QuAMP 2021

31 August - 3 September 2021

Sponsored by SWEN LTD

http://quamp2021.iopconfs.org/home
**Day 1 - Tuesday 31 August 2021**

**Session 1 - Quantum states**

*(Invited)* Exploring vibronic mixing in chlorophylls and photosynthetic complexes by polarization-controlled 2D electronic spectroscopy

Donatas Zigmantas

Lund University, Sweden

Electronic-vibrational (vibronic) coupling has been suggested to play an important role in photosynthetic processes, such as energy transfer and charge separation. Even though this coupling in molecules has been suggested eight decades ago, it has proven to be a highly elusive phenomenon to investigate. To this end we have employed polarization-controlled 2DES together with advanced Fourier analysis [1], which allows us to extract full information about coherences (superposition states), which in turn report on vibronic mixing.

I will present a couple of studies of vibronic mixing in molecular systems. In one study we investigated chlorophyll c molecule in a solution, where we found a clear evidence of vibronic mixing of the two lowest electronic states, QX and QY [2]. Interestingly, we distinguish at least two vibrational modes that are involved in vibronic mixing. Since this type of coupling is expected to be general, vibronic mixing is expected in all chlorophyll-type molecules, as have been previously suggested in a theoretical study [3].

We also revisited coherence dynamics in the light-harvesting complex FMO from green sulfur bacteria at 77 K [4]. We detected and sorted out a wide range of coherence signals. At early times purely electronic coherences were observed, which dephased on the ~100 fs time scale. All long-lived coherences, on the other hand, had clearly vibrational origin. Importantly, we observed that specific vibrational coherences are excited via vibronically-coupled excitonic transitions.

Presence of the ubiquitous vibronic mixing rises an intriguing question, if it is an unavoidable consequence of the properties of the porphyrin-type molecules, or an optimization mechanism, which nature employs to finely tune primary photosynthetic processes.


---

Fundamental Limits on Estimation of Molecular Parameters Using Entangled Photon Spectroscopy

Aiman Khan

University of Warwick, UK

Nonlinear spectroscopy using entangled photons has been shown to offer a number of apparent advantages over classical light, including increased selectivity in exciting transitions, enhanced signal-to-noise ratio of detected signal, as well as a larger set of control parameters (such as entanglement time). In this talk, I will recast the basic spectroscopic question of how much...
information about the matter system one can learn from the detected state of quantized light as that of a quantum estimation problem. By evaluating the Fisher matrix with respect to the parameters of interest of the matter system, we can estimate the optimal input field state as well as the detection scheme for the inference problem. I will illustrate this in the context of the linear biphonon spectroscopic probe of a coupled dimer, where one of the members of an entangled photon pair (resulting from a type-II parametric down-conversion (PDC) process) couples with the matter system, and is detected in coincidence with the other photon. Under the influence of various models of the bath that couples to the matter system, I will show that we can evaluate fundamental error bounds on the estimation of site energies and interstitial coupling of the coupled dimer, as well as estimate the optimal PDC state, using this proposed framework. Finally, I will demonstrate the quantum enhancement offered by our approach by comparing results to a classical analogue of the setup.

Dark and leaky exciton condensates in transition metal dichalcogenide twisted bilayers

Benjamin Remez and Nigel Cooper
University of Cambridge, UK

Bose-Einstein condensates of excitons are an interesting class of many-body quantum-degenerate phases in the solid state. Since their realization is hindered by finite exciton radiative lifetimes, they are frequently pursued in systems where the lowest-energy exciton mode is optically inactive. The resulting condensate is often referred to as a "dark condensate" to indicate the lack of optical emission. Here we show that, in fact, these condensates will emit optically, even at vanishing temperature, as a result of condensate quantum depletion due to exciton–exciton interactions, and so behave as what we call "leaky condensates". We demonstrate that this physics is relevant in transition metal dichalcogenide twisted heterobilayers, a promising new quantum simulation platform, in which the lowest-energy interlayer excitons of the moire superlattice are optically inactive, but have strong dipole–dipole interactions. We show that while a multivalley condensate may break translation symmetry, direct optical emission from the condensate is precluded by a robust three-fold rotation symmetry, necessitating other recombination mechanisms such as the “leaky” emission in which both a photon and a Bogoliubov excitation are produced. We compute the leaky condensate emission rate and spectrum within a Holstein-Primakoff approximation, supported by numerics. We find that interactions dominate over thermal excitations in driving emission around and below the superfluid transition temperature.

Session 2 - Collisions and Interactions

(Invited) Soft x-ray methods for probing chemical dynamics

Rebecca Ingle
University College London, UK

Soft X-ray techniques are powerful tools for recovering information on the electronic and structural dynamics of gas phase molecules. The combination of element-selectivity and the sensitivity of the
X-ray signal to changes in the local environment mean such techniques can be used to study chemical dynamics even for complex systems. Three of the most commonly used X-ray techniques include X-ray absorption, emission and photoelectron spectroscopy, and with more beamlines becoming capable of multiplex detection, these techniques can be combined to provide a more complete picture of the chemical dynamics.

However, for X-ray emission (XES) there are a significant number of technical challenges. In the soft X-ray regime, where the K-edge transitions for most of the light elements like carbon, nitrogen and oxygen are located, the quantum yield for X-ray fluorescence is significantly lower. The result of this is, while soft X-ray XES has become a routine technique for characterisation of solids, only very limited studies have been carried out on low-density samples, particularly at the carbon K-edge where the ‘carbon hole’ results in significantly reduced X-ray flux.

In this talk, I will demonstrate of the feasibility of resonant and non-resonant X-ray emission at the carbon K-edge on three polyatomic, gaseous molecules and how, with the aid of quantum chemical calculations, such techniques can be used to differentiate between even subtly chemically inequivalent sites and how this can be extended to time-resolved experiments on a related system, tetrakis(dimethylamino)ethylene.


Cyanoacetylene ionisation and the formation of dication states
Lilian Ellis-Gibbings, Bridgette Cooper, Jonathan Tennyson and Stephen D Price
University College London, UK

Cyanoacetylene (HCCCN) has been detected in several astrophysical environments, including in the atmosphere of Titan. CN containing molecules could be involved in chemical routes to larger organic molecules, and the prebiotic origins of life.

Dications (dipositive ions) are energetic species that are highly reactive, capable of unusual chemistry, and detected in planetary ionospheres. Molecular dications, many of which exhibit metastable states, undergo particularly interesting dissociation and collision dynamics, and are a source of cations with high kinetic energy.

Using ion-ion coincidence, the authors provide not only partial ionisation cross sections, but also precursor-specific partial ionisation cross sections for cyanoacetylene, below 200 eV. These cross sections have been converted to absolute values using a BEB calculation of the total ionisation cross section. The proportion of ionising events that result in single, double, or triple ionisation is presented.

A study of the energetics of the cation and dication states shows several cyclic geometries. These states support the observed formation of unusual ions. Further, the coincidence data provides a means to assess the energy of the parent dication states that dissociate into the detected pairs of ions. These states were found to be, on the whole, excited well above the second ionisation limit.
Towards Quantum Simulation of Multiferroics: Phase diagram and post-quench dynamics in a double spin-chain system in transverse fields

Abhishek Agarwal, Michael Hughes and Jordi Mur-Petit
National Physical Laboratory, UK

We propose and explore the physics of a toy model of a multiferroic system by coupling two distinct XXZ chains in transverse fields. We determine first the rich phase diagram using Density Matrix Renormalization Group (DMRG) techniques. Then, we explore the dynamics of the system after global as well as local quenches, using the Time-Evolving Block Decimation (TEBD) algorithm. After a global quench, the system displays decaying coupled oscillations of the electric and magnetic spins. The parity of the spin-spin interactions leads to a notable shift in the oscillation frequency as the inter-chain coupling is increased. Local quenches lead to a light-cone propagation of excitations in agreement with generalised Lieb-Robinson bounds for power-law interacting systems. In this case, the inter-chain coupling generates a new wave of excitations propagating through the 'magnetic' chain at the speed of the 'electric' wave.

Many-body theory calculations of positron scattering and annihilation in H2, N2, CH4 and CF4

Charlie Rawlins1, Jaroslav Hofierka1, Brian Cunningham1, Charles Patterson2 and Dermot Green

1Queen’s University Belfast, UK, 2Trinity College Dublin, Ireland

Understanding the fundamental interactions of positrons with matter is important to e.g., develop positron traps, beams and positron emission tomography, properly interpret positron-based materials science techniques and understand positron interactions in the Galaxy.

Calculations of positron scattering or annihilation in molecules are scarcer than those with atomic targets [1]. Calculations for small molecules have been performed using sophisticated techniques including stochastic variational, R-matrix, Kohn-variational, diffusion Monte Carlo and Schwinger-multichannel methods, but only for positron annihilation on the smallest molecule (H2) does theory agree adequately with experiment [2].

We have developed a many-body theory description of positron interactions with polyatomic molecules, demonstrating excellent agreement with experiment and elucidating the mechanism of binding [3]. Here, we use it to calculate s-wave positron scattering phase shifts and \( Z_{\text{eff}} \) \textit{ab initio} for H\(_2\), N\(_2\), CH\(_4\) and CF\(_4\) (molecules which do not bind), comparing with theory and experiment, where possible. We solve the Dyson equation in a Gaussian basis with positron-molecule self-energy calculated at the GW@RPA/TDHF/BSE levels including the virtual-positronium formation and positron-hole contributions. Our calculated \( Z_{\text{eff}} \) is in good agreement with the accurate stochastic variational method calculation and experiment [2], providing a consensus. For N\(_2\), CH\(_4\) and CF\(_4\) we find good agreement with experiment.
(Plenary) Attosecond studies of Photoionization

Eva Lindroth

Stockholm University, Sweden

The ability to generate pulses of light of attosecond duration (1 as = 10^-18 s) has given physicists access to incredibly short time scales, but how can these pulses be used to learn more about electron dynamics? In most experiments a single broadband pulse, or a train of attosecond pulses, suddenly ionizes a quantum system, creating an electronic wave packet which after varying time intervals is probed by a second pulse. These studies are sensitive not only to the ionization probability, but also to the phase of the electronic wave packet and thereby to temporal aspect of the ionization process.

During the presentation we will see how experimental results can be interpreted and how the combination and high temporal and spectral resolution can be used to disentangle contributions from resonances, shake-up processes and spin-orbit coupling.

Many-body theory of positron binding to halogenated hydrocarbons

Jaroslav Hofierka¹, Brian Cunningham¹, Charlie Rawlins¹, Charles Patterson² and Dermot Green¹

¹Queen’s University Belfast, UK, ²Trinity College Dublin, Ireland

Positrons bind to molecules leading to vibrational excitation and spectacularly enhanced annihilation.

Whilst positron binding energies have been measured via resonant annihilation spectra for around 90 molecules in the past two decades, an accurate ab initio theoretical description has remained elusive. Of the molecules studied experimentally, ab initio calculations exist for only 6, and for these, standard quantum chemistry approaches have proved severely deficient, agreeing with experiment to at best 25% accuracy for polar molecules, and failing to predict binding in non-polar molecules.

In this work, we develop a diagrammatic many-body description of positron-molecule interactions and uncover the role of strong many-body correlations. We solve the Dyson equation for the positron quasiparticle wavefunction in a Gaussian basis, constructing the positron-molecule self-energy including the GW contribution that describes polarisation, screening and electron-hole interaction interactions, the ladder series of positron-electron interactions that describes the unique virtual positronium formation process (where a molecular electron temporarily tunnels to the positron), and the ladder series of positron-hole interactions. We also elucidate the role of individual molecular orbitals, highlighting the importance of electronic π bonds. Overall, we
calculate binding energies in excellent agreement with experiment. The method also enables the calculation of the positron bound wavefunction, and the annihilation rate in the bound state.

Our approach can be extended to enable predictive ab initio calculations of positron scattering and annihilation gamma spectra in molecules, providing insight for the development of fundamental experiments and antimatter-based technologies and applications, e.g., traps, beams and positron emission tomography.


Evaluations of the Magic Wavelengths for Various Energy Transitions of Hydrogen and Hydrogenic Systems
Jonathan Canales and Chandra Adhikari
Skidmore College, USA

The magic wavelengths were determined for the 1S-2S and 1S-3S energy transitions of hydrogen and hydogenic systems, such as positronium and deuterium. Calculations were done by considering the polarizabilities of the ground state and of an excited state of interest, and the particular wavelength at which the AC Stark shifts cancel were found. Graphical analysis was employed to find the intersection of the polarizabilities for our different states. The graphs for the 1S-2S transitions of hydrogen and deuterium are constructed to show the most stable regions within the visible spectrum of light, but such is not the case for their 1S-3S transitions and both transitions of positronium. Our polarizabilities were provided by the 1S, 2S, and 3S position matrix elements of the Schrodinger Coulomb propagator, where the dimensionless variables within these quantities varied with respect to the state of the system, as well as its reduced mass. Though our neutral hydrogen and positronium systems are two-body in nature, we maintain the integrity of the two-body problem for deuterium by synthesizing a nucleic mass as the sum of the proton and neutron.

Session 4 - Solid state quantum systems

(Invited) Silicon Colour Centres
Stephanie Simmons
Photonic Inc, Canada

The future global quantum internet will require high-performance matter-photon interfaces. The highly demanding technological requirements indicate that the matter-photon interfaces currently under study all have potentially unworkable drawbacks, and there is a global race underway to identify the best possible new alternative. For overwhelming commercial and quantum reasons, silicon is the best possible host for such an interface. Silicon is not only the most developed integrated photonics and electronics platform by far, isotopically purified silicon-28 has also set records for quantum lifetimes at both cryogenic and room temperatures [1]. Despite this, the vast majority of research into photon-spin interfaces has notably focused on visible-wavelength colour centres in other materials. In this talk I will introduce a variety of silicon colour centres and discuss their properties in isotopically purified silicon-28. Some of these centres have zero-phonon optical
transitions in the telecommunications bands [2], some have long-lived spins in their ground states [3], and some, including the newly rediscovered T centre, have both [4].


Photon-number entanglement generated by sequential excitation of a two-level atom

Carlos Anton-Solanas, Stephen. C. Wein, Juan C. Loredo, Maria Maffei, Paul Hilaire, Aristide Lemaître, Loic Lanco, Olivier Krebs, Alexia Auffèves, Christoph Simon and Pascale Senellart

University of Oldenburg, Germany

During the spontaneous emission of light from an excited two-level atom, the atom briefly becomes entangled with the photonic field, producing the entangled state $\alpha |e,0> + \beta |g,1>$, where $e$ and $g$ are the ground and excited states of the atom, and 0 and 1 are the vacuum and single photon states [1].

We experimentally show that the spontaneous emission can be used to deliver on demand photon-number entanglement encoded in time. By exciting a charged quantum dot (an artificial two-level atom) with two sequential $\pi$ pulses, we generate a photon-number Bell state $\alpha |00> + \beta |11>$. We characterise the quantum properties of this state using time-resolved photon correlation measurements [2].

We theoretically show that applying longer sequences of $\pi$ pulses to a two-level atom can produce multipartite time-entangled states with properties linked to the Fibonacci sequence.

Our results show that spontaneous emission is a powerful entanglement resource and it can be further exploited to generate new quantum photonic states with applications in quantum technology.


