Monday, August 6

2.00pm - 3.40pm: Session one

- **Invited talk** - Chris Vale - Exciting sounds in Fermi superfluids

Understanding dynamics in strongly correlated quantum systems is a challenge that can now be addressed with ultracold atoms. Here, we present measurements of the low-lying excitation spectra of Fermi gases with tunable interactions using Bragg spectroscopy. At temperatures below the superfluid transition, the excitation spectra are dominated by the Goldstone mode or Bogoliubov-Anderson phonon, associated with the superfluid order parameter. At higher energies, single-particle excitations become visible and enable a direct read-off of the pairing gap. In the hydrodynamic regime, the spectral shape of the phonon mode provides insight into the transport properties of these systems including the sound velocity and diffusivity which we investigate across a range of temperatures in gases with resonant interactions.

- **Contributed talk** - Yauhen Sachkou - Two-dimensional superfluids

Two-dimensional superfluids exhibit rich quantum behaviour such as, for instance, topological quantum phase transitions. The key role in these phase transitions is played by quantized vortices that determine microscopic behaviour of 2D quantum fluids. However neither of the experimental techniques available so far have been capable of probing microscopic dynamics of 2D superfluids in real time and resolving single quantized vortices. Here we introduce a novel approach to probe microscopic physics of 2D quantum fluids based on the evanescent interaction between a few-nanometer-thick superfluid helium film and an optical whispering gallery mode microcavity. This method enables sound waves on top of the superfluid helium film to be confined to a surface of a microscale optical resonator where they interact with quantized vortices. Small area of confinement enhances interactions between sound waves, vortices, and light and combined with cavity-enhanced precise optical read-out enable measurement of vortex-phonon and vortex-vortex interactions.
We report on observation of superfluid sound modes spectral splitting induced by quantized vortices in 2D superfluid helium and detection of as few as 40 vortices which is two orders of magnitude fewer than ever before. Tracking dynamics of an ensemble of quantized vortices in real time provides a new tool to explore the microscopic behaviour of 2D strongly interacting quantum fluids. Our results could lead to a deeper understanding of 2D quantum phase transitions, dissipation mechanisms in 2D superfluid helium systems, quantum turbulence and potential realization of optomechanics with quantized vortices.

- **Contributed talk** - Guillaume Gauthier - Transport Dynamics of an Atomtronic LRC Circuit

The field of atomtronics seeks to implement analogues of electronic circuits with ultracold quantum gases confined to configurable potentials (traps), both for future quantum devices, such as inertial sensors, and also for fundamental research into particle transport. At the heart of the atomtronic perspective, and most engineering disciplines, are lumped abstraction models, that, in the electronics context, allow complex circuits to be represented as a series of simple electronic elements. Though these models are useful, in that they hide complex parts of the underlying microscopic physics, they must not leave out so much information as to be unable to make reliable predictions about the system dynamics.

The experimental study presented investigates the utility of the lumped circuit model in describing an atomtronic LRC-resonator circuit, composed of two superfluid reservoirs connected by a channel (weak link), Fig. 1. We find that the circuit model breaks down due to finite-size effects and the nonlinear interaction between the atoms, being recovered in the small atom-number limit. We examine the resistivity of the weak link and find an Ohmic relationship, consistent with a contact resistance manifest as phase-slips at the weak link location.

- Contributed talk - Kamil Korzekwa – Avoiding irreversibility: lossless interconversion of quantum resources

The rapid progress in experimental techniques to control quantum systems may soon bring the advent of new technologies that will utilize quantum effects to overcome the limitations of the current classical technology. It is thus crucial to understand which components of the quantum theory can provide such an advantage, i.e., to understand what actually constitutes quantum resources. This can be achieved within a resource-theoretic framework by identifying the set of operations that are considered free, and the set of restrictions that make other operations impossible without an additional cost. Such restrictions may arise from practical difficulties, e.g., when preparing a system in a superposition of particular states is experimentally challenging, but may also be of fundamental nature, as with the laws of thermodynamics constraining possible transformations to preserve energy and increase entropy. A resource is then defined as a physical system that allows one to lift a given restriction. A paradigmatic example is provided by the entanglement theory: Alice, facing a restriction of not sharing a quantum channel with Bob, cannot send him a quantum state $|\psi\rangle$. However, if they were in possession of a (resource) maximally entangled state, they could use it to teleport $|\psi\rangle$.

Once the resources are defined, the central question concerns the problem of interconverting them: given a particu- lar initial state ρ we want to know what are the states σ that can be obtained via free operations. The interconversion problem so far was mainly studied in the single-shot limit (transforming individual quantum systems) and the asymp- totic limit (assuming access to infinitely many copies of ρ and looking for a conversion rate to σ). However, many practically relevant and fundamentally interesting questions lie in the intermediate regime. On the one hand, quantum resources like entanglement and coherence will only be available in small amounts in the foreseeable future. Onthe other hand, in quantum thermodynamics we want to explore how the known macroscopic laws change when we go beyond the thermodynamic limit and consider thermal processes involving finite number of particles. In both cases a rigorous analysis of the interconversion between finite-size quantum resources is needed.

In this contribution we present a moderate deviation analysis of the interconversion problem for all resource theories whose single-shot transformation rules are based on the majorization relation. This way we build a unified framework to study finite-size interconversion within the resource theories of entanglement, coherence and thermodynamics. More precisely, we derive the optimal trade-off between the rate R_n at which n copies of a resource state ρ can be transformed into $R_n n$ copies of σ, and the infidelity of this transformation E_n, as a function n. Our results can be directly applied to the study of important problems such as entanglement distillation or coherence dilution, but also allow one for a rigorous analysis of the irreversibility arising when finite-size resources are interconverted. For example, it is well known that within a resource theory of thermodynamics there is a finite gap between the amount of work needed to create a state, and the amount of work that one can extract from the same state. Our tools allow one to study how quickly such gaps close for all resource states when n increases. Most intriguingly, we find that if a pair of states satisfies a particular resonance condition, one can achieve lossless interconversion, i.e., transformation that is arbitrarily close to reversible even for finite n. We discuss how this effect can be employed to avoid irreversibility, which directly affects, e.g., the performance of heat engines working with finite-size working bodies.

4.00pm - 5.30pm: Session two

- **Invited talk** - Maja Cassidy - Superconducting circuits operating in strong magnetic fields for hybrid quantum computing

Hybrid and topological quantum computing have emerged in recent years as promising avenues for the development of a practical, general purpose quantum computer. Hybrid quantum computing envisages using superconducting qubits for fast quantum information processing, while storing the quantum states in long lived spin based memories when not in use. Topological quantum computing schemes require a fast charge-parity readout sensor, as well as a method to couple spatially separated topological qubits. The proposed solution, a transmon qubit that operates at very strong magnetic fields, has been an outstanding technical challenge.

In this talk, I will present our progress towards this goal through the development of magnetic field resilient superconducting circuit elements. We have developed high quality factor superconducting resonators that maintain their performance up to several Tesla and mesoscopic Josephson junctions made from semiconductor nanowires or graphene that are resilient to strong magnetic fields. By combining these elements, we demonstrate the operation of a Transmon qubit in a 1T magnetic field.

