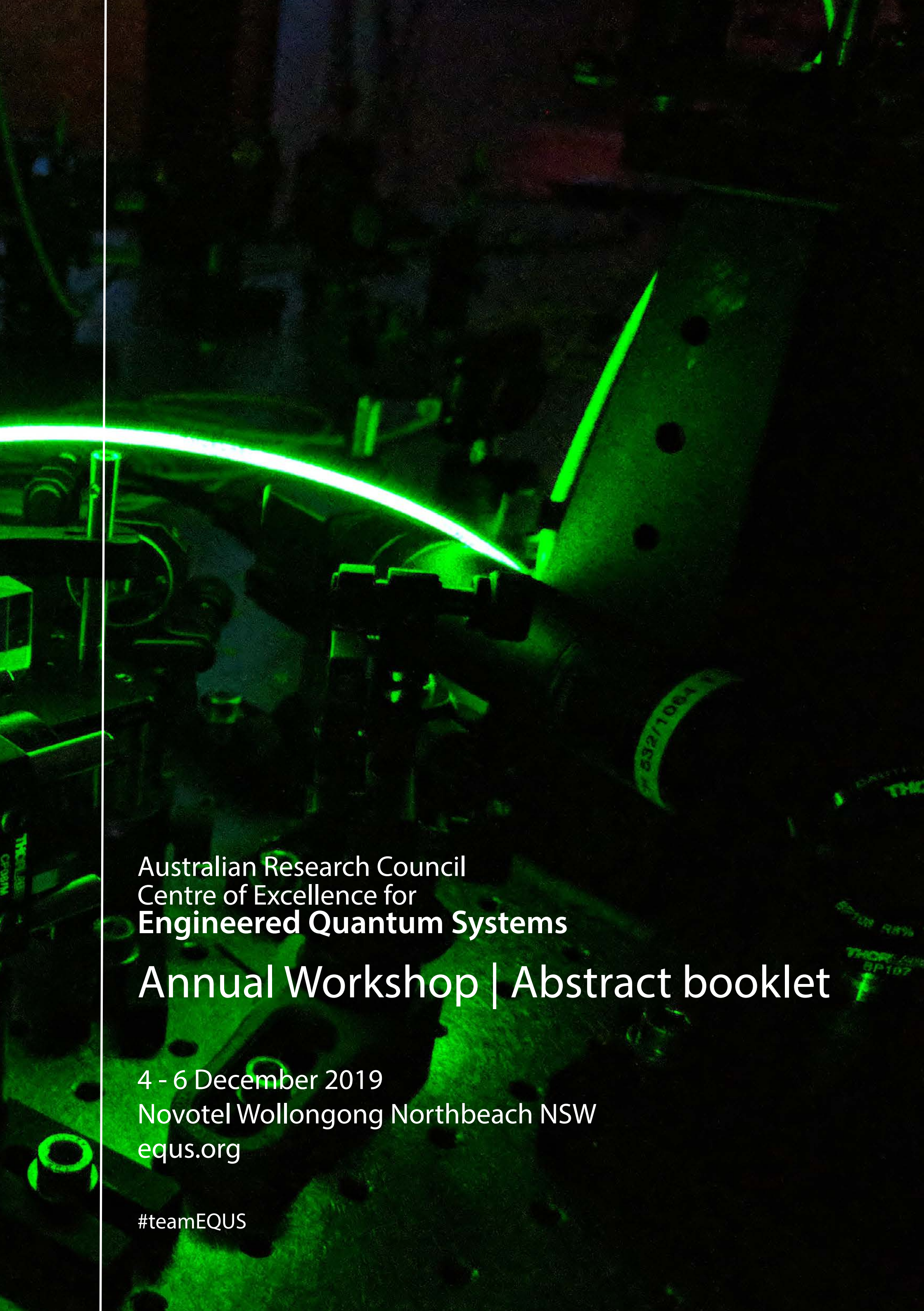

Australian Research Council
Centre of Excellence for
Engineered Quantum Systems

Annual Workshop | Abstract booklet

4 - 6 December 2019
Novotel Wollongong Northbeach NSW
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SESSION ONE