Optical rectification and plasmon-enhanced photocurrent in nanocavity molecular junctions

Dean Kos

University of Cambridge, UK

Molecular junctions offer the opportunity for downscaling optoelectronic devices. Separating two electrodes with a single layer of molecules accesses the quantum tunnelling regime at low voltages (<1V), where tunnelling currents become highly sensitive to local nm-scale geometric features of the electrodes. These features generate asymmetries in the electrical response of the junction which combine with the incident oscillating optical fields to produce optical rectification and photocurrents. Maximising photocurrents requires accurate control of the overall junction geometry...
and a large confined optical field in the optimal location. Plasmonic nanostructures such as metallic nanoparticles are prime candidates for this application, because their size and shape dictate a consistent junction geometry while strongly enhancing the optical field from incident light. Here we demonstrate a robust molecular opto-electronic device geometry, where a metallic nanoparticle on a self-assembled molecular monolayer is sandwiched between planar bottom and semi-transparent top electrodes, to create molecular junctions with reproducible geometry and electrical response. The well-defined geometry enables predictable and intense plasmonic localisation which we show creates optical frequency voltages ~30mV in the molecular junction from 100μW incident light, generating photocurrent by optical rectification (>10μA/W) from only a few hundred molecules. Quantitative agreement is thus obtained between DC- and optical-frequency quantum-tunnelling currents. By measuring the degree of junction asymmetry for different molecular monolayers, we find that molecules with a large DC rectification ratio also boost zero-bias electrical asymmetry, making them good candidates for sensing and energy harvesting applications in combination with plasmonic nanomaterials.

**Performance-Optimized Components for Quantum Technologies via Additive Manufacturing**

Nathan Cooper

University of Nottingham, UK

Novel quantum technologies and devices place unprecedented demands on the performance of experimental components, while their widespread deployment beyond the laboratory necessitates increased robustness and fast affordable production. We show how the use of additive manufacturing, together with mathematical optimization techniques and innovative designs, allows the production of compact lightweight components with greatly enhanced performance. We use such components to produce a magneto-optical trap that captures approximately $2 \times 10^8$ rubidium atoms, employing for this purpose a compact and highly stable device for spectroscopy and optical power distribution, optimized neodymium magnet arrays for magnetic field generation, and a lightweight additively manufactured ultrahigh-vacuum chamber. We show how the use of additive manufacturing enables substantial weight reduction and stability enhancement, while also illustrating the transferability of our approach to experiments and devices across the quantum technology sector and beyond.
Floor 1

Poster A (S) Actively-Stabilised Variable-Asymmetry Mach-Zehnder Interferometer for QKD Device Characterisation

Sophie Albosh, Christopher Chunnilall and Timothy Spiller
University of York and National Physical Laboratory, UK

The secure operation of a QKD protocol requires that the hardware, i.e. the transmitter and receiver, be physically characterised to quantify the potential information leakage to an eavesdropper, thereby assessing the implementation security of the system [1]. Test procedures have been specified for characterising components of QKD systems [2] and there is currently activity within ISO/IEC and ETSI to develop test procedures for complete QKD modules [3-5]. Characterising the phase relationships between the pulses of the QKD signal is of particular interest, due to the prevalence of phase-encoding and phase-based security requirements in commercially-relevant QKD protocols. A measurement device has been constructed to characterise the phase properties of QKD modules, requiring the assessment of single-photon-level pulses.

The device is based on an asymmetric Mach-Zehnder interferometer that is stabilised using a free-running external-cavity diode laser. It can be used to measure the phase relationship between pulses emitted from QKD transmitters, or it can be used with a pulsed laser source to generate pulses with a well-defined phase relationship to test QKD receivers. The interferometer asymmetry can be adjusted on the submicron length scale to vary the pulse temporal separation and can be varied further on the much finer wavelength-scale to perform phase sweeps. The active stabilisation method allows the interferometer to be locked at any arbitrary phase setting. The device is designed for operation in the C-band and can be used to characterise devices in situ. Data demonstrating the performance of the system will be presented.

Poster B  A virtual laboratory for quantum coherence
Raul Barrachina, Tamara Guarda, Francisco Navarrete and Marcelo Ciappina
National Atomic Energy Commission, Argentina

From basic courses to the most advanced applications of quantum theory, it is common to only deal with pure and therefore fully coherent states. But this complacency fails when it is necessary to consider classical uncertainties in mixed states. This relative lack of practice has permeated a recent debate on the possibility of changing the coherence conditions in atomic collision experiments [1]. In this communication we will present recent theoretical developments, and their application to the description of current experimental results [2]. We will discuss the similarities and differences with the van Cittert-Zernike theory in Optics [3], and the effects produced by classical uncertainties in momentum (e.g., angular focusing) and space (e.g., collimation) [4,5]. We will also present a fully analytical model [6] that, unlike the usual techniques based on the numerical resolution of the time-dependent Schrödinger equation, allows an instantaneous analysis of the quantum coherence conditions of a particle beam. A corresponding web-based tool will be useful both for quantum courses and for research groups testing the degree of coherence for specific experimental set-ups.


Poster C Vortex rings and surfaces in the ionization of atoms by positron impact
Raul Barrachina¹, and Francisco Navarrete²
¹National Atomic Energy Commission, Argentina, ²University of Rostock, Germany

In 1993, a deep minimum was experimentally observed in the differential cross section of the (e,2e) process in helium [1]. A similar minimum was theoretically found by Brauner and Briggs [2] for the ionization of hydrogen by the impact of positrons. Two decades later, these minima were shown to be isolated zeroes, and recognized as quantum vortices (QVs) [3, 4, 5]. Because of their geometry on the phase space of the T-matrix element of the collision, they emerge as points in two dimensions, lines in three dimensions, and surfaces in four dimensions. In this communication, we uncover the morphology of QV rings and surfaces in positron-atom ionization collisions. We analyze the characteristics of the full four-dimensional vortex structure by a detailed calculation of several vortex rings in the final momentum space without kinematic constraints.

High resolution spectroscopy of molecules is a prime candidate to measure potential temporal changes in the proton-to-electron mass ratio, $\mu$ [1]. These potential changes can be detected by comparing vibrational or rotational transitions in molecules to optical atomic transitions.

In our experiment, a vibrational Raman transition in a nitrogen ion will be compared to a quadrupole transition in a calcium ion. The N2+ ion has systematic shifts better than the currently best optical atomic clocks. To perform precision spectroscopy, a single nitrogen ion will be co-trapped, in a linear Paul trap, with a 40Ca+ ion, which will act as a frequency reference and be used for the cooling and state detection of the nitrogen ion.

Prerequisite to this is the preparation of 14N2+ in a specific rovibronic state. Recently, a 2+1’ resonance-enhanced multiphoton ionisation (REMPI) scheme was developed, using the $a_1\Sigma^+ (\nu=6) \leftarrow X_1\Sigma^+ (\nu=0)$ band in 14N2 for the resonant excitation. This scheme demonstrated a fidelity of >99% for loading into the rovibronic ground state [2]. However, simulations show that the high amplitude and inhomogeneous electric fields of the ion trap broaden the ionisation threshold and prevent state-selective loading in many cases. Rapidly switching the trap off during loading can reduce the electric field and mitigate this to allow state selective loading of the ion trap [3].


Poster E (S) Polymer encapsulated organic nanocrystals for single photon emission

Dominika Bogusz, Ross Schofield, Rowan Hoggarth, Salahuddin Nur, Kyle Major and Alex Clark

Imperial College London, UK

Organic molecules can be excellent sources of indistinguishable photons thanks to high radiative yield, narrow linewidth, high photostability and simplicity of manufacturing. In particular, dibenzoterrylene (DBT) in anthracene (Ac) has shown great potential as a single photon emitter [1]. Its collection efficiency can be drastically improved through coupling to nanophotonic cavities. A molecule placed at the correct position will preferentially emit photons into a single spatial-spectral-polarisation mode and at a much faster rate than when outside the cavity. Unfortunately, the weak van der Waals bonding in aromatic crystals results in sublimation of the Ac unless it is protected with a polymer layer, which in turn limits the potential for direct integration into semiconductor nanophotonic devices.

Here we present a newly developed way to protect the crystal by embedding DBT-doped anthracene nanocrystals in polymethyl methacrylate (PMMA) nanocapsules [2]. The nanocapsules require no further protection after fabrication and are resistant to sublimation compared to unprotected anthracene. Having sputtered a high-index TiO2 layer on top of the nanocapsules we conclude that the nanocapsules not only provide a sufficient protection against ambient conditions...
but show potential to survive a wider range of fabrication processes. We will also present work towards deterministically fabricating circular Bragg grating cavities via electron-beam lithography around pre-selected DBT/Ac/PMMA systems, overcoming the limitation of precise positioning of molecules within nanocavities.


Poster F 3D-Microfabricated ion trap array for quantum applications

Nathanaël Bullier, Scott Thomas, Guido Wilpers and Alastair Sinclair

National Physical Laboratory, UK

Ion traps are widely used for quantum sensing and quantum computing applications because they provide natural and reliable qubit systems with long coherence times. 3D-microfabricated trap arrays such as the one developed at NPL offer the advantage of combining deep potentials with low motional heating rates of the ions. We trap $^{88}\text{Sr}^+$ ions and use the $5s^2S_{1/2}$ to $4d^2D_{5/2}$ optical quadrupole transition to define the qubit states. This transition is driven by a ultra-stable high-power Ti:sapphire laser at 674 nm. Here, we report on recent work towards the entanglement of two ions using the Mølmer-Sørensen scheme. By operating the trap with a Mathieu stability parameter $q = 0.15$, we laser-cooled a two-ion string which remains stored and crystallised for several days. We present Ramsey spectroscopy results for a single ion and discuss a few known experimental sources of decoherence such as magnetic field instability. The architecture of the microtrap device permits transport of ions through the array. For quantum computing applications, shuttling protocols are intended to make experiments simpler than having many-ion strings in a single segment. Calculations to achieve those transport routines and estimations of the subsequent heating rates are discussed.

Fig. 1: Six strontium $^{88}\text{Sr}^+$ ions.

Poster G Interference-contrast optical activity: a new technique for probing the chirality of anisotropic samples and more

Robert Cameron

University of Strathclyde, UK

Optical rotation, circular dichroism and other manifestations of optical activity are measured routinely for isotropic samples, serving as hallmarks of chirality in applications ranging from the
determination of sugar concentrations to the investigation of virus structures. In contrast, measurements of optical activity are seldom reported for anisotropic samples, the main reason being that anisotropic samples usually exhibit linear birefringence, linear dichroism and other effects that convolve with and partially suppress optical activity.

In this poster we describe interference-contrast optical activity (ICOA): a new technique for probing the chirality of anisotropic samples and more [1].

[1] R P Cameron, U Vogl & N Trautmann 2020 Royal Society Open Science 7 192201

**Poster H (S) Transient trains of optical solitons and quasisimultons in atomic vapours**

Benjamin Cartwright, Steven Wrathmall and Robert Potvliege

Durham University, UK

We study the transient dynamics of an atomic vapour driven by a strong, continuous wave (cw) field during and after the field is being switched on. In particular, we consider the case of a two-colour field propagating through a medium of thermal Rb atoms and resonant on both the D1 and D2 transitions. We solve the Maxwell-Bloch equations, taking homogeneous broadening, Doppler broadening and the full hyperfine structure of the atoms into account. We predict the formation of trains of quasisimultons, i.e., copropagating soliton-like pulses on each transition similar to the isolated self-induced transparency quasisimultons found in pulsed excitation [T P Ogden et al, Phys. Rev. Lett. 123, 243604 (2019)]. The effect makes it possible for a weak field to penetrate much further into a vapour than in the absence of the other field. We also study this dynamics in few-state models and for one-colour fields. This work extends previous investigations [e.g., M D Crisp, Phys. Rev. A 5, 1365 (1972); B Horovitz and N Rosenberg, Phys. Rev. A 26, 2799 (1982)]. It extends them to the case of dampened systems, in which the pulse trains exist only transiently during and after the field is switched on, and to two-colour trains of co-propagating pulses.

**Poster I (S) Many-body theory of positron binding to halogenated hydrocarbons**

Jack Cassidy, Jaroslav Hofierka, Brian Cunningham, Charlie Rawlins, Charles Patterson and Dermot Green

1 Queen’s University Belfast, UK, 2 Trinity College Dublin, Ireland

It is now established that positrons can bind to polyatomic molecules. Binding energies have been measured for around 90 molecules using trap-based positron beams[1,2,3]. We have developed a powerful *ab initio* method to describe positron interactions with molecules using diagrammatic many-body theory, which has elucidated the mechanisms of positron binding and the role of correlations[4]. Recently, model calculations and measurements of positron binding to chlorinated hydrocarbons have been performed by Swann *et al*[5]. Their model calculations are in excellent agreement with experiment for many of the molecules they consider. However, their model assumes that the positron-molecule interactions are isotropic, and thus fails to find agreement with experiment for planar molecules where the interactions are anisotropic. Here, we use our approach to calculate positron binding energies for halogenated molecules (focussing on planars). We delineate the effect of positron-molecule correlations and the anisotropic, non-local nature of the interactions, and study the effects of fluorination and chlorination. Our results will be presented at the conference, and where possible, will be compared
with recent measurements[5], the isotropic local model-potential approach of Swann et al.[5], and
the density-functional-theory based model-potential approach of Suzuki et al[6].

[4]- J Hofierka et al., arXiv:2105.06959

Floor 2

Poster A Plans to cool polar molecules to quantum degeneracy

Arijit Chakraborty, Jing Wu, Noah J Fitch, Ben E Sauer and Michael R Tarbutt
Imperial College London, UK

There has been great progress in laser cooling of molecules to low temperatures, but the phase-
space densities reached are still far from quantum degeneracy. We are building a new apparatus
with the aim of producing Bose-Einstein condensates of calcium monofluoride (CaF) molecules.
Pulses of molecules from a cryogenic buffer gas source will be magnetically focussed into a region
of two-dimensional transverse laser cooling, producing an intense, highly collimated beam. The
molecules will be slowed down using frequency-chirped radiation-pressure slowing and then
captured in a magneto-optical trap. Our simulations suggest that 10^7 molecules could be
trapped. Using deep laser cooling methods, we will cool the molecules into a crossed beam optical
dipole trap. The trap will be formed inside an 80 K radiation shield to minimize vibrational excitation
by blackbody radiation, extending the trap lifetime to about 60 s. An electric field of 22 kV/cm will
be applied to the trapped molecules. At this field, a repulsive shield is formed which hugely
suppresses inelastic and reactive collisions between the molecules while enhancing the rate of
elastic collisions. In this environment, we expect forced evaporative cooling to proceed very rapidly.
Our simulations suggest that quantum degeneracy can be reached in about 1 s. This strongly
dipolar quantum gas will be a highly exotic form of quantum matter that is ideal for studying the
physics of strongly interacting many-body quantum systems.

