Programme and Abstract Book

Quantum, Atomic and Molecular Physics (QuAMP 2019) Conference

2–5 September 2019

University of Birmingham, Birmingham, UK

http://quamp2019.iopconfs.org

IOP Institute of Physics

Programme

Monday 2 September

11:00	Registration *Alan Walters Building – Room G01/G11*
12:00	Lunch *Alan Walters Building – Room G01/G11*

Session 1
Location: *Alan Walters Building – Room G03*
Chair: Jon Goldwin, University of Birmingham, UK

14:00	Welcome
14:10	(Invited) **Sticky collisions and rotational coherences of ultracold RbCs molecules** Simon Cornish, Durham University, UK
14:50	**Quantum networking by light-matter interfacing** Axel Kuhn, University of Oxford, UK
15:10	**Parametric heating in a 2D periodically-driven bosonic system: Beyond the weakly-interacting regime** Thomas Boulier, Joint Quantum Institute, USA
15:30	**Ultra-high-speed THz imaging using atomic vapour** Lucy Downes, Durham University, UK
15:50	Refreshment break *Alan Walters Building – Room G01/G11*

Session 2
Location: *Alan Walters Building – Room G03*
Chair: Vivien Kendon, Durham University, UK

16:20	(Invited) **Entropy production in continuously measured quantum systems** Mauro Paternostro, Queen's University Belfast, UK
17:00	**A coherent mechanical oscillator driven by single-electron tunnelling through a suspended carbon nanotube** Edward Laird, Lancaster University, UK
17:20	**A quantum dot spinterferometer: Measuring spins in low fields** Ruth Oulton, University of Bristol, UK
17:40	Close
18:30	Reception *Lapworth Museum*
19:30	End of day 1

Tuesday 3 September

Session 3
Location: *Alan Walters Building – Room G03*
Chair: Simon Cornish, Durham University, UK

09:00	(Invited) **Topological phenomena in nonlinear systems** Patrik Öhberg, Heriot-Watt University, UK
09:40	**Laser spectroscopy of BaF for an electron EDM measurement** Parul Aggarwal, University of Groningen, the Netherlands
10:00	**Bistable and nonreciprocal lasing using cold potassium-39 atoms in a ring cavity** Graeme Harvie, University of Birmingham, UK
10:20	Refreshments *Alan Walters Building – Room G01/G11*

Session 4
Location: *Alan Walters Building – Room G03*
Chair: Alex Clark, Imperial College London, UK

10:50	(Invited) **Levitating nanodiamonds containing nitrogen vacancy centres: Towards the creation of a spatial superposition** Gavin Morley, The University of Warwick, UK
11:30	**Vibrational enhancement of quadrature squeezing and phase sensitivity in resonance fluorescence** Dara McCutcheon, University of Bristol, UK
11:50	**Quantum enhanced estimation of diffusion** Dominic Branford, The University of Warwick, UK
12:10	Lunch, Posters, and Exhibition *Alan Walters Building – Room G01/G11*

Session 5
Location: *Alan Walters Building – Room G03*
Chair: Mike Holynski, University of Birmingham, UK

14:40	(Invited) **Rydberg arrays for precision measurement** Matt Jones, Durham University, UK
15:20	**Laguerre-Gauss wave mixing in rubidium vapour** Rachel Offer, University of Strathclyde, UK
15:40	**A Voigt effect based 3D vector magnetometer** Thomas Fernholz, University of Nottingham, UK

16:00	Refreshments *Alan Walters Building – Room G01/G11*

Session 6
Location: *Alan Walters Building – Room G03*
Chair: Giovanni Barontini, University of Birmingham, UK

16:30	(Invited) **Optimal quantum control with poor statistics** Florian Mintert, Imperial College London, UK
17:10	**Integrating cold atoms into optical waveguides via laser-micromachining** Elisa Da Ros, University of Nottingham, UK
17:30	**Large scale flows in two-dimensional superfluid turbulence** Andrew Groszek, Newcastle University, UK
17:50	Poster session *Alan Walters Building – Room G01/G11*
20:00	End of day 2

Wednesday 4 September

Session 7
Location: *Alan Walters Building – Room G03*
Chair: Vera Guarrera, University of Birmingham, UK

09:00	(Plenary) **Experiments with ultracold CaF and YbF molecules** Ed Hinds, Imperial College London, UK
10:00	(Invited) **Optical atomic clocks for testing fundamental physics** Rachel Godun, National Physical Laboratory, UK
10:40	Refreshments *Alan Walters Building – Room G01/G11*

Session 8
Location: *Alan Walters Building – Room G03*
Chair: Rachel Godun, National Physical Laboratory, UK

11:00	(Invited) (Bates Prize) **A dance to the death: many-body theory of positron and positronium scattering and annihilation in atomic systems** Dermot Green, Queen's University Belfast, UK
11:40	**Continuous-time quantum search algorithms with cooling** Vivien Kendon, Durham University, UK
12:00	**Noise suppression techniques in atomic magnetometry for portable sensors** Carolyn O'Dwyer, University of Strathclyde, UK

12:20	Lunch *Alan Walters Building – Room G01/G11*

Session 9 (AMIG)
Location: *Alan Walters Building – Room G03*
Chair: Michael Charlton, Swansea University, UK

14:00	(Plenary) **Precision-measurement searches for new physics – time for discovery** Marianna Safronova, University of Delaware, USA
15:00	(Invited) **Many-electron theory of attosecond pump-probe spectroscopy** Vitali Averbukh, Imperial College London, UK
15:40	(Invited) **Precision studies of Antihydrogen** Stefan Eriksson, Swansea University, UK
16:20	Refreshments *Alan Walters Building – Room G01/G11*

Session 10
Location: *Alan Walters Building – Room G03*
Chair: Vincent Boyer, University of Birmingham, UK

16:40	(Invited) **Collective excitations as quantum sensors for fundamental physics** Ivette Fuentes, University of Nottingham, UK
17:20	**Many-body effects on the thermodynamics of closed quantum systems** Amy Skelt, University of York, UK
17:40	**Entanglement between identical particles is a useful and consistent resource** Benjamin Morris, University of Nottingham, UK
18:00	Close
19:00	Conference Dinner *Birmingham Botanical Gardens, Westbourne Road, Edgbaston, Birmingham B15 3TR*
23:00	End of day 3

Thursday 5 September

Session 11
Location: *Alan Walters Building – Room G03*
Chair: Hannah Price, University of Birmingham, UK

09:20	(Invited) **Quantum logic with trapped ions: precise, fast, networked** David Lucas, University of Oxford, UK
10:00	**Nonlocal coherent perfect absorption** John Jeffers, University of Strathclyde, UK

10:20	Refreshments *Alan Walters Building – Room G01/G11*

Session 12
Location: *Alan Walters Building – Room G03*
Chair: Ivette Fuentes, University of Nottingham, UK

10:50	(Invited) **Miniature optical frequency combs for portable atomic clocks applications** Alessia Pasquazi, University of Sussex, UK
11:30	(Plenary) **Measuring motion beyond quantum limits: from nanomechanics to gravitational wave detection** Eugene Polzik, University of Copenhagen, Denmark
12:30	Lunch and Close *Alan Walters Building – Room G01/G11*
14:00	End of day 4
14:00	Optional Lab Tours *Alan Walters Building – Room G01/G11*

Poster programme

P1	**Probabilistic modeling from classical to quantum mechanics** Paolo Rocchi, IBM and LUISS University, Italy
P2	**Theory on quantum computing in radical-triplet system** Wei Wu, University College London, UK
P3	**A cold-atom clock based on a grating magneto-optical trap and lin⊥lin coherent population trapping** Michael Wright, University of Strathclyde, UK
P4	**Ultra-stable optical cavities for strontium clocks** Effy Owen, University of Birmingham, UK
P5	**A compact and robust strontium optical lattice clock testbed for benchmarking and commercialisation of super-radiant optical lattice clocks** Jonathan Jones, University of Birmingham, UK
P6	**University of Liverpool atom interferometer results and upgrades** Gedminas Elertas, University of Liverpool, UK
P7	**PicoTesla absolute field readings with a hybrid ^{3}He/^{87}Rb magnetometer** Christopher Abel, University of Sussex, UK
P8	**A Zeeman–Sisyphus decelerator for CaF molecules** Gautam Kambhampati, Imperial College London, UK

P9	**Determination of energy levels, hyperfine structure constants, lifetimes and dipole polarizabilities of Sn 3+** Mandeep Kaur, Guru Nanak Dev University, India
P10	**Towards deterministic entanglement of trapped ion systems** Hamzah Shokeir, University of Sussex, UK
P11	**A novel laser activated atom source for portable strontium optical lattice atomic clocks** Jonathan Bass, University of Birmingham, UK
P12	**Towards antihydrogen synthesis with sympathetically laser-cooled positrons** Jack Jones, Swansea University, UK
P13	**Antihydrogen physics in ALPHA** Niels Madsen, Swansea University, UK
P14	**Parity swap cat-state comparison amplifier** John Jeffers, University of Strathclyde, UK
P15	**Towards the study of quantum engines in 41K-87Rb Bose-Bose mixtures** Jorge Mellado-Munoz, University of Birmingham, UK
P16	**Generalised photon subtraction for heating or cooling thermal light** John Jeffers, University of Strathclyde, UK
P17	**The antimatter gravitational behaviour in the ALPHA-g experiment** Joanna Peszka, CERN and Swansea University, UK
P18	**Towards high-resolution spectroscopy of N2+** Laura Blackburn, University of Sussex, UK
P19	**Positron accelerator for positronium–cold ion scattering experiments** Robert Clayton, Swansea University, UK
P20	**Permanent magnet Zeeman slowers for a portable strontium optical clock** Richard Barron, University of Birmingham, UK
P21	**iqClock – the European integrated quantum clock** Markus Gellesch, University of Birmingham, UK
P22	**Negative hydrogen production in the ALPHA apparatus** Patrick Mullan, Swansea University, UK
P23	**Prospects for cold hydrogen production via laser dissociation of molecular ions** Steven Jones, Aarhus University, Denmark
P24	**Scheme to generate and filter photon pairs from atoms in a hollow core fibre** Mark A Zentile, University of Stuttgart, Germany
P25	**Positron cloud characterisation** Hywel Turner Evans, Swansea University, UK

P26	**Optical frequency metrology with an $^{171}Yb^{+}$ ion clock** Alexandra Toffu, National Physical Laboratory, UK
P27	**Towards a direct comparison of hydrogen and antihydrogen** April Cridland, Swansea University, UK
P28	**Simulating noise-assisted quantum transport mechanisms using cold atoms** Andrew White, University of Birmingham, UK
P29	**Optical gain in a potassium magneto-optical trap** Adam Butcher, University of Birmingham, UK
P30	**R-matrix calculations of the resonances contributing to symmetry breaking during dissociative electron attachment to the H2 molecule** Peter Bingham, The Open University, UK
P31	**Microwave-driven high-fidelity quantum logic with $^{43}Ca^{+}$** Ryan Hanley, University of Oxford, UK
P32	**The Design of a laser system for BECCAL – a quantum gas experiment on the ISS** Victoria Henderson, Humboldt-Universität zu Berlin, Germany
P33	**Systematic construction of scarred many-body dynamics in 1D lattice models** Kieran Bull, Leeds University, UK
P34	**Characterising adiabaticity in many-body thermal systems** Amy Skelt, University of York, UK
P35	Poster withdrawn
P36	**Quantum state verification, validation, and visualisation via phase space methods** Russell Rundle, Loughborough Univeristy, UK
P37	**Visualising spin degrees of freedom in atoms** Benjamin Davies, Loughborough University, UK
P38	**Scaling up the trapped ion quantum processor** Samuel Hile, University of Sussex, UK
P39	**Multi-photon photoionization of molecules using the "R-matrix with time" (RMT) approach** Jakub Benda, The Open University, UK
P40	**Evaluation of a MEMS-fabricated 3D ion microtrap for scalable entanglement-enhanced quantum metrology** Guido Wilpers, National Physical Laboratory, UK
P41	**Applications of polychromatic dressing of ultracold atomic ensembles** German Sinuco-Leon, University of Sussex, UK
P42	**Non-linear and parametric effects in atomic magnetometers** Vera Guarrera, University of Birmingham, UK

P43	**Non-Equilibrium Feshbach Association of Fermionic 6Li Molecules** Guy Simmonds, University of Nottingham, UK
P44	**Non-invasive diagnosis of lithium-ion cells using magnetic measurements** Mark Bason, University of Sussex, UK
P45	**A high-sensitivity electronic test apparatus for ion microtraps** Scott Thomas, National Physical Laboratory, UK
P46	**A frequency-agile laser tuner for coherent optical control of trapped ions** Scott Thomas, National Physical Laboratory, UK
P47	**OPTAMOT: Optimised designs for additively manufactured magneto-optical traps** Somaya Madkhaly, University of Nottingham, UK
P48	**Towards tweezer arrays of laser cooled molecules** Jonas Rodewald, Imperial College London, UK
P49	**Coupling organic molecules to nanophotonic devices** Alex Clark, Imperial College London, UK
P50	**A Highly Compact Cold Atom Gravity Gradiometer** Hester Thomas, University of Birmingham, UK

Session 1

(Invited) Sticky collisions and rotational coherences of ultracold RbCs molecules

S Cornish, P Gregory, M Frye, J Blackmore, R Sawant, and J Hutson

Durham University, UK

The formation of ultracold heteronuclear molecules possessing long-range dipole-dipole interactions opens up many exciting areas of research spanning quantum computation, quantum simulation and fundamental studies of quantum matter. Long-lived, trapped samples of molecules with full quantum control of the molecular internal state are crucial to many of these applications.

Here we report the results of investigations into the rotational coherence and collisional stability of ultracold RbCs molecules prepared initially in the rovibrational ground state. Using coherent microwave control of the internal state of the molecule, we study the AC Stark effect due to the trapping light in low-lying rotational levels. Our measurements reveal a rich energy structure with many avoided crossings between hyperfine states. Understanding this structure allows us to enhance the rotational coherence through a judicious choice of internal state and intensity. Understanding the trap potential also allows us to study the lifetimes of the molecules for various rotational and hyperfine states. We observe rapid loss that is insensitive to the internal state and compare our findings with the 'sticky collision' hypothesis that pairs of molecules form long-lived collision complexes. We demonstrate that the loss of molecules is best described by second-order rate equations, and that the rate differs from the limit of 'universal loss' for s-wave collisions.

As an outlook, we will briefly describe our plans for imaging and addressing of single molecules in ordered arrays as a basis for quantum simulation.