Laura Greene

The Dark Energy of Quantum Materials

The nearly 80-year-old correlated electron problems remain largely unsolved; with one stunning success being BCS electron-phonon mediated conventional superconductivity. There are dozens of families of superconductors that are unconventional, including the high-Tc cuprates, iron-based, and heavy fermion superconductors. Although these materials are disparate in many of their properties, some of their fundamental characteristics are strikingly similar, including their ubiquitous phase diagram, with intriguing correlated-electron (not-Fermi liquid) phases above the superconducting transition. These remain among the greatest unsolved problems in physics today; and I will present an analogy stressing. I will also give a short overview of the US National MagLab and mention some of our own recent work on tunneling in heavy-fermions.

Michael Kewming

Quantum Correlations in the Kerr Ising Model

Here we will present a Coherent Ising machine CIM based on a network of detuned parametrically pumped Kerr nonlinearities---the Kerr Ising model. At a critical threshold driving, the cavities undergo a pitchfork bifurcation where the two steady state solutions play the role of two `pseudo-spins' in the Ising model. Similiar treatments of the CIM model have been considered previously. In this work, we will explore the nature of a quantum phase transition and as the system undergoes the bifurcation in the 2 cavity spin model. Here we pinpoint a particular quantum advantage arising due to the in-separability of the two cavities joint state.

James Witt

Spin-orbit interaction in shallow InAs 2-dimensional electron gases

Proximitized 2-dimensional electron gases (2DEG) are promising candidates in the search for systems capable of hosting Majorana bound states -- quasiparticles whose topological protection offers advantages to quantum information technologies. In order to induce superconductivity in the 2DEG, the heterostructure must be designed with the quantum well very near to the uppermost surface, upon which the superconducting material is then deposited. The shallowness of the 2DEG increases its sensitivity to disorder at the surface and can greatly influence the materials properties. In this talk I will describe our investigations into the spin-orbit interaction in InAs heterostructure materials and the devices we are fabricating to utilise this phenomenon.

SESSION TWO

Ajit Srivastava

Single photons, phonons and spins in atomically thin WSe_2

Monolayer transition metal dichalcogenides (TMDs), such as WSe_2, are atomically thin semiconductors with a "valley" degree of freedom, which can be optically addressed, thus opening up exciting possibilities for quantum "valleytronics". Recently, naturally occurring single quantum emitters, believed to be excitons trapped in shallow potentials, were reported in TMDs [1]. They seem to inherit the valley degree of freedom from the host TMD and owing to their longer lifetimes, appear promising for quantum information processing applications.

In this talk, I will begin by highlighting some unique properties of TMDs excitons which result from the off-Gamma-point origin of the constituent single particle electronic states. After describing the basic properties of quantum dots in TMDs, I will present evidence for quantum entanglement between chiral phonons of the 2D host and single photons emitted from the quantum dots [2]. I will also present evidence for optical initialization of single spin-valley in WSe2 FET devices [3]. Finally, I will discuss our future plans for implementing a dynamically tunable array of qubits in pristine TMDs which can serve as an ideal platform for quantum information processing applications and also for understanding fundamental many-body physics.

[1] Srivastava et al., Nature Nano. 10, 491-496 (2015).
[2] X. Chen, X. Lu, S. Dubey et al., Nature Phys. 15, 221-227 (2019).
[3] X. Lu, X. Chen, S. Dubey et al., Nature Nano. 14, 426-431 (2019).

Magdalena Zych

New quantum technologies for exploring fundamental physics — and vice versa

Continuous progress in the capabilities of quantum technologies allows for quantum experiments with increasingly complex systems and over increasingly large time and distance scales. Quantum inference has been observed with molecules comprising 2000 atoms, coherence of spatial superpositions has been verified over tens of centimetres, and for over 20 seconds. I will discuss how these new capabilities open the window for exploring weird and wonderful effects at the interface of quantum theory and general relativity, and how our todays awe and wonder can lead to more accurate quantum metrology techniques in the future.