Poster B THz electrometry with Rydberg atoms and all IR lasers

Shuying Chen, Lucy A. Downes, Dominic Reed, Andrew R. MacKellar, Nourah F. Almuhawish,
Matthew J. Jamieson, Charles S. Adams and Kevin J. Weatherill
Durham University, UK

Rydberg electromagnetically induced transparency (EIT) and Autler-Townes (AT) splitting in an
atomic vapor cell can be used as novel methods for electric-magnetic field detection. Here we make
use of 3 infrared lasers to realize a Rydberg EIT system in a thermal rubidium vapor cell. With the AT
splitting induced by the THz radiation, we observe a linear trend between THz field amplitude of
1.06 THz and the frequency splitting of the absorption dips, and EIT transmission peaks. Due to the
well-known atomic transition dipole moment of the Rydberg state, the THz electric field can be calibrated from the frequency splitting, making this Rydberg atomic measurement system a practical tool for THz field detection with the advantage of low cost and simple operation.

**Poster C Photon indistinguishability measurements under pulsed and continuous excitation**

Alex Clark¹, Ross Schofield¹, Chloe Clear², Rowan Hoggarth¹, Kyle Major¹ and Dara McCutcheon²

¹Imperial College, UK, ²University of Bristol, UK

The indistinguishability of successively generated photons from a single quantum emitter is most commonly measured using two-photon interference at a beam splitter. Whilst for sources excited in the pulsed regime the measured bunching of photons reflects the full temporal wavepacket indistinguishability of the emitted photons, for continuous wave (cw) excitation the inevitable dependence on detector timing resolution and driving strength obscures the underlying photon interference process. Here I will present a method to extract the photon indistinguishability from cw measurements by considering the relevant correlation functions [1]. I will show the equivalence of pulsed and cw methods, and experimentally verify this through comparison of cw and pulsed excitation of an archetypal source of photons, a single molecule [2]. This method can be further generalised to other situations including multiple emitters, photons of differing frequency, temporal and spectral jitter, and cavity-enhanced photon sources. Finally, it opens a route to using cw lasers to simplify quantum technologies such as quantum simulation with photons.


**Poster D (S) Measuring higher order correlations of light**

Rachel Clark¹, John Hadden¹, Philip Dolan², Alastair Sinclair² and Anthony Bennett¹

¹Cardiff University, UK, ²National Physical Laboratory, UK

Quantum light sources are an enabling technology for a vast array of applications, including next generation computing and cryptography, imaging, sensing and light metrology. Particularly for quantum computing, they are a critical “building block” of its development, and efficient, easy-to-manufacture sources are necessary to ensure commercial access and widespread use in societal infrastructure. These sources can exist in a multitude of different physical systems: from nitrogen vacancy centres in diamond, to semiconductor quantum dots, to 2D materials.

A common way to make a like-for-like comparison of the source behaviour, regardless of its physical system, is to measure the second-order correlation-function of light, more commonly known as the autocorrelation function. This function can be determined from “time-stamped” data files recording the arrival time of every photon on each detector which, in principle, includes information on every detection-detection event. The correlation function can also be generalised to the Nth order, for streams of photon arrival times recorded on N detectors. However, post-
processing to determine the correlation function increases the complexity of the calculation to at least a power of N, taking considerable computing resources for modest datasets.

I will discuss my work on the development of a code that calculates the function for timestamped data files, and the benefits of this method. I will also introduce the practical complexities involved in measuring and calculating this function, with an overview of the physical significance it can provide. We have used this tool to study the photon statistics of thermal light for N=2,3.

Poster E (S) Localisation determines the optimal noise rate for quantum transport
Alexandre Coates¹, Erik Gauger¹ and Brendon Lovett²
¹Heriot-Watt University, UK, ²St. Andrews University, UK

Environmental noise plays a key role in determining the efficiency of transport in quantum systems. However, disorder and localisation alter the impact noise has on energy transport. We performed a systematic study of eigenstate localisation and the optimal decoherence rate in 1D chains, and found a simple power law relating the two. This relationship captures the varying contribution of size-dependent and size-independent effects as localisation changes, providing a unified physical picture for relating previously studied forms of noise-assisted quantum transport. In addition to quantifying this relationship we tested it on a range of system sizes and environmental noise models, showing the underlying behaviour is robust for a large range of physical circumstances, only breaking down towards the lower temperature limit.

Poster F (S) Electric and magnetic field control for a high precision measurement of the electron electric dipole moment
Freddie Collings, Rhys Jenkins, Noah Fitch, Ben Sauer and Michael Tarbutt
Imperial College London, UK

Our current understanding of the universe, through the standard model of particle physics (SM), does not contain enough violation of fundamental symmetries to explain several outstanding mysteries in physics. One such mystery is the observed matter-antimatter imbalance, which requires new physics that breaks the combined symmetry of charge conjugation and parity (CP) or, equivalently, time-reversal (T). One way to search for such physics is to measure the electric dipole moment (EDM) of a fundamental particle like an electron, which would constitute a direct demonstration of physics beyond the SM.

We are developing a new experiment at Imperial that seeks to measure the electron EDM (eEDM) using an ultracold beam of YbF molecules. The measurement is made by preparing the molecules in an EDM-sensitive state whereby the spin of its valence electron can precess around the axis of combined static electric and magnetic fields. Crucially, control over the static fields in the spin-precession region is paramount to improve the precision of the measurement. Therefore, we have designed and are building a new beamline with extremely low magnetic noise, including active magnetic field cancellation, a 4-layer passive magnetic shield, and a vacuum system composed only of materials with low Johnson noise. The relevant theoretical magnetic shielding factors have been calculated and the geometry of the shield has been optimised to produce the maximal
shielding factors for fields transverse to the shield. This will aid in providing the sensitivity required for the next generation YbF experiment to measure the eEDM with incredible precision.

Poster G Measuring energy fluctuations in out-of-equilibrium many-body quantum systems

Irene D’Amico¹, Marcela Herrera², John P. S. Peterson³ and Roberto M. Serra⁴

¹University of York, UK, ²Universidad Autonoma de Occidente, Colombia, ³University of Waterloo, Canada, ⁴Universidade Federal do ABC, Portugal

Energy fluctuations play a key role on the (strongly) out-of-equilibrium thermodynamics of quantum systems. They are inherently related to quantum fluctuation relations, which are valid for dynamics arbitrarily far from equilibrium, and which embrace both thermal and quantum energy fluctuations. However, the experimental verification of these relations in interacting quantum systems has been elusive, due to the difficulties of applying the methods that were proposed to systems with many-body interactions. Here we propose and experimentally implement a new approach to access energy fluctuations and the work distribution in a many-body quantum system [1]. We show how to obtain the related bi-stochastic matrix of transition probabilities by means of simple local measurements at the end of a protocol that drives a many-body quantum system out-of-equilibrium. As a proof-of-principle, we have tested our method in an Ising-like system composed by two interacting spin-1/2. By obtaining the bi-stochastic transition probability matrix for the system dynamics at different temperatures, we are able to verify the detailed quantum fluctuation relation for an interacting system driven out-of-equilibrium. Our method can be applied in a diversity of physical setups to investigate energy fluctuations and thermodynamical quantities such as, work, heat, and entropy production in non-equilibrium interacting quantum systems.

Poster H Quantum device design via efficient evolutionary algorithm
Irene D’Amico1, Luke Mortimer1, Marta P. Estarellas2 and Timothy P. Spiller1
1University of York, UK, 2National Institute of Informatics, Japan

As quantum devices improve in terms of number of qubits and connectivity, the power of quantum computation gets an exponential boost. However, this comes with the challenge that an increased number of degrees of freedom brings to the tuning of parameters when engineering quantum devices: determining good or even adequate parameter configurations for a given application, or for device calibration, becomes a cumbersome task. To overcome this, we present [1] an evolutionary algorithm which allows for the automatic tuning of the parameters of any arrangement of coupled qubits, to perform a given task with high fidelity. The algorithm’s use is exemplified with the generation of schemes for the distribution of quantum states and the design of multi-qubit gates. The algorithm is demonstrated to converge very rapidly, with convergence occurring approximately 5000 times faster than the equivalent randomized search for a 10-parameter network. It also scales well with an increasing number of qubits, and yields unforeseeable designs of quantum devices that perform their required tasks with excellent fidelities. Given these promising results, practical scalability and application versatility, the approach has the potential to become a powerful technique to aid the design and calibration of NISQ devices.


Poster I Near-maximal Polarisation Entanglement for Device-Independent Quantum Key Distribution at 2.1 μm
Adetunmise Dada1, Jedrzej Kaniewski2, Corin Gawith3, Martin Lavery1, Robert H. Hadfield1, Daniele Faccio1 and Matteo Clerici1
1University of Glasgow, UK, 2University of Warsaw, Poland, 3Covesion Ltd, UK

The 2- to 2.5-μm spectral region is rapidly becoming a highly promising optical telecommunications band with significant potential advantages over the traditional telecom C-band (1550 nm), making it crucial to develop and investigate quantum light sources and measurement capabilities in this waveband. For example, the 2-μm band has been demonstrated to have minimal losses in the hollow-core photonic band gap fibre (HCF), which is an emerging transmission-fibre alternative due to its ultra-low nonlinearity and providing the lowest available latency. In addition, although the 2-μm band enjoys similar atmospheric transparency as the telecom C-band, the solar background is up to 3 times lower, making it especially promising for free-space optical communications during daytime. Now, superconducting photon counting detectors and entangled photon sources are becoming available, opening this spectral window for quantum optics and communications. To be useful for device independent (DI) quantum key distribution (QKD), an entangled resource state must demonstrate a combination of low quantum bit error rate (QBER) and sufficiently large Bell inequality violation to yield a positive (i.e., greater-than-zero) secure key rate. Here, we demonstrate quantum state tomography of two-photon states in the 2-2.5-μm band and show near-maximal entanglement. Most importantly, we give the first experimental proof of the capability for a positive secure key rate in this infrared region in a DI QKD setting.
Floor 3

Poster A Quantum many-body scars in tilted Fermi-Hubbard chains
Jean-Yves Desaules, Ana Hudomal, Christopher Turner and Zlatko Papić
University of Leeds, UK

Motivated by recent observations of ergodicity breaking due to Hilbert space fragmentation in 1D Fermi-Hubbard chains with a tilted potential [Scherg et al., arXiv:2010.12965], we show that the same system also hosts quantum many-body scars in a regime $U=\Delta \gg J$ at electronic filling factor $\nu=1$. We numerically demonstrate that the scaring phenomenology in this model is similar to other known realisations such as Rydberg atom chains, including persistent dynamical revivals and ergodicity-breaking many-body eigenstates. At the same time, we show that the mechanism of scarring in the Fermi-Hubbard model is different from other examples in the literature: the scars originate from a subgraph, representing a free spin-1 paramagnet, which is weakly connected to the rest of the Hamiltonian's adjacency graph. Our work demonstrates that correlated fermions in tilted optical lattices provide a platform for understanding the interplay of many-body scarring and other forms of ergodicity breaking, such as localisation and Hilbert space fragmentation.

Poster B (S) Towards ultracold atoms in a kagome optical lattice with single-site-resolved imaging
Luca Donini, Max Melchner Von Dydiowa, Daniel Reed, Sompob Shanokprasith, Xintong Su, Mehedi Hasan, Tiffany Harte and Ulrich Schneider
University of Cambridge, UK

We are building a quantum simulation experiment to study ultracold atoms in an optical kagome lattice [1]. This lattice displays strong geometric frustration, which results in a flat band. For fermions, this makes the kagome antiferromagnet a candidate for studying the quantum spin liquid phase. For bosons, frustration has been predicted to e.g. give rise to interaction-driven condensation and a supersolid state [2]. Since the flat band is the highest-lying subband, we will access it by creating a negative temperature state [3]. Our experiment will be capable of cooling and confining bosonic $^{87}\text{Rb}$ and $^{39}\text{K}$, and fermionic $^{40}\text{K}$, thus enabling studies of correlated physics in bosons, fermions, and mixtures. In addition to time-of-flight imaging, the apparatus will include a quantum gas microscope (QGM) with single-site resolution, which will allow access to local observables.

Poster C Pulsed Generation of Symmetry-Protected Long-Range Entanglement

Shovan Dutta\textsuperscript{1}, Anton Buyskik\textsuperscript{2}, Andrew Daley\textsuperscript{2} and Erich Mueller\textsuperscript{3}

\textsuperscript{1}University of Cambridge, UK, \textsuperscript{2}University of Strathclyde, UK, \textsuperscript{3}Cornell University, UK

I will demonstrate a new versatile and practical framework for applying matrix product state techniques to continuous quantum systems. Our method uses a spatial partitioning to map a continuous many-body Hamiltonian onto a discrete sum over segments. By combining this mapping with existing DMRG routines, one can accurately obtain the ground-state wave function, spatial correlations, and entanglement directly in the continuum, with fast convergence not achieved by a grid-based discretisation. I will illustrate this technique for a superfluid-insulator transition of strongly-interacting bosons in a variable external potential. I will outline how one can apply this framework to a wide variety of experimentally relevant problems.

Poster E (S) The Free-Expansion of Toroidal and Hollow-Shell Wave-Packets in Three-Dimensions

Andrew Elbourn and Barry Garraway

University of Sussex, UK

We propose a method for obtaining analytical expressions for the expansion of wave-packets in three dimensions utilising a distribution of individual Gaussian wave-packets. Applying this method to toroidal and hollow-shell geometries, we demonstrate that our methodology produces results that have a high fidelity when compared to numerical simulations of the same system utilising a split-step Fourier method. In addition, we see an emergence of interference fringes whose locations and visibilities we can predict through analysis of our expressions. In these examples, the interference fringes are of experimental interest since they are highly dependent on the system’s initial state and can be realised with ultra-cold atoms. Additionally, we note the emergence of an area of high density, located in the centre, in both geometries. In the case of the torus, this central fringe forms a high-density column. The general approach may have applicability to other topologies and geometries.
Poster F Towards a compact cold-atom $\text{lin\perp lin}$ CPT clock
Rachel Elvin, Michael W. Wright, Ben Lewis, Paul F. Griffin, Aidan S. Arnold and Erling Riis
University of Strathclyde, UK

We present some recent progress of a microwave atomic clock that is based on a Rb grating magneto-optical trap (GMOT) and the coherent population trapping (CPT) technique. Around $10^7$ atoms, provided by the GMOT, are probed for the hyperfine ground state splitting frequency using Ramsey-CPT in a $\text{lin\perp lin}$ polarisation scheme. During this conference, we will discuss our recent progress in characterising the frequency sensitivity of the CPT-GMOT apparatus. We use a Ramsey-CPT scheme with a free evolution time of 10 ms in order to observe fringes with a linewidth of 50 Hz. The central fringe provide the means for sensitive frequency measurements of systematic effects, such as that caused by the ambient magnetic field or induced velocity of the atoms. The former allows us to observe the second order Zeeman shift experience by the clock state and in the latter, we can measure the Doppler shift that arises during the dark time of the Ramsey sequence. As we work towards developing a compact device, these measurements provide a good foundation for characterising probe-induced frequency shifts.

Poster G (S) The controlled SWAP test for determining quantum entanglement
Steph Foulds1, Viv Kendon1 and Tim Spiller2
1Durham University, UK, 2University of York, UK

Quantum entanglement is essential to the development of quantum computation, communications, and technology. The controlled SWAP (c-SWAP) test, widely used for state comparison, can be adapted to an efficient and useful test for entanglement of a pure state (US Patent 7,559,101 B2, 2008).

