red line).

It is well known that during nonlinear propagation scalar LG modes fragment into solitons, with the number of solitons equal to twice the OAM of the beam [3]. We show that for fully structured beams, the fragmentation tends to occur along lines of polarisation singularities. This allows us to predict the number of solitons that will be produced by a particular polarisation distribution and tailor it accordingly. For example, FIG.2. shows the breakup of a higher-order star beam (made from an OAM of 1 and -2 in the left and right circularly polarised modes, respectively) and lemon beam (made from an OAM of 1 and 2).

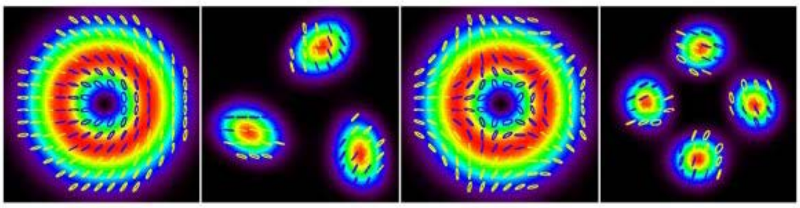

FIG.2. Initial and fragmented states of a higher order lemon (left) and star beam (right).

[1] Q. Zhan, "Cylindrical vector beams: from mathematical concepts to applications," Adv. Opt. Photon. 1, 1-57 (2009)
[2] F. Bouchard et al, "Polarization Shaping for Control of Nonlinear Propagation,"Phys. Rev. Lett. 117, 233903 (2016)
[3] W. J. Firth and D. Skryabin, "Optical Solitons Carrying Orbital Angular Momentum," Phys. Rev. Lett. 79, 2450 (1997)

P65. Quantum state comparison amplifier with feedforward state correction

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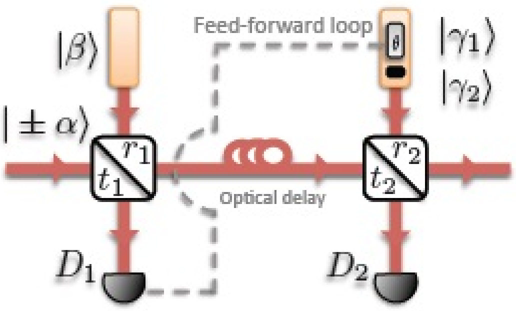
Quantum mechanics poses stringent constraints on the way a quantum signal can be amplified. Deterministic amplification of an unknown quantum state always imply the addition of a minimal amount of noise. Linear and noiseless amplification is in principle allowed provided it works only probabilistically [1] and [2].

The State Comparison AMPlifier (SCAMP) [3] is an approximate probabilistic amplifier that works for a set of coherent states with unknown phase but known mean photon number. Alice picks uniformly at random an input state from the set $\{|+\alpha\rangle, |+\alpha\rangle\}$ and pass it to Bob who has to amplify it.



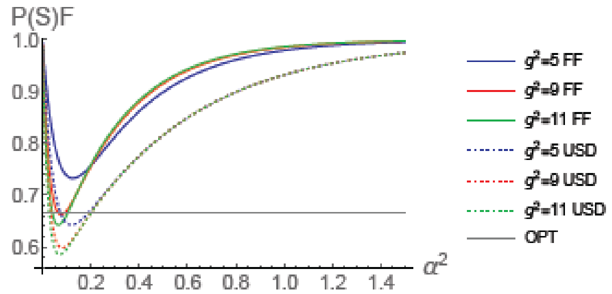


FIG. 1. Bob mixes Alice's input, $|\pm\alpha\rangle$ with a guess coherent state $|\beta\rangle$ at the first beam splitter. The input of the second stage is chosen according to the outcome of the first detector. FIG. 2. Success probability-fidelity product for the SCSCAMP for the USD based amplifier, as explainedin the main text, with gains of 5 (blue), 8 (red) and 11(green) and for the no-cloning limit (gray). The detector efficiency are assumed to be equal to 1 for simplicity but the system is resilient to inefficient detectors.

Our device is shown in figure 1. Bob mixes Alice's input with two suitable guess coherent states at the beam splitters in attempt to achieve destructive interference in both the arms that go to the APD detectors. The lack of trigger is an imperfect indication that Bob's guess is right and that the output contain the correct amplified state (the indication is imperfect because there could be undetected light due to a wrong guess). In this case the output state is passed to the second stage for further amplification. On the other hand, if D_1 fires Bob know that his guess was wrong but he can still correct the output by changing the input state for the second stage via the feed-forward loop.

The overall gain of the system is given by $g = \frac{1}{r_1 r_2}$. Since the key working point for this improved SCAMP is this feed-forward State Correction we call it SCSCAMP. Bob declares success and postselects the output corresponding to the events S = {{D_1 = 0;D_2 = 0};D_1 = 1} (or simply S = {{0; 0}; 1}).

The fidelity of the SCSCAMP is the probability of passing a measurement test on the output comparing it to $|g\alpha\rangle$ and the *success probability-fidelity product* [2] is the joint probability of success and of passing the measurement test:
P(T;S) = P(T; {0; 0}) + P(T; 1)

$$= \frac{1}{2}\left(2 - e^{-4\eta\left(1-\frac{1}{g}\right)\alpha^2} + e^{-4\eta\left(1-\frac{1}{g^2}\right)\alpha^2} e^{-4\left(1-\frac{1}{g}\right)^2\alpha^2}\right)$$

Our figures of merit compare favorably with other schemes. In figure 2 we show that the success probability-fidelity product of the SCSCAMP is always bigger than the one of an USD based amplifier (see for example [2]) that, when inconclusive, delivers an uniformly at random output $|\pm g\alpha\rangle$. Furthermore, SCSCAMP is almost always bigger than the $1 \rightarrow 2$ deterministic no-cloning limit of 2/3 for an arbitrary coherent state.