- **Contributed talk** - Clemens Mueller - A passive, on-chip microwave circulator using a ring of tunnel junctions

The unavailability of integrated microwave circulators is currently one of the major roadblocks on the way towards true scaling up of superconductor based quantum tech- nology, with many recent proposals aimed at overcoming this capability gap. In general, these require additional microwave or radiofrequency components and therefore increase control complexity significantly. Here, I will present our recent proposal for a fully passive, on-chip microwave circulator based on a ring of superconducting tunnel junctions. We investigate two distinct physical realisations, based on either Josephson junctions (JJ) or quantum phase slip elements (QPS), with microwave ports coupled either capacitively (JJ) or inductively (QPS) to the ring structure. A constant bias applied to the center of the ring provides the symmetry breaking (effective) magnetic field, and no microwave or rf bias is required. We find that this design offers high isolation even when taking into account fabrication imperfections and environmentally induced bias perturbations and find a bandwidth in excess of 500 MHz for realistic device parameters.

- **Contributed talk** - Andres Rosario Hamann - Nonreciprocal superconducting circuit based on quantum nonlinearity

Nonreciprocal devices are essential for signal routing and noise isolation. Rapid development of quantum technologies boosted demand for a new generation of miniaturized and low-loss nonreciprocal components. Here we use a pair of tunable superconducting artificial atoms in a 1D waveguide to experimentally realize a minimal passive nonreciprocal device. Taking advantage of control over frequencies of the atoms and of their quantum nonlinearities we achieve nonreciprocal transmission through the waveguide in a wide range of powers. We provide evidence that nonreciprocity is associated with population of the two-qubit non-local entangled quasi-dark state which responds asymmetrically to incident fields from opposing directions. Our experiment enlightens the role of quantum correlations for enabling nonreciprocal behavior and shows the path to build passive quantum nonreciprocal devices without using magnetic fields.

- **Contributed talk** - Janna Hinchliff - A nuclear spin quantum memory in an InGaAs quantum dot system

An excess electron spin in a quantum dot (QD) is a two-level spin qubit, behaving much like an atom [1]. However, QDs contain 105 atoms, each of which have some non-zero spin value. This means the system is subject to the hyperfine interaction, as the inherent strain introduced into the QD during its growth process causes each nucleus to have a position-dependent hyperfine coupling to the electron spin, creating an effective, varying magnetic field (the Overhauser field), which decoheres the electron spin state. To create a nuclear spin quantum memory, we require the electron to interact with a single nucleus, such that the spin state of the electron can be transferred to this target nucleus via the hyperfine interaction between these two particles only. We show that in the absence of a nuclear spin bath, the two-spin subsystem of the electron and nucleus will precess coherently due to the hyperfine interaction. If there is no external field acvting on this system, the two spins will periodically become maximally entangled, taking on the SWAP configuration. At the point of maximal entanglement, we show that it is possible to disentangle the electron spin from the nucleus by applying a π to project the electron onto the axis perpendicular to the nucleus. This leaves the electron spin state contained in the nucleus. We also show that it is possible to perform a quantum non-demolition measurement on the nucleus via an ancilla photon to read out the spin state projected onto the nucleus.

In reality, we do not have this ideal two-spin subsystem within our QD. Instead, we have a quickly decohering electron spin in a huge bath of nuclei, which we are unable to model effectively, due to the size of the Hilbert space the system occupies. However, we propose to use a protocol known as nuclear frequency focusing (NFF) to narrow the state of this nuclear spin bath, using a train of circularly polarised laser pulses along the optical axis and a small (200mT) external magnetic field in the plane of the QD [2]. This acts to align the nuclei along the axis of the external field, whilst simultaneously driving the electron spin along the optical axis. We define the number of nuclei aligned with the external field as $N_{\rightarrow}$ and the number anti-aligned as $N_{\leftarrow}$. A pulse on resonance with the QD will give $N_{\rightarrow}$ $N_{\leftarrow}$ = 0, equivalent to an Overhauser field of 0. Varying the pulse power and detuning and the external introduces asymmetry in the direction of alignment of the nuclei, giving control over the magnitude of the Overhauser field. As the protocol requires a total field of 0, we show that by controlling the detuning and power of the laser pulse, we can set the size of the Overhauser field to be equal to the external field in the opposing direction.

We now need to perturb a single nucleus from this narrowed configuration, and project it into the plane of the electron spin. To address a single nucleus we need to consider the strain profile of the QD. Many of the nuclei in the bath will have a spin quantum number > 1/2 and will therefore be subject to the quadrupolar interaction, introducing a quadrupolar coupling, A_Q dictated by strain [3]. Modeling the distribution of values A_Q for each nucleus allows us to choose a 5MHz region with high probability of containing a single nucleus. We can then address this nucleus using a radiofrequency pulse with 5MHz linewidth (equivalent to an intialisation time of 200ns), and project it into the plane of the electron spin. The electron and nucleus then evolve according due to their hyperfine coupling, as discussed above and we show that the coherence time of the nuclear spin bath is sufficiently long to implement the nuclear spin quantum memory protocol.

Tuesday, August 7

9.00am - 10.30am - Session three

- **Invited talk** - Arne Laucht - Spin Qubits in Silicon – Control and Characterization

Spin qubits in silicon are one of the big contenders for a scalable, solid state-based quantum computing platform. The qubits are encoded as the spin states of individual electrons and nuclei localised inside silicon chips, either confined in electrostatically-gated quantum dots or on donor atoms that are implanted in the chip. The great potential of this system has been demonstrated through various experiments over the last few years, with coherence times of up to a second for the electron spin and half a minute for the nuclear spin, and qubit control fidelities exceeding 99.9 %.
In my presentation, I will give an introduction to the donor and quantum dot spin qubits that we employ within the teams of Andrea Morello and Andrew Dzurak at UNSW. I will showcase some of the key experiments of the last years and discuss the current state-of-the-art in performance. Close to the fault-tolerant limit, it is necessary to understand the origin of decoherence and infidelities to further improve the qubits. Thus, techniques like noise spectroscopy and benchmarking, that allow us to find and mitigate sources of error, become important tools in an experimentalist's toolbox.

- **Contributed talk** - Marcin Piotrowski - Thorium Ion Trap – Not Only for Nuclear Clock

The nuclear clock based on thorium ion in radio-frequency trap is attractive from a number of technical perspectives and provide us with a clock transition with expected spectacular fractional accuracy and stability [1,2]. Design and simulation work has shown that a trapped Th^{3+} ion could be developed in a compact and relatively low cost package, making field deployment in a dispersed network achievable. In addition, it has been shown that the Th^{3+} is an excellent system for precision measurement of the drift in the fine structure constant [3]. In view of recent advances in spectroscopic characterization of nuclear isomer transition in thorium [4,5] we can expect the demonstration of nuclear clock in very near future.

Our project aims at a compact and low cost-platform for thorium ion trap. It is a result of a collaboration between CSIRO and Griffith University. We present our experimental setup for investigating thorium ions in Paul trap and studies of a laser ablation as a method of loading it. We also discuss our findings from other ions traps and their possible implementation in future miniaturised thorium traps, crucial element of future atomic clocks networks.

Our initial motivation for nuclear clock development was a disperse network of clocks for gravity monitoring, but in course of further studies we found other interesting applications for compact thorium trap. The high sensitivity broadband force sensing can be realized through super-resolution imaging of single ions co-trapped with large biomolecules, like nucleic acids and proteins [6]. Thorium might be particularly useful in studies of forces in such molecules.