Terry Ferrelly

Interacting scalar field theory as a quantum circuit

One of the driving forces behind the development of quantum computers is their potential as highly efficient simulators of quantum physics. In particular, quantum algorithms have been proposed for simulating quantum field theories. These rely on Hamiltonian lattice quantum field theory as a stepping stone to approximate the dynamics of the quantum field. Here we consider an alternative: a discretization of quantum field theory with dynamics simply given by local unitary gates, something which is naturally suited to running on a quantum computer. (These discrete models are also known as quantum cellular automata.) We look at scalar field theory in both the free and interacting cases (phi 4 theory). By solving the free models and introducing a discrete version of the interaction picture, we derive discrete spacetime Feynman rules for the interacting model.

John McFerran

Atomic clocks and King plots

King plots are a means of extracting nuclear parameters from isotopic frequency shifts in atoms. Recent proposals suggest that King plot nonlinearities may relate to phenomena beyond the standard model of elementary particles. We construct a King plot from the 1S0-3P1 (intercombination) and 1S0-3P0 (clock) transitions in ytterbium. We have carried out sub-Doppler fluorescence spectroscopy and frequency comb measurements to determine all the hyperfine separations and isotope shifts for the 1S0-3P1 line in Yb (Phys. Rev. A, 100, 042505, 2019). Clock transition frequencies are known for three of the Yb isotopes, which is used to generate a King plot, but with only two data points. We aim to measure the clock-line isotope shifts for a number of Yb isotopes and thus explore the degree of linearity of the King plot.

SESSION THREE

Janet Anders

Thermodynamics in the presence of coherences and strong coupling corrections

I will talk about a selection of my group's results in the field of quantum thermodynamics [1]. We will first ask what is truly "quantum" in quantum thermodynamics. To answer this question we set up a quantum thermodynamic process that removes quantum information in analogy to Landauer's erasure of classical information. The thermodynamic analysis of such a process uncovers that work can be extracted from quantum coherences in addition to the work that can be extracted from classical non-equilibrium states [2]. At the end of the talk I will briefly report on a new thermodynamic uncertainty relation that limits the accuracy of measuring the temperature and energy of a thermal quantum system [3]. Corrections to the standard uncertainty relation arise here because, unlike in standard thermodynamics, a small system's interaction with its environment is not negligible. The emerging relation unites thermodynamic and quantum uncertainties for the first time.

[1] Quantum thermodynamics, S. Vinjanampathy, J. Anders, Contemporary Physics 57, 545 (2016).
[2] Coherence and measurement in quantum thermodynamics, P. Kammerlander, J. Anders, Scientific Reports 6, 22174 (2016).
[3] Energy-temperature uncertainty relation in quantum thermodynamics, H. Miller, J. Anders, Nature Communications 9:2203 (2018).

Tyler Neely

Spun-up and stirred BEC superfluids

Optical dipole traps provide the best means for trapping and microscopically patterning and manipulating Bose-Einstein condensate (BEC) superfluid systems. In my talk, I will describe the newly refined optical trapping approaches developed at the UQ BEC laboratory in this past year. These techniques are leading to new avenues for configuration and control of our BEC superfluids. Our primary technology is based around direct imaging of a digital micromirror array (DMD). While these optical traps allow for the generation of configurable and homogenous BECs, enabling new types of nonequilibrium superfluid experiments in quasi-2D, we have now been able to realise smoothly-varying DMD optical potentials. One utility these techniques provide is the rapid imprinting of high-angular momentum currents in ring-shaped BECs. I will contrast the phase-imprinting method with machine learning optimised stirring. Starting with a persistent current, we create a vortex cluster by releasing the current into a uniform disc-shaped BEC. I will describe our study of the relaxation dynamics of such clusters from both near equilibrium and far-from-equilibrium initial conditions, realising new states of absolute negative temperature vortex matter. Finally, I will outline the recent progress with superfluids composed of atoms in mixed internal states. By utilising magnetic traps and spin-dependent optical potentials, we have demonstrated spin-dependent driving of superfluid currents in both ring and linear traps.