Quantum networking by light-matter interfacing

A Kuhn[1], T Barrett[1], J Matthews[2], A Rubenok[2], N Holland[1], M Mohammed[1], T Doherty[1], M Ijspeert[1], J Alvarez-Velasquez[1], E Kassa[1], and B Yuen[1]

[1]University of Oxford, UK, [2]University of Bristol, UK

We demonstrate quantum logic and multi-mode interferometry in a small-scale photonic quantum network. The network nodes are realised with rubidium atoms strongly coupled to high-finesse cavities, which provide narrow-linewidth single photons on demand, using an a-priori non-probabilistic emission scheme [1]. We use a controlled-NOT gate integrated into a photonic chip to entangle these photons [2], and we show how to use a multi-mode-interferometer for the measurement-induced preparation of distributed entangled cluster states in large quantum networks [3].

Furthermore, we investigate the role of external fields, non-linear Zeeman effects [4] and the lifting of polarisation-degeneracy in bimodal cavities [5]. These effects are present in most real systems and strongly influence the performance and efficiency [6] of any anticipated light-matter coupling scheme.

[1] A. Kuhn, Chapter 1 in Engineering the Atom-Photon Interaction, Springer (2015)
[2] A. Holleczek et al., Phys. Rev. Lett. 117, 023602 (2016)
[3] T. D. Barrett et al., Quantum Science and Technology 4, 025008 (2019)

[4] T. D. Barrett et al., New J. Phys. 20, 073030 (2018)
[5] T. D. Barrett et al., Phys. Rev. Lett. 122, 083602 (2019)
[6] T. D. Barrett et al., arXiv:1903.08628 (2019)

Parametric heating in a 2D periodically-driven bosonic system: Beyond the weakly-interacting regime

T Boulier[1], J Bukov[1], M Bukov[2], C Bracamontes[1], E Magnan[1], S Lellouch[3], E Demler[4], N Goldman[5], and T Porto[1]

[1]Joint Quantum Institute, USA, [2]University of California Berkely, USA, [3]Univesite Lille 1, France, [4]Havard University, USA, [5]Universite Libre de Bruxelles, France

A promising approach to creating new and complex states of matter is to force some physical property to rapidly oscillate in a system. This technique is known as Floquet engineering, and it is emerging as a promising way to expand the quantum engineering toolbox. One might expect that the induced oscillations heat up the target system, but energy absorption in an ensemble of interacting quantum particles remains a complex open question. Recent theoretical work predicted that for interacting bosons, Floquet systems can be inherently unstable [1], which would lead to rapid heating. We experimentally confirm that this is the case, and we also find an unexpected heating behavior, pointing to effects beyond current theories [2].

We study a Bose-Einstein condensate in a periodically shaken 2D optical lattice, where the position of the lattice is the oscillating parameter. In the presence of the drive, Bogoliubov modes spontaneously grow and deplete the condensate. We study the lifetime of the condensate to characterize the instability. At large shaking amplitude, circular drives heat faster than linear drives, which illustrates the non-trivial dependence of the heating on the choice of 2D drive. In all cases, we demonstrate that the BEC decay is dominated by the emergence of unstable Bogoliubov modes, rather than scattering in higher Floquet bands. We also report an unexpected additional heating, pointing to effects beyond current theories.

[1] S. Lellouch, et al, Phys. Rev. X 7, 021015 (2017)
[2] T. Boulier, et al, Phys. Rev. X 9, 011047 (2019)

Ultra-high-speed THz imaging using atomic vapour

L Downes, A Mackellar, C Adams, and K Weatherill

Durham University, UK

Terahertz (THz) radiation lies on the electromagnetic spectrum between the microwave and infrared regions, falling in the gap between optical and electronic detection techniques. Despite THz radiation having applications across areas including security, biomedical and quality control, a lack of fast detection and imaging techniques has meant that it has not seen widespread commercial uptake. Atoms have been used to sense a range of electromagnetic fields at microwave, radio and THz frequencies, but their application to imaging has so far been limited. Here we present a new and novel THz imaging system capable of capturing images 100 times faster than the prior state of the art. Our simple and versatile technique is based on efficient THz-to-optical conversion in a room-temperature atomic Rydberg vapour, allowing THz images to be captured using conventional camera technology. We demonstrate and characterise a 1 cm^2 sensor with 1 mm spatial resolution and sensitivity comparable to the best cryogenic sensors. We show that this system is capable of image capture at 3000 frames per second and describe how this is relevant across a wide range of scientific, industrial and commercial settings. Finally, we highlight future improvements to the system that could enable image capture at framerates over 10 kHz.

Session 2

(Invited) Entropy production in continuously measured quantum systems

M Paternostro

Queen's University Belfast, UK

The entropy production rate is a central object in non-equilibrium thermodynamics. It characterises thermodynamic irreversibility and sets important quantitative bounds to the efficiency of thermodynamic cycles.

Yet, we lack definitions of this quantity that are easily manageable and general enough to encompass various experimentally interesting set-ups. In this work, we characterise the excess entropy produced by a continuously monitored Gaussian system – a.k.a., the situation often encountered in actual laboratories – due to the observation process.

We isolate the entropy production rate using the dynamics of the system in phase space. The key result that we achieve is a generalised second-law which account for the information acquired by measuring the system [2]. We then apply such novel formalism to the dynamics of a levitated optomechanical system, showing the observability of the framework and its relevance for the energetics of the system [1,2].

[1] M. Brunelli *et al.*, Phys. Rev. Lett. **121**, 160604 (2018)
[2] A. Belenchia, L. Mancino, G. Landi, and M. Paternostro, arXiv:1908.09382 (2019)

A coherent mechanical oscillator driven by single-electron tunnelling through a suspended carbon nanotube

E Laird[1], Y Wen[2], N Ares[2], F Schupp[2], T Pei[2], and A Briggs[2]

[1]Lancaster University, UK, [2]University of Oxford, UK

Suspended carbon nanotubes are mechanical resonators with low mass, high compliance, and high quality factor, which make them sensitive electromechanical detectors for tiny forces and masses. These same properties are favourable for studying the effects of strong measurement backaction. While backaction is usually recognised by incoherent effects such as excess dissipation, under conditions of strong coupling it is also predicted to create self-sustaining coherent mechanical oscillations. This talk describes the verification of this prediction using time-resolved measurements of a vibrating nanotube transistor.

Our device consists of a clean carbon nanotube, spanned across a trench. A pair of tunnel barriers defines a single-electron transistor, whose conductance is proportional to the displacement. With low coupling, the single-electron transistor is a sensitive transducer of driven vibrations. At intermediate coupling, electrical backaction damps the vibrations. However, at strong coupling, the resonator can enter a regime where the damping becomes negative; it becomes a self-excited oscillator.

This electromechanical oscillator has many similarities to a laser, with the population inversion provided by the electrical bias and the resonator acting as a phonon cavity. We characterize the resulting coherence and demonstrate other laser characteristics, including injection locking and feedback narrowing of the emitted signal.

A quantum dot spinterferometer: Measuring spins in low fields

A Young[1], P Androvitsaneas[1], T Nutz[2], J Lennon[1], C Schneider[3], S Maier[3], J Hinchliff[1], E Harbord[1], S Hoefling[3], J Rarity[1], and R Oulton[1]

[1]University of Bristol, UK, [2]Imperial College London, UK, [3]University of Wuerzburg, Germany

The idea of using quantum dots (QDs) to generate entangled states was first proposed over ten years ago and relies on generating entanglement between the ground state of a resident electron spin in a QD and single photons as they are emitted. The protocol proposes using an electron spin, whose state coherently evolves in an applied magnetic field. The system is then inverted (optically) to the exited state to produce photons at specific time intervals forming an entangled chain of photons emitted from the QD, whose length is then limited by the collection efficiency of the photons and the coherence time of the electron spin. A key feature of the protocol is that the electron spin precession must be slower that the rate that photons are emitted by the QD. For QD's this necessitates the application of a low (in plane) magnetic field (typically <100mT). This poses some interesting questions mainly due to the challenge of measuring the spin in such B-fields. The optical transitions are, by definition, not spectrally resolvable so cannot be spectrally filtered. This means standard approaches to characterisation of the electron spin are not applicable. In this talk we will present a novel method to measure the behaviour of a QD electron spin. Using this we can accurately determine several key figures of merit for the electron spin, such as the Lamor frequency, the g-factor and the coherence time.

Session 3

(Invited) Topological phenomena in nonlinear systems

P Öhberg

Heriot-Watt University, UK

In this talk we will discuss the role of interactions and nonlinearities in topologically non-trivial systems. We will consider two different physical scenarios: nonlinear gauge potentials in superfluids and the prospect of flux attachment, and edge states in photonic lattices in combination with strong nonlinearities which are induced by a feedback mechanism.

Laser spectroscopy of BaF for an electron EDM measurement

P Aggarwal[1], and NL-eEDM Collaboration[2]

[1]University of Groniningen, The Netherlands, [2]Vrije Universiteit Amsterdam, The Netherlands

Permanent electric dipole moments (EDMs) are signatures of time reversal and parity violation, which acts as a sensitive probe of physics beyond the Standard Model (BSM). Within the NL-*e*EDM collaboration, we plan to measure the electron EDM using a cold, intense beam of barium monofluoride (BaF) molecules.

Key to the increased statistical sensitivity of our experiment is an increase in the coherent measurement time. This will be achieved through a combination of Stark deceleration and transverse laser cooling of a cryogenic beam of BaF. Currently, we are performing laser spectroscopy on a supersonic beam of BaF molecules, to determine various parameters crucial for laser cooling such as Frank Condon factors and lifetimes of the excited states. We are also working on quantum state control and sensitive detection schemes. I will present the recent results of the BaF spectroscopy along with an overview of the work towards the final eEDM measurement within the collaboration.

Bistable and nonreciprocal lasing using cold potassium-39 atoms in a ring cavity

G Harvie, A Butcher, B Megyeri, A Lampis, and J Goldwin

University of Birmingham, UK

We present recent work with a potassium-39 magneto-optical trap (MOT) overlapped with a high finesse ring cavity. This system results in lasing into both directions of the ring cavity, without any additional pump fields. The observed lasing is due to Raman gain between hyperfine ground states, which has not previously been seen under ordinary MOT conditions. This gain mechanism is made possible by the unusual beam powers and detunings in a potassium-39 MOT.

The bidirectional nature of a ring cavity leads to interesting dynamics between the two modes. In particular the system is bistable, lasing into only one direction at a given time. The lasing is also nonreciprocal, in that the two directions lase at slightly different cavity lengths. The strength and sign of this nonreciprocity can be controlled by physically moving the MOT.

Session 4

(Invited) Levitating nanodiamonds containing nitrogen vacancy centres: towards the creation of a spatial superposition

G Morley

University of Warwick, UK

We are building an experiment in which a magnetically levitated nanodiamond containing a nitrogen vacancy (NV) centre would be put into a spatial quantum superposition. With theory collaborators, we have proposed how to do this in order to test if there is a macroscopic limit to the quantum superposition principle. The nanodiamonds we have made are 1000 times purer than commercially-available nanodiamonds, and our levitation experiments show that this purity is needed to reduce problems with overheating.

In a second experiment we have built the most sensitive fibre-coupled diamond magnetometer and begun exploring its commercial potential for diagnosing heart problems.

Finally, we have shown that the spin coherence times for single laser-written NV centres are as long as for naturally occurring NV centres. Our arrays would allow 10,000 NV centres on a diamond which could permit scaling up to a future quantum computer.

Vibrational enhancement of quadrature squeezing and phase sensitivity in resonance fluorescence

D McCutcheon[1], J Iles-Smith[2] and A Nazir[3]

[1]University of Bristol, UK, [2]University of Sheffield, UK, [3]University of Manchester, UK

Vibrational environments are commonly considered to be detrimental to the optical emission properties of solid-state systems, limiting their performance as single photon sources. Given that such environments arise naturally it is important to ask whether they can instead be turned to our advantage. Here we show that vibrational interactions can be harnessed within resonance fluorescence to generate optical states with a higher degree of quadrature squeezing than in isolated atomic systems [2]. Considering the example of a driven quantum dot coupled to phonons, we demonstrate that it is feasible to surpass the maximum level of squeezing theoretically obtainable in an isolated atomic system, and indeed come close to saturating the fundamental upper bound on squeezing from a two-level emitter.

We also analyse the performance of these vibrationally-enhanced squeezed states in a typical phase estimation protocol. We find that not only can phonons lead to an increased phase sensitivity, but that they can lead to a state that outperforms the squeezed vacuum with the same photon number. These results therefore point towards a new field of sensing and metrology applications using solid-state single photon emitters such as quantum dots, colour centres in diamond, or defects in 2D materials.

[1] J. Iles-Smith, D. P. S. McCutcheon, A. Nazir and J. Mørk, Nat. Photon. 11, 521 (2017)

[2] J. Iles-Smith, A. Nazir and D. P. S. McCutcheon, Nat. Communs 10, 3034 (2019)

Quantum enhanced estimation of diffusion

D Branford[1], C Gagatsos[2], J Grover[3], A Hickey[3], and A Datta[1]

[1]University of Warwick, UK, [2]University of Arizona, USA, [3]European Space Agency, France

Intrinsic decoherence effects have been predicted through collapse models which could explain the natural absence of quantum effects in macroscopic systems. Localisation of a test particle due to collapse models causes additional spreading of the particle's wavefunction. This effect appears as dephasing in the position basis—momentum diffusion—of a continuous variable quantum system. We evaluate the effectiveness of estimating such diffusion in quantum-mechanical systems with a free-particle Hamiltonian.

Our analytical results can for example be applied to the proposed MAQRO mission which proposes space-based tests of macroscopic quantum states. MAQRO seeks to probe the fundamentals of quantum mechanics and test theories such as collapse models. In the context of the MAQRO mission we see the potential to improve by several orders of magnitude over measuring the particle's position. Such methods would enable conclusive tests of continuous spontaneous localisation. Squeezing can also reduce the required free-fall time, with 10 dB compensating for an order of magnitude reduction in free-fall time.

Session 5

(Invited) Rydberg arrays for precision measurement

M Jones

Durham University, UK

Addressable arrays of single atoms and molecules are currently at the forefront of research in AMO physics, with applications in cold chemistry, quantum simulation and quantum computation. In Durham we have trapped individual strontium atoms in optical tweezers, and are exploring potential applications in quantum metrology, where Rydberg-mediated long-range interactions may be used to create squeezed states in optical and atomic clocks. I will also outline how a similar platform might be used for possible future precision tests of the standard model.