[1] Peik, E. and Okhapkin, M. Comptes Rendus Physique 16(5), (2015)
[2] Campbell, C. J. et al. Phys. Rev. Lett. 108, 120802 (2012)
[3] V. V. Flambaum and S. G. Porsev, Phys. Rev. A 80, 064502 (2009)
[4] L. von der Wense et al. Nature 533, 4751 (2016)
[5] J. Thielking et al. Nature 556, 321–325 (2018)
[6] V. Blums et al. Science Advances 4(3) eaao4453 (2018)

- **Contributed talk** - Tobias Vogl - Next-generation single-photon sources in two-dimensional hexagonal boron nitride

Color centers in solid state crystals have become a frequently used system for single-photon generation, advancing the development of integrated photonic devices for quantum optics and

quantum communication applications. Recently, defects hosted by two-dimensional (2D) hexagonal boron nitride (hBN) attracted the attention of many researchers around the world, due to its chemical and thermal robustness as well as high single-photon luminosity at room temperature. Unlike for NV centers in diamond and other solid-state quantum emitters in 3D systems, the 2D crystal lattice of hBN allows for an intrinsically ideal extraction efficiency, as none of the emitters are embedded in any high refractive index material and are consequently not affected by Fresnel or total internal reflection. In addition, atomically-thin crystals can be integrated into photonic circuits easily.
Here we present recent advances in engineering this new type of emitter. Particularly, the yield of high quality single-photon emitters is enhanced by plasma etching and optimizing the fabrication parameters. A full optical characterization reveals a narrow spectrum, an exceptionally short excited state lifetime, and high single-photon purity, with all properties remaining photostable over very long time scales. We deterministically transfer hBN crystals hosting single-photon emitters onto arbitrary substrates, while maintaining their single-photon emission capabilities, allowing for the usage in photonic networks.

Finally, we will discuss promising directions and challenges, specifically preliminary results on coupling the emitters with nanophotonic cavities and consider the feasibility of these single-photon sources for practical quantum information processing protocols. We also assess the usage on Nanosatellites because of the source's high temperature robustness as well as its SWaP (Size, Weight and Power) requirements and show preliminary results on our implementation on a 1U CubeSat.

- Contributed talk - Kavan Modi - Stochastic processes are ubiquitous in nature

Stochastic processes are ubiquitous in nature. The field of stochastic processes is a mainstream topic in engineering, mathematics, and physics. These mathematical tools are used to model traffic, ecosystems, chemical reactions, fundamental physical processes (like Brownian motion), and most importantly the stock market! Thusly, it is a highly productive field with measurable impact on topics of foundational and economic importance. Yet, the quantum counterpart to this field is surprisingly underdeveloped and an overarching theory was missing till recently. I will describe a universal framework for quantum stochastic processes and how this framework could play an important in developing quantum technologies of the future and even answering some foundational questions.

10.50am - 11.30am: Session four

- Invited talk - Emma Mitchell - Effect of array geometry on SQIF sensitivity

One and two dimensional arrays of dc SQUID loops connected in series and/or parallel have been used to improve the periodic voltage-magnetic field output and noise response compared to that of single SQUIDs [1]. When the areas of the individual SQUID loops vary throughout the array, the voltage response as a function of magnetic field is dominated by a steep anti-peak at zero field with weaker, aperiodic voltage oscillations at non-zero fields due to interferometric processes. These SQIF arrays were developed for absolute magnetic field detection because the anti-peak is located at zero magnetic field [2]. Large 2D SQIF arrays with total junction number $N \sim 20{,}000$ are possible using YBCO junctions due to the flexibility of the technology [3]. The voltage output from arrays is expected to scale with N_s, the number of Josephson junctions in series whilst the anti-peak width is expected to decrease with an increasing number of loops in parallel, N_p [4]. Therefore as the total number of loops N increases, the sensitivity (dV/dB) should also increase. Results from investigations of small SQUID and SQIF arrays fabricated using YBCO step-edge Josephson junctions [5] show that the sensitivity can depend on the array geometry. Using both analytical and numerical methods, we present theoretical simulations of SQIF performance with different geometries and in different parameter regimes. These new simulations extend earlier work [2], and investigate the effect of the loop inductance and the junction parameters on the voltage response of small ($N < 50$) arrays. These simulations predict the general trends seen in the experimental data and highlight methods to optimize array design.

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[2] J. Oppenlander *et al*., *Phys. Rev. B,* **63**, 024511 (2000).
[3] E.E. Mitchell *et al*. *Supercond. Sci. Technol*. **29**, LT0601 (2016).
[4] V. Schultze, R. Ijsselsteihn and H-G Meyer, *Supercond. Sci. Technol.* **19** S411-S415 (2006).
[5] E. E. Mitchell & C. P. Foley *Supercond. Sci. Technol*. **23**, 065007 (2010).

- **Contributed talk** - Gavin Brennen - Robust symmetry-protected metrology with the Haldane phase

I will describe a metrology scheme that is made robust to a wide range of noise processes by using the passive, error-preventing properties of a symmetry-protected topological phase [1]. The so-called fractionalized edge mode of an antiferromagnetic Heisenberg spin-1 chain in a rotationally-symmetric Haldane phase can be used to measure the direction of an unknown electric field, by exploiting the way in which the field direction reduces the symmetry of the chain. Specifically, the direction of the field is registered in the holonomy under an adiabatic sensing protocol, and the degenerate fractionalized edge mode is protected through this process by the remaining reduced symmetry. Furthermore, by applying a known background field one can also measure the strength of the unknown field. Potential realisations are trapped Rydberg atoms in optical lattices, trapped ion chains, and superconducting circuit arrays.

[1] S. Bartlett, G.K. Brennen, and A. Miyake, "Robust symmetry-protected metrology with the Haldane phase," Quantum Science and Technology 3, 014010 (2017).

- **Contributed talk** - Bixuan Fan - Stochastic resonance

Stochastic resonance (SR) is an interesting nonlinear phenomenon, whereby the presence of noise can counter-intuitively improve the quality of a feeble signal passing through a nonlinear system. In the classical world, it has been widely applied in weak signal amplification and detection with the assistance of thermal noises. Recently, increasing interest has been directed toward studying SR in the quantum domain, however, work on SR induced by pure quantum fluctuations at zero temperature has been very rare. Here we numerically demonstrate the occurrence of SR induced by zero-point quantum fluctuations in the Jaynes-Cummings model. Under experimentally accessible conditions, we find that quantum fluctuations can convert a weak signal to the large-amplitude coherent switching between metastable states of the system. Besides, we present a route for searching for conditions that favor SR in a general quantum system. Our results provide a theoretical basis for experimentally observing and studying the SR phenomenon of the Jaynes-Cummings model in the deep quantum regime.

2.00pm - 3.30pm: Session five

- **Workforce Science Review** - Cathy Foley
- **Workforce Science Review** - Andre Luiten

4.00pm - 6.00pm: Session six

- **Industry talk** - John Weston / Julian Fay - Keys to the future - the impact of Quantum technology on the cyber security industry

The rise of Quantum technologies and in particular the promise (threat?) of quantum computing is already having a profound impact on the cyber security industry, some are calling this a 'Y2Q' moment for cyber security.

We are at the dawn of a transition to Quantum Safe computing and standards bodies around the world are quite rightly reacting to the challenges of keeping our digital ecosystems safe in a Quantum enabled world. New cryptography standards are being drafted by regulatory bodies and vendors are planning their product strategies.