The SCSCAMP can be realized with classical resources (i.e., lasers, linear optics and APD detectors), the ability to switch between input states on the fly requires delay lines and fast switching but it can still be achieved with classical resources. Similar systems, with no state correction, proved to achieve high-gain, high fidelity and high repetition rates [4], [5] and [6].

Due to its simplicity, a SCSCAMP might represents an ideal candidate either as a recovery station to counteract quantum signal degradation due to propagation in a lossy fibre or across the turbulent atmosphere. The system is also suitable for on-chip implementation.

The work was supported by the QComm Quantum Communication Hub of the UK Engineering and Physical Sciences Research Council (EP/M013472/1).

[1] T.C. Ralph & A.P. Lund, in Proceedings of the 9th QCMC, Conference, edited by A. Lvovsky (AIP, Melville, NY, 2009)
[2] S. Pandey, et al., Phys. Rev. A 88, 033852 (2013)
[3] E. Eleftheriadou et al., Phys. Rev. Lett.111, 213601 (2013)
[4] R. Donaldson et al., Phys. Rev. Lett. 114, 120505 (2015)
[5] M.A. Usuga et al., Nat. Phys. 6, 767 (2010)
[6] R. Donaldson et al., in preparation

P66. Single-shot, phase-insensitive readout of an atom interferometer

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Atom interferometry is a precision measurement technique which maps something difficult to measure (atomic phase) to something comparatively easy to measure (such as relative atomic population). The sensitivity of atoms to electromagnetic and gravitational fields allows atom interferometry to examine physics that conventional photon interferometers cannot.

We have constructed an atom interferometer, using a time-varying optical lattice as atom-optics, to perform the coherent off-resonant scattering of a ^{87}Rb Bose-Einstein condensate into the momentum states $p = \pm 2n\hbar k$. 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 spatially-flat magnetic fields, without destroying sensitivity to gradient fields or accelerations.

Here we present preliminary measurement of a phase-contrast interferometry signal. This technique maps the energy of our atom-light interaction to the phase oscillation 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.

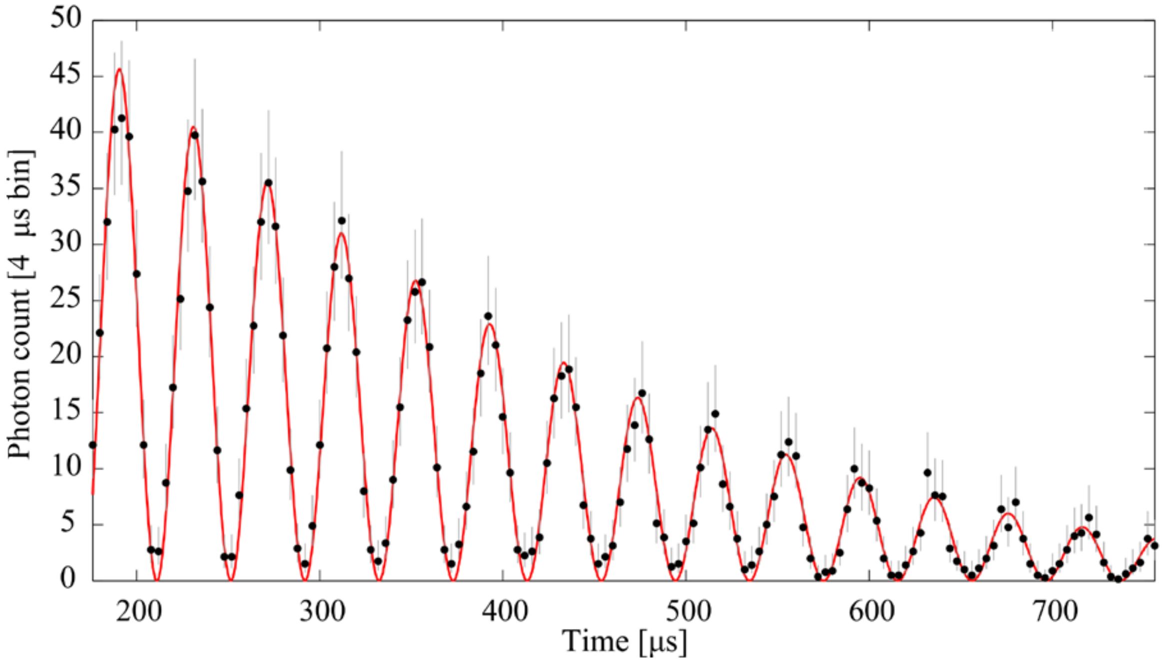

Figure 1: A single-shot measurement of recoil frequency from our interferometer. We generate the 0ħk, and ±2ħk momentum states of a Bose-Einstein condensate using a pulsed optical grating. While these momentum states interfere the resulting fringes can be considered as an atomic hologram with a phase oscillating at eight times the recoil frequency. We shine a probe laser into this hologram, and measure the reflection using a single-photon detector. From the frequency of this oscillation we extract the energy of the atom-light interaction used to generate the momentum states, and in turn can extract a measurement, for example, of the fine structure constant.

P67. Benchmarking probabilistic quantum amplifiers

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The state comparison amplifier [1, 2] is a recently proposed probabilistic quantum amplifier, intended especially for amplifying coherent states. Its realization is simple and uses only linear optics and photodetectors, and the preparation of a "guess" state, typically a coherent state.

Fidelity and success probability can be high compared with other probabilistic amplifiers. State comparison amplification does however extract information about the amplified state, which means that it would have to be used in a secure node in a quantum communication network. Also, for this same reason, that it extracts information about the amplified state, a simple measure-and-resend procedure [3] might be an alternative.

In this contribution, we compare the state comparison amplifier to measure-and-resend strategies in terms of success probability and average fidelity and when used in a lossy communication channel. In certain regimes, the success probability and average fidelity of state comparison amplifiers can beat those of measure-resend strategies. As for use in a lossy communication channel, we have however been unable to find any regimes where a state comparison amplifier will increase the probability for the end receiver to unambiguously distinguish between two coherent states.