Cyril Laplane

Harnessing atomic forces for the opto-mechanical manipulation of a mesoscopic object

Optically active centers in diamond are one of the pinnacles of modern quantum physics in the solid-state. Their intrinsic brightness and quantum coherence properties make them pristine candidates for applications ranging from ultra-precise sensing to quantum information processing. In our experiments, we are interested in the opto-mechanical manipulation of nanodiamonds with a high concentration of SiV centers. Optical tweezers usually rely on the interaction of light and the 'bulk' polarizability of the nanoparticle itself. Here we exploit the polarizability of electronic resonances of optical centers embedded in the solid-state matrix to enhance the optical forces. This effect becomes particularly relevant for ensembles of active centers. The emitters being closely packed in a sub-wavelength volume, can act cooperatively, enhancing further the optical forces. We investigate dipole and scattering components of these resonant optical forces and their dependence on the density of centers in order to understand collective effects and how to harness them for nanomanipulation. This opens the possibility to apply the powerful toolbox of atomic physics for the quantum manipulation of 'massive' mesoscopic objects.

Steve Flammia

Efficient learning of quantum noise

Noise is the central obstacle to building large-scale quantum computers. Quantum systems with sufficiently uncorrelated and weak noise could be used to solve computational problems that are intractable with current digital computers. There has been substantial progress towards engineering such systems. tum noise reliably and efficiently with high precision. Here we introduce a protocol that completely and efficiently characterizes the error rates of quantum noise and we experimentally implement it on a 14-qubit superconducting quantum architecture. The method returns an estimate of the effective noise with relative precision and detects all correlated errors. We show how to construct a quantum noise correlation matrix allowing the easy visualization of all pairwise correlated errors, enabling the discovery of long-range two-qubit correlations in the 14 qubit device that had not previously been detected. These properties of the protocol make it exceptionally well suited for high-precision noise metrology in quantum information processors. Our results are the first implementation of a provably rigorous, full diagnostic protocol capable of being run on state of the art devices and beyond. These results pave the way for noise metrology in next-generation quantum devices, calibration in the presence of crosstalk, bespoke quantum error-correcting codes, and customized fault-tolerance protocols that can greatly reduce the overhead in a quantum computation.

SESSION FOUR

Laura Greene
Leadership Skills and Networking for Women

Women scientists take on leadership roles everyday, in the classroom, in their department or institution and in their professional organizations. This workshop is designed to give participants the basic concepts of leadership, describe some research on leadership qualities that lead to success and failure, provide techniques and strategies for career advancement into leadership roles, and assist in developing and maintaining strong leadership networks. Topics also include effective communication styles for women, projecting confidence and credibility through voice, image and body language, dealing with difficult conversations and questions, using powerful rather than weak words, and effective scientific presentations. Role-playing activities provide practice in using learned strategies and practices.

Tim Evans
Scalable Bayesian learning of local Hamiltonians and Lindbladians

To date, most understanding of open quantum systems is restricted either to weak system-bath couplings, or to special cases where specific numerical techniques become effective. Here I present a general and yet exact numerical method to calculate the dynamics of an open quantum system coupled to a non-Markovian environment. The method is to express the equations of motion for such an open quantum system as a tensor network, whose structure allows for a decomposition in terms of matrix products that can be efficiently compressed in size. To demonstrate the power and flexibility of this approach it is used to numerically identify the localisation transition of the Ohmic spin-boson model, and to solve a model with widely separated environmental timescales arising for a pair of spins embedded in a common environment.