A huge amount of uncertainty remains however, we don't yet have probably safe Quantum resistant tools and we face the daunting but necessary task of making all our digital devices from PCs to mobile phones to IOT appliances ready for this new reality.

Senetas is one of Australia's leading developers and exporters of encryption technology to many of the world's largest government, defence and enterprise organisations.

In this session Senetas CTO Julian Fay and Chief Engineer John Weston will discuss the real world implications of Quantum technology on the global cyber security industry and provide insights into how the the industry is handling the challenges and opportunities presented.

- Industry talk - Anna Phan - The IBM Q Program: from research to commercialisation and beyond

- Panel discussion on Quantum Technology themes - Chair: Ben Greene (EOS); Maja Cassidy (Microsoft), Halina Rubinsztein-Dunlop (EQUS/UQ), Vikram Sharma (Quintessence), Jared Cole (RMIT/FLEET)

Wednesday, August 8

9.00am - 10.50am: Session seven

- **Industry talk** - Ben Greene - Societal Wealth from Quantum Technology: Elements of Commercialisation

- **Industry talk** - Susannah Jones - Quantum Technology in the Military Domain

- **Panel session on Industry Sectors** - Chair: Cathy Foley (CSIRO);   Susannah Jones (DSTL), Cather Simpson (UAuckland), Julian Fay (Senetas), Emma Mitchell (CSIRO)

11.10am - 12.00pm: Session eight

- **Workforce needs Panel** - Chair: Mohan Krishnamoorthy (UQ); Anna Phan (IBM), Clemens Mueller (IBM/ETH) Zurich, Tom Stace (EQUS/UQ), Andrew White (EQUS/UQ)

2.00pm - 3.30pm: Session nine

- **Invited talk** - Meera Parish - Many-body quantum batteries

"Quantum batteries" seek to use non-classical effects, such as quantum entanglement, to impart an advantage compared with classical batteries. Typically, quantum batteries have been modelled as a collection of independent and identical subsystems, to which a temporary global charging field is applied in order to extract or deposit work. In this talk, I will extend the notion of a quantum battery to a many-body quantum system with intrinsic interactions that are physically realistic.

- **Contributed talk** - Christopher Perrella - Optical Quantum Information Processing with Warm Atom-Filled Hollow-Core Photonic Crystal Fibres

Hollow-core photonic-crystal fibres (HC-PCF) provide efficient and strong atom-light interaction that can be utilised to produce strong multi-photon transitions for use in quantum logic gates (cross-Kerr nonlinearities) or quantum memories. We present a broad study of photon-photon interactions mediated via a two-photon transition in a rubidium vapor which is excited within hollow-core fibers of different core diameters, d, [1]. Limited light-atom interaction times lead to transit-time broadening, increasing the spectral line-width proportional to 1/d, (Fig. 1(a)). As a result, the interaction strength increases proportional to the optical mode diameter, 1/d, rather than that typically expected from an increasing field intensity, 1/d^2. This allows accurate estimation of the expected photon-photon interaction strength for a given waveguide geometry, allowing waveguide designs to target specific photon-photon interaction strengths. We utilise this understanding to perform off-resonance cascaded absorption (ORCA) [2] (Fig. 1(b,c)). Preliminary results show a 10% memory efficiency, a bandwidth of hundreds of MHz to GHz, and a 30ns coherent storage time which we expect to increase to 90ns.

[1] C. Perrella, et al., Engineering Photon-Photon Interactions within Rubidium-Filled Waveguides, Physical Review Applied, 9, 044001 (2018).
[2] K. T. Kaczmarek, et al., A high-speed noise-free optical quantum memory, arXiv:1704.00013v2 (2017).

- **Contributed talk** - Paul Sibley - Phase measurement performance of Digital Interferometry for Optical Phased Arrays

Digitally Enhanced Heterodyne Interferometry (DEHI) is an optical metrology technique that enables the isolation and simultaneous phase measurement of a number signals at a single photodetector. It is a spread spectrum modulation technique where the optical signals are tagged with a pseudo-random noise code similar to Code Division Multiple Access (CDMA) used in Radio Frequency communications, notably GPS and the CDMA mobile network. Since the original presentation of its optical counterpart [1], it has been successfully implemented in a variety of optical applications. These include an Optical Phased Array [2] with λ /194 RMS phase noise for three emitters, distributed fibre sensing [3] and wavefront sensing [4] using spatial light modulation. It has also been used to measure the phase of reflections separated by down to 36cm [5].

Optical Phased Arrays coherently combine multiple lasers in a tiled output array. This allows for increased power, a rapidly steerable beam and a fast actuator stage for adaptive optics. These properties make them an ideal basis for establishing free space links. In order to achieve these features with a high level of performance, 10’s to 100’s of emitters will be required. The performance of DEHI in isolating the phase of a single channel, whilst suppressing the others, determines the limit in scaling up the number of emitters in our demonstrator. This is because each additional signal channels increases the total remnant phase noise.

This noise floor is of particular importance for a low noise laser link, as reduction in the fidelity of the phase measurement will increase the amplitude noise and jitter on the coherently combined beam. For designing new or more sophisticated implementations of an OPA with an increased number of emitters, a rigorous understanding of the effects contributing to the suppression and their net effect on introduced phase noise for different number of signals is required.

Existing implementations of DEHI have had varied phase measurement bandwidth, phase measurement precision and total number of signals isolated but have yet to have dedicated investigation into this parameter space. This work provides a series of investigations into the fundamental and practical effects which change the sen- sitivity of DEHI as the number of signal channels is increased in different configurations. A combination of an analytical description of the technique, with simulation of characteristic experimental implementations are used to show the influence of these effects. A fiber based DEHI implementation is used to assess the validity of the noise floors derived from simulation for an increasing number of signal channels. Recommendations for maximizing the precision of the phase measurement for particular experimental configurations are also provided.

1. D.A. Shaddock, *Digitally enhanced heterodyne interferometry*, Opt. Lett. 32(22), 3355-3357 (2007)
2. L.E. Roberts, et al., *High power compatible internally sensed optical phased array*, Opt. Express 24(12), 13467-13479 (2016)
3. D.M.R. Wuchenich, T.Y. Lam, J.H. Chow, D.E. McClelland, D.A. Shaddock, *Laser frequency noise immunity in multiplexed displacement sensing*, Opt. Lett. 36(5), 672-674 (2011)
4. D.T.Ralph,P.A.Altin,D.S.Rabeling,D.E.McClelland,D.A.Shaddock,*Interferometricwavefrontsensing with a single diode using spatial light modulation*, Appl. Opt. 56(8), 2353-2358 (2017)
5. K.S. Isleif, et al., *Highspeed multiplexed heterodyne interferometry*, Opt. Express 22(20), 24689-24696 (2014)

- **Contributed talk** – Erik Streed - Towards building a telecom compatible Quantum Repeater using trapped ions.

Secure communication between distant parties is a critical strategic capability for both defence and civilian applications. Quantum Key Distribution (QKD) relies on using quantum properties, such as superposition and entanglement, to securely share a common encryption key between two remote parties. These same quantum properties also precludes the use of conventional amplification, limiting the present generation of terrestrial QKD systems to operational ranges of <200 km due to losses in telecom optical fibres. One solution to this distance limitation is to use a quantum repeater architecture where the transmission line is divided into smaller segments connected by processing nodes that can temporarily store quantum information and perform basic quantum computational tasks, enabling an end-to-end quantum link that is not dependent on the physical security of each of the intermediate nodes.

