Event Programme and Abstract Book

Low Temperature Group
Early Career Researcher Meeting

8–9 January 2025
Newcastle University, Newcastle, UK

Low temperature physics is an evolving area covering many aspects of scientific research and technology. The field incorporates superfluids, condensates, quantum technology, condensed matter physics and even the search for dark matter.

The 2025 ECR Forum career development workshop will be held at Newcastle University from the 8th to 9th January 2025, featuring talks on current and future research, developing skills for research, and opportunities for collaboration building. Guest speakers include Simon Midlik (Lancaster University), Kali Wilson (Strathclyde University), Anna Marchant (RAL Space), Phil Gregory (Durham University) and Scott Manifold (Oxford Quantum Circuits).

All in the community are invited to attend to support our ECRs; the programme is aimed at PhD students, PDRAs and other ECRs.

The Organising Committee

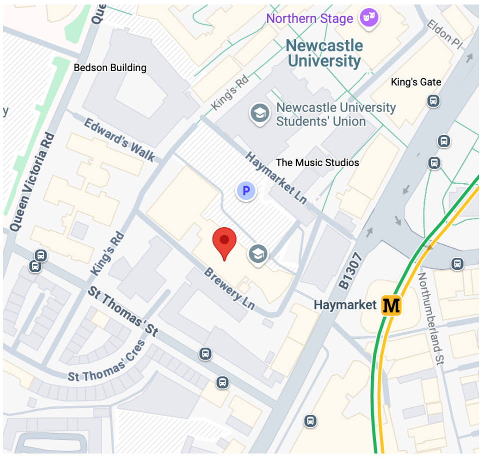
Sean Giblin (Cardiff University), Ryan Doran (Newcastle University), Andrew Armour (University of Nottingham), and Ocean Bach (MR solutions Group) would like to thank the Institute of Physics, EPSRC and Newcastle University for support in organising this workshop.

Workshop Venue:

The workshop will take place in **Lecture Theatre 3 on the ground floor of the Herschel Building** (NE1 7RU).

The Herschel Building is located on the main Newcastle University Campus, which is close to the City Centre.

The registration desk and lunches will be in the foyer of this building.



Getting Here:

Metro: Newcastle's light rail transport system, the Metro, connects Newcastle's City centre to the airport, the coast, and to Sunderland. The nearest station to the Herschel Building is Haymarket, which is just over the road (approximately 2 minutes walk).

Rail: Newcastle Central train station has frequent connections to London Kings Cross and Edinburgh. It is in the centre of the city (around 20 minutes from the Herschel Building) and is connected to the Metro system.

Air: Newcastle Airport has regular flights to European hubs such as Amsterdam, Paris and Frankfurt. There are also frequent connecting flights to London Heathrow. The Airport is connected to the city by the Metro system, the journey from the airport to the city centre takes approximately 40 minutes on the metro.

Car: There are some paid public car parks near the Herschel Building, these include Eldon Square Multi-Story (NE1 7RZ) and the College Street car park (NE1 8JJ). Both of these car parks are approximately 10 minutes walk from the Herschel Building.

Session 1 – Abstracts

Quantum paraelectricity in search of dark matter

<u>Deepanjan Das</u>[1], Edward Laird[1]
[1]Lancaster University

Detecting galactic axions holds the potential to resolve one of the greatest mysteries of physics: the identification of dark matter. This requires cutting-edge electronics and highly advanced cryogenic measurement techniques. In the presence of a strong magnetic field, axions decay into photons, producing an extremely weak electromagnetic signal. The signal is so tiny that any unexpected power loss along the readout line must be avoided. Therefore, an impedance matching device is essential to prevent signal degradation caused by impedance mismatch. Additionally, a low-noise cryogenic amplifier capable of operating in an external magnetic field is crucial to achieve performance at the standard quantum limit. To this end, we are developing a novel measurement setup for the QSHS axion search experiment [1], which includes an amplifier and an impedance matching device, by exploring quantum paraelectricity [2].

Quantum paraelectric materials (such as strontium titanate and potassium tantalate) are incipient ferroelectrics which are characterised by an extremely high dielectric response at low temperatures. The permittivity of these materials can be tuned by an external electric field in a cryogenic environment. In this talk, I will demonstrate the nonlinear phenomena exhibited by these materials while investigating their cryogenic properties, including high dielectric constant and electric field-dependent permittivity. By harnessing these unique characteristics, paraelectric materials could be utilised to develop an impedance matching device [3] and a parametric amplifier [4].