Laguerre-Gauss wave mixing in rubidium vapour

R Offer[1], A Daffurn[1], D Stulga[1], E Riis[1], S Franke-Arnold[2], and A Arnold[1]

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

We explore the high-efficiency frequency conversion of Laguerre-Gauss modes via four-wave mixing in rubidium vapour. These modes, and more generally the orbital angular momentum (OAM) they carry, provide valuable research tools for optical manipulation, processing and imaging. They also present a large basis set for use in quantum communication, with the potential to improve both the bandwidth and security of current systems.

When studying OAM transfer in our FWM process, we find that the distribution of the input OAM between the two generated fields is strongly mode dependent. A small pump OAM is transferred almost completely to only one of the fields, but increasing the input OAM broadens the OAM spectrum of the generated light. This indicates the fields are generated in an OAM-entangled state, with a spiral bandwidth that increases with increasing pump OAM.

We also study four-wave mixing with more general pump beams, including beams with opposite handedness of OAM and, for the first time in this system, radial Laguerre Gauss modes. This work highlights the importance of phase matching throughout the atomic medium, with the Gouy phase shift of the beams strongly affecting the transverse mode of the generated fields.

A voigt effect based 3D vector magnetometer

T Fernholz, T Pyragius, and H Marin Florez

University of Nottingham, UK

We describe a method to dispersively detect all three vector components of an external magnetic field using alkali atoms based on the Voigt effect. Our method relies on measuring the linear birefringence of the radio frequency dressed atomic medium via polarization homodyning. This gives rise to modulated polarization signals at the first and second harmonic of the dressing frequency. The vector components of the external magnetic field are mapped onto the quadratures of these harmonics. We find that our scheme can be utilised in both cold and hot atomic gases to detect such external fields in shielded and unshielded environments. In the shielded hot vapour case we achieve field sensitivities in the pT/sqrt{Hz} range for all 3 vector components, using pump-probe cycles with 125 Hz repetition rate, and limited by the short coherence time of the cell. Finally, our scheme has a simple single axis beam geometry making it advantageous for miniature magnetic field sensors.

Session 6

(Invited) Optimal quantum control with poor statistics

F Mintert

Imperial College London, UK

Optimal control allows us to substantially increase the precision of an experiment and it can help us to build a well-functioning device. Typically, we learn how to control a quantum system in theoretical simulations before applying the identified control strategies experimentally. Since this is limited by our ability to simulate quantum systems on classical computers, it is often necessary to devise control strategies directly on the experiment. Given limited experimental resources, it is important to find good control strategies also with limited experimental data.

Since experiments on individual quantum systems require many repetitions to obtain a reliable estimate for the expectation value of an observable, the ability to find control strategies based on noisy data helps to reduce the required experimental effort substantially.

I will discuss how to use data with large measurement noise as basis for optimal control and show that such strategies can be used to design gate sequences for the preparation of highly entangled quantum states.

Integrating cold atoms into optical waveguides via laser-micromachining

E Da Ros, N Cooper, B Mather, and L Hackermueller

University of Nottingham, UK

We present a method for interfacing cold atoms with optical waveguides. Unlike many previous approaches, this technique can be applied in almost any existing waveguide system, including chip-based waveguide arrays and other complex environments. It therefore has great promise as a way of creating hybrid atom-photon quantum devices. Using this method, we demonstrate coupling between dipole-trapped caesium atoms and light propagating in the core of an untapered single-mode optical fibre. This was achieved by laser-drilling a cylindrical, transverse hole (30 micrometer diameter) through the core of the fibre. Probe light, resonant with the Cs D_2 line, was then coupled into the fibre. By measuring the transmitted optical power, it was determined that up to 87% of the probe power could be absorbed by the atoms. The corresponding optical depth per unit length of the atom cloud is over 700 cm^{-1}, higher than any value reported to date for a comparable system. This will be a key parameter for the miniaturisation of atom-optical systems as well as for enhancing spatial resolution in sensing applications. The dependence of this absorption on several experimental parameters was also characterised and found to be in line with theoretical expectations. We have proven that tailored hole geometries can enable enhanced optical transmission. The achievable degree of improvement is such that, by placing the hole within an optical resonator, strong coupling can be achieved between the atoms and the guided light.

Large scale flows in two-dimensional superfluid turbulence

A Groszek[1], S Johnstone[2], P Starkey[2], C Billington[3, 4], M Davis[5], T Simula[6], and K Helmerson[1]

[1]Newcastle University, UK, [2]Monash University, Australia, [3]National Institute of Standards and Technology, USA, [4]University of Maryland, USA, [5]University of Queensland, Australia, [6]Swinburne University, Australia

Non-equilibrium interacting systems can evolve to exhibit large-scale structure and order. In two-dimensional turbulent flow the seemingly random swirling motion of a fluid can evolve towards persistent large-scale vortices. To explain such behavior, Lars Onsager proposed a statistical hydrodynamic model based on quantised vortices. Our work provides an experimental confirmation of Onsager's model (Johnstone et al., Science **364**, 1267, 2019). We drag a grid barrier through an oblate superfluid Bose-Einstein condensate to generate non-equilibrium distributions of quantised vortices. We observe signatures of an inverse energy cascade driven by the "evaporative heating" of these vortices, which leads to steady-state vortex configurations characterised by negative absolute temperatures. We measure these temperatures directly using our recently developed thermometry technique for two-dimensional superfluid turbulence. Complementary observations of negative temperature vortex states have also recently been presented in a similar experiment by Gauthier et al. (Science **364**, 1264, 2019).

Session 7

(Plenary) Experiments with ultracold CaF and YbF molecules

E Hinds

Imperial College London, UK

The production of ultracold atoms by laser cooling has been the key to preparing quantum degenerate gases, optical lattices, atomic fountains and many other applications. A broad set of new applications [1] has been awaiting the extension of laser cooling to produce ultracold molecules by magneto-optical trapping and sub-Doppler cooling. That has now begun, with the realisation of magneto-optical traps of SrF [2, 3, 4] and CaF [5, 6]. Recently we have shown that CaF [7, 8] and YbF [9] can be cooled far below the Doppler temperature, by making use of their dark states to give strong cooling in a blue-detuned molasses. Further, we have loaded ultracold CaF molecules into a magnetic trap and have demonstrated coherent control of the rotational states while the molecules are trapped [10]. I will summarise the current state of laser cooling molecules and will comment on some of the imminent applications to a wide range of problems.

(Invited) Optical atomic clocks for testing fundamental physics

R Godun and the Time & Frequency Team

National Physical Laboratory, UK

Optical clocks are based on precision spectroscopy of narrow-linewidth atomic transitions. In the best clocks, perturbations to the atomic transition frequency can be controlled and evaluated to within a fractional uncertainty of just 1 part in 10^{18}. This exceptional accuracy has enabled optical clocks to be used in precision tests of fundamental physics.

The UK's National Physical Laboratory is developing a range of optical atomic clocks and frequency combs with fibre links to allow high-accuracy optical frequencies to be compared against each other, both locally and internationally. Such comparisons provide data that probe physical theories at unprecedented levels. For example, frequency comparisons between clocks in different locations on the rotating Earth have placed new constraints on violations of Lorentz Invariance.

Physics beyond the Standard Model can also be probed by searching for changes in the internal energy levels of atoms, which can be detected from the corresponding changes in transition frequencies. Measurements with clocks at NPL and other institutes have revealed tighter limits on the present-day time-variation of the fine structure constant as well as a three-fold tighter constraint on any variation of the proton-to-electron mass ratio. Searches for transient variations of the fine structure constant, which could be an indicator of Dark Matter in the form of topological defects, have also been carried out with increased sensitivity using fibre-linked optical clocks in different locations.

Session 8

(Invited) Bates prize – A dance to the death: many-body theory of positron and positronium scattering and annihilation in atomic systems

D G Green

Queen's University Belfast, UK

The ability of positrons to annihilate with atomic electrons, forming two detectable gamma rays whose energy is characteristic of the electron environment makes positrons and positronium (Ps, a bound electron-positron pair) unique probes of matter. As such, they have important use in medical imaging in PET (Positron Emission Tomography) scans, for studies of surfaces, defects and porosity in industrially important materials, and in understanding antimatter in the Universe.

Low-energy positron-atom and Ps-atom systems are characterised by strong positron-atom and positron-electron correlations (e.g., polarisation of the atom, and the non-perturbative process of virtual-Ps formation, where an atomic electron temporarily tunnels to the positron). They significantly effect positron and Ps interactions with atoms, molecules and condensed matter. For example, they modify the scattering behaviour, and can enhance the positron annihilation rate by orders of magnitude. They also make accurate theoretical description of the systems a challenging many-body problem. Beyond the fundamental interest, proper interpretation of the materials science techniques, and development of antimatter-based technologies (e.g., positron traps and beams, and PET) rely on its solution.

A powerful method developed by us that takes account of the correlations in a natural and systematic way, and which provides keen insight, is many-body theory (see [1–2]). I will discuss how it has provided a complete understanding of positron interactions with noble-gas atoms, and the most accurate calculations of Ps interactions with noble-gas atoms: notably producing scattering cross sections, cooling rates, and annihilation rates and gamma spectra in excellent agreement with experiment, and solving a number of long-standing outstanding `puzzles' in the field along the way (see e.g., [1-5]).

**In collaboration with Dr G. F. Gribakin and Dr A. R. Swann, Queen's University Belfast, United Kingdom*

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[3] D. G. Green and G. F. Gribakin, *Phys. Rev. Lett.* **114**, 093201 (2015).
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Continuous-time quantum search algorithms with cooling

V Kendon, and P Patel

Durham University, UK

Quantum search is useful as a test problem with a quadratic speed up over classical random guessing. In a continuous-time setting -- adiabatic quantum computing, quantum annealing, and quantum walks -- it can be mapped to the symmetric subspace and solved analytically.

In the large size limit, the solution corresponds to a two-state single avoided crossing model. We use computational methods to study this limit in the presence of a low temperature bath, to determine the role played by cooling in finding the solution.

For a model in which each qubit is coupled to its own bath at the same temperature, for low temperature and in the large size limit, this also corresponds to a single two-state system coupled to a single bath.

We determine the effect of finite temperature on the search success in this setting, and hence characterise the regimes in which cooling assists the algorithm, and when the coupling to the bath destroys the quantum speed up. Our results are applicable to test bed problems for quantum computing hardware, and can be generalised to other permutation symmetric problems which exhibit a quantum advantage.

Noise suppression techniques in atomic magnetometry for portable sensors

C O'Dwyer, S Ingleby, I Chambers, A Arnold, E Riis, and P Griffin

University of Strathclyde, UK

Unshielded atomic magnetometry is well suited for portable, compact sensors. Operating in an unshielded environment brings specific challenges - magnetic noise in particular can limit sensitivity. A variety of noise suppression and compensation techniques have been demonstrated [1,2], but noise still remains a concern. We report on noise suppression techniques for use in small sensors constructed with micro-fabricated components and simple geometry.

The dominant magnetic noise source in many unshielded environments is the 50-Hz mains current. In our double-resonance magnetometers this large amplitude periodic noise slews the Larmor frequency outside the linear regime of the resonant response to the RF field. We have developed a measurement scheme that dynamically follows the ambient noise using a feed-forward technique, achieving 50-Hz noise suppression by 20 dB and a reduced total white noise floor. Our efforts to produce unshielded devices insensitive to periodic noise will be discussed here, including feed-forward and gradiometric schemes.

[1] C. Deans, L. Marmugi, F. Renzoni, Sub-picotesla widely tunable atomic magnetometer operating at room-temperature in unshielded environments, Review of Scientific Instruments, 89, 083111 (2018)

[2] G. Bevilacqua, V. Biancalana, Y. Dancheva, A. Vigilante, Self-adaptive loop for external disturbance reduction in a differential measurement setup, Phys. Rev. Applied 11, 014029 (2019)

Session 9 (AMIG)

(Plenary) Precision-measurement Searches for New Physics - Time for Discovery

M Safrononvsa

University of Delaware, USA

The extraordinary advances in quantum control of matter and light have been transformative for precision measurements enabling probes of the most basic laws of Nature to gain fundamental understanding of the physical Universe. While one can search for new particles directly with large-scale collider experiments at the TeV energy scale, such as those carried out at the Large Hadron Collider at CERN, new physics may also be observed via low-energy precision measurements. Exceptional versatility, inventiveness, and rapid development of precision experiments supported by continuous technological advances and improved theory give a high chance for paradigm-shifting discovery. I will give a brief outline of such experiments with atoms and molecules and focus of various searches for new physics with atomic clocks.

(Invited) Many-electron theory of attosecond pump-probe spectroscopy

M Ruberti[1], P Decleva[2], and V Averbukh[1]

Imperial College London, UK, University of Trieste, Italy

We present an *ab initio* approach to full simulation of an attosecond molecular pump-probe experiment. Sequential molecular double ionization by the pump and probe laser pulses with controlled delay is described from first principles with full account of the continuum dynamics of the photoelectrons. Many-electron bound-continuum dynamics is simulated using the time-dependent version of the B-spline algebraic diagrammatic construction (ADC) method [1,2,3]. Our calculations give a quantitatively accurate prediction about the creation of a coherent superposition of molecular cationic states in the photo-ionization process [4,5] and simulate the probe of the ensuing attosecond dynamics by a second ionising pulse within a single first-principles many-electron framework.

We thus demonstrate the capability to simulate and interpret the results of a prototypical molecular pump-probe experiment of interest in attoscience [4].

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[2] M. Ruberti, P. Decleva and V. Averbukh, *Phys. Chem. Chem. Phys.* **20**, 8311 (2018).
[3] M. Ruberti and V. Averbukh in *Attosecond Molecular Dynamics,* edited by M. Vrakking and F. Lepine, Theoretical and Computational Chemistry Series **13**, 68 (2018).
[4] M. Ruberti, P. Decleva and V. Averbukh, *J. Chem. Theory Comput.* **14**, 4991 (2018).
[5] M. Ruberti, *Phys. Chem. Chem. Phys.* **21**, 17584 (2019).

(Invited) Precision studies of Antihydrogen

S Eriksson

Swansea University, UK

Antihydrogen offers a unique way to test matter-antimatter symmetry. Antihydrogen can be trapped in the ALPHA-experiment at CERN for extended periods of time, offering an opportunity to study the properties of antimatter with high precision. Recently, the two-photon 1S-2S transition in antihydrogen has been characterized with a relative frequency precision of 2×10^{-12} [1] and the ground state hyperfine spectrum in the microwave domain with a relative frequency precision of 4 parts in 10^{-4} [2]. Very recently, the 1S-2P Lyman-α transition in antihydrogen has been observed [3]. In addition to the fundamental significance of observing the line in an antiatom, the result represents a major technological advance towards laser cooling of antihydrogen, which in turn enables improvement in the precision of measurements. Results from spectroscopy in both the optical and microwave domains are consistent with CPT-invariance.