Trapped ions are a well established platform for performing quantum information processing tasks and a promising candidate for implementing quantum repeaters. Two of the limiting factors are scaling to operate with a large number of ions and efficiently converting the fixed frequency UV atomic fluorescence at 370 nm which is strongly absorbed by long lengths of optical fibre to the much lower absorption IR telecom band. To this end we have demonstrated a microfabricated surface trap with an array of integrated diffractive mirrors (Ghadimi et al., NPJ Quantum Information 3, 4(2017)) that exhibits both a high collection efficiency of 4.1(6)% of the total ion fluorescence and diffraction-limited imaging performance resulting in coupling 71(5)% of that light into a single mode optical fibre. Complimentary to this we have also demonstrated by mixing a weak single mode UV with a strong blue beam at 485 nm in a custom made periodically poled lithium niobate waveguide, light can be converted to telecom wavelength at 1550 nm by difference frequency generation (Kasture et al., Journal of Optics 18, 104007(2016)). Current progress towards combining these two system to create source of trapped ions entangled with tunable telecom IR band photons will also be reported.

4.00pm - 5.30pm: Session ten

- **Invited talk** - Cather Simpson - Optical Methods for Sorting Particles – Lasers and Sperm

- **Contributed talk** - Jesper Levinsen - Impurities in quantum matter

Controllable impurities act as sensitive probes of how few-body correlations emerge in strongly correlated quantum matter. I will discuss recent progress in the understanding of quantum impurity physics, both in the context of ultracold atomic gases and in exciton-polariton systems. Ultimately, the understanding of correlations in many-particle systems can allow us to harness their properties for a new generation of quantum devices.

- **Lightning talks**

6.00pm - 7.30pm: Posters and networking - Atrium

Poster presenters:

- Felix Pollock - Quantum speed limits

The rate at which quantum systems can be transformed, in contexts ranging from the application of logic gates in a quantum computer to the state preparation and readout of metrological probes, is a limiting factor for many quantum technology platforms. So-called quantum speed limits can be used to estimate the fastest time possible to perform a particular transformation, but existing results are often only useful in the limit of ideal unitary transformations on clean systems with full control. Here, I will present new, operationally meaningful speed limits that allow for the accurate estimation of bounds on the evolution time of realistic noisy systems. I will go on to discuss their relation to the underlying geometry of quantum state space, hinting at how time optimal transformations could be achieved in practice.

- Tapio Simula - A case for topological quantum computation with Bose-Einstein condensates

The future of computational physics will be strongly influenced by the development of quantum computers. Topological quantum computers are a class of quantum computers whose intrinsic fault-tolerance is thought to be outstanding. Much effort has been dispensed on the search of non-Abelian anyons---exotic quasiparticles out of which the topological qubits of a topological quantum computer will be constructed. Perhaps the most prominent candidates of such non-Abelian anyons are Majorana zero modes in certain chiral p-wave superfluids and superconductor-semiconductor nanowires. In an effort to find new 'materials' for topological quantum computers, we have recently studied Bose-Einstein condensates capable of hosting non-Abelian anyons in the form of non-Abelian fractional vortices, potentially useful for topological quantum computation. We have proposed several new non-Abelian anyon models and have computationally demonstrated the actions required for braiding and fusion of such anyons to achieve single qubit and two-qubit operations. A road map for developing a topological quantum computer platform using non-Abelian fractional vortex anyons in Bose-Einstein condensates will be presented.

- Hui Hu - Two recent developments on collective modes of a strongly interacting atomic Fermi gas

Low-lying collective excitations play a fundamental role in understanding quantum many-body systems. The recent realization of ultracold atomic Fermi gases provides a unique setting for investigating various intriguing collective phenomena. In this talk, I will briefly introduce two recent theoretical challenges on understanding collective modes of a strongly interacting atomic Fermi gas, i.e., the phonon damping and quantum anomaly of a strongly interacting unitary Fermi gas [1, 2, 3].

- Robert Harris - Quantum Error Correction

Recently a link between Quantum Error Correction and AdS/CFT correspondence has been proposed using Holographic Codes created with perfect tensors. Additionally recent work has demonstrated how to create any CSS code with cluster states. We combine these developments in a procedure to create a CSS Holographic Code using cluster states, and a mechanism to recover and correct information after loss of physical qubits. This high rate code opens the possibility of the fault tolerant computation on many logical qubits from a single state.

- Thomas Bell - Gyroscopes & Magnetometers using Spin-Orbit Coupled Bose-Einstein Condensates

Interferometers are devices which accumulate a phase difference between coherent modes as they independently interact with an interrogated system, and subsequently measure an interference signal. While inertial sensors aboard aircraft colloquially use laser fields, massive 87Rb particles are 5 1010 times more sensitive to rota- tions given identical interrogation conditions. Engineer- ing suitable systems however presents an ongoing tech- nical challenge. Thermal atom gyroscopes have suc- cessfully demonstrated sensitivities greater than optical counterparts [1]. These systems typically propagate laser cooled ensembles through parabolic free space trajecto- ries, forming Mach-Zender style interferometers. Inter- rogation times are normally limited by the system size. Longer interrogation, reduced shot noise and quantum enhancement each motivate waveguided and condensed atom protocols. Many theoretical strategies overcome deleterious phase diffusion within confined systems [2–4], though each introduce unique experimental hurdles.

We here outline how the spin-orbit coupling scheme for Sagnac interferometry and magnetometry proposed in [5] may be achieved straightforwardly following our recent experimental progress [6, 7]. We experimentally produce ring-shaped condensates through the rapid scan- ning of an optical potential [Fig. 1]. Though the bulk superfluid responds to the time-averaged potential, the instantaneous potential coincidentally serves to imprint a local phase gradient, strongest at the optical beam lo- cation. Understanding this mechanism was crucial to re- moving the resulting perturbations, and produce smooth optically confined condensates [Fig. 1(I-II)]. Using global magnetic field ramps and radio frequency state transition pulses, we should now capably perform rotation sensitive measurements.

- Russell Anderson - Realisation of a fractional period adiabatic lattice

We propose and realised a strongly sub-wavelength optical lattice for ultracold neutral atoms using N resonantly Raman-coupled internal atomic degrees of freedom. Although the Raman lasers had wavelength λ, the resultant lattice-period was $\lambda/2N$, an N-fold reduction as compared to the conventional $\lambda/2$ lattice period. We experimentally demonstrated this lattice using three hyperfine states in a ^{87}Rb Bose-Einstein condensate, and generated a lattice with a 132nm period from λ = 790nm lasers.

- Kwan Goddard Lee - Experimental Superfluid Vortex Dynamics in a BEC

Turbulence is encountered everywhere from atmospheric flows, airflow in jet engines to when milk is mixed with coffee. While everyone has some experience of turbulence or turbulent flows, it still isn't well understood mathematically. As Richard Feynman once said "turbulence is the most important unsolved problem of classical physics".

Using the experimental apparatus at UQ we can perform highly controllable and repeatable experiments on Bose-Einstein Condensates (BECs) tightly confined in two dimensions. These are almost ideal quantum fluids which are perfect for studying the fundamentals of many classical turbulent phenomena without the effects of friction and viscosity. The vortices such as eddies and cyclones in a normal fluid are quantised in a quantum fluid and behave like quasi-particles. Interestingly groups of vortices that spin in the same direction cluster together and rotate around each other for long periods of time. This is known as an inverse energy cascade where energy travels from small scales to large scale essentially creating large vortices from small vortices. This is quite a suprising result and a consequence of the dimensionality of the system. This explains many atmospherical and oceanic phenomena such as how the great red spot on Jupiter has persisted for centuries.