Measuring and resending a quantum state with regular intervals can, on the other hand, increase the probability that a receiver at the end of a lossy channel will correctly infer what the original input state was, even when the allowed amplitude of the resent state, that is, the "gain", is limited. This does however require that the information whether the measurement was successful or not is sent along with the amplified state. Therefore, as one would expect, this type of "amplifier" will not increase the classical information-carrying capacity of the communication channel. This still leaves the possibility that measure-resend "amplifiers" could in principle be useful e.g. as simple secure relay stations in a quantum communication network. However, in the scenario we are considering, measure-resend amplifiers turn out not to be useful for low coherent state amplitudes. Therefore, even when used in secure nodes, they are less likely to be of practical relevance for quantum cryptography, which typically operates with weak coherent states.

[1] E. Eleftheriadou, S. M Barnett, J. Je_ers, Quantum optical state comparison ampli_er, Phys. Rev. Lett. 111, 213601 (2013)
[2] R. J. Donaldson, R. J Collins, E. Eleftheriadou, S. M. Barnett, J. Je_ers, G. S Buller, Experimental implementation of a quantum optical state comparison ampli_er, Phys. Rev. Lett. 114, 120505 (2015)
[3] V. Dunjko and E. Andersson, Truly noiseless probabilistic ampli_cation, Phys. Rev. A 86, 042322 (2012)

P68. Single organic molecule coupling to a hybrid plasmonic waveguide

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Efficient photon sources will enable many quantum technologies. Single dibenzoterrylene (DBT) molecules are promising photon sources, but often emit in an unknown direction making photon collection challenging. Dielectric structures redirect emission into single optical modes [1], but are relatively large due to the diffraction limit of light. Plasmonic devices, such as antennae, can concentrate the electromagnetic field at the site of an emitter on a surface in volumes below the diffraction limit and redirect emission into well-controlled directions, but often suffer from losses. Recently, planar dielectric antennae have shown promise for redirecting emission [2], however often they do not provide single mode operation or compatibility with integrated photonics.

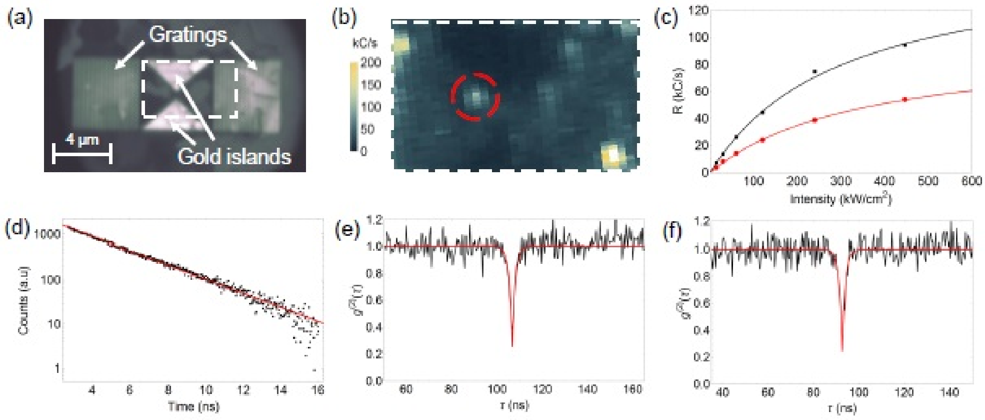

Fig. 1: (a) White-light image of a HPW showing input/output grating couplers and anthracene crystals on the surface. (b) Molecule fluorescence from the dashed box in (a). (c) Saturation curves for the molecule indicated with a red dashed circle in (b), showing count rates collected from the confocal microscope (black squares) and from a grating coupler (red circles). (d) Pulsed laser measurement of the molecule excited state lifetime. (e) $g^{(2)}(\tau)$ measured from the microscope only and (f) $g^{(2)}(\tau)$ measured from the grating and microscope.

Here we present a hybrid dielectric–metal approach in coupling a single molecule to an optical mode in an integrated planar device. We designed and fabricated a hybrid plasmonic waveguide (HPW) consisting of a dielectric slab with a nanoscale gap patterned in gold on the surface, as shown in Fig. 1(a). Replacing the silicon layer used in our previous work [3] with titanium dioxide (TiO_2) allows operation at $\sim$785 nm, the emission wavelength of DBT. Light propagating in the TiO_2 layer passes through the gap between the islands of gold. The width of the gap controls mode confinement: when the gap is <100 nm the propagating mode is mainly in the gap providing strong confinement; but when the gap is wider the mode decouples from the gold and propagates mainly in the TiO_2 with low loss. We deposited DBT-doped anthracene crystals on the surface (Fig. 1(a)) using a supersaturated vapour growth technique [4]. Using confocal fluorescence microscopy we found a DBT molecule positioned near the gap (Fig. 1(b)). We then measured the saturation intensity of the molecule (Fig. 1(c)) to be I_{sat} = 325(27) kW/cm^2. Illuminating the molecule with a pulsed laser (Fig. 1(d)) we measured the lifetime of the molecule to be 2.74(2) ns. Under CW excitation we measured the second-order correlation function $g^{(2)}(\tau)$ of the light emitted directly into the microscope. This shows clear anti-bunching (Fig. 1(e)) with $g^{(2)}(0)$ = 0:25(6) proving this to be a single molecule. By detecting photons simultaneously from the microscope and from the grating coupler we measured $g^{(2)}(0)$ = 0:24(6) (Fig. 1(f)), demonstrating that this single molecule was emitting into the waveguide mode. By measuring the optical losses in our setup we calculated the coupling efficiency from the molecule to the HPW to be $\sim$ 22%. This method provides a route to building waveguide sources of photons in planar integrated quantum photonic circuits for applications in quantum technology.