Here, I present an overview of antihydrogen synthesis and trapping in the ALPHA-experiment, detailing some of the improvements that enable work with larger antihydrogen samples [4,5] together with the latest results on spectroscopy of trapped antihydrogen. I present an outlook on the future of probing fundamental symmetry with antihydrogen in the era of CERN's new extra-low-energy antiproton source ELENA, including gravitational studies in a new vertically oriented trap.

[1] M. Ahmadi et al. (ALPHA collaboration), *Characterization of the 1S–2S transition in antihydrogen.* Nature **557**, 71 (2018).
[2] M. Ahmadi et al. (ALPHA collaboration), *Observation of the hyperfine spectrum of antihydrogen*, Nature **548**, 66 (2018).
[3] M. Ahmadi et al. (ALPHA collaboration), *Observation of the 1S–2P Lyman-α transition in antihydrogen*, Nature **561**, 211 (2018).
[4] M. Ahmadi et al. (ALPHA collaboration), *Antihydrogen accumulation for fundamental symmetry tests*, Nature Comm. **8**, 681 (2017).
[5] M. Ahmadi et al. (ALPHA collaboration), *Enhanced Control and Reproducibility of Non-Neutral Plasmas*, Phys. Rev. Lett. **120** 025001 (2018).

Session 10

(Invited) Collective excitations as quantum sensors for fundamental physics

I Fuentes

University of Nottingham, UK

Quantum sensors that are used to measure gravitational fields and detect dark energy typically use single particle interferometric techniques that are limited by the time of flight in the interferometer arm. In this talk I will present a new detection method that uses quantum resonances and the sensitivity of collective excitations (phonons) to gravitational fields. When phonons in a Bose-Einstein condensate are initially prepared in a squeezed state, spacetime distortions can create additional excitations through parametric amplification. This effect can be used to detect gravitational waves at high frequencies. We have also developed a phonon based scheme to estimate spacetime parameters, miniaturize devices to measure gravitational fields and gradients and set further constrains on dark energy models.

Many-body effects on the thermodynamics of closed quantum systems

A Skelt[1], K Zawadzki[2], and I D'Amico[1]

[1]University of York, UK, [2]Notheastern University, USA

Quantum Thermodynamics strives to understand quantum fluctuations at the nanoscale, with particular importance being given to the determination of thermodynamic properties in out-of-equilibrium systems. This in itself is a challenging task, but when many-body interactions give rise to strongly correlated systems, the challenge increases exponentially. Here we study the work extraction and entropy production in the epitome of the strongly-correlated systems, the Hubbard model, for chains up to 6 sites. Strikingly, we show that, even considering a completely non-interacting approximation for the evolution operator, just starting from the exact initial thermal state is sufficient to recover most of the accuracy. Our results demonstrate that this is the case in any dynamical regime – sudden quench to quasi-adiabatic – as well as for any temperature, including low temperatures where a non interacting approximation would be clearly a poor choice.

Entanglement between identical particles is a useful and consistent resource

B Morris[1], B Yadin[1], M Fadel[2], T Zilbold[2], P Treutlein[2], and G Adesso[1]

[1]University of Nottingham, UK, [2]University of Basel, Switzerland

The nature of the entanglement present in systems of identical particles has been a long standing issue of debate within both the theoretical and experimental community. Take for example a system of two identical Bosons existing in the same spatial mode where each Boson has some internal degree of freedom, because these Bosons are identical, they adhere to the symmetrization principle resulting in the *apparently* maximally entangled state,

$$1/\sqrt{2}\,(|0\rangle|1\rangle+|1\rangle|0\rangle).$$

However, because the particles are individually unaddressable this entanglement is not directly operational. This leads to the question:

'is there any meaningful definition of entanglement between subsystems of identical particles when the subsystems are operationally inaccessible?'

In this work we not only demonstrate that the Particle Entanglement (PE) present in such systems can be understood within the framework of resource theories but also, within the framework, can be activated as a resource in a quantum information paradigm. In particular we derive the set of states which possess no PE and an operational set of unitaries/measurements that conserve this set. The activation of PE as a resource is also used to establish a set of consistent measures which we lower bound with experimental results. In addition to this, strong links are drawn between PE and the resource theory of non-classicality reaffirming PE to be a uniquely quantum resource. This work is hoped to provide clarity to the debate by motivating both a conceptual and practical understanding of the entanglement between identical particles.

Session 11

(Invited) Quantum logic with trapped ions: precise, fast, networked

D Lucas

University of Oxford, UK

The concepts of quantum information processing date back at least 35 years, to the ideas of quantum simulation and computing suggested by Feynman and Deutsch respectively. Experimental progress in the field often appears slow, partly because of the demanding precision required in the elementary logic operations for quantum error correction, partly because of the technical challenges associated with scaling systems up to larger numbers of qubits, and partly because our expectations are coloured by the enormous power and progress of classical computing technology over the last hundred years. I will give a brief survey of the state of the art across the various platforms which are being explored for quantum computing, and show that progress is in fact extremely encouraging. I will then report on recent work in Oxford on improving the precision and speed of quantum logic operations in the ion trap platform, and on building an elementary quantum network to distribute entanglement between two different ion trap "nodes" separated by macroscopic distances.

Nonlocal coherent perfect absorption

J Jeffers

University of Strathclyde, UK

Loss in optics is normally thought of as a purely local absorption of light energy, although there have been nonlocal quantum effects based on absorption coefficients [1]. Coherent absorption is a form of optical loss which, at its purest, allows a 50% lossy optical medium to cycle between complete transparency and full absorption [2-4]. Excitations of one particular phased superposition of the input modes pass completely and excitations of the orthogonal one are absorbed. The effects are typically seen in sub-wavelength films for both classical [5] and quantum [6,7] input light.

Here I describe a different form of coherent absorption that occurs jointly at two (or more) spatially separated, macroscopic lossy beam splitters. A superposition mode of *any* phase can be *chosen* as fully-absorbed or transparent. For two-photon NOON-state input a single photon can survive the pair of beam splitters with certainty, implying nonlocal absorption of one photon and entanglement between two separated beam splitters. This can be detected via the interference in the two-photon survival probability. The consequences for lossy quantum-optical networks are explored.

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Session 12

(Invited) Miniature optical frequency combs for portable atomic clocks applications

A Pasquazi

University of Sussex, UK

Precise timing has led to many advances, such as GPS and the Internet, which depend critically on frequency and time standards. The currently limited accuracy, however, is hindering the progress towards societal-changing technologies such as telecommunications beyond 5G or precise earth mapping.

Optical atomic clocks based on *optical frequency combs* – Nobel prize in Physics in 2005 to Hall and Hänsch – are the only technology capable of providing timing accurate up to 10^{-18} seconds, answering such a demand of time precision. The realisation of such clocks in portable scale is expected to change the technology landscape.

Optical frequency combs based on micro-cavity resonators also called ‘micro-combs’, offer the promise of achieving the full capability of their bulk counterparts in an integrated footprint [1]. They have enabled major breakthroughs in spectroscopy, communications, microwave photonics, frequency synthesis, optical ranging, quantum sources and metrology.

This talk will review the key advancement of optical frequency combs in the field and the recent challenges in employing these devices in end-user portable atomic clock applications.

In particular, we will review the physics of *temporal cavity-solitons* [2,3] in compact micro-resonators and, in particular, our recent observation of micro-comb laser cavity-solitons, which are the most efficient class of cavity-solitons. Our recent results achieved a mode-efficiency [4] above 75%, compared to typical 1% to 5% of bright solitons achieved with standard approaches. Furthermore, we can tune the repetition-rate to well over a megahertz with no-active control [5].

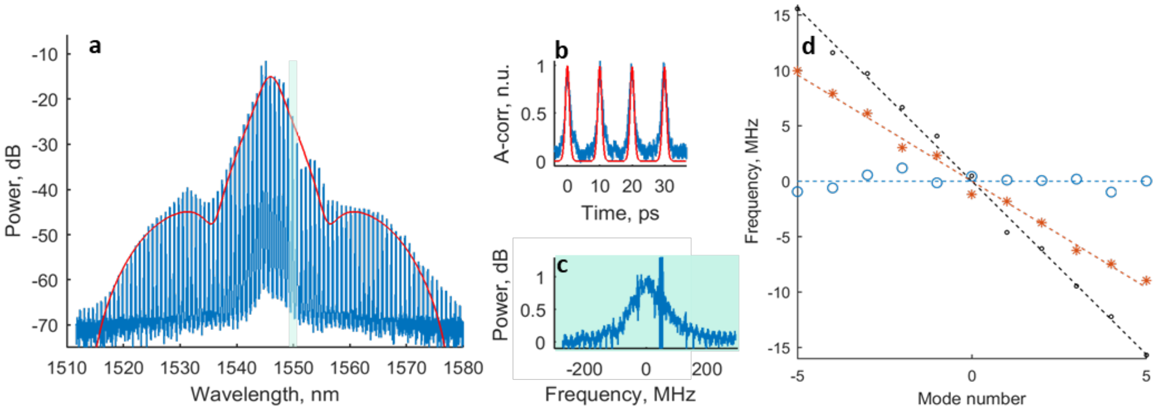

Fig. 1: Micro-comb based on a laser-cavity soliton approach. (a) Measured comb spectrum with more than 150 lines over 50 nm (blue plot), fitted with theoretical curve, (red plot). (b) Optical autocorrelation (blue plot), showing coherent pulses in agreement with theory (red plot). (c) High-resolution spectrum of a line around 1550 nm, showing a narrow comb line oscillating within the micro-cavity resonance. (d) Measurement of the mode frequency vs comb mode. Three cases correspond to few microns' variation of the length of the laser cavity. Lines with different slopes indicate that the repetition rate is changed of few MHz and can be controlled.

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[2] F. Leo, et al. Temporal cavity-solitons in one-dimensional Kerr media as bits in an all-optical buffer. *Nat. Photonics* **4**, 471–476 (2010).

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(Plenary) Measuring motion beyond quantum limits: from nanomechanics to gravitational wave detection

E S Polzik

University of Copenhagen, Denmark

A hybrid quantum system of a mechanical oscillator and a spin ensemble coupled by light provides a rich playground enabling a number of opportunities. Those range from backaction-free measurements [1] to entanglement between motion and spins [2], to measurements beyond the standard quantum limit. In the talk I will overview the progress towards generation of entanglement between distant mechanical and spin objects and its applications, including gravitational wave detection beyond the standard quantum limit [3].

[1] Quantum back action evading measurement of motion in a negative mass reference frame. C. B. Møller, R. A. Thomas, G. Vasilakis, E. Zeuthen, Y. Tsaturyan, K. Jensen, A. Schliesser, K. Hammerer, and E. S. Polzik. **Nature**, 547, 191 (2017).

[2] Unconditional steady-state entanglement in macroscopic hybrid systems by coherent noise cancellation. X. Huang, E. Zeuthen, D. V. Vasilyev, Q. He, K. Hammerer and E. S. Polzik. **Phys. Rev. Lett.** 121, 103602 (2018)

[3] Overcoming the Standard Quantum Limit in Gravitational Wave Detectors Using Spin Systems with a Negative Effective Mass. F. Ya. Khalili and E. S. Polzik, **Phys. Rev. Lett.** 121, 031101 (2018); E. Zeuthen, F.Ya. Khalili and E.S. Polzik, to appear in PRD.

Posters

P1. Probabilistic modeling from classical to quantum mechanic

P Rocchi[1, 2], and O Panella[3]

[1]IBM, USA, [2]Libera Università Internazionale degli Studi Sociali "Guido Carli", Italy, [3]Istituto Nazionale di Fisica Nucleare, Italy

This work is subdivided into three parts.

The probability theory has various questionable aspects. Beside the axiomatic approach, the frequentist and the subjective schools present diverging and irreconcilable interpretations of the concept of probability. The first part of this paper recalls how two theorems prove that the probability of long-term events (or frequentist) and the probability of a single event (or subjective) are not incompatible [1].

The second part infers two theorems from the previous pair of statements. They describe the temporal evolution of the outcomes emitted from the long-term event and the single event respectively. In particular it is proved that the outcome of the single random event switches from the indeterministic to the deterministic state when the event winds up. This change is intrinsic to the random event and is not due to the observer unless the observer interferes with it and causes the event to end.

The third part applies the mathematical results to quantum mechanics, in particular to the quantum wave collapse. We use the double slits experiment to verify the conclusions.

In summary this work calculates some aspects of QM which derive directly from the probability theory.

[1] Rocchi P. – *Janus-Faced Probability* – Springer (2014)

P2. Theory on quantum computing in radical-triplet system

W Wu, and A Fisher

University College London, UK

Organic radicals are promising candidates for a range of quantum and classical information technologies based on electron spin. A single spin-1/2 is a natural realization of a quantum bit (qubit) and the spin relaxation times in organic materials can be very long (up to seconds) due to the low atomic numbers, hence small spin-orbit coupling, and weak hyperfine interactions. Another attractive feature is the ability to exploit the vast experience of organic chemistry which means that a large number of possible molecular structures can be assembled incorporating organic radical groups.

Here we calculate exchange interactions between radicals and optically induced electron spin triplets in bi-4,4,5,5-tetramethyl-1-yloxyimidazolin-2-yl-diphenyl-anthracene (biTYY-DPA) and biTYYcoronene (designed theoretically) using hybrid exchange density functional theory (HDFT). Both molecules have stable spin-1/2 radical centres connected by a conjugated 'coupler'. Our computed interactions from first principles are consistent with previous time-domain spin resonance experiment on biTYY-DPA, and predict strong optically-induced antiferromagnetic couplings in biTYY-coronene. The computed spin densities suggest that the interactions are due to indirect-exchange with the sign of the coupling controlled by the topology of the conjugated coupler. In addition, we have simulated the time-resolved electron-spin-resonance (TRESR) spectra starting with a spin Hamiltonian by using Fermi's golden rule. Our simulations are in a qualitative agreement with the previous TRESR spectra. The theoretical method adopted is sufficiently general to facilitate studies of a wide range of radical-bearing molecular structures and thus may be the basis for the computational discovery of molecules with exchange interactions tailored for quantum computation.

P3. A cold-atom clock based on a grating magneto-optical trap and Lin⊥Lin coherent population trapping

M Wright, G Hoth, R Elvin, B Lewis, P Griffin, and E Riis

University of Strathclyde, UK

While research into atomic clocks continues to push the limits of accuracy and stability, compact atomic clocks based on microwave interrogation continue to be a primary candidate for commercial applications. Due to increased demand, commercial atomic clocks based on laser-cooled atoms are becoming available, achieving short-term fractional frequency stabilities on the order of $10^{-13}/\sqrt{\tau}$ with long-term averaging down to the level of 10^{-15}.