Quantum state tomography (QST) as a method for evidencing entanglement is inefficient for large systems. When using the c-SWAP test, the number of copies of the test state required to evidence entanglement decreases for larger systems, to four on average for many ($n \geq 8$) qubits for maximally entangled states. For non-maximally entangled states, the average number of copies required to detect entanglement increases with decreasing entanglement. For $n \geq 5$ test states, there is a very large entanglement regime for which the c-SWAP test requires on average fewer copies than QST (Foulds et al., 2021).

We also propose a multipartite measure of entanglement based on concurrence that relates the test’s results to the degree of entanglement of the $n$-qubit test state, which has since been classes as a specific case of Concentratable Entanglements (arXiv:2104.06923).

The suitability of the entanglement SWAP test for experimental implementation is highlighted by the fact that various typical state errors all give second order errors in the final probabilities for any number of qubits.

We are looking to implement the test experimentally with Rydberg state mediated gates with the technique realised in Levine et al., 2019. To this end we are investigating the effect of gate errors on the c-SWAP test’s results.
Poster H Using the oscillator model to describe 2D materials. Application to graphene

Juana Gervasoni
CNEA-CONICET, Argentina

We model the 2D materials as a monolayer of atoms represented by harmonic oscillators [1], with isotropic and anisotropic electronic vibration modes. We obtain the energy loss of relativistic charged particles interacting with it; consider a wide range of incident energies for different trajectories of the particle. In particular, we apply the model to describe the case of electrons interacting with graphene.

We obtain several useful analytical expressions for the energy loss considering isotropic and anisotropic in-plane oscillators, for parallel and perpendicular trajectories of the particle. The results shown for stopping power and energy loss are analyzed for generic materials by the use of adequate normalization factors, absorbing the dependencies on the specific properties of the material, namely the oscillator’s areal density $\eta$ and their resonant frequency $\omega$ [2].

We notice that in an anisotropic 2D-oscillators system, the energy loss due to single oscillator presents a reduction with respect to the isotropic case, especially in the parallel trajectory. We ascribe this effect to the lower availability of oscillation modes, and hence to a reduction of the interaction channels.

Finally, we remark that the present model stands out for its generality and provides a direct evaluation of the energy loss processes in a generic 2D material.


Day 2 - Wednesday 1 September 2021
Session 5 - Quantum optics

(Invited) Quantum Imaging with photon pairs

Daniele Faccio, University of Glasgow, UK

Our research is largely driven by the quest for imaging modalities that are enabled by quantum properties of light and that cannot be achieved classically. As seen in the past for example with ghost imaging, this quest can sometimes uncover imaging modalities that can be replicated classically but are nevertheless still very useful. Other times, this quest does indeed uncover new imaging approaches that could potentially lead to innovations in healthcare and bio-imaging. We will discuss two cases, both based on the same underlying concept of characterising two-photon images as the result of a 2D projection of a 4D joint probability distribution. This approach allows for example to spatially resolve on a camera a Bell inequality test. This can then be generalised to phase-imaging based on a quantum holographic reconstruction of the `entanglement phase’ that encodes the object spatial phase information. We will then show a second quantum imaging example in which we adapt a Hong-Ou-Mandel interferometer, typically used for sensing but now used for wide-field microscopy on a SPAD camera. We also show super-resolution imaging that can
be achieved by both raster scanning the camera or by careful choice of how the 4D joint probability distribution is projected onto the final 2D image.

Gouy phase-matched angular and radial mode conversion in four-wave mixing
Aidan Arnold¹, Andrew Daffurn¹, Rachel Offer², Paul Griffin¹, Erling Riis¹ and Sonja Franke-Arnold³
¹University of Strathclyde, UK, ²University of Adelaide, Australia, ³University of Glasgow, UK

Studying the conversion between transverse light modes via four-wave mixing in a heated rubidium vapor, we demonstrate and explain a transfer between azimuthal and radial mode numbers. They relate to orthogonal modal dimensions, which one would not normally expect to interact. While angular momentum conservation in this nonlinear process dictates the selection rules for the angular mode number, the role of the radial mode number is more esoteric. We demonstrate systematically that the Gouy phase is the key to understanding this conversion, leading to strikingly different conversion behavior in the thick- and thin-medium regimes. Our experimental investigation of the transition between these regimes bridges the gap between previous experiments in atomic thick media and work in nonlinear crystals. Our work sets a clear starting point to explore the thick-medium regime, allowing efficient radial-to-azimuthal and radial-to-radial mode conversion.

Balancing gains and losses in nonlinear interferometers

Jefferson Florez, Nathan R. Gemmell, Emma Pearce, Olaf Czerwinski, Jiaye Ding, C. Phillips, Rupert F. M. Oulton and Alexander Clark

Imperial College London, UK

Nonlinear interferometry has been gaining attention since the publication of 'Quantum Imaging with undetected photons' by Lemos et al [1]. The ability to sense losses and phase shifts at wavelengths for which detection is difficult is an enticing prospect for those in the imaging community. However, a full characterization of their behaviour under different regimes of pumping and loss remains unproven. Theoretical models [2] suggest that high visibility can still be retained in the presence of significant signal loss if the interferometer can be 'unbalanced', i.e. the two nonlinear optical amplifiers (NLAs) have different gains to compensate for the losses in one arm. Here we present an experimental proof of the theoretical description of these loss and gain regimes within nonlinear interferometers, fully mapping the loss and gain balance parameter space. Our interferometer is a ‘Michelson’ style, with all fields double passing a single PPLN crystal. The two pump fields are derived from a single laser (1064nm) split by a polarizing beamsplitter, allowing full control of the gain of the two non-linear processes. Arbitrary phase shifts and/or losses can be independently introduced into both the signal (1550nm) and idler (3400nm) fields produced in the first pass of the NLA. We find that indeed losses in the signal path between the nonlinear amplifiers can be compensated for by adjusting the pump power to the second NLA, matching well with the theory.


Session 6 - Cold atoms

(Invited) Open quantum systems in finite baths: what is different?

Anna Sanpera

Universitat Autonoma Barcelona, Spain

The miniaturization of quantum experiments towards the microscopic scale often concerns quantum systems interacting with finite baths or environments. Such situations demands a novel description of open quantum systems, in which the effects of the system on the environment and its back-action on the system cannot anymore be ignored. I will discuss a route to treat open quantum systems in finite environments and the physics encountered in such cases.

Multimode Collective Scattering of Light Possessing Orbital Angular Momentum

Gordon Robb¹, David McLellan¹, Nicola Piovella² and Angel Tarramera Gisbert²

¹University of Strathclyde, UK, ²Universita degli Studi di Milano, Italy

Rayleigh scattering of light by atoms involves transfer of linear momentum. When the atoms are sufficiently cold and dense and the incident light (pump) is sufficiently intense, the scattering process becomes collective in nature due to spatial bunching of the atoms. This collective scattering, also
termed “collective atomic recoil lasing” (CARL) [1] was observed in experiments involving cold atoms enclosed in a ring cavity [2], which are well described by “mean-field” models where the scattered field consists of a single spatial mode defined by the cavity axis. Recently, a multi-mode model of CARL in free space was developed [3].

A mean-field/single-mode model of collective scattering by cold atoms where the pump has linear and orbital angular momentum (OAM) was developed in [4]. Here we extend this to describe multi-mode collective scattering of pump light possessing OAM by cold atoms in free space.

For an atomic cloud with annular geometry (Fig. 1), the multi-mode model predicts that an initially uniform atomic distribution is unstable, resulting in collective scattering involving spontaneous rotation and bunching of the atoms.

Figure 1: Schematic diagram of scattering by an annular atomic cloud

For an atomic cloud with annular geometry (Fig. 1), the multi-mode model predicts that an initially uniform atomic distribution is unstable, resulting in collective scattering involving spontaneous rotation and bunching of the atoms.


Two dimensional supersolids induced by light mediated coupling

J G M Walker, G R M Robb, G.-L. Oppo and T Ackemann

University of Strathclyde, UK

Recent years have seen considerable advances in creating supersolids in dipolar gases in 1D [1] and recently 2D [2] and in crossed cavities (quasi-1D [3]). An alternative approach using light mediated coupling relies on a system with a single distinguished pump axis [4]. The scheme utilizes a BEC driven by a detuned broad-area laser beam. The transmitted beam is feed back into the medium by a retroreflecting plane mirror behind the cloud.
For excitation of an infinite 2D BEC with a plane wave, hexagonal patterns form in the BEC density as well as the optical intensity after a transient. For red detuning, atoms accumulate in intensity maxima (Fig. 1). For blue detuning, the light organizes in a honeycomb pattern and atoms accumulate in the voids forming a hexagonal pattern. For both detunings, the structures are slightly disordered and remain dynamic on long time scales, i.e. the atomic spots oscillate slightly around their average position in an irregular fashion. We attribute this to the fact that the system cannot shed energy to arrive in the ground state as the model is conservative.

The simulations indicate a promising path for a 2D supersolid using existing BEC technology.


Figure 1: Snapshots of asymptotic states for BEC density (left) and optical intensity (right).

Robust storage qubits in ultracold RbCs molecules

Philip Gregory, Jacob Blackmore, Sarah Bromley, Jeremy Hutson and Simon Comish
Durham University, UK

Quantum states with long-lived coherence are essential for quantum computation, simulation and metrology. The nuclear spin states of ultracold molecules prepared in the singlet rovibrational ground state are an excellent candidate for encoding and storing quantum information. However, it is important to understand all sources of decoherence for these qubits, and then eliminate them, in order to reach the longest possible coherence times. Here, we fully characterise the dominant mechanisms for decoherence of a storage qubit in an optically trapped ultracold gas of RbCs molecules using high-resolution Ramsey spectroscopy. Guided by a detailed understanding of the hyperfine structure of the molecule, we tune the magnetic field to where a pair of hyperfine states have the same magnetic moment. These states form a qubit, which is insensitive to variations in magnetic field. Our experiments reveal a subtle differential tensor light shift between the states, caused by weak mixing of rotational states. We demonstrate how this light shift can be eliminated by setting the angle between the linearly polarised trap light and the applied magnetic field to a
magic angle of $\text{arccos}(1/\sqrt{3}) \approx 55^\circ$. This leads to a coherence time exceeding 5.6 seconds at the 95% confidence level.

Session 7 - Quantum photonics

(Plenary) The quest of quantum advantage with an integrated photonics platform
Fabio Sciarrino
Sapienza Università di Roma, Italy

Boson sampling is a computational problem that has been proposed as a candidate to obtain an unequivocal quantum computational advantage. The problem consists in sampling from the output distribution of indistinguishable bosons in a linear interferometer. There is strong evidence that such an experiment is hard to classically simulate, but it is naturally solved by dedicated integrated photonic quantum hardware, comprising single photons, linear evolution, and photodetection. This prospect has stimulated much effort resulting in the experimental implementation of progressively larger devices. We will review recent advances in photonic boson sampling, describing both the technological improvements achieved and the future challenges. We will discuss recent proposals and implementations of variants of the original problem.

A 12-mode Universal Photonic Processor for Quantum Information Processing
Jelmer Renema
University of Twente, Netherlands

Recently, a quantum advantage over classical computation has been claimed using photons [1]. To control photonic quantum computations, large-scale quantum processors are needed [2,3]. To realize scalable and robust photonic quantum processors, integrated photonics is a key technology. Here, we present a universal 12-mode quantum photonics processor which is the largest of its kind to date, based on silicon nitride waveguides [4]. The presented quantum photonic processor is fully reconfigurable by using a matrix of 156 thermally tunable Mach-Zehnder interferometers.

Our processor achieves a transformation fidelity of 98%, and optical losses of 2.5 dB. To validate the functionality of the processor for quantum optical experiments, we characterized the Hong-Ou-Mandel interference of every single MZI of our processor.

Coupling A Single Molecule To An Interrupted Nanophotonic Waveguide

Ross Schofield¹, Sebastien Boissier, Lin Jin², Anna Ovvyan², Salahuddin Nur¹, Frank H. L. Koppens³, Costanza Toninelli⁴, Wolfram H. P. Pernice², Kyle D. Major¹, E. A. Hinds¹ and Alex S. Clark¹

¹Imperial College London, UK, ²Universitat Münster, Germany, ³ICFO, Spain, ⁴LENS

Single organic molecules are promising single photon sources [1]. They emit photons with high efficiency and at favourable wavelengths for coupling to other systems, however the generated photons are difficult to efficiently collect. There is a large amount of work on coupling organic molecules to nanophotonic structures to enhance the collection. Evanescent coupling to nanophotonic [2] and hybrid plasmonic [3] waveguides has shown promise but has limitations, as the close proximity of the molecules to the waveguide can cause instability. Here I present our recent work on coupling organic molecules to interrupted waveguides [4].

A silicon nitride waveguide with a 300 nm interruption was patterned using electron beam lithography. A polymer layer was then patterned in the desired capillary shape and covered with SiO2. We heated the device to 400°C to remove the polymer, leaving open channels which intersected the nanophotonic waveguides which were then filled with a molten mixture of dibenzoterrylene (DBT) molecules in an anthracene host. As this structure cannot be decomposed into a set of well-defined optical modes due to the gap, we developed a generalized theoretical framework to calculate the coupling efficiency using extinction spectroscopy. We found a coupling efficiency of 9(2)% and are working to improve this using periodic air holes in the waveguide to make a photonic crystal nanobeam cavity.


Session 8 - Cold atoms
(Plenary) Catching, interfering, and entangling single bosonic atoms

Cindy Regal
JILA, USA

I will discuss perspectives on experiments that seek to build interesting quantum states atom by atom with neutral particles. This frontier aims to control single atoms, and even molecules, by individual catching and manipulation, often in tiny focused laser beams referred to as “optical tweezers”. These particles can then be tailored to interact with each other controllably over short or long range scales. In my research group, we have carried out experiments that catch bosonic atom nearly deterministically, place them in their motional ground state, and look at Hong-Ou-Mandel interference of the bosonic atoms and spin entanglement. I will examine how access to microscale traps and single-particle imaging is providing us with new windows on laser cooling and ultracold collisions.
Collisions Between Ultracold Molecules and Atoms in a Magnetic Trap

Sarunas Jurgilas\textsuperscript{1}, Arijit Chakraborty\textsuperscript{1}, Caleb Rich\textsuperscript{1}, Luke Caldwell\textsuperscript{1}, Hannah Williams\textsuperscript{1}, Noah Fitch\textsuperscript{1}, Ben Sauer\textsuperscript{1}, Matthew Frye\textsuperscript{2}, Jeremy Hutson\textsuperscript{2} and Michael Tarbutt\textsuperscript{1}

\textsuperscript{1}Imperial College London, UK, \textsuperscript{2}Durham University, UK

Recent work has demonstrated direct laser cooling of diatomic molecules to temperatures of around 5 μK. A promising route to increase the phase-space density is sympathetic cooling with evaporatively cooled atoms. This requires a favourable ratio of elastic to inelastic collisions rates.