[1] S. Faez et al., Phys. Rev. Lett. 113, 213601 (2014)
[2] X. L. Chu et al., Optica 5, 203–208 (2014)
[3] M. A. Nielsen et al., Nano. Lett. 16, 1410–1414 (2016)
[4] C. Polisenni et al., Opt. Express 24, 5615–5627 (2016)

P69. Tightly confined cold atomic media for contactless non-linear optics mediated by long-range Rydberg interactions

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Rydberg non-linear optics [1] has emerged as a viable approach to induce strong effective photon-photon interactions, e.g. for applications in optical quantum information processing [2]. Using electromagnetically induced transparency and photon storage, the µm-ranged van-der-Waals interactions between Rydberg atoms can be mapped onto light-fields to create optical non-linearities at the single photon level. So far, non-linearities between overlapping modes within the same medium have been experimentally observed [1]. Recently, we have demonstrated an interaction between photons in non-overlapping spatial modes over distances corresponding to 15 times their optical wavelength, while stored as collective Rydberg excitations in spatially separated cold atom ensembles [3]. The interaction induces spatially non-uniform phase shifts that lead to reduced retrieval in the original modes.

Currently, the atomic storage media are confined in two microscopic, side-by-side optical dipole traps [4] which provide tight radial, but limited axial confinement. Therefore, we are implementing an additional crossed dipole trap, intersecting the existing traps at a 90 degree angle. The design of the new cross trap is – in principle – self aligning, allowing for adjustment of the angle between the trapping beams. This new trap will function as a reservoir of atoms to assist the loading of the current dipole traps, increasing the optical depth. It will also help to reduce the length of the storage media. Tighter confinement is desirable not only to access a regime where both media are contained within the range of Rydberg blockade [5] (preventing simultaneous photon storage), but also to imprint more uniform phase gradients that should lead to a more controlled modification of the retrieval modes.

[1] O. Firstenberg *et al.,* J. Phys. B: At. Mol. Opt. Phys. 49, 152003 (2016)
[2] D. Paredes-Barato and C. S. Adams, Phys. Rev. Lett. 112, 040501 (2014)
[3] H. Busche *et al.,* Nat. Phys. 13, 655-658 (2017)
[4] R. Grimm *et al.,* Adv. At. Mol. Opt. Phys. 42, 95-170 (1999)
[5] M. D. Lukin *et al.,* Phys. Rev. Lett. 87, 037901 (2001)

P70. A framework for measures of non-Gaussian operations

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Non-Gaussian operations are important in continuous variable quantum information processing, as they are required for many interesting protocols such as entanglement distillation, distinguishing Gaussian states and computation [1]. Measures have been proposed to characterize non-Gaussian properties of states [2],some have been extended to operations [3]. Here we aim to provide a framework by which state measures can be promoted to channel measures via the Choi-Jamiołkowski isomorphism (CJI). Thus we can compare different mathematical formulations and their physical/operational significance. In particular we seek measures that combine the notions of non-Gaussianity and coherence.

We attempt to construct a measure using the CJI. This is defined for the discrete variable finite dimensional case, but with care it can be used in infinite dimensions [4, 5]. Informally, by following the procedure as in figure 1 with a suitable input state ρ_{in}, this isomorphism constructs a correspondence between operators $\wedge$ and states $\rho_{out}^{\wedge}$.

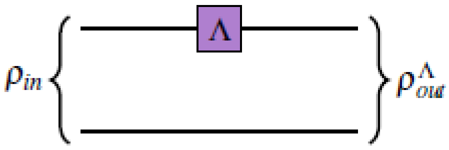

Figure 1: The Choi-Jamiołkowski isomorphism. A 2 mode maximally entangled state ρ_{in} undergoes the transformation; $\wedge \otimes 1$ the resulting state $\rho_{out}^{\wedge}$ is isomorphic to $\wedge$.

An ideal input state would be maximally entangled, although this is non-physical in infinite dimensions. An alternative is a state such that the reduced density matrix has full rank [5].

With a correspondence between operators and states established, we may then 'promote' a state measure of non-Gaussianity to an operator measure of non-Gaussianity. Many existing measures are based upon a distance to a Gaussian reference state. Utilizing this concept, we explore physical motivations for the choice of distance measure, including measures in phase space that have particular appeal when discussing non-Gaussianity [6]. Such a measure should fulfil certain properties. Let $\wedge$ be an operation, NG ($\wedge$) be the non-Gaussianity of $\wedge$ and $G \in \mathfrak{G}$ be a Gaussian operation. Then we require:

1. $\mathrm{NG}(\wedge) = 0 \iff \wedge \in \mathfrak{G}$ (Gaussian and non-Gaussian operators are distinguished)
2. $\mathrm{NG}(\wedge) \geq 0$
3. $\mathrm{NG}(\wedge) \geq \mathrm{NG}\,(\mathrm{G} \circ \wedge)$ (Gaussian operations cannot increase non-Gaussianity)
4. $\mathrm{NG}(\wedge_1 \circ \wedge_2) \leq \mathrm{NG}(\wedge_1) + \mathrm{NG}(\wedge_2)$ (Combining operations should not make them more non-Gaussian than their constituent parts)

Combining these requirements with the CJI we aim to construct an operationally relevant, computationally tractable measure of non-Gaussianity relevant to continuous variable non-Gaussian operations.