A common challenge faced by systems based on laser-cooled atoms is simplifying the laser-cooling apparatus. Our approach utilises the grating magneto-optical trap (gMOT), which uses a single beam incident on a nano-fabricated diffraction chip to provide the necessary optical forces for cooling ^{87}Rb. With the gMOT and optical molasses we routinely trap more than 10^7 atoms at sub-Doppler temperatures, $T \approx 10\ \mu K$.

Here, we realise an atomic clock by combining cold atoms from the gMOT with coherent population trapping (CPT) in a Lin⊥Lin polarisation scheme to optically probe the ground state splitting. By applying these fields in a Ramsey-like sequence, we have achieved a short-term stability of $3\times10^{-11}/\sqrt{\tau}$. We discuss techniques for improving the signal-to-noise ratio (SNR) by recapturing atoms between experiment cycles and using a phase-locked-loop (PLL) to suppress relative phase noise. We describe the current status of our experiment and the ongoing efforts to improve the SNR. In the long-term we hope to realise a compact cold-atom frequency standard with a short-term stability on the order of $10^{-13}/\sqrt{\tau}$ at short averaging times.

P4. Ultra-stable optical cavities for strontium clocks

E Owen, J Jones, M Gellesch, R Barron, Y Singh, A Singh, and K Bongs

University of Birmingham, UK

Cavities are an integral part of many cold atoms experiments, in the Strontium optical clocks group we utilise several designs of cavities for different purposes. This project looks into decreasing the effects of environmental change on Ultra-stable high finesse cavities by better understanding of the mechanical properties of the materials used to build it; and then looks into the piezo control to better control the length of the cavity. These cavities can be used to enhance the power of a beam going into it, or to produce a high intensity standing wave for use in a lattice trap.

Ultra-stable, high finesse optical cavities are used in quantum clocks to stabilise the laser. In these optical cavities one of the main causes of instability is caused thermal noise/vibrations. Optical cavities are often made from ULE glass for the spacer and fused silica (FS) as the mirror material; the mirrors display axial displacement (bending in the mirrors) due to these materials having different coefficients of thermal expansion. By simulating the thermal expansion of these types of cavities, the zero crossing temperature can be found where the mirror is most thermally stable. By adding a ULE ring on the outside of the FS mirror, it is found that the zero-crossing temperature can be tuned and increased closer to room temperature.

P5. A compact and robust strontium optical lattice clock testbed for benchmarking and commercialisation of super-radiant optical lattice clocks

J Jones, R Barron, M Gellesch, F Owen, A Singh, Y Singh, and K Bongs

University of Birmingham, UK

Atomic clocks are a key technology that underpins modern society, forming the basis of telecommunication networks and navigation systems, among other applications. In recent years optical atomic clocks have demonstrated performance many orders of magnitude beyond the state of the art microwave atomic clocks, with much desire to see this new technology made robust and compact enough to have real commercial impact outside of the lab. The next frontier for optical clocks is to use super radiance to operate in an active fashion. This changes the noise profile of the clock output and drastically increases stability.

The integrated quantum clock (iqClock, https://www.iqclock.eu) project brings together academic and industrial partners to translate strontium optical lattice clock technology from the laboratory to a product ready for commercialisation. The end goal of the project is to incorporate steady state super radiant techniques, developed by the academic partners, in the clock system developed by the industrial partners and University of Birmingham. This poster will outline developments of the testbed system at the University of Birmingham, which will be used for verification and development of individual components and techniques for the industrial system, and act as the master clock for performance validation of the final iqClock system.

P6. University of Liverpool atom interferometer results and upgrades

G Elertas, A Carroll, J Coleman, S Hindley, C Metelko, J Ralph, J Ringwood, A Webber-Date, 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 Rb-85 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.

The University of Liverpool atom interferometer is undergoing a major upgrade phase. The upgrade involves a new vacuum chamber, improved atom-optics set-up, an active vibration control system and a new detection system. A new vacuum chamber with larger viewports is necessary to accommodate larger trapping/cooling and atom manipulation laser beams. The new design allows the launch of atoms upwards into the atom interferometry region, increasing the time for phase difference to accumulate. Additional chambers for state selection and detection will be installed. The re-design will also allow for the installation of a vibration isolation system, and two-dimensional magneto-optical trap to increase the repetition rate of the experiment.

P7. PicoTesla absolute field readings with a hybrid ^{3}He/^{87}Rb magnetometer

C Abel[1], G Bison[2], and W Griffith[1]

[1]University of Sussex, UK, [2]Paul Scherrer Institute, Switzerland

Many precision measurements require a thorough knowledge of surrounding magnetic fields, such as fundamental physics searches, exotic spin coupling forces as well as general calibration of magnetic sensors. It is difficult to produce an absolutely correct magnetic field in a shielded environment with precise knowledge of both the direction and magnitude, due to the presence of small residual fields after a typical degaussing procedure.

Here we present a hybrid ^{3}He/^{87}Rb magnetometer that has been shown to minimise residual fields inside a shielded environment with absolute magnetic fields down to the 5 pT level. Furthermore, the device also demonstrated the ability to minimise first-order magnetic field gradients through optimisation of the T_2 time. The hybrid magnetometer provides absolute magnetic field readings based on the free spin precession of ^{3}He, where the precession signal is monitored by optically pumped ^{87}Rb magnetometers that detect small magnetic field variations generated by the precessing ^{3}He polarisation. Although atomic magnetometers with excellent sensitivity have been demonstrated, equivalent accuracy is difficult to achieve, especially due to light shifts present in alkali optically pumped magnetometers.

This procedure represents a convenient and consistent way to provide a near zero magnetic field environment which can be potentially used as a base for generating desired magnetic field configurations for use in precision measurements.

P8. A Zeeman-Sisyphus decelerator for CaF molecules

G Kambhampati, H Williams, B Sauer, M Tarbutt, and N Fitch

Imperial College London, UK

Experiments attempting to slow molecular beams into a trap would benefit from more molecules arriving at the trap from the source. Transverse spreading of the beam during laser slowing is one significant cause of loss. Decay of molecules into unaddressed vibrational states is another. Molecules with a Zeeman split ground state and unsplit excited state can be both guided and decelerated by a static, spatially periodic magnetic field with a transverse field gradient. Optical pumping between the weak and strong field seeking states in a Sisyphus-type scheme is required. This typically requires one-hundredth the number of photons compared with direct laser cooling at typical buffer gas source speeds. We call this Zeeman-Sisyphus deceleration.

We have built an 80 cm long Zeeman-Sisyphus decelerator applying this scheme for slowing CaF into a magneto-optical trap (MOT). The bore of the decelerator is 4mm in diameter. At the maxima, the field strength is uniformly 1.5T and at the minima it is transversely quartic, starting at 0.05T and increasing to 0.25T at the edges. We have observed molecules guided along the beamline and we aim to test optical pumping and deceleration next. The decelerator will slow molecules to around 50m/s, after which a short stage of laser cooling will be needed to reduce the speed to the MOT capture velocity of 10m/s. We expect the process will scatter 4,000 photons, compared with 10,000 photons for direct laser cooling.

P9. Determination of energy levels, hyperfine structure constants, lifetimes and dipole polarizabilities of Sn^{3+}

M Kaur, and B Arora

Guru Nanak Dev University, India

The energies, electric dipole matrix elements and hyperfine structure constants are estimated for triply ionized tin isotope using relativistic coupled cluster theory. Contributions from Breit interactions and lower order Quantum electrodynamics i.e. QED effects are also taken into account for above calculations. The relativistic effects are found to be important in energy calculations whereas the QED effects contribute significantly for the estimation of hyperfine structure constants. Reported hyperfine structure constants will be useful for guiding measurements of hyperfine levels in stable isotopes of Sn IV. Our calculated dipole matrix elements are further utilized for the calculation of transition probabilities, oscillator strengths and dipole polarizabilities for many states. The given polarizability values will be useful for carrying out high precision measurements using Sn IV ions in future experiments.

P10. Towards deterministic entanglement of trapped ion systems

H Shokeir, B Megyeri, and M Keller

University of Sussex, UK

Cavity quantum electrodynamics (cQED) with trapped ions are a strong candidate for the implementation of distributive quantum computing. A prerequisite is the strong coupling between the atomic ion and the optical cavity. This was recently achieved for the first time at Sussex with an end cap Paul trap with an integrated fibre cavity.

To improve the current system, we are in the process of designing and building a new ion-cavity setup with improved optical access and stability. To this end our cQED system will feature modified fibre cavities with integrated mode matching optics comprised of a single mode-GRIN-multi mode assembly. Such modified cavities feature a mode matching of up to 90% (for cavity lengths up to 400 μm) and will greatly enhance the coupling of the photons from the cavity into the single mode fibre.

We present the preliminary components and design of the next generation cQED system with a re-engineered end cap electrode-cavity structure for improved mechanical stability. The system will also utilise a novel means of controlling the ion's position that will be achieved by distorting the trapping potential by mechanically altering the positions of the electrodes that provide the RF ground. We present data from a finite element modelling program that simulate the behavior of the trapping potential under different conditions and model the various secular frequencies of the ion.

P11. A novel laser activated atom source for portable strontium optical lattice atomic clocks

J Bass, M Aldous, D Morris, Y Singh, J Jones, and K Bongs

University of Birmingham, UK

Atomic clocks have been in common use since the 1950s and over this period the clock community has had two main goals: increasing the performance of the clocks and increasing their portability. At Birmingham we aim to compress a strontium optical lattice clock, a clock with an extremely high accuracy, into a portable package. Many novel approaches need to be employed to allow such a clock to operate with a favorable SWaP while maintaining the low instability and uncertainty that makes optical clocks a desirable frequency standard. The focus of this work is to use laser activation of a strontium compound as the atomic source for the clock. Previously work published by this group [1] demonstrated that it is possible to release the strontium atoms from strontium oxide successfully load a magneto-optical trap (MOT). It is our desire to take this work further, improving the reliability and longevity of the source for use in a portable atomic clock. This work will reduce dramatically the size of the physics package while results indicate it also reduces the loading time of the MOT without the need for a pre-cooling stage such as a Zeeman slower.

P12. Towards antihydrogen synthesis with sympathetically laser-cooled positrons

J Jones, and D Maxwell

Swansea University, UK

The ALPHA collaboration has recently demonstrated laser and microwave spectroscopy of several different transitions in the antihydrogen atom. Since we typically trap around only twenty antihydrogen atoms per experimental cycle, in these experiments we choose to accumulate antihydrogen atoms over time scales ranging from tens of minutes to many hours in order to have a sufficient number of antihydrogen atoms for a given measurement. These long experimental runs limit the number of experiments that can be performed, especially due to our finite allocation of the antiproton beam.

To increase the rate of data acquisition, and potentially the precision of future spectroscopic measurements, we are currently working towards increasing the antihydrogen trapping rate. The positron temperature is thought to play a vital role in both the rate of antihydrogen formation, and on the trapping rate of antihydrogen. Currently, positron temperatures reach around 30 K when mixed with antiprotons for antihydrogen synthesis. We propose sympathetically cooling the positrons using laser-cooled beryllium ions, 9Be+, a technique that has previously been demonstrated.

Simulations in ALPHA have shown that the temperature of the positrons could potentially be reduced to less than 5K if cooling is maintained during antihydrogen formation. We have recently demonstrated trapping and laser-cooling of beryllium ions, using an ion source which was designed to operate under the significant constraints imposed by the ALPHA apparatus. We are currently performing experiments where we mix the laser-cooled ions with positrons and will present our latest results towards sympathetic cooling.

P13. Antihydrogen physics in ALPHA

N Madsen

Swansea University, UK

The ALPHA Antihydrogen experiment synthesizes and traps antihydrogen in order to study its properties and compare them to those of hydrogen as a test of fundamental symmetries such at CPT symmetry and the weak equivalence principle.

In the last few years the experiment has matured to a state where we’re trapping around 20 antihydrogen atoms every four minutes, allowing in principle the accumulation of thousands of atoms. Simultaneously, and thanks to this development we have measured the ground state hyperfine splitting to a precision of $4x10^{-4}$, and the 1S-2S two photon transition to a precision of $2x10^{-12}$, currently the most precise and accurate measurement on antimatter. Furthermore we have observed the 1S-2P Lyman-alpha transition (precision $5x10^{-8}$) that may eventually be used for laser-cooling of the trapped antihydrogen, a feat that should lead to improved precision of the 1S-2S transition.

In addition to these spectroscopic efforts we have recently expanded our setup with a second, vertical, trapping system called ALPHA-g, which has been commissioned and will allow for the first direct measurements of the gravitational to inertial mass of antihydrogen when CERN restarts delivery of antiprotons in 2021.

P14. Parity swap cat-state comparison amplifier

G Tatsi, L Mazzarella, and J Jeffers

University of Strathclyde, UK

Optical Schrödinger cat states are superpositions of coherent states and have been widely studied for the significant role they could play in quantum information, computation and in fundamental tests as resource states. For such applications cat states with high coherent amplitude (α>1.2) and high fidelity are desirable, but difficult to produce. This gives rise to the need for amplification.

Most suggestions rely on cat state *breeding*; a process whereby small amplitude *kittens* are mixed coherently at a beam splitter and a postselection measurement projects one of the two outputs in an amplified state based on the constructive interference of the two input modes. Such a process relies upon the fact that cat states of same parity must be bred to generate the larger output cat state and therefore one needs to know the input cat state beforehand. This is not amplification.

Here we introduce, to the best of our knowledge, the first amplifier for optical Schrödinger cat states that works without requiring *a priori* knowledge of the input state. The device is based on the state comparison amplifier and relies only on Gaussian resources, beamsplitters and on/off detectors. It offers reasonable gain at high fidelity for the range of input cat sizes of interest, and produces cat states of the required output amplitude range.