In a quantum fluid, clusters of same-signed vortices are known as Onsager vortices and interestingly have a negative thermodynamic temperature. So far we have managed to create and trap vortices and are able to arbitrarily position them allowing us to probe the dynamics of single and multiple vortex clusters. We have found that a single Onsager vortex precesses around the condensate at a very regular angular velocity. We also observe an almost constant vortex number over the duration of the experiment indicating that all the vortices have the same sign. Our experimental results agree very well with simulations and provide a very attractive approach for future studies.

- James Spollard - Optical Phased Arrays as an Enabler for Free Space Quantum Key Distribution

Whilst secure Quantum Key Distribution (QKD) networks can in theory be established in either free space or in fibre, there exist many additional challenges in setting up and maintaining a long range QKD link through free space. The vast majority of these additional challenges stem from the need to transmit through the atmosphere, which is time-varying and requires active compensation for a successful link to be made. Any loss in the free space channel will significantly degrade the performance of the QKD system. A rapid and precise beam steering system is required to overcome the very small spot size and low signal-to-noise-ratio seen at the receiver due to the long transmission distance. The need for precise beam steering is only heightened if the receiver is non-stationary relative to the transmitter, as would be the case in a satellite-to-satellite or satellite-to-terrestrial link due to the need to actively track the moving target. Furthermore, transmittance through the dense lower layers of the earths atmosphere results in wavefront distortion which can impact bit error rate, beam pointing capabilities and QKD performance.

In this talk, we describe the design and initial experimental results of a 1550nm Optical Phased Array (OPA) for use in QKD networks as a means to deliver the precise beam pointing and active wavefront correction capabilities required for long range links. The OPA can achieve beam steering at up to MHz bandwidth, with sub milliradian pointing accuracy. This is critical for initial link acquisition where a rapid scan of the field of regard is required to coarsely identify the location of the target receiver. The precise pointing accuracy of the OPA can then be used to actively track moving targets using an algorithm such as dither locking. Furthermore, in a high emitter density OPA where each emitter has individual phase control, the far field wavefront can be manipulated to any arbitrary shape to correct for atmospheric effects. This is very similar to what is currently implemented in conventional adaptive-optics systems for astronomy which instead of an OPA, use a deformable mirror for wavefront actuation. By minimising the wavefront distortion experienced through transmission, the bit error rate and QKD performance of the system are enhanced. Both the agile beam steering and active wavefront manipulation are two crucial capabilities for supporting free-space QKD.

Though we have demonstrated the beam steering and wavefront manipulation with a 3- emitter and soon a 7-emitter array, we are focused on the goal of miniaturising the optical head to allow for ever increasing emitter counts and increased emitter density. Our medium term research will concentrate on the use of silicon photonic waveguide chips as a means to improve beam quality by decreasing the distance between emitters. We are also currently exploring on chip EOMs to be used with the photonic waveguide to create a robust and compact OPA unit that we can then explore using for commercial purposes such as LiDAR and short range free space optical communication links through very turbulent channels.

- Alexander Pritchard - Bose Einstein Condensates

The increased attention and development behind Bose-Einstein condensates (BECs) provides a system to study a wide range of phenomena to questions that haven't been answered to date. The extension to multi-component Bose-Einstein condensates in ring traps, of various miscibility, allows the exploration of complex phenomena, including superfluid counterflow and drag, soliton generation and non-linear dynamics, pattern formation, turbulence, and the link between quantized and classical rotations in superfluid systems. My PhD project aims to experimentally investigate the counterflow instability of a mixture of two BECs in miscible/immiscible systems, the emergence of classical rotation in a BEC superfluid, and spin-orbit-coupled interferometry.

- Guillaume Gauthier - Atomic-Density Based Optimization of Arbitrary 2D Optical Potentials

Advancing the control over the potential has been a driving factor behind the development of the cold atoms field. As such, the direct imaging of a digital micromirror device (DMD) onto a plane has become a popular technique which has expanded the range of dynamic potentials available for 2D cold atom experiments. One of the drawbacks of this technique is that direct imaging does not allow for correction of aberrations in the projecting optical system, also non-uniformity and imperfections in the illumination field cause imperfection in the projected potential. To remedy these limitations, we have developed a density-based feedforward optimization technique which uses the grayscaling and dynamic capabilities of the DMD to correct imperfections in the projected trapping potential. This technique can be used to correct for non-uniformity in the tapping potential (See Fig. 1) and will be used in the future to create step potentials for the purposes of vortex optics experiment.

- Carlo Kuhn - Low-momentum Bragg Spectroscopy of a Strong Interacting Fermi Gas

Bragg spectroscopy has been proven to be extremely useful in different areas of science. In this work, we use low-momentum Bragg spectroscopy to investigate elementary excitation in an ultracold cloud of Li6 atoms at unitarity. In this particular regime, the scattering length goes to infinity and is theoretically untouchable, leaving experimental realisation as the sole means of studying these fascinating systems. Probing the local properties of such a system presents experimental challenges.

Our Bragg system was designed to overcome these challenges by focusing the Bragg beams into the centre of the sample, which has recently been used to observe the Gold- stone mode in an atomic Fermi superfluid [1]. Figure 1(a) shows a schematic illustrating how we probe the local excitation spectrum. Figure 1(b) and (c) are typical of the response as a result of these excitations in the cloud after a 4ms time of flight.

By perturbing the system through the transfer of momentum to the atoms, in units smaller than its natural units (Fermi momentum, kF), we can excite the first sound and extract its physical properties such as damping, which is related to the width of the spectrum shown in Figure 1(bottom). The peak of the spectrum gives us information about the speed of the first sound. Figure 1(bottom) shows the elementary excitation spectrum for four temperatures, where we observe increased damping across the critical temperature (Tc = 0.167TF). From the spectrum, we can present a detailed study of the propagation of the first sound as a function of the temperature in a unitary Fermi gas.

It is not yet clear as to which transport theory would be the best to describe the dynamics of these systems. We are hoping to provide answers by com- paring the information extracted from the low excitation spectrum with the Landau's two-fluid hydrodynamic theory, used to explain first sound damping in superfluid 4He. This will allow us extract additional information such as the local shear viscosity, which is very difficult to experimentally probe.

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- Christina Giarmatzi - Witnessing quantum versus classical non-Markovianity

The study of open quantum systems is a very active field in physics. It deals with the challenge to isolate the desired system in quantum experiments, such that all the observed correlations are solely due to the in- teractions of the systems. In this case we can have the complete characterisation of the dynamics and we say that the process is Markovian.

Non-Markovian processes, on the other hand, are processes in which the systems that are subject to some external noise from their environment. In this case, the observed correlations cannot be accounted only by the systems involved and so some external system is affect- ing the results. These processes can be divided into two classes, depending on the nature of the noise being classical or quantum.