[1] C. Weedbrook, S. Pirandola, R. Garc´ıa-Patr ´on, N.J. Cerf, T.C. Ralph, J.H. Shapiro, and S. Lloyd, Rev. Mod. Phys. 84, 621 (2012)
[2] See, for example: M.G. Genoni, M.G.A. Paris, and K. Banaszek, Phys. Rev. A 76, 1 (2007).; J.S. Ivan, M.S. Kumar, and R. Simon, Quantum Inf. Process. 11, 853 (2012).; and others
[3] M.G. Genoni and M.G.A. Paris, Phys. Rev. A 82, 1 (2010)
[4] G. Giedke and J.I. Cirac, Phys. Rev. A 66, 32316 (2002)
[5] M.E. Shirokov and A.S. Holevo, Probl. Inf. Transm. 44, 73 (2008)
[6] K. Zyczkowski and W. Slomczynski, J. Phys. A. Math. Gen. 31, 9095 (1998)

P71. Ellipsoidal plasma mirror focusing of high power laser pulses to ultra-high intensities

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Increasing the achievable peak intensity of laser systems has enabled several new research avenues in laser-plasma science; including laser-driven particle acceleration, radiation sources and laboratory astrophysics, to name a few. Current state-of-the-art facilities are capable of producing laser intensities of $\sim 10^{21}$ Wcm^{-2}, and in the coming years systems expected to achieve $10^{22} - 10^{23}$ Wcm^{-2} will commence operation, enabling the exploration of new physics in the ultra-intense laser-plasma regime. These facilities include APOLLON [1] and the extreme light infrastructure (ELI) [2].

To open up exploration of this intensity regime employing current state-of-the-art facilities, characteristic parameters of the drive laser pulse beyond present capabilities; primarily focal intensity and temporal intensity contrast. To improve both parameters simultaneously we have developed a low F-number (~F/1) ellipsoidal focusing plasma mirror (FPM).

We present the design, development and testing of a FPM, produced for employment on the Vulcan petawatt laser system at Rutherford Appleton Laboratories. A factor 2.5 reduction in focal spot size was achieved when compared to F/3 focusing using a conventional solid state optic. Accounting for plasma reflectivity and focal spot quality this testing indicated a x3.6 enhancement in peak intensity. An example use of a FPM, in an investigation of laser-driven proton acceleration, is demonstrated. The intensity increase results in a factor 2 increase in the maximum energy of protons accelerated from a foil target, consistent with TNSA laser intensity scaling.

This study will help to further the field of plasma-based optics, bringing this technology closer to maturity and allow for a window into the future research of ultra-intense laser-plasma interactions.

[1] J. P. Zou *et al*, Mod. Phys. 3, e2 (2015)

[2] B. Rus *et al*, Proc. SPIE 8780, High-Power, High-Energy, and High-Intensity Laser Technology; and Research Using Extreme Light: Entering New Frontiers with Petawatt-Class Lasers, 87801T (2013)

P72. Microplasmas for selective surface cleaning in microfabricated ion-traps

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Ion traps have applications in optical atomic clocks [1], quantum metrology [2] and quantum information processing [3]. Quantum coherence is of paramount importance in these applications, yet motional decoherence of ions remains a significant limitation. The Rabi frequency gives the strength of the laser-ion interaction; it depends on the ion's vibrational quantum number *n*, so motional heating will introduce infidelities in coherent control of the ion's state.

Recent studies have shown that hydrocarbon monolayers, adsorbed onto the surface of the trap electrodes, are a likely source of electric field noise [4-6]. Plasma beam cleaning has been used to remove this contamination and significantly reduce the ion motional heating rate [5]. The microfabricated trap developed at NPL [7] has a 3D electrode geometry which results in a highly harmonic potential and tight ion confinement. Plasma beam cleaning here would be inappropriate; it would sputter electrode material and risk electrical breakdown.

We have developed an alternative method that uses the trap electrodes themselves to generate an RF, *in-situ*, capacitively-coupled microdischarge with strong prospects for selective surface cleaning. The gas temperature and electron density, which are plasma parameters necessary for calculating the average ion bombardment energies, were determined by optical emission spectroscopy. An example of a spectrum used to obtain the gas temperature and the electron density can be seen in Fig. 1. Measurements were made over a range of pressures and voltages. The results show that the microplasma can be operated with average ion energies above the threshold for sputtering contaminants, yet below that for the electrode material. These results show that RF microdischarges have the potential to improve ion trap performance through the selective cleaning of trap electrodes.

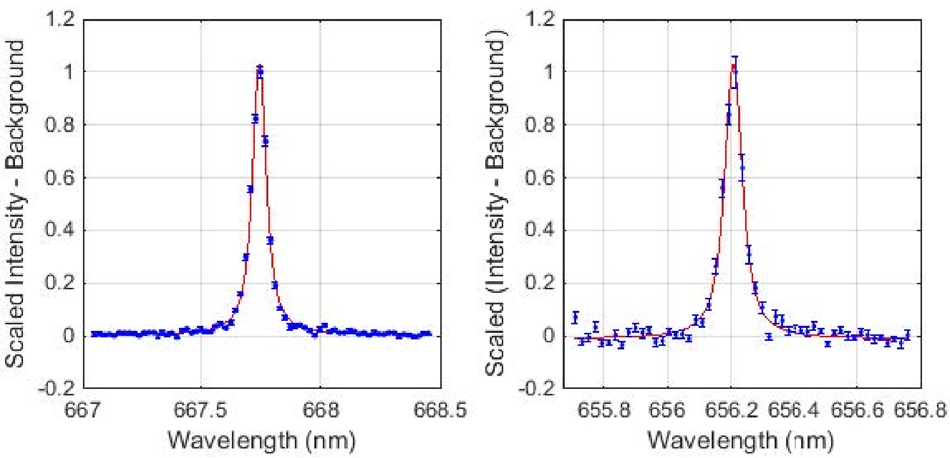

Fig. 1. He plasma emission spectroscopy at 23 MHz, 450 mbar and 158 V (a) He I 667 nm Voigt fit, gas temperature T= 282±10 K; (b) Hα 656nm Voigt fit assuming T = 282 K, electron density $n_e = 5\pm1\times10^{14}$ cm^{-3}.