P15. Towards the study of quantum engines in 41K-87Rb Bose-Bose mixtures

J Mellado-Munoz, X Wang, A Smith, and G Barontini

University of Birmingham, UK

We are building an experimental setup for the realization of thermo-machines operating at the single-atom quantum level (quantum engines). This will allow the study of engines at the microscopic level where quantum effects are not negligible. Our single-atom quantum engines are assembled starting from three basic elements: i) a single ultracold atom that is the working fluid, ii) a species-selective optical tweezer that acts as a piston, iii) a thermal cloud of ultracold atoms of a different species that embodies the thermal bath. The use of two ultra-cold atomic species allows the control of the fluid-bath interaction with an external magnetic field through Feshbach resonances and zero-crossings of the scattering length. [1]

To realize such architecture, we have designed a system for the attainment of an ultracold mixture of 41K and 87Rb. The chosen species present brad low-field intraspecies Feshbach resonances that will allow us to control their interactions. Our plan is to use 41K as the working fluid and 87Rb as our thermal bath. Exploiting the high degree of control of our systems, we will be able to implement three paradigmatic heat engines -- Carnot, Otto and Diesel -- and to benchmark their performances experimentally.

[1] G Barontini, M Paternostro, arXiv:1812.10929 (2018)

P16. Generalised photon subtraction for heating or cooling thermal light

G Tatsi, L Mazarella, and J Jeffers

University of Strathclyde, UK

Photon subtraction is a process by which photons are removed from a mode of the electromagnetic field. It has been shown that this non-unitary operation, realisable probabilistically using a beam splitter, a vacuum auxiliary state and a photodetector, can lead to counterintuitive results such as preservation of the mean photon number of coherent states and increase of the mean photon number of thermal states. It is used in many applications ranging from amplification of the amplitude of quantum states to generation of Schrödinger cat states.

Thermal states have played an important role in experiments such as that of Hanbury-Brown and Twiss. The application of photon subtraction to thermal states has shown phenomena such as the “quantum vampire” effect[6] and the possibility to realise an all photonic Maxwell demon.

In this work we investigate the effect on thermal states of a process that we dub displaced photon subtraction, in which we displace a thermal state and then perform a photon subtraction whose auxiliary state is an anti-displacing coherent state. We show that displaced photon subtraction can lead to a “cooling” effect on input thermal states and that this can be harnessed to realise a linear optical photonic Maxwell demon.

P17. The antimatter gravitational behaviour in the ALPHA-g experiment

J Peszka[1, 2]

[1]CERN, Switzerland, [2]Swansea University, UK

ALPHA experiment at CERN focuses on antimatter research and recently has measured the first electronic exited energy level in the antihydrogen atom and Lyman-α transition. Among all antimatter properties investigated so far, its gravitational behaviour is still unknown. The gravitational force is vastly weaker than the electromagnetic force, so external electric and magnetic fields make it really difficult to test the gravitational behaviour of charged particles. However since it is possible to produce and trap neutral antihydrogen, now it is feasible to measure gravitational interaction of antimatter with matter and test of the Weak Equivalence Principle.

The recently built ALPHA-g experiment plans to detect gravitational acceleration of antihydrogen released from a vertical Ioffe-Pritchard trap. The idea of the so-called 'up-down measurement' was proposed and demonstrated in the old ALPHA trap, where antihydrogen atoms were trapped in a magnetic field minimum, then released to annihilate with the inner apparatus walls. The spatial distribution of annihilation events after time of drift to the trap's wall can allow one to determine the ratio of gravitational mass to the inertial mass.

Using a long vertical trap will reduce systematic errors and allows to measure a value of antihydrogen acceleration in the Earth’s gravitational field. Detection of antihydrogen positions will be performed with a 3 meters tall radial Time Projection Chamber through reconstruction tracks of charged pions produced in annihilations events. The key to the success of this measurement will be precise magnetometry of the experimental environment and accurate control over the magnetic field trap.

P18. Towards high-resolution spectroscopy of N_2^+

L Blackburn, A Gardner, and M Keller

University of Sussex, UK

High resolution spectroscopy of molecular nitrogen ions is a prime candidate to measure potential temporal changes in the proton-to-electron mass ratio, μ.

Ion traps facilitate a high degree of localisation in a highly isolated and stable environment. In addition, the shared motional modes of ions co-trapped in the same potential enable techniques such as sympathetic cooling and quantum logic spectroscopy. These techniques allow cooling and read-out of the internal state of a molecular ion, provided a suitable auxiliary ion can be found.

In this experiment, a single $^{14}N_2^+$ ion will be co-trapped, in a linear Paul trap, with a $^{40}Ca^+$ ion which will act as a frequency reference and be used for the sympathetic cooling and state detection of the nitrogen ion. A vibrational Raman transition in the electronic ground state of $^{14}N_2^+$ will be compared to a quadrupole transition in the $^{40}Ca^+$ ion. After excitation, the state of the $^{14}N_2^+$ ion will be transferred to the $^{40}Ca^+$ ion via the shared motion of the ions in a quantum logic spectroscopy scheme.

Prerequisite to this are the preparation of $^{14}N_2^+$ into a specific rovibronic state and its non-destructive state detection. Recently, a 2+1' resonance-enhanced multi-photon ionisation (REMPI) scheme was developed, using the $a^1\sum_g(v=6) \leftarrow X^1\Sigma_g^+(v=0)$ band in $^{14}N_2$ for the resonant excitation. This scheme was demonstrated to prepare $^{14}N_2^+$ in the rovibronic ground state with high purity.

P19. Positron accelerator for positronium - cold ion scattering experiments

R Clayton[1], C Baker[1], W Bertsche[2], M Charlton[1], S Eriksson[1], H Evans[1], A Isaac[1], and D van der Werf[1]

[1]Swansea University, UK, [2]University of Manchester, UK

Positron trajectories through an accelerator, designed for positronium (Ps) production via implantation into mesoporous silica (SiO_2), were simulated in preparation for scattering experiments involving Ps and laser cooled ions in an RF-trap[1]. This would allow for high implantation depths into the SiO_2 sample with a low local electric field. The design consists of a single electrode to which an electric potential is applied, while positrons from a two-stage positron accumulator[2] are within the device.

Simulations (run on Simion 8.0.8) used a positron cloud of 10^4 particles with a Gaussian energy distribution of 26.68 eV with standard deviation 0.18 eV and three-dimensional Gaussian spatial distribution corresponding to 11 ns length and 1.5 mm radius to match obtained experimental data. The simulated positron cloud is accelerated by an electrode of length, inner diameter and outer diameter of 130 mm, 26 mm and 28 mm respectively, to which a potential of -2.0 kV is applied with a 20 ns rise time. Characterisation of the simulated particle cloud will be discussed with respect to trigger delay time of accelerator electrode. At optimum efficiency 93.21 ± 0.01 % of positrons were accelerated to 2021.4 ± 0.3 eV with a similar time width to the input (11.18 ± 0.19 ns). Progress towards experimental realisation of the proposal in [1] will be discussed.

[1] A. Bertsche et al., New Jour. Phys, 19, (2017), 053020
[2] Clarke et al., Rev. Sci. Instrum., 77, (2006), 0663302

P20. Permanent magnet Zeeman slowers for a portable Strontium optical clock

R Barron, J Jones, M Gellesch, F Owens, A Singh, Y Singh, and K Bongs

University of Birmingham, UK

Zeeman slowers are an integral part of many cold atom systems. By increasing the time that atoms interact with the slowing beam, the velocity of the beam can be decreased further and more atoms can be trapped later in the system. Often Zeeman slowers are based on solenoids, as the magnetic field is easily characterised and can be turned on and off at will. However in a portable system where power is at a premium, permanent magnet Zeeman slower are an attractive proposition, despite the fact that the stray fields they produce are a perpetual factor over the rest of the system.

This project looks into improving the robustness of the permanent magnet Zeeman slower currently in use in the Strontium clocks group at Birmingham; as well as investigating new designs of permanent magnet Zeeman slower. By improving the robustness of our design we can take it into more rugged terrain and minimise maintenance that may have to be performed on the system. The investigations into new designs look into both transverse and longitudinal magnetic field Zeeman slower designs, and how to reduce the stray magnetic field produced by them without the need for magnetic shielding; whilst still maintaining the necessary magnetic field profile for efficient slowing of the atomic beam.

P21. iqClock - The European integrated quantum clock

M Gellesch[1], R Barron[1], J Jones[1], E Owen[1], A Singh[1], Y Singh[1], K Bongs[1], and the iqClock Consortium[2]

[1]University of Birmingham, UK, [2]University of Amsterdam, The Netherlands

Optical clocks are frequency standards with unmatched stability. Bringing those clocks from the laboratory into a robust and compact form will have a large impact on telecommunication, geology, astronomy, and other fields. Likewise, techniques developed for robust clocks will improve laboratory clocks, potentially leading to physics beyond the standard model. To make this transition a reality, we have brought together the iqClock consortium (https://www.iqclock.eu), assembling leading experts from academia, strong industry partners, and relevant end users. We will seize on recent developments in clock concepts and technology to start-up a clock development pipeline along the TRL scale. Our first product prototype will be a field-ready strontium optical clock, which we will benchmark in real use cases. This clock will be based on a modular concept, already with the next-generation clocks in mind, which our academic partners will realize. The modules and components of the integrated quantum clock, e.g., laser systems, atom source, or Zeeman slower, will be evaluated with a versatile and flexible optical lattice clock testbed system which we are developing at the Cold Atom Group of the University of Birmingham.

P22. Negative hydrogen production in the ALPHA apparatus

P Mullan

Swansea University, UK

The ALPHA (Antihydrogen Laser Physics Apparatus) Collaboration based at CERN, has been focusing on the production and spectroscopic investigation of antihydrogen using the ALPHA-2 apparatus to determine whether CPT symmetry breaking occurs. The collaboration’s investigation has been extended to questioning the Weak Equivalence Principle through the gravitational behaviour of antihydrogen in the Earth's gravitational field, by using the currently under commission ALPHA-g experiment. With the increasing complexity of the ALPHA apparatus, a more effective use of the anti-protons delivered by CERN's Antiproton Decelerator must be considered.

This could allow for the introduction of negative hydrogen to be used as a pseudo antiproton for optimising calibrations of particle transport between different experimental regions. This could also be used as a source of hydrogen by electron-detachment.

A minimal change to the current apparatus is a priority in order to ensure operational systems remain operational. Therefore, a study has been started into whether negative hydrogen can be generated by manipulating an electron plasma to magnify its interaction with residual gas in the vacuum environment, this has been inspired by a recent result of A.A. Kabantseva, K.A. Thompson, and C.F. Driscoll at University of California at San Diego.

P23. Prospects for cold hydrogen production via laser dissociation of molecular ions

S Jones

Aarhus University, Denmark

Comparisons between the spectroscopic energy levels of hydrogen and antihydrogen test the validity of CPT (charge conjugation, parity and time reversal) symmetry, and comparisons between the rate of fall of hydrogen and antihydrogen in a gravitational field test the weak equivalence principle. However, due partially to the large magnetic fields necessary to create and confine antihydrogen, systematic effects plague these measurements. By performing a simultaneous or near-simultaneous measurement on hydrogen and antihydrogen in the same trap, many of the systematic effects cancel out, and such a direct comparison could feasibly exceed the absolute precision of present measurements on hydrogen.

Laser dissociation of molecular hydride ions could provide a simple and ultra-high vacuum compatible way to produce relatively large quantities of trappable atomic hydrogen. The molecular ions can be trapped in a Penning trap, and a laser can be used to dissociate them into their constituent atoms with very little excess energy. Several of the alkali-earth-metal hydride molecular ions have promising cross sections for laser dissociation, and since the alkali-earth-metal ions can be efficiently laser cooled, they can be used to sympathetically cool the molecular ions. BaH^+ is particularly appealing, since its dissociation wavelength of 411 nm and the cooling and repumping wavelengths of Ba^+ at 493 and 650 nm are readily available. In this poster, I will examine the dissociation process, and explore the effects of the Penning trap dynamics on the quantities and temperatures at which hydrogen atoms can be produced.

P24. Scheme to generate and filter photon pairs from atoms in a hollow-core fibre

M Zentile, I Caltzidis, H Kübler, and R Löw

Universität Stuttgart, Germany

Single-photon sources are essential for quantum optics. It has been shown that a heralded source with high-spectral brightness can be achieved using four-wave mixing (4WM) in a thermal-atomic vapour [1]. These systems are particularly useful when the photons are to be interfaced with other atomic systems, e.g. quantum memories [2]. However, the schemes used so far require expensive high-power lasers (~1 W) to pump the 4WM process. The aim of this project is to develop a source of heralded single photons with a much higher efficiency, thereby allowing the use of a single diode laser as the pump. We will achieve this by using an alkali-vapour contained in a hollow-core micro-structured fibre and exploit the higher efficiency expected [3]. A challenge of this scheme will be to split the photon pairs. Since the wavelengths of the light emerging from the fibre are close to each other, and the beams are overlapped, many common techniques (such as using interference filters and/or spatial filtering) will not work. However, we have identified a scheme using an atomic vapour as a beam splitter for the photon pairs.

[1] MacRae, A. et al., Phys. Rev. Lett. 109, 033601 (2012)
[2] Sprague, M. R. Et al., Nature Photon. 8, 287 (2014)
[3] Londero, P. et al., Phys. Rev. Lett. 103, 043602 (2009)

P25. Positron Cloud Characterisation

H T Evans, C J Baker, M Charlton, and C A Isaac

Swansea University, UK

Low energy positron clouds from a two-stage buffer gas accumulator have been characterised with the aim of implementing resistive cooling. Resistive cooling can be described by a Stokes's viscous drag term, which offers a more correct test of the independent particle compression model. The lifetime, energy distribution, magnetron frequency and axial bounce frequency have all been determined using destructive diagnostic methods. Without the use of rotating wall electric fields, positron clouds have been held in a deep, harmonic potential well within a '3rd stage' Penning-Malmberg trap for more than 100 s.

P26. Optical frequency metrology with an $^{171}Yb^{+}$ ion clock

[1]A Tofful, [1]C Baynham, [1]B Robertson, [1]E Curtis, [1]R Godun, [2]R Thompson, and [1]P Gill

[1]National Physical Laboratory, UK, [2]Imperial College London, UK

Optical clocks are playing an important role in the advancement of frequency metrology. They are based on spectroscopy of transitions in the optical range, which allows a considerable improvement in frequency stability compared with atomic clocks based on microwave transitions. The ytterbium ion is a suitable candidate for the role of an accurate frequency reference, since it has relatively low sensitivity to external perturbations such as electric and magnetic fields.

With optical clocks already outperforming caesium primary standards by nearly two orders of magnitude, it is anticipated that the SI second will soon be redefined in terms of an optical frequency. To strengthen the basis of this redefinition, international clock comparisons are being carried out through optical fibre links to ensure that optical clocks developed in different institutions agree within their estimated uncertainties.