Here, we use the process matrix formalism [1, 2] to characterize non-Markovian processes. In particular, the set of classical non-Markovian processes forms a convex set. Using convex optimization techniques we can test whether a given process is falls inside or out- side the convex set—if it is classical or quantum non- Markovian. The problem can be cast as a SemiDefinite Program (SDP). The SDP provides us with information about the nature of the noise, and, for a quantum non- Markovian process, it finds a witness. A witness con- sists of a set of operations to be performed at the vari- ous measurement stations of the process to prove quan- tum non-Markovianity and its advantage is that the op- erations are far less than those needed for a full process tomography.

The situation is completely analogous to the search for an entanglement witness. The set of separable states forms a convex set, and numerous SDPs have been writ- ten for the search of entanglement witnesses. However, in both cases of states and processes, there is a limi- tation: in order for the SDP to provide conclusive re- sults, the characterization of the convex set needs to be written as a set of linear constraints with respect to the variables of the problem; in both cases, this cannot be done.

To overcome this problem, in the case of states, several techniques have been developed for the search of entanglement witnesses, based on various separability criteria: a simple property that is proved to hold for all separable states. These criteria provide necessary (but not sufficient) conditions for a state to be separable. The most notable criterion is based on partial transposition: if a bipartite state is separable, then it must have a posi- tive partial transpose (PPT) [3]. A family of separability criteria was introduced by Doherty et al. [4]. This crite- ria is based on the PPT criterion applied on symmetric extensions of the initial state. It was proven that every family of such criteria, for every new extension, is at least as strong as the previous one. For example, for a bipartite state ρAB, if the PPT criterion does not con- clude that the state is entangled, then it might still be. If we take the state ρ̃ABA, its extension with a copy of the first system, and apply the PPT criterion on ρ̃TA and ρ̃TB , the state might turn out entangled. If not, one can extend the state even further, and continue to apply the PPT criterion on the new extension.

We apply the above necessary conditions for sepa- rability in our quest for distinguishing classical versus quantum non-Markovianity. We find that indeed in some quantum processes the PPT criterion is enough to distinguish quantum non-Markovianity while in other cases we need to use symmetric extensions of the PPT criterion. The second problem is an SDP that can be solved efficiently and provides us with a witness for quantum non-Markovianity, which we call quantum noise witness.

We test our codes with quantum processes that in- clude two parties, generated in a random way. We also tested a quantum process where the channel be- tween the two parties is characterized by the Hamilto- nian $-(\sigma x \otimes \sigma x + \sigma y \otimes \sigma y + \sigma z \otimes \sigma z)$ which is the nearest- neighbor interaction on an Ising spin model. We test the precision of our codes by varying the time of the inter- action. Obviously for time t = 0 there is no interaction and the process is Markovian (an interior point of the convex set). We find the critical time $t = t*$ for which the process becomes quantum non-Markovian.

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- Tyler Neely - Giant vorte clusters in a 2D superfluid

In a turbulent three-dimensional fluid, the Richardson cascade transports energy from large scale eddies to small, terminating with viscous dissipation at the small length scales. By contrast, a two-dimensional (2D) system can see energy transport in the inverse cascade --- under continuous forcing the fluid will begin to concentrate energy at large length scales. In 1949, inspired to investigate these final stages of 2D turbulence, Lars Onsager studied a closed system of idealised 2D point vortices, showing that increasing vortex energy leads to equilibria characterised by concentrated vortex clusters [1]. As the entropy of these states decreases with increasing energy, they can be characterised by negative absolute temperatures.

Onsager's theory has proved highly-influential, providing understanding of diverse quasi-2D systems such as turbulent soap films [2] and guiding-centre plasmas [3]. It also predicts the striking tendency of 2D turbulence to spontaneously form large-scale, long-lived vortices --- Jupiter's Great Red Spot is a well-known example. However, Onsager's theory doesn't quantitatively apply to classical fluids where vorticity is continuous, and experimental systems demonstrating Onsager's point-vortex statistical mechanics have remained elusive.

Bose-Einstein condensates (BECs) confined in sheet-like uniform potentials present a nearly ideal experimental test-bed for 2D vortex physics, as the dynamics of the quantum vortices correspond closely to a point vortex system. BECs have thus been proposed as system for observing the high-energy states of vortex motion first predicted by Onsager. We report our observation of negative-temperature vortex clusters injected directly into a uniform elliptical BEC [4], though stirring the condensate with a pair of elliptical barriers. We find that over many seconds of hold time vortex annihilation is suppressed and the clustered fraction is stable. However, the system exhibits energy loss (cooling) with increasing hold time. We characterise the cooling rate in response to variable non-uniformity of the BEC density and finite temperature. We contrast these results with an grid-stir of the cloud that injects vortices in a low energy configuration, remaining close to the uncorrelated (infinite temperature) configuration for all hold times. These results provide evidence that deep negative temperature states cannot be accessed through the decay of quantised turbulence alone.

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- Fabio Isa - Group-IV colour centres in nano-diamonds

The diamond colour centres have attracted enormous research interest thanks to their unique spin and optical properties. So far, the most investigated colour centre is the nitrogen-vacancy (NV) centre, which presents promising applications in the field of quantum information processing, electromagnetic sensing and bio-imaging.

Despite the exceptional spin properties of NV centres, photonic quantum communication architectures suffer from the weak zero-phonon line (ZPL) emission.

A possible alternative to address this limitation, is to employ other colour centres with similar spin, but superior photonic properties. The SiV centre has the advantage of being among the brightest in diamond, emitting at room temperature about 80% of light at the ZPL. Recently, quantum emitters based on other group-IV colours centres, namely GeV and SnV, have been achieved using diamond single crystal and ion implantation or chemical vapour deposition (CVD).

Here, we investigate the structural and the optical properties of nano-diamonds (NDs) deposited by microwave plasma CVD (MPCVD) on group-IV semiconductor substrates consisting of SiGeSn/Si layers. The crystal morphology of NDs is analysed by scanning electron microscopy (SEM); the NDS are unequivocally labelled in situ with markers fabricated by the focused ion beam (FIB) technique. The FIB markers are about 10 µm wide and 1 µm deep and can be easily distinguished by a microscope objective in a confocal photoluminescence (PL) setup.

This allows the investigation of the structural and optical properties on individual NDs. The optical properties of group-IV colour centres are studied by confocal PL spectroscopy. The structural properties and crystal morphology are obtained by SEM, electron backscattered diffraction to investigate the grain boundaries, and confocal micro-Raman spectroscopy to determine the crystal strain.

We demonstrate that colour centres can be incorporated into high quality NDs by MPCVD deposition on foreign group-IV semiconductor substrates. NDs with multiple colour centres may be achieved by engineering the stoichiometry of semiconductor substrate.

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Thursday, August 9

9.00am - 10.30am: Session twelve

- **Invited talk** - Ben Sparkes - Optical Quantum Information Processing with Cold Atom-Filled Hollow-Core Photonic Crystal Fibres

The development of an optical quantum network will allow for the transmission and manipulation of quantum information over much greater distances and at much faster speeds than is currently possible. This will enable provably-secure communications via quantum key distribution, as well as optical quantum computing. Such networks will consist of nodes to localise and manipulate information-carrying photons, interconnected with channels to transmit the photons between nodes.

Optical fibres are the obvious choice for providing links between nodes, as they are relatively low-loss and can remove atmospheric and line-of-sight issues arising from free-space transmission. Our work makes use of hollow-core photonic crystal fibres filled with either warm [1], or laser-cooled [2] rubidium atoms to create a system that is directly integrable with current optical fibre technology. The tight transverse confinement (diameter of tens of microns) and extended interaction lengths (centimetres) of the fibres provide an extremely optically dense medium, ideal for efficient quantum information storage and for achieving strong atom-mediated photon-photon interactions.