[1] C.W. Chou, et.al., Phys. Rev. Lett. 104, 070802 (2010)
[2] V. Giovannetti, et. al., 5, (2011)
[3] T.D. Ladd, et. al., Nature 464, 45 (2010)
[4] M. Brownnutt, et. al., Rev. Mod. Phys. 87, 1419 (2015)
[5] D. A. Hite, et. al., Phys. Rev. Lett. 109, 1 (2012)
[6] N. Daniilidis, et. al., New J. Phys. 14, 079504 (2012)
[7] G. Wilpers, et. al., Nat. Nanotechnol. 7, 572 (2012)

P73. Interfacing dipole-trapped single atoms with individual photons in fiber-tip cavities

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A deterministic and coherent interface between atomic excitations and photonic states is a fundamental building block of hybrid quantum computation [1,2]. This should allow for static processing nodes, nominally comprised of trapped atoms or ions, to communicate over significant distance without decoherence. However, significant engineering challenges have to be addressed before such a device can be realized. Here we present our progress towards a robust quantum interface, outlining a novel experimental arrangement for coupling an individual trapped ^{87}Rb atom to the field mode of a high finesse optical cavity, made by two strongly curved mirrors, laser-machined on the end facets of single-mode optical fibers.

In contrast to our previous atom-cavity coupling scheme, which uses macroscopic cavities loaded stochastically by atomic fountains, we now explore a Fabry-Pérot cavity between two fiber tips, depicted in Fig. 1(a), which simultaneously possesses stronger atomic coupling and greater mirror separation. It will accommodate an intracavity atomic dipoleforce trap, which is shaped into a bespoke trapping profile via a Spatial Light Modulator [3],an example of which is shown in Fig. 1(b). The trapping profile can be controlled dynamically to realize a versatile array of individually moveable trapped atoms, which we then can transport into the resonator mode as required.

A sustained and enhanced photonic interaction with a localized trapped atom constitutes a significant step towards a universal interface for quantum information processing. The combination of dipole-trapped atoms with fiber-tip cavities which we pursue is going to provide an excellent platform for examining potential schemes for atom-light interaction, single photon generation, quantum teleportation and quantum memories.

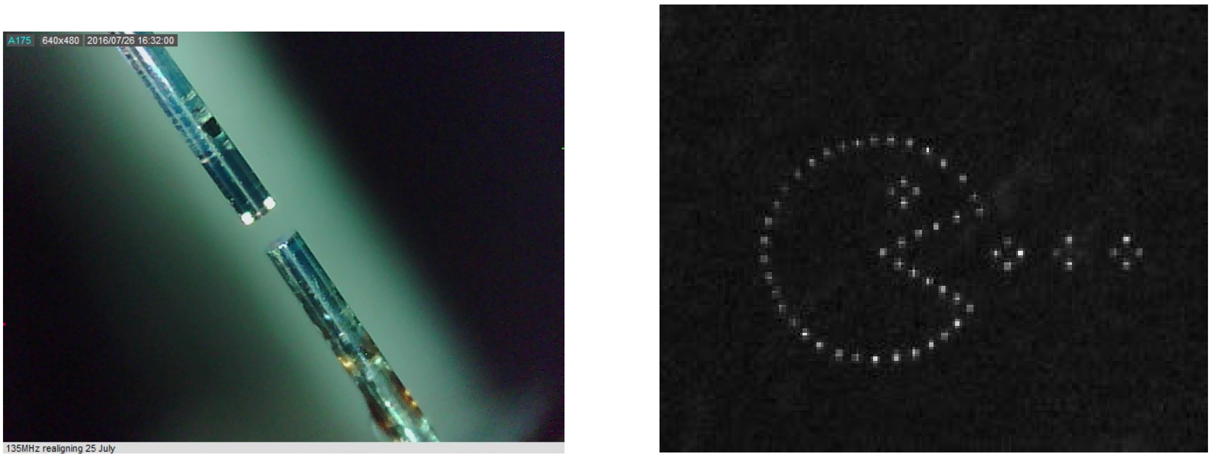

Fig. 1 (a) Fibertip cavity of 125µm length and 4µm waist; (b) Pattern of single atoms in 1.7µm-waist dipole traps.

[1] J. I. Cirac et al., Phys. Rev. Lett. 78, 3221-3224 (1997)
[2] A. Reiserer, G. Rempe, Rev. Mod. Phys. 87, 1379-1418 (2015)
[3] D. Stuart et al., arXiv 1409.1841 (2014)

P74. A cold atom gravity gradiometer for field applications

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Cold atom interferometry provides an exceptional approach for inertial measurement, allowing sensitive and low drift measurements of rotation and acceleration. Since the early 90's its use in measuring gravity in laboratory based systems has been well demonstrated [M. Kasevich, S. Chu,Phys. Rev. Lett. 67.181, 1991], reaching sensitivities of significant relevance for fundamental physics such as the search for violations of Einstein's equivalence principle and the detection of gravitational waves. More recently there has been a growing push towards making devices of relevance for commercial applications, resulting in systems which are operable in non-laboratory environments.

The UK National Quantum Technology Hub in Sensors and Metrology is focused on the next generation of sensors, targeting significant improvements in the technology readiness of cold atom based sensing and demonstrating their potential use within practical applications such as micro-gravity survey. A particular focus is on the development of a cold atom gravity gradiometer for field applications, aiming to detect targets such as sub-surface tunnels or pipes. This involves a significant push in improving the system robustness, size, weight and power, while also aiming to achieve high sensitivities. In this poster presentation, I will provide an overview of the ongoing work of the hub, and our progress in performing field trials.