We demonstrate a dual species magneto-optical trap of CaF molecules and Rb atoms. After a stage of sub-Doppler cooling and quantum state preparation both species are transferred into a magnetic quadrupole trap. When the molecules are prepared in the first rotationally-excited state, we observe rapid loss due to rotation-changing collisions with the atoms. By contrast, when the molecules are in the ground rotational state we see no inelastic loss. Comparing these measurements to the results of a single-channel loss model based on quantum defect theory, we find a short-range loss parameter close to unity for rotationally excited molecules, but below 0.04 for molecules in the rotational ground state. These results are promising for the prospects of sympathetic cooling of molecules using ultracold atoms.

Quantum thermodynamics with ultracold atoms

Rahul Sawant, Jorge Muñoz, Xi Wang, Thomas Hewitt, Anna Maffei, Anna Kowalczyk and Giovanni Barontini

University of Birmingham, UK

Understanding non-equilibrium thermodynamics at the quantum level is one of the grand challenges in physics. In our experiment, we realized a method to produce non-equilibrium Bose-Einstein condensates above the critical temperature. To do this, we immerse an evaporating ultracold Bose gas of Rb in a cloud of K atoms with a substantially higher temperature. This provides a controlled source of dissipation that allows us to produce supercritical Bose-Einstein condensates. Further, our experimental system is geared towards the implementation of heat engines in the quantum regime. We will discuss how we plan to realize these engines in our experiment. We will report on the experimental progress we have made on the trapping of a single \(^{41}\)K atom in contact with a bath of ultracold \(^{87}\)Rb atoms. The thermalization of a single atom with the bath will also be discussed.
Poster session 2
Day 2 - 1 September- 6:00 - 7:30pm

Please note that the posters that have been marked with (S) indicates student work that will be judged for the Ian Gibson Poster Prize.

Floor 1

Poster A (S) Wavefunctions can Simultaneously Represent Knowledge and Reality
Jonte Hance, John Rarity and James Ladyman
University of Bristol, UK

In discussion of the interpretation of quantum mechanics the terms `ontic' and `epistemic' are often used in the standard senses of `pertaining to reality' and `pertaining to knowledge' respectively. The terms are also often associated with the formal definitions given by Harrigan and Spekkens for the wavefunction in quantum mechanics to be $\psi$-ontic or $\psi$-epistemic in the setting of the ontological models framework. The formal definitions are contradictories, so that the wavefunction can be either epistemic or ontic but not both. However, we argue, nothing about the informal ideas of epistemic and ontic interpretations rules out wavefunctions representing both reality and knowledge. The implications of the Pusey-Barrett-Rudolph theorem and many other issues may be rethought in the light of our analysis.

Poster B (S) Mutual self structuring and novel Kerr-like fragmentation in coupled light/matter-wave interactions
Grant Henderson, Gordon R. M. Robb, Gian-Luca Oppo and Alison M. Yao
University of Strathclyde, UK

Optical solitons are self-localized light wave packets that can propagate without significant change to their spatial profile. They are formed when the diffraction of a Gaussian beam is carefully balanced by the self-focusing due to a Kerr-type nonlinearity and are of interest for modern optical technologies and high-power laser systems. Propagation is well described using a (2+1)D nonlinear Schrödinger equation where the nonlinear term depends on the intensity of the beam and includes saturation to prevent collapse.

Uniformly polarized light with a helical phase structure carries orbital angular momentum (OAM) and is characterized by an on-axis optical vortex. During propagation in self-focusing media, these fragment into solitons carrying angular momentum, with the number of solitons formed depending on the OAM.

We investigate the propagation of coherent vortex beams through a matter-wave i.e., a Bose-Einstein Condensate (BEC). Here the nonlinear term for the optical field becomes spatially dependent on the BEC which is itself coupled to the optical field. The evolution of the BEC is accurately described by the Non-Polynomial Schrödinger equation and a term describing three-body loss.
We show that propagation of vortex beams in a self-focusing medium with repulsive BEC interactions results in the novel formation of coupled optical and BEC solitons carrying angular momentum, in spite of repulsive BEC interactions. Despite fundamental differences between our model and the pure Kerr case, the results are in remarkable qualitative agreement, and in all cases we find that the number of solitons depends on the OAM of the vortex light beam.

**Poster C The Design of the BECCAL Laser System and its Capabilities**

Victoria Henderson¹, Jean-Pierre Marburger², André Wenzlawski², Ahmad Bawamia³, Andreas Wicht³, Patrick Windpassinger³, Achim Peters⁴, Mustafa Gündoğan⁴, Oliver Anton⁴, Markus Krutzik⁴ – and The BECCAL Collaboration

¹Universitat-Humboldt Berlin, Germany, ²Johannes Gutenberg-Universität, Germany, ³Ferdinand-Braun-Institut, Germany, ⁴Humboldt-Universität zu Berlin, Germany

BECCAL (Bose-Einstein Condensate and Cold Atom Laboratory) is a cold atom experiment designed for operation on the ISS. It is a DLR and NASA collaboration, built on a heritage of sounding rocket and drop tower experiments, and NASA's CAL. This multiuser facility enables the exploration of fundamental physics with Rb and K BECs and ultra-cold atoms in microgravity, facilitating prolonged timescales and ultra-low energy scales. The scientific envelope targets atom interferometry, atom optics, scalar and spinor BECs, quantum gas mixtures, strongly interacting gases and molecules, and quantum information.

We will present an overview of the current design and capabilities of the BECCAL laser system, focusing on the unique challenges faced when designing for such ambitious functionality. To meet stringent size, weight and power limitations, we combine micro-integrated diode lasers, and Zerodur boards of miniaturized free-space optics, connected via fibre optics. For prototyping BECCAL experiments and technologies for future space payloads, a ground testbed system is currently being set up. This will be capable of rapid production of Rb BECs in various optical dipole trap architectures, and is extendable to K. To this end, we will also present two potential experiments: an investigation to examine non-linear contributions to the Schrödinger equation at long time-scales, and a proof of principle electromagnetically induced transparency scheme for quantum memories.

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 numbers DLR 50WP1702, 50WM1958, and 50WM1953.

**Poster D (S) Number-resolved imaging of ⁸⁸Sr atoms**

Matthew Hill, Niamh Jackson, Zhongxiao Xu, Frédéric Leroux, Charles Adams and Matthew Jones - Durham University, UK

Arrays of atoms in optical tweezers have emerged as a powerful tool in areas such as quantum computation and simulation. Recently, this work has expanded from using alkali atoms, to rapid advancements in trapping single divalent atoms such as Sr and Yb. We demonstrate number-resolved detection of Sr atoms in an optical tweezer, with single atom imaging fidelity of >99%.
We are now in the process of upgrading our experiment to a magic wavelength tweezer array produced by a spatial light modulator (SLM). This will allow us to improve imaging fidelity further, and to use our clock and Rydberg lasers towards implementing a spin-squeezed atomic clock.

doi: 10.21468/SciPostPhys.8.3.038

**Poster E (S) Rotational Optomechanics**

Yanhui Hu¹, Maryam Nikkhou¹, James Sabin¹, Muddassar Rashid¹, Benjamin Stickler² and James Millen

¹King’s College London, UK, ²University of Duisburg-Essen, Germany

Levitated optomechanics opens the door for many quantum experiments and sensing applications with the advantage of minimising the dissipation to the environment. This has enabled control and cooling the motion of levitated nanoparticles to quantum level, yielding great potential for detecting a wide range of forces.

In this project, we present a clean, vacuum compatible method for loading nanoparticles into optical traps, based on laser-induced acoustic desorption (LIAD). We investigate the effect of the pulsed laser intensity and the pressure on trapping efficiency for an optical standing wave trap in vacuum. Furthermore, full control and cooling of all degrees of freedom (center-of-mass and rotational degrees of freedom) will be researched and demonstrated. By trapping a particle with anisotropic susceptibility (a silicon nanorod) in an optical tweezer, the trapping frequencies are increased, and rotations can be driven using circularly polarized light. Feedback will be applied to cool the librational motion by controlling the polarization of the trapping light field. A second trap is also being built using a cavity with a counter-propagating tweezer. This trap will use the tweezer to hold nanoparticles and use coherent scattering in order to cool the particles. By using elliptically polarised light in the tweezer, the translational and rotational degrees of freedom can be cooled simultaneously.

**Poster F (S) Intensity Averaging High Harmonic Spectra**

Lynda Hutcheson, Andrew Brown and Hugo van der Hart

Queen’s University Belfast, UK

While attoscience experiments address macroscopic ensembles of atoms or molecules, new techniques are increasingly sensitive to the detailed and complex internal dynamics of the individual particles. Such measurements can benefit from the support of ab initio calculations which provide insight into the microscopic detail.

One important experimental effect is the structure of the laser focal spot, which introduces a range of intensities in the electric field. To account for this effect, simple model simulations, which are computationally cheap, may simply calculate thousands of intensities. However, this approach is not tractable with ab initio methods which are, generally, more computationally expensive.

We propose an alternative approach, appropriate for computationally demanding applications, which uses a sample of intensities, weighting the contributions of each intensity in the sample and then summing them. This has been employed previously for incoherently summed observables,
such as photoelectron distributions [1], but here we extend the technique to harmonic generation, which necessitates a coherent sum of the individual intensity components.

We investigate the robustness of this coherent intensity averaging method using results obtained using the R-Matrix with Time-dependence (RMT) codes [2]. We address harmonic spectra produced by both Xenon and Argon in several different laser regimes to provide a guide for obtaining intensity-averaged data. Ultimately we demonstrate that our scheme affords improved agreement with experiment without sacrificing the accuracy of the underlying calculations.


Poster G Stern-Gerlach effect in high magnetic fields - radiative decay of spin superpositions
Markku Jääskeläinen
Mälardalen University, Sweden

The Stern Gerlach experiment is a cornerstone of quantum mechanics, both historically and with respect to quantum measurements, which are fundamental to the interpretation of the theory. Textbooks contain simplified descriptions of the dynamics of an atom in an inhomogeneous magnetic field, although the detailed dynamics of the system remains an active topic of research with implications for the foundations of quantum theory.

In this work I present a quantum dynamical treatment of a splitting wave-packet interacting with a semiclassical field mode. The atom is described by a spinor wave-packet, and the superposition state in space and momentum space resulting from the inhomogeneous field produces a distribution of a multipole moment that acts as a source for the field mode, thus driving the propagating field.

The interaction with the field causes the state to transfer into the energetically lower, and thus stable, spin-state. As a result, the interaction switches off in a natural way as the field propagates away from the interaction region of the localized wave-packets after the driving coherence dies out as the superposition ceases to exist. The dynamics is studied numerically for both resonant and off-resonant driving of the emitted field mode.

Poster H (S) Monte Carlo study of magnetic properties and hysteresis behavior of the square Ising nanowire with core-shell structure
El mostafa Jalal1, Abdellatif Hasnaoui1, Hasnae Saadi1, Nabil Hachem Mohammed2 and El bouziani2
1Université Sultan Moulay Slimane, Morocco, 2Université Chouaib doukkali, Morocco

Using Monte Carlo simulation to study magnetic and thermodynamic properties of a ferrimagnetic mixed-spin (1, 3/2) square Ising nanowire with core-shell structure. The phase diagrams are obtained for different single-ion anisotropies. The obtained results show the existence of some interesting phenomena, such as the second- and first order phase transitions, tricritical end points, the tricritical points and the compensation phenomena. Especially, emphasis has been given to the effects of the single-ion anisotropy and the temperature on the magnetization, the internal energy,
the specific heat, the compensation points and hysteresis loops of the system as well as two sublattices. A number of characteristic phenomena such as multi-cycle hysteresis behaviors of the total system and sublattices have been observed for certain physical parameters, originating from the competitions among the anisotropies, temperature and the longitudinal magnetic field. It is found that the single-ion anisotropy and the temperature strongly affect the coercivity and the remanence of the system [1]. A satisfactory agreement can be achieved from comparisons between our results and previous theoretical and experimental works.

**Poster I Krylov variational quantum algorithm for first principles materials simulations**

*Francois Jamet*

National physical laboratory, UK

In the last few decades, progress in electronic structure calculations has permitted to improve our understanding of exotic phenomena such as high-temperature superconductivity. However, these calculations are limited due to the inherent exponential increase of computational cost with respect to the size of the quantum system. Quantum computers have the potential to overcome this limitation.

In this talk, I will present a recent developed algorithm (arXiv: 2105.13298) to compute the electronic structure of real materials using a near-term quantum computer, and demonstrate it on a cuprate material using the algorithm within the dynamical mean field theory (DMFT). Near-term quantum computers offer a potential of unprecedented increase of computer power. However, their exploitation is challenging since they have a limited number of qubits and they are noisy. Our algorithm is designed to have the requirements satisfied on such a realistic quantum computer.

We implemented a variational quantum algorithm based on a combination of the Krylov and Lanczos algorithms. We demonstrate this algorithm with first principles material science simulations by computing the density of states of a La2CuO4 using the state-of-the-art quasiparticle self-consistent GW, combined with DMFT executed on a quantum computing emulator.

**Floor 2**

**Poster A (S) A Shielded, Optically Pumped, RF Atomic Magnetometer**

*Ross Johnston*, Harry Pulham, Stuart Ingleby, Paul Griffin and Erling Riis

University of Strathclyde, UK

A shielded atomic magnetometer using a paraffin-coated caesium cell and employing double resonance techniques, is used to detect weak, oscillating magnetic fields. Applications of such a device will include zero- and ultralow-field nuclear magnetic resonance (ZULF NMR) measurements, where small magnetic fields in the kHz range are generated. Experiments of this type remove the need for costly superconducting magnet systems involved in conventional NMR, and yield structural information relating to the chemical bonds between nuclei in a molecule, providing a unique zero-field spectrum which can be used as a fingerprint for chemical identification, including liquid explosives. Whilst conventional NMR experiments use inductive sensors to measure high frequency magnetic fields, atomic magnetometers measure magnetic fields directly, resulting in better performance at the frequency range required for ZULF NMR. In this work, a scheme employing
individual pump and probe lasers is optimised regarding intensity and frequency. A sensitivity of 5 fT/√Hz is estimated.

**Poster B Fast and robust magnon transport in a spin chain**  
**Anthony Kiely** and **Steve Campbell**  
University College Dublin, The Republic of Ireland

A protocol for fast and robust magnon transport in a one-dimensional spin chain is devised. Employing an approximate mapping between the chain and a single harmonically trapped particle, we exploit the known analytic control protocols for the latter and adopt them to achieve fast, high-fidelity transport in the chain. We compare the performance with finite time adiabatic protocols, showing that the designed scheme allows for significantly faster and more stable transport. Furthermore, we show that a sharp transition exists between regions in which the protocol is effective and when it breaks down, giving rise to a heuristic speed limit for the process.

**Poster C Parametric broadening of the molecular vibronic band due to zero-point oscillations and thermal fluctuations of interatomic bonds**  
**Peter Lebedev-Stepanov**  
FSRC Crystallography and Photonics RAS, Russia

Numerous computations of the spectra of molecules are performed by mainstream methods based on the fundamental work [1] for smoothing a series of individual transitions represented by delta functions. There is an assumption that the linewidth of an individual rovibronic transition spectrum is many orders of magnitude smaller than the rovibronic bandwidth. However, the presence of rotational–vibrational structure in the molecular spectrum masks the broadening of each individual rovibronic transition. In the framework of harmonic approximation of potential energy surfaces, a new kind of contribution to homogenous broadening is considered to describe the optical spectrum of any single rovibronic transition [2]. Its origin is in zero-point oscillations and thermal fluctuations around equilibrium positions of nuclei.