We will present our latest work loading a record number of laser-cooled atoms into a hollow-core fibre [2], providing a platform for realising long-lifetime quantum memories, which can create larger optical quantum networks. Our initial results show an optical depth of greater than 600. We will present the approach we have taken to achieve such a larger number of atoms loaded into the fibre and discuss experimental methods to increase coherence times to milliseconds.

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- **Contributed talk** - Anatoly Kulikov - Experimental realization of a quantum random number generator

Random numbers are required for a variety of applications from secure communications to Monte-Carlo simulation. Yet randomness is an asymptotic property and no output string generated by a physical device can be strictly proven to be random. I will present an experimental realization of a quantum random number generator (QRNG) with randomness certified by quantum contextuality and the Kochen-Specker theorem. The certification is not performed in a device-independent way but through a rigorous theoretical proof of each outcome being value indefinite even in the presence of experimental imperfections. Our realization is based on cavity QED and transmon type qutrit. The coherent control and the single-shot quantum non-demolition readout enabled by the Josephson parametric amplifier has been recently used to demonstrate contextuality of the transmon based qutrit, the resource underlying the operation of the QNRG. We extend this technique to enable three-level single-shot non-demolition readout required by the protocol and we generate 10 GBit of raw data with the bitrate of 50 kBit/s. The generated data passes the standard statistical test suites. Analysis of the data with tests related to the algorithmic randomness of a sequence provides evidence of incomputable nature of the QNRG.

- **Contributed talk** - Alexander Wood - Quantum measurement and control of nitrogen vacancy (NV) center qubits

Quantum control of qubits in a physically rotating frame opens new opportunities to probe fundamental quantum physics, such as geometric phases, and has technological implications, improving the sensitivity of magnetometers and gyroscopes. We describe quantum measurement and control of nitrogen vacancy (NV) center qubits in a diamond rotating with a period comparable to the qubit electron spin coherence time T2. We have used these rotating-frame quantum sensors to detect rotationally-induced magnetic pseudofields acting on a bath of 13C nuclear spins surrounding the NV centres [Nat Phys 13, 1070-1073 (2017)]. We have also used physical rotation on quantum timescales to improve the sensitivity of NV magnetometers to DC fields [arXiv:1802.03845]. I will also discuss work towards a measurement of Berry's phase, which requires control of single NV qubits in a rotating diamond [Sci Adv 4, eaar7691 (2018)].

- Contributed talk - Xia-Ji Liu - Route to observing Fulde-Ferrell superfluids via a dark-state control of Feshbach resonances

We propose that the long-sought Fulde-Ferrell superfluidity with nonzero momentum pairing can be realized in ultracold two-component Fermi gases of K-40 or Li-6 atoms, by optically tuning their magnetic Feshbach resonances via the creation of a closed-channel dark state with a Doppler-shifted Stark effect. In this scheme, two counter-propagating optical fields are applied to couple two molecular states in the closed channel to an excited molecular state, leading to a significant violation of Galilean invariance in the dark-state regime and hence to the possibility of Fulde-Ferrell superfluids. We develop a field theoretical formulation for both two-body and many-body problems and predict that the Fulde-Ferrell state has remarkable properties, such as anisotropic single-particle dispersion relation, suppressed superfluid density at zero temperature, anisotropic sound velocity and rotonic collective mode. The latter two features can be experimentally probed using Bragg spectroscopy, providing a smoking gun proof of Fulde-Ferrell superfluidity.

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10.50am - 12.00pm: Session thirteen

- Invited talk - Alastair Stacey - Real world applications of diamond quantum systems at room temperature

Diamond quantum defects exhibit remarkable properties at the confluence of biological and quantum sciences. The crystalline carbon lattice of this material acts as both a quantum vacuum, allowing long lived coherent states at room temperature, while also presenting a bio-friendly interface. Because of these properties, defect centres (qubits) in diamond are driving advances in quantum computing and sensing applications.[1,2] As these technologies begin to be applied in real devices, these optically active defects are being increasingly located within nanometres of the diamond surface,[3] where their quantum properties such as coherence time and spectral width are reported to experience significant degradation,[4] compared to their bulk properties. There have been recent advances in theoretical proposals for ideal diamond surface chemistries,[5] which link unoccupied electronic surfaces states with degraded photophysical properties. To date experimental achievements have included the introduction of novel surface terminations,[6] and process optimization efforts, yielding significant improvements in near-surface defect coherence values.[7] Despite these efforts, surface noise and defect instability near surfaces remains a significant challenge for any quantum application and are a major hurdle for realization of real-world devices.

I will detail our efforts to deal with these challenges, through novel measurements and modification of the diamond surface chemistry. I will provide experimental evidence of unexpected crystalline defects at the diamond surface, as well as theoretical calculations showing that these defects produce low-lying trap states in the near-surface region, inhibiting the charge population and stability of near-surface NV centres; and provide pathways for the removal of these defects.

I will also provide an overview of our efforts to apply diamond quantum defects to real-world problems, including bio-imaging and novel solid-state sensing experiments.

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- **Contributed talk** - Behnam Tonekaboni - Autonomous Quantum Heat Engine Using an Electron Shuttle

With the advancement in experimental techniques, we are able to control systems with truly quantum degrees of freedom. At this scale, the energetics and thermodynamics of the control field become important. Quantum heat engines which have been proposed and studied [1-2] use an external time-dependent classical control field to switch the interaction between the working system and the heat baths. There is an energetic cost to these control fields which is often ignored. To overcome the energetic cost of the control field we need an autonomous heat engine with a time-independent Hamiltonian via an internal quantum controller. Autonomous heat engines have received recent attentions [3,4] but these researches did not address the energetic effect of the controller. In this research, we introduce an autonomous quantum heat engine based on the oscillation of a single-electron shuttle [5]. And we analyse the energetic effect of the internal quantum controller.

- **Contributed talk** - Erick Romero - High-Q mechanical trampoline resonators for quantum optomechanics at room temperature

Optomechanics has shown a fruitful field of modern physics research due to its direct application to precision metrology and technological development. Mechanical systems used for ultra-high precision measurements are required to be extremely sensitive to its surrounding environment, which makes them extremely susceptible to decoherence. Here we present an engineered design that considers the different sources of decoherence of a mechanical systems such as clamping losses, bending losses and Thermoelastic losses.

The design consist of a membrane trampoline mechanical oscillator suspended by another trampoline-like resonator Fig.1 . This system operates as a mechanical low pass filter and reduces the mechanical radiation losses due to the clamping. We also consider the bending losses and design a trampoline geometry that reduces the bending of the trampoline confining the mode of the oscillation far from the clamping boundaries. Finally, we consider the reduction of Thermoelastic losses by using an epitaxially grown single crystal SiC on Si. The SiC monocrystalline layer intrinsically stressed reduces the mechanical losses of our resonator.

These resonators with a mode as large as 1mm have achieved resonance frequencies of a few hundreds of kHz and mechanical quality factors above Q>108 , (Fig. 2) exceeding the required f*Q >6X1012Hz required to perform quantum optomechanics experiments at room temperature. It is also relevant to mention that compared to other confined systems with such a high quality factor [1,2], the size of the mode of our oscillator approaches to the macroscopic scale.

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