P75. A Rydberg-dressed magneto-optical trap

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The strong dipolar interactions between Rydberg atoms have been exploited to perform numerous experimental studies of interacting many-body systems. A promising approach to create an interacting many-body quantum gas with tunable interactions is to off-resonantly couple a low-lying atomic state to a Rydberg state [1,2]. It has been shown that this so-called Rydberg dressing approach could facilitate the formation of interesting states of matter, such as supersolids [3,4]. Recently, experimental work has demonstrated the tunability of the Rydberg-dressed interaction in optical lattices [5,6], however the effect of these interactions in a randomly distributed ensemble are yet to be observed. Here we present a novel Rydberg-dressing experiment where the excited state of a narrow-line strontium MOT is coupled off-resonantly to a high-lying Rydberg state, producing an operational MOT with measurable Rydberg character. This is supported by a quantitative Monte-Carlo model of the MOT. We are able to measure the Rydberg character of the MOT through its sensitivity to an applied electric field, which without the Rydberg admixture would be nonexistent. Here we present recent experiments which strive to observe a mechanical effect of the long-range dressed interactions in a laser-cooled gas.

Fig. 1: MOT images after 10ms of dressing at different values of coupling beam Rabi frequency and MOT beam detunings. The coupling beam is detuned +12MHz from resonance. (a) MOT image in the absence of the coupling laser with a MOT beam detuning of -110kHz. (b-c) MOT image in the presence of the coupling beam with 4MHz Rabi frequency and MOT beam detuning of -110kHz and +190kHz respectively. The presence of the coupling beam causes an AC Stark shift of the MOT transition. If the MOT beam detuning remains unchanged (b), the MOT moves to a lower position. By compensating the AC Stark shift (c), the atoms remain in the coupling beam resulting in a functioning dressed MOT.

[1] L. Santos et al., Phys. Rev. Lett. 85, 1791 (2000)
[2] I. Bouchoule and K. M¨olmer, Phys. Rev. A 65, 041803 (2002)
[3] N. Henkel, R. Nath, and T. Pohl, Phys. Rev. Lett. 104, 195302 (2010)
[4] G. Pupillo et al., Phys. Rev. Lett. 104, 223002 (2010)
[5] Y. Y. Jau et al., Nat. Phys 12, 71 (2015)
[6] J. Zeiher et al., Nat. Phys 12, 1095 (2016)

P76. Towards a space compatible atom gravity gradiometer

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Atom Interferometery (AI) has revealed great potential for the precise measurement of inertial forces. Their development into compact portable devices will find applications in fundamental physics [1], geophysics and Earth sciences [2]. Yet, on the ground, the sensitivity of these devices is limited because of the short interrogation times due to the Earth's gravity. Therefore, it is beneficial to take AI instruments into space, where the micro-gravity environment can potentially increase their sensitivity by several orders of magnitude.

STFC RAL Space has a long history in developing space instruments and our Cold Atoms Laboratory is utilizing this heritage to build a space compatible atom gravity gradiometer. This involves the development of space qualified control electronics for our atom interferometer. In addition, we are in collaboration with the Midlands Ultracold Atom Research Centre at the University of Birmingham, DLR and the Institute of Quantum Optics at the University of Hannover to design a physics package envelope (Fig.1a) for an Earth gravity gradiometer based on AI for the European Space Agency.

This presentation will outline the technological difficulties concerning the space qualification of cold atom devices with the predictions and requirements for next generation gravity missions [3]. We will also present the development of our AI based gravity gradiometer (Fig.1b) and some initial results.

a) 

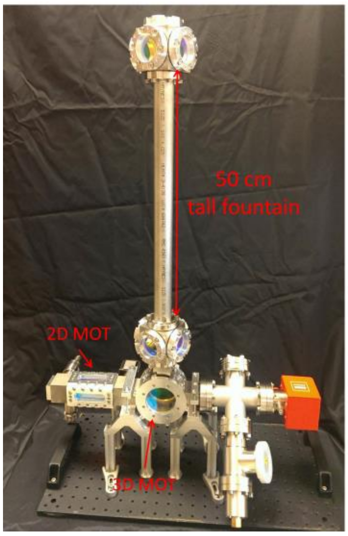
b) 

Figure 1 (a) Compact vacuum chamber for ESA; (b) Atom interferometer at RAL Space.

[1] J. Williams, et.al, Quantum test of the equivalence principle and Space-Time aboard the international space station, New Journal of Physics 18, (2015)

[2] R. Geiger, et.al. Matter-wave laser interferometric gravitation antenna (MIGA): New perspectives for fundamental physics and geosciences, (2015)

[3] O. Carraz, et.al. A spaceborne gravity gradiometer concept based on cold atom interferometers for measuring Earth's gravity field, Microgravity Sci. Technol, (2014)

P77. Quantal and classical mobility calculations of open-shell ions in cooled helium gas

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According to recent ion mobility measurements, performed by Matoba *et al.*, [1] and Sandreson *et al.*, [2] with a mass-selected-ion-injected drift tube mass spectrometer, of ionic open-shell systems such as C^+, N^+ and O^+ ions, evolving in a helium gas at very low temperatures (4.3 and 77 K), the results could not be explained at 4.3 K. The authors suggested to improve the calculations by using *full quantum-mechanical* transport cross sections and a higher-level kinetic theory of gas mobility.

On the light of the quantum-mechanical [3] and classical calculations [4] of ground and metastableexcited C^+ ion mobility in helium at temperatures 77 and 4.3 K, we have aimed to show the difference between quantum-mechanical and classical mobility calculations of the open-shell ions in a cooled buffer helium gas. For this reason, we use the interaction potentials corresponding to the ground state and the metastable-excited state of open-shell ions which are achieved with MORPLO. Then we use the computed quantum-mechanical and classical transport cross sections in the Viehland gram-char Fortran code as to get the mobility of open-shell ions at 4.3K helium gas temperature.