This poster presents the ytterbium ion clock at the National Physical Laboratory, which is based on an end-cap style RF Paul trap that was designed to minimise trap-induced systematic shifts on the ion. In ideal conditions, it is possible to reach a level of uncertainty in the frequency measurement of parts in 10^{-18}. The ytterbium clock's exceptional sensitivity can be exploited for a wide range of applications, for instance to study the variation of the fine structure constant, predicted by some theoretical models of dark matter. Furthermore, this level of sensitivity allows the optical clock to distinguish the gravity potential difference between two locations with exceptional accuracy, paving the way towards a possible use in geodetic surveying.

P27. Towards a direct comparison of hydrogen and antihydrogen

A Cridland

Swansea University, UK

The ALPHA-collaboration at CERN has been precisely measuring the spectrum of antihydrogen with a view to studying the fundamental symmetries between matter and antimatter. In 2018, ALPHA published the most precise measurement of a transition in antihydrogen with the characterization of the 1S-2S lineshape. The resonance frequency was found to agree with the expected hydrogen value in the 1 T magnetic field of ALPHA to within ~5 kHz, which is consistent with CPT invariance to a relative precision of 2×10^{-12}. Measuring the resonance frequency in hydrogen and antihydrogen in the same environment would allow a direct comparison. Currently, the annihilation signal from antihydrogen escaping the trap due to a resonant interaction with the laser beam is used to construct the spectrum. However, annihilation detection is not available for hydrogen atoms. We are investigating ways to detect trapped hydrogen in the ALPHA apparatus. One possible route is a detection system capable of sensitively detecting 121 nm (Lyman α) photons from excited hydrogen (and antihydrogen) atoms. This poses a formidable technical challenge due to the comparatively low number of atoms and the cryogenic environment. Here, we present the progress towards this goal.

P28. Simulating noise-assisted quantum transport mechanisms using cold atoms

A White, and P Petrov

University of Birmingham, UK

Since the discovery of long-lived quantum coherence in the photosynthetic Fenna-Matthews-Olson (FMO) complex there has been considerable interest in understanding the underlying transport mechanisms. The FMO complex is a photosynthetic complex composed of eight molecular sites that connects the light absorbing chlorosome to the reaction centre where chemical energy storage occurs. Excitons are generated in the chlorosome and are rapidly transported through the FMO complex with extremely high efficiency. It is thought that this behaviour is due to a strong interplay between the quantum coherence and the noisy protein environment.

In this study a quantum simulation of a similar three-site system is performed using the coupled magnetic sub-states of the F=1 state of Rubidium 87. The effect of a noisy environment is modelled by a noisy pure dephasing classical field, which perturbs the energy levels of the sites. An optimum noise power for efficient transport is observed with the typical localisation, environmental noise assisted quantum transport and Zeno like regimes identified. In addition, the transport through the system is found to be strongly dependent on the frequency components of the perturbation. Low frequency perturbations, below the dressed state splitting of the system, have been found to induce transport due to the presence of sub-resonances. Dephasing assisted transport (modelled using a broadband noise source), and vibration assisted transport (modelled as a structured environment with a Lorentzian centred on the dressed state energy splitting) are compared with wide ranging implications.

P29. Optical gain in a potassium magneto-optical trap

A Butcher, G Harvie, and J Goldwin

University of Birmingham, UK

We describe experimental studies of optical gain in a cloud of cold atoms in a ring cavity. Potassium-39 atoms are initially cooled in a 2D magneto-optical trap (MOT) and transferred via a push laser into a 3D MOT which is positioned to overlap with the mode of a three-mirror ring cavity. When probed from the side of the cavity, the transmission spectrum of the atoms demonstrates a gain peak to the red of the |F=2> to |F'> absorption features. By changing the detuning of the MOT repump light, we are able to control the gain resonance frequency. This process also causes the magnitude of the gain to vary in a way that suggests that the mechanism responsible for the gain is one of stimulated Raman scattering between the |F=1> and |F=2> ground states. Measurements of photon bunching and cavity ring-down show that the presence of gain in the cavity increases the coherence time below the lasing threshold.

P30. R-matrix calculations of the resonances contributing to symmetry breaking during dissociative electron attachment to the H2 molecule

P Bingham, and J Gorfinkiel

The Open University, UK

Recent velocity slice imaging experiments (Nat. Phys. 14 (2017) 149) looking at dissociative electron attachment (DEA) to the hydrogen molecule have revealed in the angular distributions of the dissociated hydrogen ions (around 14.5eV) a loss of symmetry from what would be expected when the dissociation is via a single completely symmetric resonant state. This asymmetry has been proposed to arise from the attachment of the scattering electron to two resonant states of opposite parities, which are close enough in energy for their widths to overlap. Under these conditions, the DEA takes place via a coherent superposition of the two resonances. These resonances have so far not been well characterized.

We present results of calculations using the ab initio R-matrix method aiming at accurately describing the resonances involved. This technique divides configuration space into an internal region, where the electron-molecule interaction is complex and an external region, where it is typically much simpler. Scattering quantities are obtained by matching the internal and external solutions at the boundary between the two regions and then propagating them to an asymptotic region.

We used the d-aug-cc-pVTZ basis set, 29 target states (in D2h symmetry), full configuration interaction and a continuum modelled using B-splines. An internal region radius of 40 bohr was used with propagation to 100 bohr sufficient for most bondlengths. The resonances involved in the DEA process around 14.5 eV have been identified and their behaviour as a function of bondlength studied. We will discuss the experimental results in light of our findings.

P31. Microwave-driven high-fidelity quantum logic with $^{43}Ca^{+}$

R Hanley, J Wolf, C Loschnauer, M Weber, J Goodwin, T Harty, A Steane, and D Lucas

University of Oxford, UK

Laser-cooled ions are a promising candidate for the creation of a general-purpose quantum processor. We have previously shown that near-field microwave control of trapped-ion qubits is possible with two-qubit gate fidelities of 99.7 ± 0.1%, a fidelity which is approaching the state-of-the-art previously attained using laser-driven techniques. Here we present the design and initial characterisation of a next-generation surface-electrode ion-trap, designed to improve the previous two-qubit gate speed and fidelity. The ion is trapped at 40μm above the trap surface, approximately half the ion-trap distance of our previous work. This increases the achievable magnetic field gradient and hence the two-qubit gate speed. A consequence however is the increase in electric field noise. To mitigate this noise increase, the trap is designed to be cooled to cryogenic temperatures of approximately 20K using a flow cryostat. A novel trap design and new choice of qubit states should lead to improvements in gate fidelity. The trap is designed to produce large magnetic field gradients whilst passively partially-nulling the field amplitude, which reduces off-resonant excitation of the qubits. The use of $^{43}Ca^{+}$ π-clock qubits operating at 288G also reduces the off-resonant excitation of 'spectator' transitions. The larger static magnetic field, compared to our previous work, leads to an increase in the Zeeman splitting of the hyperfine sub-levels and hence a reduction in the off-resonant excitation rate. Also, the π-polarisation of the microwave field reduces the coupling strength to neighbouring 'spectator' transitions.

P32. The Design of a Laser System for BECCAL – a Quantum Gas Experiment on the ISS

V Henderson[1], A Wenzlawski[2], A Bawamia[3], J-P Marburger[2], A Wicht[3], P Windpassinger[2], M Krutzik[1], A Peters[1], C Braxmaier[4], E Rasel[5], and W Schleich[6]

[1]Humboldt-Universität zu Berlin, Germany, [2]Johannes Gutenberg-Universität , Germany, [3]Ferdinand-Braun-Institut, Germany, [4]DLR Institute for Space Systems, Germany, [5]Leibniz Universität Hannover, Germany, [6]Universität Ulm, Germany

BECCAL (Bose-Einstein-Condensate – Cold Atom Laboratory) is a cold atom experiment designed to be operated on the ISS. It is a collaboration between DLR and NASA, built upon the heritage of previous sounding rocket and drop tower experiments as well as NASA's CAL. This multi-user facility will enable us to explore fundamental physics research with Rb and K BECs and ultra-cold atoms in microgravity, facilitating prolonged timescales and ultra-low energy scales compared to those achievable on Earth.

The complexity of the light fields required presents a unique challenge for laser system design. Especially in terms of both the stringent size weight and power limitations, and the need for long-term operation. To address this we combine microintegrated diode lasers with miniaturized free-space optics mounted onto Zerodur boards, all interconnected via fibre optics. These technologies have proven their reliability in many qualification tests and successful sounding rocket missions. We will present an overview of the current design of the BECCAL laser system, alongside the requirements, concepts, heritage, and underpinning technology which have formed it.

This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry of Economic Affairs and Energy (BMWi) under grant number DLR50WP1702.

P33. Systematic construction of scarred many-body dynamics in 1D lattice models

K Bull[1], I Martin[2], and Z Papic[1]

[1]Leeds University, UK, [2]Argonne National Lab, USA

We introduce a family of non-integrable 1D lattice models that feature robust periodic revivals under a global quench from certain initial product states, thus generalizing the phenomenon of many-body scarring recently observed in Rydberg atom quantum simulators. Our construction is based on a systematic embedding of the single-site unitary dynamics into a kinetically-constrained many-body system. We numerically demonstrate that this construction yields new families of models with robust wave-function revivals, and it includes kinetically-constrained quantum clock models as a special case. We show that scarring dynamics in these models can be decomposed into a period of nearly free clock precession and an interacting bottleneck, shedding light on their anomalously slow thermalization when quenched from special initial states.

P34. Characterising adiabaticity in many-body thermal systems

A Skelt, and I D'Amico

University of York, UK

Characterising adiabaticity is still an open fundamental problem that is vital for understanding adiabatic quantum computing and maximising quantum work among other applications. We recently showed that 'natural' metrics can be used as a simple and graphical method of characterising adiabaticity at zero temperature using the relationship between ground state wavefunctions and densities. Here we consider finite temperatures looking at the distances of the mixed states and of their densities. In principle, at finite temperatures, it is no longer only the ground state which must be considered to characterise an adiabatic dynamics, but the population of all eigenstates. We show how, by using the Bures distance (which extends the natural metrics to finite temperature), we can determine if an evolution is adiabatic without monitoring the eigenstate populations. In addition, the trace distance, a widely used mixed-state metric, can also be used provide such information.

P35. Poster Withdrawn

P36. Quantum state verification, validation, and visualisation via phase space methods

R Rundle, B Davies, V Dwyer, T Tilma, and M Everitt

Loughborough University, UK

Since its introduction in the 1930s by Wigner, and its generalisations by Moyal and Weyl, the ability to associate an operator on Hilbert space by a quasi-probability distribution function on phase space has found extensive use in the physics of continuous variable systems. Lacking, however, is finite system applications; to date, such functions have taken a back seat to state vector, path integration, and Heisenberg representations.

In recent work we have addressed this lack of application by giving a general framework to generate a Wigner distribution function for any system in displaced parity form. Using this work, we have shown how varied quantum systems can be easily represented in phase space as well as visualise certain quantum properties, such as entanglement, within these systems.

Utilising this framework, we developed techniques to visualise systems of atoms coupled to a field mode. Using our visualisation methods, investigated the full behaviour of evolution models such as the Jaynes-Cummings model. Earlier Wigner function treatment of the Jaynes-Cummings model simply traced out the spin degree of freedom, leading to important information of entanglement correlations to be integrated out. Using our methods, we get a much more informationally complete picture of the quantum correlations in atom-cavity interaction.

P37. Visualising spin degrees of freedom in atoms

B Davies[1], R Rundle[1], V Dwyer[1], J Samson[1], T Tilma[2], and M Everitt[1]

[1]Loughborough University, UK, [2]Tokyo Institute of Technology, Japan

We show how constructing Wigner functions of heterogeneous quantum systems leads to new capability in the visualisation of quantum states of atoms and molecules. This method allows us to display quantum correlations (entanglement) between spin and spatial degrees of freedom (spin-orbit coupling) and between spin degrees of freedom, as well as more complex combinations of spin and spatial entanglement for the first time. This is important as there is growing recognition that such properties affect the physical characteristics, and chemistry, of atoms and molecules. Our visualisations are sufficiently accessible that, with some preparation, those with a non-technical background can gain an appreciation of subtle quantum properties of atomic and other systems. By providing new insights and modelling capability, our phase-space representation will be of great utility in understanding aspects of atomic physics and chemistry not available with current techniques.

P38. Scaling up the trapped ion quantum processor

S Hile[1], S Weidt[1], R Puddy[1], T Naickas[1], S Hong[1], D Bertaud[2], A Owens[1], F Le Brun-Ricalens[1], Z Romaszko[1], M Siegele[1], and W Hensinger[1]

[1]University of Sussex, UK, [2]Imperial College London, UK

Trapped ion qubits achieve excellent coherence times and gate fidelities, well below the threshold for fault tolerant quantum error correction. A key challenge now is to scale ion based quantum processors to the large number of qubits required for error corrected algorithms to run. We present progress on the implementation of a high fidelity logical qubit in a modular architecture designed for true scalability, based on robust microwave-driven quantum gates and physical shuttling of ion qubits.

The architecture is based on X-junction surface ion traps, made using industrial silicon microfabrication techniques. The 4-arm geometry permits dedicated zones, optimised for ion loading, memory, entangling interactions and readout.

Qubits are defined in the internal hyperfine states of the 171Yb+ ion. We utilise different qubit representations within the 4 natural spin states defined by the electron and nuclear spins, dressing the states to engineer an artificial clock-like qubit less sensitive to environmental noise.

Entanglement is generated by modulating the Coulomb interaction between ion pairs in a strong magnetic field gradient. Driving the spin-motion entangling (Molmer-Sorenen) gate directly with global AC magnetic fields rather than using locally focussed laser excitation relives much of the complexity in laser stabilisation found in traditional ion trap processors based on optical transitions.

We will outline progress toward implementing ion transport between physically separate ion trap modules, in dynamically generating the strong magnetic field gradients used for robust entanglement generation, and in developing an error-corrected logical qubit within our architecture.

P39. Multi-photon photoionization of molecules using the "R-matrix with time" (RMT) approach

J Benda[1], Z Masin[2], G Armstrong[3], D Clarke[3], A Brown[3], J Gorfinkiel[1], and H van der Hart[3]

[1]The Open University, UK, [2]Charles University in Prague, Czech Republic, [3]Queen's University Belfast, UK

In our contribution we study one-, two- and four-photon photoionization of the hydrogen molecule by monochromatic pulses using the recent extension to molecules of the originally atomic-only R-matrix with time dependence (RMT) method. The molecular RMT combines the accuracy of the time propagation provided by RMT and the ab initio target description by the stationary molecular R-matrix package UKRmol+, enabling the correct description of multi-electron effects and electron correlation in the response of the target to the external field.