We propose the Franck–Condon diagram with slanting equidistant vibrational levels to explain this kind of broadening. Expressions of spectral intensity of a single vibronic transition are derived from the first principles. The value of such broadening depends on the environment that restricts internal degrees of freedom of the molecule.

We use this theory to estimate the broadening magnitude of the vibronic (0-0) transition in linear polymethine dyes with an extended π-electron system. We have shown that parametric broadening can be significant and has to be taken into account in quantum chemistry calculations of width and shape of the optical spectrum band of organic molecule. Until now, this effect has not been taken into account [2].

Poster D (S) Frequency stabilisation of a 422 nm diode laser for Doppler cooling of trapped 88Sr+ ions

Binod Limbu1,2 and Alastair Sinclair 2

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

Trapped ions are often used for research in quantum information, quantum simulation, and quantum metrology. A requirement is that the ions are Doppler cooled before applying any quantum control routines. Frequency stability of the cooling laser is necessary to maintain an efficient ion cooling rate and a constant fluorescence signal. Unlike neutral atoms, ions have no straightforward means to reference the cooling laser to a vapour of the atomic species under study.

88Sr+ is laser cooled using the 5s 2S1/2 – 5p 2P1/2 transition at 422 nm. Conveniently, the 5s 2S1/2 (F'' = 2) – 6p 2P1/2 (F' = 3) transition in 85Rb vapour, which is only 440 MHz from the 88Sr cooling transition, can be used for stabilising the 422 nm laser. To date, we have used the frequency-doubled output of an 844 nm extended-cavity diode laser (ECDL); this is more complex and yields lower optical power than the present generation of blue ECDLs.

Frequency-modulated light from a 422 nm ECDL performs saturated absorption spectroscopy of the 85Rb transition. Lock-in detection yields the first derivative of the absorption signal, which serves as the discriminant for stabilising the laser frequency. Fourier analysis of the locked discriminant was used to optimise the servo PID parameters. A wavemeter monitoring the laser frequency showed stabilisation was maintained for more than 90 hours, which is a vast improvement over the previous system. These tests demonstrate the suitability of the 422 nm ECDL for Doppler cooling of trapped 88Sr+ ions.
Poster E (S) How can I improve my atomic bandpass filter?: Cascaded Cells, Off Axis Fields and Field Gradients

Fraser Logue, Steven Wrathmall and Ifan Hughes
Durham University, UK

Birefringent Rb vapour bandpass filters rely on optical rotation. Light input is decomposed into the two eigenmodes of the system, with refractive indices $n_1$ and $n_2$ which slow and attenuate the two polarisations [1]. Typically, this has been studied in either the Faraday geometry [2] where a magnetic field is directed parallel to the light k-vector or the Voigt geometry [3,4] where a magnetic field is directed perpendicularly. Having experimentally realised the highest figure of merit Rb filter to date (1.22 GHz$^{-1}$), we want to understand the atom-light interactions underpinning good filters. Our theoretical model ElecSus [5,6] has recently been updated and can now analyse off-axis B-field setups, B-field gradients and cascaded cells all of which can be used to significantly improve filter performance. Initial polarimetry investigations have uncovered novel optical rotation effects including input independent trajectories on the Poincaré sphere which may point to the mechanisms behind improved filter performance.

Figure: The normalised Stokes vectors of four input polarisations; LHC (purple), RHC (blue), linear +45° (red) and linear -45° (yellow) which converge towards similar paths on the Poincaré sphere.

Poster F (S) Characterising the complexity of non-integrable quantum spin chains and the efficiency of their ground-state preparation on quantum computers

Gabriel Matos\textsuperscript{1}, Sonika Johri\textsuperscript{2} and Zlatko Papić\textsuperscript{1}

\textsuperscript{1}University of Leeds, UK, \textsuperscript{2}IonQ Inc, USA

Recently, there has been much interest in preparing the ground states of strongly-correlated quantum systems using algorithms implementable in near-term quantum computers, such as the Quantum Approximate Optimization Algorithm (QAOA). While it has been numerically shown that such algorithms can prepare certain highly-correlated states of quantum spins, such as the Ising model in a transverse magnetic field, with surprising accuracy, a systematic way of quantifying the efficiency of state preparation in general classes of models has been lacking. Here, we propose that the success of QAOA in preparing ordered states is related to the property of the target state called "interaction distance", which measures how close that state is to the manifold of all Gaussian states in an arbitrary basis of single-particle modes. We numerically verify this for several examples of non-integrable quantum systems, including the Ising model in both transverse and longitudinal fields, a three-spin Ising model in the Potts universality class, and an interacting model of symmetry-protected topological phase. Our results suggest that the structure of the entanglement spectrum, as witnessed by the interaction distance, correlates with the success of QAOA state preparation, and that this correlation also contains information about different phases of matter present in the model. We conclude that QAOA typically finds a solution that perturbs around the closest free-fermion state.

Poster G Towards Scalable Qubit Arrays for Quantum Computation and Optimisation

Boyko Nikolov, Elliot Diamond-Hitchcock, Jonathan Bass, Nicholas Spong and Jonathan Pritchard

University of Strathclyde, UK

Quantum computation offers a revolutionary approach to how information is processed, offering new applications in material design, quantum chemistry and speed up of real-world optimisation problems, however a large number of qubits are required to obtain quantum advantage over classical hardware.

Neutral atoms are an excellent candidate for practical quantum computing, enabling large numbers of identical qubits to be cooled and trapped, overcoming major barriers to scaling experienced by competing architectures. A crucial ingredient for quantum computing is the ability to perform controlled two-qubit gate operations, for which the strong, long-range dipole-dipole interaction between Rydberg atoms can be exploited to implement deterministic gate operations between atoms within a radius of \( R < 10 \, \mu \text{m} \).

We present progress towards a new experimental platform for quantum computation at the University of Strathclyde based on reconfigurable atom arrays of Cs atoms, including demonstration of loading and characterisation of arrays of \( > 100 \) qubits as the first step to creating a scalable architecture for quantum computing.

This work is supported by the EPSRC Prosperity Partnership with M Squared Lasers, Grant No. EP/T005386/1.
Poster H (S) Bloch oscillations in a synthetic dimension of harmonic trap states

Christopher Oliver
University of Birmingham, UK

Since the proposals of [1][2], synthetic dimensions have become a powerful method for realising theoretical models in artificial systems such as ultracold atoms [3]. In this approach, a set of states are coupled together, with the coupling then being interpreted in terms of a particle hopping along a synthetic lattice formed by the states. Synthetic dimensions have proven useful as they can allow for more straightforward implementations, particularly of topological models, than is otherwise possible.

In this poster, we report on progress towards implementing a synthetic dimension based on harmonic trap states [4]. In this approach, a harmonic trap containing cold atoms is resonantly shaken around the trapping frequency, so that the shaking potential couples nearest-neighbour harmonic trap states. Within this framework, the harmonic trap states are re-interpreted as lattice sites along a synthetic dimension, where the shaking amplitude sets the effective hopping amplitude and the shaking detuning generates an effective force along the lattice. A predicted signature of the synthetic dimension is the emergence of 1D Bloch oscillations with respect to the harmonic trap states [4]. Here, we shall discuss the observation of this effect based on a cold-atom set-up with a digital micro-mirror device. The implementation of such a synthetic dimension will pave the way for the investigation of 2D quantum Hall physics in this system, when a position-dependent shaking phase is included.


Floor 3

Poster A (S) Towards an optical tweezer array of ultracold RbCs molecules

Stefan Spence, Vincent Brooks, Daniel Ruttley, Alexander Guttridge and Simon Cornish
University of Durham, UK

The exquisite control demonstrated over both internal and external states of single atoms and molecules in optical tweezers makes them an ideal tool for a ground-up approach to quantum research. Manipulating the dipole-dipole force between heteronuclear ultracold molecules through its angular dependence and long-range $r^{-3}$ dependence provides the basis for experiments in precision metrology, proposals for quantum gates, quantum simulation of spin-lattice models, or investigating interactions between a deterministic number of particles.

At Durham, species-specific optical tweezers selectively load $^{87}$Rb and $^{133}$Cs atoms into separate optical tweezer traps. The collisional blockade enforced by the ~1 micron beam waist ensures single occupancy.
We have demonstrated moving and merging two atoms into a single trap using an acousto-optical deflector. We are using Raman sideband cooling to prepare the atoms in the 3D motional ground state of the trap and have demonstrated ground state occupancy of >80% for both species. High fidelity ground state preparation will provide the atomic wave function overlap required for efficient association into a $^{87}$Rb$^{133}$Cs molecule and is also useful for increasing the 2-body and 3-body collision rates that are often used to signal Feshbach resonances. This method may be scaled up to arrays of tweezers by driving AODs with a multitone RF signal.

**Poster B Towards an array of single CaF molecules in optical tweezer traps for quantum simulations**

Bharath Srivathsan, Jonas Rodewald, Joshua Blunsden, Hongyu Chen, Noah Fitch, Ben Sauer and Michael Tarbutt

Imperial College London, UK

Recent progress in laser cooling and trapping of polar molecules has brought quantum simulations with single trapped molecules as qubits within reach. Due to their large electric dipole moments, the timescale for a two-qubit gate realized through the dipole-dipole interaction is much shorter than coherence times already demonstrated. We have built an experiment to trap an array of single calcium monofluoride (CaF) molecules in optical tweezer traps, and cool them to the motional ground state of the trap to achieve full quantum state control. The molecules are captured in a magneto-optical trap, cooled to low temperature in an optical molasses and then optically pumped to a magnetically trappable state. We then load these molecules into a moveable quadrupole magnetic trap which transports them to a science chamber. Here, the tweezer traps are created by focusing far-off resonant trapping light using a high numerical aperture aspheric lens. To create an array of traps, we use an acousto-optic deflector driven by multiple RF tones. We will present our recent experimental progress including efficient optical pumping and magnetic transport of molecules and characterization of the optical setup which is used to create a linear array of tweezer traps.

**Poster C (S) An open microcavity platform for solid-state spin-photon interfaces**

Alexander Stramma, Urs Haeusler, Eizagirre Barker, Claire Le Gall, Mete Atatüre and Dorian Gangloff

University of Cambridge, UK,

A light-matter quantum interface constitutes the central building block for many scalable quantum information technologies. Solid-state spins in the optical domain are amongst the most promising approaches, combining a local quantum register of electrons and nearby nuclear spins with long-distance transmission of coherent optical photons [1]. However, the efficient extraction of photons is hindered for emitters in high refractive index materials. Here, open Fabry-Perot microcavities offer the possibility to increase the count rates of indistinguishable photons [2, 3].

In this poster, a versatile and cryo-compatible open microcavity platform for different materials is shown. Due to the non-monolithic design, the cavity length must be stabilised on the pm-scale in the presence of mechanical vibrations. Passive and active stabilisation, compatible with confined sample spaces in cryostats, will be used. An optimized rigid positioner design will reduce in-coupling of vibrations into the cavity. It offers both in-situ spectral and spatial tunability so that
emitters with desirable spin and optical properties can be selected. The cavity length will be actively locked to the frequency of a laser in the Pound-Drever-Hall scheme. By combining home-made piezo drivers with digital filters, we expect locking bandwidths of up to 100 kHz.


**Poster D (S) A flexible ion-photon interface for distributed quantum information**

Graham Stutter, Samuel Snowden, David Kay and Matthias Keller

University of Sussex, United Kingdom

The problem of scalability remains a potential stumbling block for all emergent quantum computing technologies. One possible approach uses a distributed architecture to address this issue, in which modular ion trap 'nodes' are connected by photonic interlinks. Quantum information can then be transferred between the nodes using photons. An ion strongly coupled to an optical cavity acts as a platform for the production and collection of single photons, which are then used for generating high-fidelity and high-rate remote entanglement between spatially-separated nodes.

We present a novel segmented linear ion trap combined with a low-birefringence, high-finesse optical cavity, which can be used as a node for quantum networking and distributed quantum computing. Laser-assisted chemical etching defines the electrodes in hybrid blade/wafer layout with optical access along all three trap axes, while shielding the ion from the dielectric material of the cavity mirrors. Small ion-blade distances (~75μm) enable high trapping frequencies for relatively low voltages compared with surface traps of similar scale.

Results of ion transport simulations demonstrate the capability to perform all processes needed for a linear QCCD architecture: shuttling, swapping and separating mixed Sr-Ca chains; while cavity calculations estimate an ion-cavity coupling of ~20 MHz.

**Poster E (S) An atomic compass – detecting 3D magnetic field alignment with vector vortex light**

Jinwen Wang¹², Francesco Castellucci¹, Thomas W. Clark³, Adam Selyem⁴ and Sonja Franke-Arnold¹

¹University of Glasgow, ²Xi'an Jiaotong University, China, ³Hungarian Academy of Sciences, Hungary, ⁴Fraunhofer Centre for Applied Photonics, UK

Recent progress in generating complex vector light fields with structured transverse polarization profiles now allows the full exploration of vectorial light matter interaction [1]. Here, we describe and demonstrate how 3D magnetic field alignment can be inferred from single absorption images of an atomic cloud. Using a vector vortex beam, composed of light that carries opposite orbital angular momentum index ±l in the left and right handed polarization components and drives the Λ transition from mF = ±1 to the excited state [2], we inscribe structured atomic spin polarization in a cloud of cold rubidium atoms [3], and record images of the resulting absorption patterns. The transmission depends strongly on the alignment of an external magnetic field, specified by its
inclination angle with respect to the light propagation direction and the azimuthal angle. An azimuthal rotation of the magnetic field results in a rotation of the absorption profile, whereas an inclination results in splitting of the absorption pattern. We demonstrate that we can infer the alignment of the external magnetic field from an azimuthal Fourier analysis of the absorption profile [4].


Poster F (S) Emission of indistinguishable photons from an Ion-cavity System
Travers Ward
University of Sussex, UK

We investigate two schemes for generating indistinguishable single photons, a key prerequisite of quantum networks, from a trapped ion coupled to an optical cavity. Through selection of the initial state in a cavity-assisted Raman transition, we suppress the detrimental effects of spontaneous emission on the photon’s coherence length, measuring a visibility of 81(2)% without subtraction of background counts in a Hong-Ou-Mandel (HOM) interference measurement, the highest reported for an ion-cavity system. In comparison, a visibility of 50(2)% was measured using a more conventional single-photon scheme. We demonstrate through numerical analysis of the single-photon generation process that our scheme produces photons of a given indistinguishability with a greater efficiency than the conventional one. Further work has begun on demonstrating the system’s ability to produce time-bin encoded single photons while maintaining a high indistinguishability. This is achieved by performing a HOM experiment, interfering photons of a ‘double hump’ shape and looking for characteristic changes in the interference patterns. Single-photon schemes such as the one demonstrated here have applications in distributed quantum computing and communications, which rely on high-fidelity entanglement swapping and state transfer through indistinguishable single photons.