Jacqui Romero
Hiding Ignorance Using Higher Dimensions

The absence of information—entirely or partly—is called ignorance. Naturally, one might ask if ignorance of a whole system implies ignorance of its parts. Our classical intuition tells us yes, however quantum theory tells us no: it is possible to encode information in a quantum system so that despite some ignorance of the whole, it is impossible to identify the unknown part. Experimental proof of this counter-intuitive fact requires controlling and measuring quantum systems of high dimension ($d>9$). We provide this experimental evidence using the transverse spatial modes of light, a resource for testing high dimensional quantum phenomenon.

SESSION FIVE

Elisabetta Barberio

ARC Centre of Excellence for Dark Matter Particle Physics: Research plans and synergies with EQUS

The recently funded ARC Centre of Excellence for Dark Matter Particle Physics will deliver breakthroughs in our understanding of the Universe through the pursuit of the discovery of dark matter particles which comprise 80% of the mass of the universe. The Centre will exploit the unique geographical location of the first underground physics lab in the Southern Hemisphere. It assembles a diverse team of physicists from particle, nuclear, and quantum physics as well as particle astrophysics. The diverse expertise will lead to new synergies and cross-fertilisation of techniques. In particular, it has become possible to explore the mysteries of dark matter with experiments where ultra-precise quantum sensors can make decisive contributions. I will summarize the research plans for this new centre emphasising possible research synergies with EQUUS.

Glen Harris

Probing Superfluid Helium with Light

Superfluid helium was one of the very first macroscopic quantum mechanical systems to be observed, and yet it remains one of the last to be completely described by a microscopic model. This lack of pro-gress is, in large part, due to the immense difficulty in measuring the dynamics of superfluid helium's fundamental excitations, namely vortices, phonons and rotons. In this talk, I will present how we have circumvented many of the issues associated to this "measurement problem" by developing on-chip optical micro-cavities which are covered by a film of superfluid helium. Amazingly, these devices have the capacity to both measure and control excitations within the superfluid film, enabling a number of novel experimental demonstrations, such as the optical control of low frequency and high frequency phonons as well as non-destructive tracking of vortices.

Ben McAllister

Axion Search Update: ORGAN, UPLOAD-DOWNLOAD, Quantum Technologies, and other experiments

An update on the status and progress of the various axion search projects within EQUS. We will introduce UPLOAD-DOWNLOAD, a room-temperature table-top phase-sensitive axion haloscope experiment offering high potential for sensitivity improvements over the power-detection approach. The first results from UPLOAD/DOWNLOAD, which place axion exclusion limits between 11.6 - 19.4 neV, excluding a coupling strength above 2*10^(-6) 1/GeV, and simultaneously place limits between 74.45 - 74.46 mu-eV at 7*10^(-3) 1/GeV, will be presented. We will also discuss new resonator designs, and the current status of ORGAN - our high frequency haloscope. This will include progress in the development of GHz single photon counters for use with our various axion detection experiments. Finally, we will briefly touch on a few other axion experiments.

Arghavan Safavi-Naini

Many-body dynamics in dipolar lattice gases

Arrays of ultra-cold dipolar gases loaded in optical lattices are emerging as powerful quantum simulators of the many-body physics associated with the rich interplay between long-range dipolar interactions, contact interactions, motion, and quantum statistics. In this work we report on our investigation of the quantum many-body dynamics of a large ensemble of bosonic magnetic chromium atoms with spin S = 3 in a three-dimensional lattice as a function of lattice depth. We use extensive theory and experimental comparisons to study the dynamics of the population of the different Zeeman levels and the total magnetization of the gas across the superfluid to the Mott insulator transition. To this end we employ a number of theoretical methods, including Gutzwiller mean-field theory, and the general discrete Truncated Wigner Approximation. We discuss the regime of validity for each approach.