The RMT approach is very general and allows the study of a range of processes from the perturbative to highly non-linear regimes. Detailed understanding of the molecular RMT models for multi-photon ionization is a prerequisite for its application to processes such as strong-field ionization and high-harmonic generation.

This work validates the UKRmol+/RMT combination on several processes well studied in the past. The generalized multi-photon cross sections for photoionization of H2 by a weak, linearly polarized field obtained using the UKRmol+/RMT suites are compared to results from the Floquet R-matrix method, those of a direct solution of the Schrödinger equation in DVR basis with ECS boundary conditions, as well as to other approaches. Furthermore, we identify and study the time dependent dynamics of the resonant states, including Rabi oscillations and the loss of coherence between the direct and resonant ionization pathways. Prior time-independent calculations were unable to model these effects that are well described by the RMT method and have an effect on the cross sections near the resonances.

P40. Evaluation of a MEMS-fabricated 3D ion microtrap for scalable entanglement-enhanced quantum metrology

G Wilpers, M Akhtar, S Thomas, K Chonee, and A Sinclair

National Physical Laboratory, UK

Trapped ion experiments have reached world-leading fidelity in controlled quantum-information processing operations, utilised entanglement for improved optical clocks and demonstrated non-classical approaches to tailor spectroscopic sensitivity. Scaling from small linear strings to larger arrays of ions is increasingly important.

Our monolithic devices have a 3D electrode geometry and contain a linear microtrap array of 1 loading and 7 operation segments. Devices are produced with high yield in a wafer-scale fabrication process and operate at room temperature. Using the 674 nm optical qubit transition in $^{88}Sr^+$, coherent spectroscopy of single ions and 2-ion strings shows confinement at the Lamb-Dicke limit. 2-ion strings have been trapped for 3 hours and we measured a single ion motional heating rate of 2.6(2) quanta/s (axial mode at $w_z/2p$ = 1.05 MHz). The trap stability has been evaluated to optimise parameters for long storage times, high motional frequencies, and to realise shuttling and splitting operations with up to four ions.

To minimise decoherence, we implemented an active magnetic field stabilisation system which achieves a relative noise level dB/B ~ 10^{-6}. Additionally, a Ti:sapphire laser (~ 1 Hz linewidth) drives the optical qubit transition with minimised Rabi frequency fluctuations via a power- and position-stabilised beam.

Experiments towards demonstration of the Mølmer-Sørensen entanglement scheme with 2 ions are in progress and latest results will be presented.

P41. Applications of polychromatic dressing of ultracold atomic ensembles

G Sinuco-Leon, and B Garraway

University of Sussex, UK

In this work we present a study of the use of radio-frequency (RF) and microwave (MW) fields for controlling ultracold atomic ensembles of alkali atoms, considering three common experimental situations. First, we study and interpret experimental microwave spectrum of resonantly RF-dressed 87Rb [1]. Second, we study the control over the DC sensitivity of microwave transitions of 87Rb using a bichromatic RF-dressing scheme [2]. Finally, we study the adiabatic potential landscape resulting from double dressing with RF and MW fields in an atom-chip configuration producing a bubble trapping potential [3,4]. Our work demonstrates the flexibility of the control offered by multifrequency dressing of quantum systems, which are within reach of state-of-the-art experimental setups with cold atoms.

[1] G.A. Sinuco-Leon, B.M. Garraway, H. Mas, S. Pandey, G. Vasilakis, V. Bolpasi, W. von Klitzing, B. Foxon, S. Jammi, K. Poulios and T. Fernholz. Microwave spectroscopy of radio-frequency dressed 87Rb, arXiv 1904.12073, (2019)

[2] H. Mass, G.A. Sinuco-Leon, B.M. Garraway and W. Von Klitzing. In preparation, (2019)

[3] B.M. Garraway and H. Perrin, Recent developments in trapping and manipulation of atoms with adiabatic potentials, J. of Phys. B 49, 172001 (2016)

[4] G.A. Sinuco-Leon, N. Lundblad and B.M. Garraway, in preparation, (2019)

P42. Non-linear and parametric effects in atomic magnetometers

V Guarrera[1], R Gartman[2], G Bevilacqua[3], G Barontini[1], and W Chalupczak[2]

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

We theoretically and experimentally demonstrate that non-linear spin exchange coupling, acting in an analogous way to a wave-mixing mechanism, can create new modes of coherent excitation in an atomic Bell-Bloom magnetometer, which inherit the magnetic properties of the natural Larmor coherence. The generated coherences further couple via linear spin-exchange interaction, leading to an increase of the natural coherence lifetime of the system. Notably, the measurements are performed in a low-density caesium vapour and for non-zero magnetic field, outside the standard conditions for collisional coherence transfer.

We also report on the use of parametric excitation to coherently manipulate the collective spin state of the atomic vapour. Signatures of the parametric excitation are detected in the ground-state spin evolution. These include the excitation spectrum of the atomic coherences, which contains resonances at frequencies characteristic of the parametric process. The amplitudes of the signal quadratures show amplification and attenuation, and their noise distribution is characterized by a strong asymmetry, similar to those observed in mechanical oscillators. Notably, we find that the noise squeezing obtained by this technique enhances the signal-to-noise ratio of the measurements up to a factor of 10, and improves the performance of a Bell-Bloom magnetometer by a factor of 3.

Finally, we present preliminary results on spin noise spectroscopy of the noise-squeezed ensembles and characterization of the relative steady-state dynamics.

P43. Non-equilibrium Feshbach Association of fermionic ^{6}Li molecules

G Simmonds, V Naniyil, N Cooper, and L Hackermuller

University of Nottingham, UK

Recent proposals for quantum heat engines [1] and entangled systems [2] have suggested the use of Feshbach Molecules in Molecular Bose-Einstein condensates (mBEC) to be viable candidates for experimental tests. Both of these require large molecule numbers and high densities. In experiments utilizing mBECs, adiabacity in molecule formation is assumed, but is not necessarily the case. We measure the molecular conversion efficiency when ramping from the BCS to the BEC side of the broad Feshbach resonance in ^{6}Li at 832G, as a function of both the sweep rate and the cloud temperature. We also perform statistical tests of the Landau-Zener and power law models of the BCS-BEC atom-molecule pairing transition. Finally, the effect of the cut-off magnetic field of the sweep is explored and its effect on molecule production compared to simulations using mean field theory.

[1] An efficient non-linear Feshbach engine – Jing Li et al New J. Phys. 20 015005 (2018)

[2] Entanglement between two spatially separated ultracold interacting Fermi gases – P. A. Bouvrie et al – Phys. Rev. A 99 063601

P44. Non-invasive diagnosis of lithium-ion cells using magnetic measurements

M Bason[1], M Withers[2], C Abel[1], T Coussens[1], G Kendal[2] and P Krueger[1]

[1]University of Susses, UK, [2]CDO[2] Ltd., UK

Though the adoption of battery technology continues at pace, several challenges remain. Among these are safety issues concerning cell malfunction due to production defects and the growth of lithium deposits known as dendrites [1]. In addition to destructive measurements, non-invasive techniques, such as x-ray CT and MRI, are beginning to be used to diagnose these devices [2]. In contrast, we show how magnetic images can be used to assess the condition of lithium-ion cells and discuss pathways towards using such images for the diagnosis of other cell electrochemistries. We discuss our developments of optically-pumped magnetometer arrays –a technology which has recently been applied to magnetic susceptibility measurements of charged lithium-ion cells [3].

[1] Yu, C. et al. Nature Commun. 8, 1086 (2017); Han, F. et al. Nature Energy 1 (2019) doi:10.1038/s41560-018-0312-z

[2] Ilott, A. J., et al., Nat. Commun. 9, 1776 (2018)

[3] Yinan H. et al. Arxiv.org/abs/1905.12507

P45. A high-sensitivity electronic test apparatus for ion microtraps

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

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

Microtrap devices are becoming ubiquitous components in quantum technologies based on strings of trapped ions. Deep trapping potentials for long ion storage times, and tight confinement for motional frequencies in the MHz range are made possible by the application of a high amplitude Radio Frequency (RF) voltage to the electrodes. A potential limitation of chip-scale microtrap devices is their ability to withstand these RF voltages. Significant breakdown due to fabrication imperfections can be obvious and easily detected, eg by visible flashover and sputtered material. In the very early stages of breakdown this is barely visible, yet creates a noisy trapping potential resulting in excessive heating rates and motional decoherence. We have developed an apparatus for testing the electronic performance of our ion microtrap chips before vacuum packaging; these devices have a monolithic 3D electrode geometry and contain a linear array of one loading and seven operation segments. The apparatus enables calibration of the applied RF amplitude and detection of surface flashover. CCD cameras monitor those microtrap surfaces subject to the highest electric fields. Images of these surfaces are processed by applying thresholding, filtering and morphology operations to enable sensitive detection of the onset of surface flashover. With this processing procedure, it is possible to detect the faintest onset of flashover which is masked by noise in an unprocessed image. This technique is routinely applied to certify the electrical performance characteristics of our ion microtrap chips, and hence determine their fitness for purpose.

P46. A frequency-agile laser tuner for coherent optical control of trapped ions

S Thomas[1], A Sinclair[1], G Wilpers[1] and E Riis[2]

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

Coherent control of trapped ions using optical fields requires agile manipulation of frequency, phase and amplitude of the laser driving the qubit transition. Our work concerns quantum control of $^{88}Sr^+$ in a microfabricated ion trap; we use a CW ultra-stable Ti:sapphire laser (1 Hz linewidth) to drive the $^{88}Sr^+$ S-D optical qubit transition at 674 nm. For procedures such as state initialisation via sideband cooling, entanglement and spectroscopy, the laser frequency needs to be tuned to different Zeeman components and motional sidebands over a ~ 40 MHz range. Moreover, a constant optical power (and hence Rabi frequency) is required over the full tuning range. To achieve the requisite agility in frequency, independent of the laser’s frequency stabilisation apparatus, we have developed an optical tuner. Laser light is frequency shifted by a tunable, double-pass Acousto-Optic Modulator (AOM), coupled to an optical fibre, the output of which is power stabilised using a radiometric photodiode. A Direct Digital Synthesis (DDS) RF source drives the AOM which permits agile frequency operation. With the power stabilised, the laser can be tuned across a $\sim$ 60 MHz range with an overall optical efficiency of 40 %. Frequency agility is demonstrated by applying a stream of 2000 random frequencies within the tuning range, each of 500 ms duration. After a frequency change, the tuner’s power set-point is restored within 20 ms; this is presently limited by the bandwidth of the servo and the photodiode. A power instability $dP/P = 10^{-3}$ is achieved.

P47. OPTAMOT: Optimised Designs for Additively Manufactured Magneto-Optical Traps

S Madkhaly, and N Cooper

University of Nottingham, UK

We establish a robust, low-cost, compact and portable apparatus capable of creating a magneto-optical trap for Rb atoms. The integrated system incorporates a 3D printed UHV chamber weights 245g and reaches a pressure below 10^{10}, 3D printed optomechanics (ALLAMO), digital and off-the-shelf electronics for laser frequency stabilization, as well as a magneto-optical trap based on ferromagnetic rings rather than coils. Based on preliminary results, we believe that our system will be a basis for many applications and quantum technologies e.g. quantum gravity sensors, magnetometers, and outer space and satellite.

P48. Towards tweezer arrays of laser cooled molecules

J Rodewald, B Srivathsan, N Finch, J Blunsden, B Sauer, E Hinds, and M Tarbutt

Imperial College London, UK

Recent advances in the production of ultracold molecules bring the construction of a molecular quantum simulator into reach. Such simulators may be used to investigate quantum many body phenomena intractable to even the most powerful conventional computers. Working towards this goal, we are building an experiment to trap single laser cooled Calcium Monofluoride (CaF) molecules in the sites of a scalable optical tweezer array, cool each molecule to the motional ground state of its trap and demonstrate full quantum state control of the system. The large electric dipole moment of CaF will allow us to tune interaction potentials to mimic a wide range of quantum many body systems. The experimental sequence for trapping single molecules will begin by capturing CaF in a MOT. The molecules will then be transported to a science chamber and compressed in a high power dipole trap. Subsequently, an optical molasses will provide a dissipative mechanism for the molecule to cool into the sub-micron sized sites of an optical trap array and make the molecules bright to our imaging system. A high numerical aperture aspheric lens inside the vacuum chamber will be used to both focus the far off-resonant trapping light and collect the fluorescence of the trapped molecules. An imaging system capable of registering small numbers of photons will be used to detect the presence of a trapped molecule and trigger the single particle experiments.

We will present our progress in setting up this new apparatus for studying many-body quantum physics.

P49. Coupling organic molecules to nanophotonic devices

A Clark

Imperial College London, UK

Single photons lie at the heart of many quantum technologies, but are often difficult to generate and collect with high efficiency. Organic molecules present many favourable characteristics to overcome these issues. When dibenzoterrylene (DBT) is embedded in anthracene it is photostable and forms a pseudo-two-level system which can be used to generate narrowband photons at cryogenic temperature. Here I will present recent developments in coupling DBT emission into optical fibres using a microcavity, and into photonic and plasmonic waveguides using nano-fabricated devices. Such devices not only form the basis for building efficient photon sources, but can also be used for other applications where a strong light-matter interaction is required, including photon switching, number filtering, nonlinear photon-photon interactions, and quantum memories. The transition frequency of molecules can be tuned using a DC electric field via the Stark effect. I will show that single DBT molecules can be tuned across the D2 line hyperfine resonances of rubidium, making solid-state molecular photon sources compatible with atomic quantum memories.

P50. A highly compact cold atom gravity gradiometer

H Thomas, M Langlois, L Earl, M Holynski, and K Bongs

University of Birmingham, UK

Atom interferometry currently leads in the most sensitive absolute gravity measurements, however these devices have not yet met the same portability constraints as the commercially available classical gravimeters. The challenge is to develop the technology of atom interferometry based gradiometers and demonstrate their potential as a field deployable device. Gravity gradiometry involves performing a differential measurement of gravity using a single laser, allowing all common mode noise, such as vibration noise, to be subtracted out. The sensor can be operated without need for vibration isolation or tilt alignment, enabling use in the field. We are developing a gravity gradiometer combining several state of the art tools from atom interferometry including a moving lattice and Bragg splitting; and the telecoms industry with the us of IQ modulators to match the size and robustness requirements of commercially available gravimeters. We have demonstrated the use of a single laser arm for cooling, Bragg Splitting, Bloch elevator, Raman interrogation and detection of atoms. This enables a very compact system, building towards use in environments previously inaccessible to quantum sensors.

Institute of Physics
37 Caledonian Road, London N1 9BU
Telephone: +44 (0)20 7470 4800
iop.org/conferences