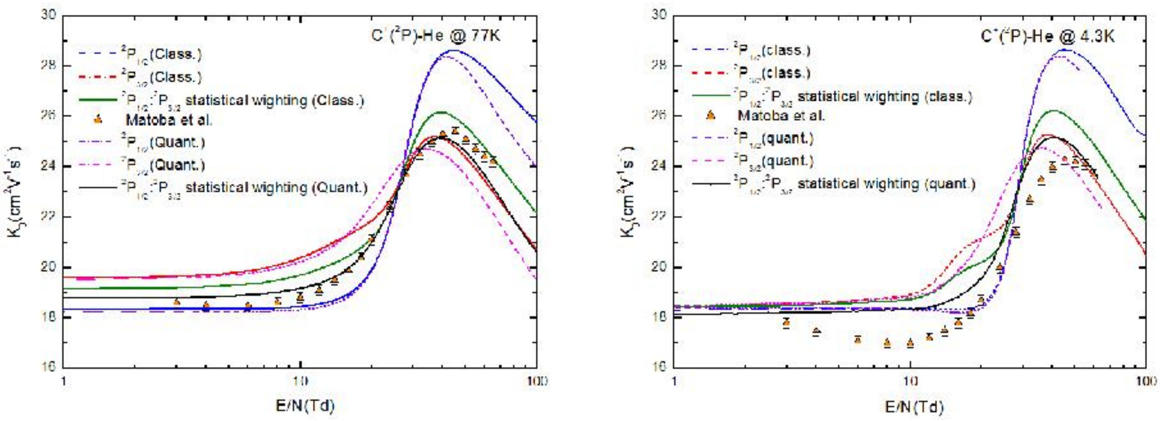

Fig. 1. Comparison of the classical and quantum-mechanical calculated C+(2*P*) mobilities in helium at 4.3 K, 77 K and 300 K, as a function of *E*/*N*.

[1] S. Matoba, H. Tanuma, and K. Ohtsuki, J. Phys. B 41, 145205 (2008)
[2] J. Sanderson, H. Tanuma, N. Kobayashi, Y. Kaneko, J. Chem. Phys. 103, 16 (1995)
[3] L. Aissaoui, M. Bouledroua, K. Alioua, Mol. Phys. 113, N°. 23, 3740 (2015)
[4] W.D. Tuttle, R. L. Thoringtona, L. A. Viehland, T. G. Wrighta, Mol. Phys. 113, N°. 23, 3767 (2015)

P78. Quantum Digital Signatures based on measurement-device-independent framework

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Digital signatures play an important role in software distribution, modern communication and financial transactions, where it is important to detect forgery and tampering. Signatures are a cryptographic technique for validating the authenticity and integrity of messages, software, or digital documents. The security of currently used classical schemes relies on computational assumptions. Quantum digital signatures (QDS) [1,2], on the other hand, provide information-theoretic security based on the laws of quantum physics.

In practical QDS, just as in quantum key distribution (QKD), the detectors can be subjected to attacks caused by eavesdroppers exploiting imperfections in detectors (called side-channel attacks), which can make the actual implementations insecure. Motivated by the idea of measurement-device-independent quantum key distribution (MDI-QKD) [3], we present a measurement-device-independent QDS (MDI-QDS) scheme [4], which is secure against side-channel attacks. In MDI-QKD the legitimate parties do not perform any measurement but only send quantum signals to be measured. Thus, the parties need not hold a measurement device and may treat the measurement apparatus as a "black box", which may be fully controlled by Eve, as shown in Fig.1. This is desirable for actual practical use of QDS schemes. In our work, we adapt the rigorous security proof of MDI-QKD given in [5], taking into account finite-size effects, to the QDS protocol proposed in [6]. The resulting security proof is valid against general forging and repudiation attacks.

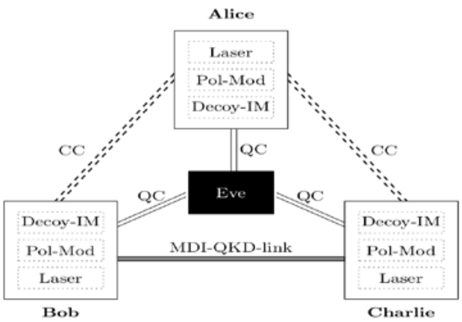

Fig. 1. A schematic diagram of a setup for three participant MDI-QDS protocol. Alice, Bob and Charlie prepare quantum signals in different BB84 polarisation states, using a polarisation modulator (Pol-Mod). In addition, they generate decoy-states with an intensity modulator (Decoy-IM). The signals are then sent to an untrusted party Eve, who is supposed to perform a Bell state measurement, which projects the incoming signals into a Bell state. The channels between Alice-Eve, Bob-Eve and Charlie-Eve are quantum channels (QC). Eve performs the measurement separately for the pairs Alice-Bob and Alice-Charlie. Bob and Charlie share a MDI-QKD link (grey channel), which can be used to transmit classical messages in full secrecy. The pairs Alice-Bob and Alice-Charlie have pair wise authenticated classical channels (CC) indicated as dashed lines, through which they can communicate their basis settings for the different key positions.

Based on the rapid development of MDI-QKD, our MDI-QDS protocol has been experimentally realised independently by two leading quantum crypto groups [7,8].

[1] D. Gottesman, I. Chuang, arxiv: quant-ph/0105032 (2001).
[2] E. Andersson, M. Curty, I. Jex, Phys. Rev. A **74,** 022304 (2006).
[3] H.-K. Lo, M. Curty, B. Qi, Phys. Rev. Lett. **108,** 1030503 (2012).
[4] I. V. Puthoor, R. Amiri, P. Wallden, M. Curty, E. Andersson, Phys. Rev. A **94**, 022328 (2016).
[5] M. Curty, F. Xu, W. Cui, C. C. W. Lim, K. Tamaki, H.-K. Lo, Nat. Commun. **5** (2014).
[6] R. Amiri, P. Wallden, A. Kent, E. Andersson, Phys. Rev. A **93**, 032325 (2016).
[7] G. L. Roberts, *et al.*, arxiv preprint: 1703.00493 (2017).
[8] H.-L. Yin, *et al.*, Phys. Rev. A **95**, 042338 (2017).

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