Poster G An experiment to measure the electron’s electric dipole moment using trapped ultracold molecules.
Andrew White, Jorge Mellado Munoz, Stefan Popa, Jongseok Lim, Xavier Y Alauze, Chi Zhang, Noah J Fitch, Ben E Sauer and Michael R Tarbutt
Imperial College London, UK

The large asymmetry between matter and antimatter in the Universe is a mystery. The formation of this extra matter requires charge parity (CP) violation beyond that contained in the standard model, and therefore points towards new physics. The electron’s electric dipole moment (eEDM) is sensitive to this new physics. Precision measurement of the eEDM tests physics beyond the
Standard Model and will expand our understanding of the fundamental principles of nature. We aim to improve the precision of the eEDM measurement by 3 orders of magnitude using an array of ultracold ytterbium monofluoride (YbF) molecules held in an optical lattice.

We produce a beam of YbF using a cryogenic buffer gas source cooled to 2 K. In this source, YbF is formed by laser ablation of an ytterbium target in the presence of sulphur hexafluoride (SF6), and is then entrained in a flow of cold helium gas. We plan to decelerate these molecules, capture them in a magneto-optical trap, cool them to a few microkelvin and then load them into an optical lattice where spin coherence times of several seconds seem feasible. We will present the parts of the apparatus built so far, and our plans for the future.

**Poster H An ultrastable, low-noise laser for high-fidelity control of 88Sr+ optical qubits**

Guido Wilpers¹, Nathanael Bullier¹, Scott Thomas¹², Alastair Sinclair¹

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

Optical qubit transitions in laser-cooled, trapped ions are used in precision quantum metrology and in quantum information processing. In linear ion strings, each qubit and the quantised collective motion are controlled coherently via the ion-laser laser interaction to create scalable entanglement. Such systems could realise a gain in precision and overcome the quantum projection noise limit of single ion clocks with short averaging timescales.

Coherent control of trapped-ion optical qubits for scalable entanglement requires a high-power, ultrastable laser with minimal noise in the Fourier spectrum. Typically present in semiconductor laser systems, noise on the MHz scale causes off-resonant ion-laser interactions and degrades the fidelity of coherent operations. An initial high-power source is needed to generate laser pulses agile in amplitude, phase and frequency that illuminate an ion string evenly with the requisite Rabi frequency.

We report the realization of an ultrastable 674-nm laser suited to coherent control of ⁸⁸Sr⁺. We use a titanium-sapphire laser which is optimized for the low wavelength end of its gain range and emits 1.4 W. It exhibits a 1 Hz fluctuation in optical frequency measured from 1 s to 300 s averaging times. Noise is minimal; at Fourier frequencies from 10 Hz to 10 MHz we measure this to be below a white frequency noise level of a few Hz·Hz⁻¹/². The characteristically rapid decrease of intrinsic noise enables use of the frequency-stabilised, high-power output, without the need for further spectral filtering to minimise infidelities in coherent control of optical qubits in ⁸⁸Sr⁺.

**Poster I Density-Matrix Renormalization Group for Continuous Quantum Systems**

Shovan Dutta¹, Anton Buyskikh², Andrew Daley² and Erich Mueller³

¹University of Cambridge, UK, ²University of Strathclyde, UK, ³Cornell University, UK

I will demonstrate a new versatile and practical framework for applying matrix product state techniques to continuous quantum systems. Our method uses a spatial partitioning to map a continuous many-body Hamiltonian onto a discrete sum over segments. By combining this mapping with existing DMRG routines, one can accurately obtain the ground-state wave function, spatial correlations, and entanglement directly in the continuum, with fast convergence not achieved by a grid-based discretisation. I will illustrate this technique for a superfluid-insulator
transition of strongly-interacting bosons in a variable external potential. I will outline how one can apply this framework to a wide variety of experimentally relevant problems.

Day 3 – Thursday 2 September
Session 9 Rydberg excitations

(Invented) Collective effects of Rydberg atoms in optical cavities

Sebastian Slama
University of Tübingen, Germany

Atoms in optical cavities are paradigmatic for collective light scattering and self-organization, as occurring in collective atomic recoil lasing [1] and the Dicke phase transition [2]. The cavity-mediated interaction in these systems is all-to-all and infinite-range. In contrast, Rydberg atoms interact with each other via binary interactions which are long-range with a length scale up to several micrometers. The combinations of both interactions can be used to implement a Dicke-Ising model and study quantum optical magnets with competing interactions [3,4]. I will report on our experimental work towards this goal by exciting laser-cooled Rubidium atoms in a cavity to Rydberg states using a two-photon transition. In a first experiment we have observed cavity Rydberg EIT, which allows us to determine the Rabi frequency in the excitation process. In a second experiment, we detect the Rydberg excitation dynamics in real-time using the cavity transmission.

Broadband microwave/optical conversion using Rydberg excitons in Cuprous Oxide

Jonathan Pritchett, Liam Gallagher, Joshua Rogers, Danielle Pizzey, Matthew Jones and Charles Adams
Durham University, UK

Hybrid quantum systems made up of two or more distinct physical platforms coupled together are of growing importance in quantum science and technology. For example, superconducting microwave circuits are at the forefront of quantum computing, but the transfer of information over large distances is challenging due to the effects of thermal noise. Conversely, optical quantum communication has been shown to be successful over large distances. Hybrid quantum systems combine the advantages of these platforms allowing for on-chip microwave to optical conversion at low temperature.

We present a coupling between microwave and optical fields at 4K utilising the discrete hydrogen-like energy levels of Rydberg excitons in the bulk single crystal of the semiconductor Cu$_2$O. Excitonic states are probed using one and two-photon (absorption and second harmonic generation respectively) excitation schemes. In one-photon spectroscopy the addition of a microwave field changes transmission near an exciton resonance by more than 15\%. The second harmonic spectrum exhibited sidebands at the applied microwave frequency, with a complex dependence on the principal and angular momentum quantum numbers of the exciton. In contrast to atomic Rydberg states non-radiative broadening of the excitonic spectrum gives rise to a continuous microwave spectrum. The results are in good qualitative agreement with a model based on intraband electric-dipole transitions. Unlike laser-cooled atoms, Rydberg excitons are inherently compatible with the dilution fridge environment used for superconducting quantum devices, opening a possible route for robust coupling of such devices to optical fields in future.

Optimal State Choice for Rydberg Atom Microwave Sensors

Aurelien Chopinaud and Jonathan Pritchard
University of Strathclyde, UK

Rydberg electromagnetically induced transparency offers great possibilities for the development of atom-based SI-traceable microwave (MW) sensing and communication devices. It utilises the Autler-Townes (AT) splitting resulting from the coupling of two Rydberg states by a MW field. To create reliable and accurate devices, sources of systematic uncertainty must be carefully quantified. In particular, knowing the conditions under which the AT splitting is linear with the MW field is of great importance. In this work, using cesium atoms in a vapour cell, we investigate non-linearities originating from multi-photon couplings between neighbouring Rydberg states. By studying four different Rydberg transitions in the same frequency range we show that those couplings can break the linearity and symmetry of the observed AT splitting. We present a model which accurately predicts the behaviour of the AT splitting for any Rydberg transition accounting for multi-photon transitions. We also show that these couplings are strongly dependent on polarisation and use our model to advantageously determine the polarisation purity of the MW field.

Session 10 - Cold molecules

(Invited) Precision Physics with Antihydrogen
S. A. Jones1 and the ALPHA collaboration2
1Swansea University, UK, 2ALPHA, Switzerland

Antihydrogen is an exciting tool for testing matter-antimatter symmetries, and in the last decade, the field of antihydrogen physics has advanced from proof-of-principle type measurements to precision spectroscopy. At ALPHA, we are now able to accumulate more than 1000 simultaneously trapped antihydrogen atoms, and probe their optical and microwave transitions. In this talk, I will give an overview of the state-of-the-art techniques we use to produce, trap, and accumulate antihydrogen. I will report our latest spectroscopy results, and detail how we have applied 121 nm light to laser cool the trapped atoms, resulting in a significant narrowing of the 1S-2S transition linewidth. I will also introduce the next generation of ALPHA machines: ALPHA-3, an upgraded version of our spectroscopy apparatus with the target of reaching hydrogen-like precision, and ALPHA-g, a new apparatus designed to measure the gravitational interaction between matter and antimatter. Finally, I will discuss routes towards making a direct comparison between hydrogen and antihydrogen in the same trap, which would eliminate many systematic effects.

Ultracold laser-assisted scattering of polar molecules with reservoir Rydberg atoms
Vanessa Carolina Olaya Agudelo1, Jesús Pérez-Ríos2 and Felipe Herrera1
1University of Santiago, Chile, 2Fritz-Haber-Institut der Max-Planck-Gesellschaft, Germany

Ultracold scattering experiments with Rydberg atoms in dense neutral atom-Rydberg mixtures has led to the discovery of exotic bound long-range Rydberg molecules, with a ground state atom residing within the orbit of a Rydberg electron [1]. We now study the long-range interaction of Rydberg alkali-metal atoms with heteronuclear alkali-metal dimers in the regime of low molecular densities, such that the Rydberg-dimer interaction is dominated by van der Waals forces. We compute accurate C6 coefficients for a large set of atomic Rydberg states n2Lj interacting with ground state molecules [2]. For the (52S1/2)87Rb-KRb(J=0) collision pair, we predict large probabilities for forming long-range Rydberg-molecule bound states (trimers) with (n ~ 50)2D3/2 atomic Rydberg character, in a two-photon photoassociation scheme. We discuss the feasibility of detecting Rb-KRb trimers in currently available atom-molecule co-trapping experiments.


Stability of a dipolar gas in a power-law potential
Péter Juhász1, Milan Krstajić2,3, David Strachan1, Edward Gandar1, Robert Smith1
1University of Oxford, UK, 2University of Oxford & Cavendish Laboratory, UK, 3University of Cambridge, UK
We solve the time-independent Gross–Pitaevskii and the Bogoliubov–de Gennes equations numerically to explore the stability of a purely dipolar Bose–Einstein condensate (BEC) in a cylindrically-symmetric trap. The atoms are polarised and confined to a harmonic potential along the cylinder's axis, and are trapped in a general power-law ($r^n$) potential in the perpendicular direction. We vary and explore the effect of both the power law and the trap aspect ratio.

For small aspect ratios, we find the instability is seeded by high density at the centre of the trap. However, for larger aspect ratios this transforms into a roton-like instability, which is seeded by finite-$k$, roton-like density oscillations. For high-$n$ (box-like) potentials, we find that however large the aspect ratio is, a confined gas is always less stable than a completely uniform one as instability is seeded by the hard wall. Interestingly, we observe that a softer potential ($n \sim 6$) actually produces a more homogeneous 2D-density than a simple box-potential.

Two-dimensional supersolidity in a dipolar quantum gas

Thomas Bland
IQOQI, Innsbruck, Austria

Dipolar condensates have recently been coaxed into supersolid phases supporting both superfluid and crystal excitations. While the first dipolar supersolids consisted of one dimensional (1D) droplet arrays, an experiment has now achieved two dimensional (2D) supersolidity. We theoretically explore the role of dimensionality, ranging from 1D to zigzag, through to 2D supersolids in circular traps. We predict that 2D supersolids may be as favorable as their 1D counterparts, provided that one scales the atom number to the trap volume. While 1D supersolids may be prepared from condensates via a roton instability, such a procedure in 2D tends to destabilise the supersolid. The 2D roton modes have little in common with the supersolid configuration -- instead, unstable rotons produce a small number of central droplets, which triggers a nonlinear process of crystal growth. We calculate excitations for a 2D supersolid ground state, and make comparisons with 1D arrays using the static structure factor. By evaporatively cooling directly into the supersolid phase--hence bypassing the first-order roton instability--we experimentally produce a 2D supersolid in a near-circular trap.

Session 11 - Trapping

(Ivited) Controlled interactions of cold trapped negative ions

Roland Wester,
University of Innsbruck, Austria

Negative molecular ions have drawn a lot of attention in recent years, in particular owing to the detection of several molecular anions in cold interstellar molecular clouds. Cryogenic radiofrequency ion traps are well suited tools to study the spectroscopy as well as cold collision processes of negative ions with high resolution and high sensitivity.

Using photodetachment spectroscopy we have probed rotational quantum states of cold trapped anions. We have used this to study rotational state-changing collisions of the negative ions OH- and NH2- with neutral helium atoms at low temperature and to perform rotational terahertz spectroscopy and infrared overtone spectroscopy. We have also studied photodetachment of the
interstellar anions CN- and C3N- near threshold and used these data to improve the accuracies of the respective electronic affinities. For CN- the data are well described by the Wigner threshold law, if the permanent electric dipole moment of the neutral product is included in the analysis. For C3N- the large permanent dipole moment of C3N leads to a qualitatively different cross section behavior near threshold. Furthermore, the rotational contour of a dipole bound state was resolved slightly below the detachment threshold in agreement with calculations. This state could serve as a doorway state to negative ion formation in interstellar clouds.

Recently, we have developed a two-photon scheme to probe the rotational and vibrational states of the homonuclear anion C2-, a candidate proposed for negative ion laser cooling. Results on electronic spectroscopy and vibrational relaxation collisions of this ion will be presented.

Machine learning based optimization of an optical nanofiber evanescent dipole rubidium trap

Ratnesh Gupta1, Jesse Everett1, Aaron Tranter2, Vandna Gokhroo1, Ping Koy Lam1, Nic Chormaic1

1Okinawa Institute of Science and Technology Graduate University, Japan, 2Australian National University, Australia

We used a machine learner based on a stochastic artificial neural net (SANN) to explore and find optima in a parameter space for loading cold rubidium atoms from a magneto-optic trap into an evanescent dipole trap array along an optical nanofiber. The learner was used to set the magnetic fields, MOT cooling, repump, and evanescent trapping field intensities and frequencies during the loading of the MOT and then the trap, and received costs based on the absorption of a near-resonant probe sent through the nanofiber after loading. After building up parameter-cost data from random sets of parameters, the SANN was then trained on the cost-parameter data and used to predict optimal parameters in the cost landscape. The predicted optima were tested and used to update the SANN in an automated iterative process that effectively explored the large parameter space.

We trapped around 500 atoms in an array of traps approximately 0.8 mK deep, improving on a manual optimization of about 300 atoms. We characterized atom number by building a detailed microscopic model of the trapped atoms to reproduce the AC-Stark broadened spectra, which included mf levels of the atoms, optical pumping by the probe.

Developing a portable optical atomic clock based on a single Ca+ ion

Xavier Fernandez Gonzalvo and Matthias Keller

University of Sussex, UK

Optical clocks are the most accurate time keeping instruments to date. However, widespread use is being prevented by their large size, high cost and high technical complexity of operation. To overcome these hindrances we are developing a compact, turn-key-operation portable optical clock based on trapped single Ca+ ions. The system is designed to fit in a 4 unit 19 inch module (50x52x16 cm), with a target weight under 20 kg and a target power consumption under 100 W. The expected fractional uncertainty of our system is $\sim 10^{-16}$. 
The key component for the miniaturisation of the system is optical fibre integration, which provides not only compactness but also robustness. A fibre-based laser system provides all the necessary frequencies to ionise and laser-cool a Ca\(^+\) ion. The ion trap is an endcap style trap. Light is delivered to the ion via optical fibres and GRIN lenses inside the vacuum chamber. Fluorescence from the ion is collected using multimode fibres embedded inside the trap electrodes, offering a collection efficiency similar or even superior to traditional high NA lens approaches. Combining this with the clean beam profiles offered by the delivery assemblies we can measure the presence of an ion with outstanding signal to background ratios. The Ca\(^+\) quadrupole transition at 729 nm will be probed using a reference laser stabilised to an ultra-stable optical cavity (developed at NPL). Finally, on-board electronics controlling the various subsystems will run the system autonomously, making it a “black box” from the user’s perspective.