SESSION SIX

Liang Jiang

Achieving the Heisenberg limit in quantum metrology using quantum error correction

Quantum metrology has many important applications in science and technology, ranging from frequency spectroscopy to gravitational wave detection. Quantum mechanics imposes a fundamental limit on measurement precision, called the Heisenberg limit, which can be achieved for noiseless quantum systems, but is not achievable in general for systems subject to noise. Here we study how measurement precision can be enhanced through quantum error correction, a general method for protecting a quantum system from the damaging effects of noise. We find a necessary and sufficient condition for achieving the Heisenberg limit using quantum probes subject to Markovian noise, assuming that noiseless ancilla systems are available, and that fast, accurate quantum processing can be performed. When the sufficient condition is satisfied, the quantum error-correcting code achieving the best possible precision can be found by solving a semidefinite program. We also discuss various extensions, such as multi-parameter sensing enhanced by quantum error correction.

Gavin Brennen

Scalable preparation of entangled states for sensing and simulation

I'll describe two new strategies for preparing large scale entangled states for quantum sensing and simulation.
The first [1] is a geometric control sequence for preparing permutational invariant states for precision metrology. The method uses a highly non-linear spin interaction generated by dispersive coupling to a bosonic mode and does not require selective addressing, fine tuning, or direct interactions between the spins. Using a control sequence inspired by Grover's algorithm, a target Dicke state can be prepared using geometric phase gates and the sequence has dynamical

decoupling built in which provides resilience to dephasing errors.

The second [2] is a proposed physical realization of quantum cellular automata (QCA) using arrays of ultracold atoms trapped in optical microtrap arrays. We show how to generate unitary and non-unitary QCA rules using environment dependent shifts and dissipation channels enabled by Rydberg blockade. By embedding the Rydberg QCA within a variational quantum optimization loop, local rules can be inferred which allow to steer a system to target entangled states.

[1] Mattias T. Johnsson, Nabomita Roy Mukty, Daniel Burgarth, Thomas Volz, Gavin K. Brennen, "Scalable preparation of Dicke states for quantum sensing," arXiv:1908.01120.
[2] T. M. Wintermantel, Y. Wang, G. Lochead, S. Shevate, G. K. Brennen, S. Whitlock, "Unitary and non-unitary quantum cellular automata with Rydberg arrays," arXiv:1909.10193.

Anatoly Kulikov

Qubit as a quantum probe of control distortions and temperature

Physical qubits are prone to various sources of errors. Imperfect control lines lead to gate infidelities, non-zero effective temperature leads to improper initialization of qubits' states, coupling to spurious unwanted two-level systems cause both. Characterization of these imperfections and distortions becomes imperative to progress towards real-world applications and breaking the error-correcting threshold for current noisy intermediate-scale quantum processors. Using external sensors for that purpose may not always yield accurate results. For example, the effective temperature of a qubit T_{eff} is known to be different from the reading T_{base} of a base stage temperature sensor of a dilution cryostat. In this talk I am going to describe a set of tools we have developed to employ a qubit itself as a probe of the transfer functions of control lines and an effective qubit temperature. We also show how these set of tools can provide useful information about an origin of these errors and how to use the results to improve the fidelity of entangling gates.

Alistair Milne

Noise spectroscopy and robust entangling gates in qubit-oscillator systems

I will outline a technique for the characterization and suppression of noise in oscillator-mediated entangling operations applicable to a range of gate implementations in both trapped ion and superconducting circuit architectures, with experimental demonstrations using a system of trapped 171-Ytterbium ions. A major source of error in this class of entangling gates is residual coupling between the system of qubits and the intermediate oscillator modes, often caused by noise on the mode frequencies. In order to characterize this leading source of gate error, we utilize discrete phase modulation of the field driving the interaction to construct operations that are sensitive to noise in a desired band. Using a single value decomposition technique developed at Q-CTRL, the oscillator noise spectrum can be reconstructed from a series of operations with susceptibility to noise in different frequency bands. Phase-modulated operations may also be used to increase gate fidelity and robustness by minimising residual coupling to additional spectator modes – even in the presence of static offsets and fluctuations in the qubit and mode frequencies.

Picture taken by
Matthew van Breugel

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