**Session 12 - AMOP for fundamental physics**

**(Plenary) Quantum Methods for Testing the Standard Model: A Tale of two Dipole Moments**

**Gerald Gabrielse**

Northwestern University, USA

Measurements of the electron and positron magnetic moments (in Bohr magnetons) are underway with the goal of determining these moments to 3 parts in $10^{-14}$. These measurements will be the most accurate measurements ever made of any property of an elementary particle. They will be used to test the standard model’s most precise prediction, will provide the most sensitive test of the fundamental CPT symmetry invariance of the Standard Model (SM) with leptons, will make it possible to make better muon magnetic moment measurements, and will provide the most accurate determination of the fine structure constant. A one-lepton quantum cyclotron is realized at cryogenic temperatures below 0.1 K, within a vacuum better than $10^{-17}$ Torr. A new method to circumvent detection backaction will be employed, along with the incorporation of quantum limited detection that is in addition to the quantum nondemolition methods already employed.

A new measurement of the electron electric dipole moment (EDM) by our ACME collaboration seeks a sensitivity at least ten times better than the current best measurement. Most models intended to fix the Standard Model predict an electron EDM much larger than the unmeasurably small prediction of the SM.

**Bridging the gap between spectroscopy of hot, radioactive ion beams, and cold, precise measurements**

**Adam Vernon**

Massachusetts Institute of Technology, USA

Atomic and molecular ions contained in RF traps are demonstrating to provide some of the most precise measurements possible of electron-nucleon interactions.

Atoms and molecules containing radioactive nuclei are predicted to offer significant enhancements to constrain beyond the Standard Model effects, including searches for time-reversal symmetry, dark matter candidates and yet to be observed nuclear properties.
However, radioactive atoms and molecules present challenges for precision spectroscopy: they are produced at low rates (often <1000 per second), in hot environments (>300 K) and require accelerated beam energies to isolate (>10 keV).

This contribution presents a setup under construction to efficiently adapt bunches of radioactive ions to a cryogenic ion trapping environment, which will additionally permit electric-field polarisation of molecules to allow for searches of eEDMs, nuclear Schiff moments and magnetic quadrupole moments.

Day 4 – Friday 3 September
Session 13 - Quantum metrology

(Invited) Optical atomic clocks - applications: from redefining the SI second to tests of fundamental physics
E Anne Curtis
National Physical Laboratory, UK

Frequency is the most accurately measurable quantity available in our science toolkit. If a scientific query can be posed in terms of measuring changes in frequency over time, then state-of-the-art optical atomic clocks can be used as highly sensitive metrological tools due to their unprecedented accuracy and/or stability. Experiments with such clocks have been designed around searching for variations of fundamental constants and in order to show evidence of dark matter in all its potential guises. These measurements can help place constraints on dark matter or “beyond the standard model” physics properties and guide research across competing theories in these areas.

In this talk I will discuss the latest optical clock developments including the use of composite clock systems for improved accuracy and stability. Recent advances in clock performance have allowed the international optical clock community to plan out a roadmap of necessary milestones for the redefinition of the SI second. I will described the roadmap and the extended clock networks connected by optical fibres and other links that are being utilised for this work. Finally, I will explore applications directly related to time and frequency measurements and dissemination, miniaturised and portable atomic clocks, as well as how networks of clocks can be used to investigate a number of open questions in our understanding of fundamental physics.

Machine Learning Multi-Parameter Optimisation for a Zero-Field Optically Pumped Magnetometer
Rach Dawson, Carolyn O’Dwyer Edward Irwin, Marcin Mrozowski, Paul F Griffin and Erling Riis
University of Strathclyde, UK

The measurement of magnetic fields in the human body is already having a significant impact in a wide range of healthcare applications, including magnetoencephalography (MEG) and magnetocardiography, (MCG) [1,2]. Optically pumped magnetometers (OPMs) have been demonstrated as a transformative technology for these types of applications, achieving suitable signal resolution with a low SWAP [3].
We have developed a caesium zero-field OPM with a view to miniaturising this device for medical applications. Here we will present a single-beam setup using a microfabricated atomic vapour cell and custom electronics for low-noise operation which achieves femtoTesla-level sensitivity.

There are several key operating parameters which significantly impact the sensitivity of the OPM and consequently there are a high number of parameter configurations. In order to optimise for both sensitivity and SWAP, we have implemented a number of automated machine learning (ML) strategies.

Machine learning is an effective tool to interrogate systems with complex dynamics to find optimal parameters more efficiently than through human selection [4]. We will present several ML techniques which have been effective in significantly improving the sensitivity beyond that achieved using a manual approach.


Quantum Optics in the hyperfine Paschen Back regime

Ifan Hughes, Clare Higgins, Lina-Marieth Hoyos-Campo and Danielle Pizzey

Durham University, UK

The study of light propagation through thermal atomic vapours subject to external magnetic fields is a flourishing area of research. At Durham we have spent 20 years studying the spectroscopy of alkali-metal vapours. The applications range from devices (a compact optical isolator, narrow-line filters, solar filters) to fundamental physics (measuring the cooperative Lamb shift, single-photon generation). In this presentation I will describe experimental and theoretical work to model the electric susceptibility of a vapour of alkali-metal atoms in a large magnetic field, where a great simplification of the energy levels occurs (the hyperfine Paschen Back regime). This allows for the generation of ideal few-level systems, with very clean EIT (electromagnetically induced transparency) and four-wave mixing spectra. For example, in atomic Rb subject to a strong magnetic field of 0.6 T generated with permanent magnets, heralded single-photon generation was achieved with a greatly simplified internal level structure, which facilitated the theoretical modelling of the system.

Session 14 - Quantum theory

Uniqueness of the Phase Transition in Many-Dipole Cavity Quantum Electrodynamical Systems

Adam Stokes and Ahsan Nazir
University of Manchester, UK

The possibility of a superradiant phase transition is one of the most surprising collective phenomena to have been predicted in light-matter physics. It is however, still debated, because of numerous apparently conflicting no-go and counter no-go theorems which are proven in different gauges. It has been suggested for example, that artificial systems are required to circumvent the no-go theorem. We show that a unique phase transition does occur in archetypal many-dipole cavity QED systems, and that it manifests unambiguously via a macroscopic gauge-invariant polarisation. We show further that the gauge choice controls the extent to which this polarisation is included as part of the radiative quantum subsystem and thereby determines the degree to which the abnormal phase is classed as superradiant. This resolves the long-standing paradox of no-go and counter no-go theorems for superradiance, which refer to different definitions of radiation and are therefore not contradictory, but actually equivalent. A separate issue is that each gauge provides a different two-level approximation of the material dipoles. Our approach enables characterisation of physical behaviour in terms of any chosen material and radiation subsystems, using any of the non-equivalent approximate models. We provide exact numerical results for a finite number of dipoles, exhibiting clear precursors to the phase transition and demonstrating how accurate approximate predictions can be identified. Arbitrary-gauge QED therefore eliminates all apparent inconsistencies in the description of many-dipole cavity QED systems and their thermodynamic phases.

Quantum control to probe non-equilibrium dynamics

Steve Campbell¹, Ricardo Puebla² and Sebastian Deffner³

¹University College Dublin, Ireland, ²Instituto de Física Fundamental, ³University of Maryland, Baltimore County, USA

Steady progress has been made in developing tools to achieve high fidelity control of complex quantum systems. Within the plethora of techniques shortcuts to adiabaticity present a uniquely insightful perspective since they are often analytically determined. By knowing precisely how to suppress an otherwise non-equilibrium dynamics it seems reasonable that, rather than simply being a means to an end, quantum control actually provides a versatile window through which one can study and understand these processes, albeit not without some limitations.

This intuition can be explicitly demonstrated by employing another fundamental bound: the quantum speed limit. Geometric quantum speed limits quantify the tradeoff between the rate at which quantum states can change and the resources that are expended during the evolution. Combining with counterdiabatic driving, which is a unique tool from shortcuts to adiabaticity to speed up quantum dynamics while completely suppressing nonequilibrium excitations, we show that the quantum speed limit for counterdiabatically driven systems undergoing quantum phase transitions fully captures the relevant non-equilibrium properties entailed by the Kibble-Zurek
mechanism by correctly predicting the transition from adiabatic to impulse regimes, cfr. Fig 1, thus
demonstrating that quantum control can be an effective tool in studying non-equilibrium dynamics.

**Fig. 1:** The quantum speed limit for a controlled system increases at different rates for various
quench times (shown in different colours) only when the system is being driven in the impulse
regime.

![Diagram](image)

REF:
Puebla, Deffner, Campbell,
"Kibble-Zurek scaling in quantum speed limits for shortcuts to adiabaticity"

**Emergence of Gaussianity in the thermodynamic limit of interacting fermions**

Andrew Hallam, Gabriel Matos, Aydin Deger, Zlatko Papic and Jiannis Pachos
University of Leeds, UK

Systems of interacting fermions can give rise to ground states whose correlations become
effectively free-fermion-like in the thermodynamic limit, as shown by Baxter for a class of integrable
models that include the one-dimensional XYZ spin-1/2 chain. Here, we quantitatively analyse this
behaviour by establishing the relation between system size and correlation length required for the
fermionic Gaussianity to emerge. Importantly, we demonstrate that this behaviour can be observed
through the applicability of Wick’s theorem and thus it is experimentally accessible. To establish
the relevance of our results to possible experimental realisations of XYZ-related models, we
demonstrate that the emergent Gaussianity is insensitive to weak variations in the range of
interactions, coupling inhomogeneities and local random potentials.
Landscape sculpturing and dynamical decoupling of quantum systems with multifrequency driving

German Sinuco
University of Durham, UK

Accurate control of atomic and condensed matter systems is achieved using harmonic perturbations, resulting from their interaction with electromagnetic fields. In addition to enable investigating the properties of a system (e.g., via spectroscopy), harmonic drivings can be used for coherent manipulation of the system’s state (e.g., qubit rotations) as well as to modify its response to external fields (e.g., electromagnetically induced transparency). These mechanisms underline the potential of quantum systems to develop technological applications that take advantage of quantum mechanical effects. With this general principle in mind, we study the dynamics of atomic systems driven by several harmonic fields [1].

As concrete examples, we consider two applications for manipulating atomic ensembles of 87Rb using radio-frequency and microwave radiation. First, we show how shell trapping geometries produced by a combination of inhomogeneous MW and RF fields potentials present advantages over single dressed ones [2]. Second, we also propose a bichromatic scheme for dynamical decoupling of the full hyperfine ground state manifold [3].

We conclude with a discussion of the advantages of multifrequency driving offers for applications across different platforms for quantum technology.


Session 15 - Bates Prize

(Bates Prize talk) Extreme Plasmonics: Confining light to individual atoms, molecules and bond Vibrations

Rohit Chikkaraddy
University of Cambridge, UK

It has long been thought that light cannot be confined into volumes smaller than its wavelength due to the limit set by diffraction. Negative index materials such as metal nanoparticles, however, support quasiparticles called surface plasmons which trap light at metal-dielectric interfaces allowing us to ‘see’ the nanoworld. Extreme confinement of light can be achieved by coupling surface plasmons between two metallic nanostructures spaced a few nanometres apart.

In this talk, I will show the confinement of light down to 1nm3 approaching quantum limits. This is achieved with a robust optical cavity formed by placing a metal nanoparticle on mirror coated with a monolayer of molecules. The confined optical field in the gap amplifies the local density of states and supports enhanced light-matter coupling at room temperature and ambient conditions. I will also show how these unique features now enable strong coupling with electronic states of
molecules, Purcell-enhanced emission and optomechanics with single-bond vibrations, which are considered impossible to achieve with dielectric systems.

I will further show the applications of extreme nano-gap optics providing potential lead in single-photon detectors for mid-infrared light and sensing dynamic topology of cell membranes with sub-nm resolution. Finally, I will present the vision of building a light-controlled soft machinery that assembles quantum components and perform on-demand work, desirable in sustainable material design, low-energy information devices and point-of-care diagnostics.

Challenges and Opportunities for Matter-Wave Interferometry with Solids

Julen S. Pedernales and Martin B. Plenio

University Ulm, Germany

Recent developments in the field of optomechanics, including the flourishing subfield of levitated optomechanics, are promising the tantalizing possibility of matter-wave interferometry with solid objects in the nano- and micrometer scale. This would allow, in principle, exploring the high-mass regime of quantum mechanics (e.g., collapse models, quantum aspects of gravity) and would constitute a metrological device of unprecedented sensitivity to weak forces. However, the latter makes such a system also highly susceptible to interactions with its uncontrolled environment. This, together with the long experimental times that are typically required to operate objects of such sizes, demands the development of novel experimental protocols that can both extend the coherence times and shorten the duration of the experiments.

In my talk, I will provide an overview of several recent works, where we propose a collection of experimental techniques that can, in principle, achieve both of these goals. First, I will focus on decoupling the interferometer from its environment while retaining sensitivity to the signal of interest. This will include both active decoupling techniques, where the dynamics of the system is modulated to average out slowly fluctuating noises, as well as passive experimental arrangements that are inherently less sensitive to their environments. Second, I will discuss techniques aimed at enhancing the interaction of the interferometer with either a signal of interest or a second interferometer. The latter could then be used to achieve entanglement between two interferometers, which would offer insight into the nature of the forces mediating the interaction.

On the problem of the back-reaction in optomechanics and analogue models of pre-heating

Salvatore Butera1 and Iacopo Carusotto2

1The University of Glasgow, UK, 2INO-CNR Bec Center, Italy

We present an overview on our most recent results concerning the study of the back-reaction, that is a self-consistent theory of the interaction between a quantum field and its background. The problem of the back-reaction plunges its roots in the field of gravity but, nevertheless, is a general concept, and relevant to a wide range of physical systems. We pursue this study within the frameworks of optomechanics and analogue models based on Bose-Einstein condensates of ultra-cold atoms.

In the former case, we consider an optical cavity enclosed by a freely moving mirror. In this case, the back-reaction is exerted onto the moving mirror by the particles created in the cavity by
dynamical Casimir effect. At the mean-field (semi-classical) level, this appears as an effective damping experienced by the moving mirror. Beyond the semi-classical level, observable signatures of the interplay of the nonlinear nature of the effective mirror-cavity coupling and of the discreteness of the emitted photons are pointed out, in particular as a fast diffusion of the mirror oscillation phase.

In the latter case, a time-dependent background is implemented by considering a non-stationary condensate. We simulate the phenomenon of the Pre-Heating in the early Universe by letting an elongated condensate oscillate in its transverse direction. We observe the parametric amplification of the vacuum fluctuations in the longitudinal modes and the damping of the transverse oscillations. Signature of the back-reaction beyond the semi-classical level is observed in the decoherence of the transverse dynamics.