This presentation will describe the design principles, simulations, experimental results, and practical implications of these materials charaterised as an impedance matching device. The talk will also highlight the demonstration of wave mixing in these nonlinear media indicating the possibility of parametric amplification.

References:
[1] www.qshs.org.
[2] D. Davidovikj *et al.*, Physical Review B **95** (21), 214513 (2017).
[3] P. Apostolidis *et al.*, Nature Electronics, **7**, 760–767 (2024).
[4] M. A. Castellanos-Beltran *et al.*, Appl. Phys. Lett. **91**, 083509 (2007).

Vortex Avalanches and Collective Motions in Neutron Stars

Gary Liu[1], Andrew Baggaley[1], Carlo Barenghi[1], Toby Wood[1]
[1]Newcastle University

We simulate the dynamics of about 600 quantum vortices in a spinning-down cylindrical container using a Gross--Pitaevskii model. For the first time, we find convincing spatial-temporal evidence of avalanching behaviour resulting from vortex depinning and collective motion. During a typical avalanche, about 10 to 20 vortices exit the container in a short period, producing a glitch in the superfluid angular momentum and a localised void in the vorticity. After the glitch, vortices continue to depin and circulate around the vorticity void in a similar manner to that seen in previous point-vortex simulations.
We present evidence of collective vortex motion throughout this avalanche process. We also show that the effective Magnus force can be used to predict when and where avalanches will occur. Lastly, we comment on the challenge of extrapolating these results to conditions in real neutron stars, which contain many orders of magnitude more vortices.

Kinetic Theory of Confined Soliton Gas

Michael Armstrong[1]
[1]Northumbria University

We investigate the dynamics of soliton gases in the focusing nonlinear Schrödinger (fNLS) equation under the influence of moving boundaries, modeled as a piston. Solitons interacting with these boundaries undergo transformations that significantly alter their velocities and trajectories. Using the method of images [1] and Galilean invariance, we analytically derive the conditions governing these interactions and demonstrate that solitons reflect off the moving boundaries with an effective velocity change proportional to twice the boundary velocity. This analytic framework highlights the critical role of boundary dynamics in shaping the behavior of soliton gases.

To complement the theoretical analysis, we implement a numerical approach employing boundary immobilization techniques, which transform the moving boundary problem into a fixed domain for efficient computation. The numerical results align closely with the analytic predictions, providing robust validation of the theoretical framework. This agreement confirms the effectiveness of combining analytical and numerical methods to study complex soliton dynamics in bounded systems.

Our findings offer insights into how moving boundaries influence soliton gases, including the redistribution of soliton velocities and the impact on the overall dynamics of the system. This work contributes to the broader understanding of nonlinear wave phenomena in confined geometries, with potential implications for fields such as fluid dynamics, nonlinear optics, and Bose-Einstein condensates. By bridging analytical and numerical perspectives, this study establishes a comprehensive framework for

exploring soliton interactions in bounded domains, paving the way for future investigations into more complex boundary conditions and multi-component soliton systems.

Reference:
[1] Biondini, G., & Bui, A. (2012). '*On the Nonlinear Schrödinger Equation on the Half Line with Homogeneous Robin Boundary Conditions*'. Studies in Applied Mathematics, **129** (3), 249–271 (2012).

Out of Equilibrium Behaviour of Quantum Vortices: A Comparison of Point Vortex Dynamics and Fokker-Planck Evolution

Mr Richard Tattersall[1], Andrew Baggaley[1], Thomas Billam[1]
[1]Newcastle University

When a system undergoes a rapid quench to a more ordered phase, it does not order instantly but instead relaxes towards equilibrium over time. At late times during this relaxation, the dynamical scaling hypothesis predicts that the length scale of ordered regions should grow, following a power law in time. Here we compare two methods for modelling a coarsening process of this kind in a two-dimensional quantum gas. In both models the annihilation of vortices and antivortices that come into close proximity is the key driver of domain growth. First we compute fully thermalized initial configurations of point vortices and antivortices at given energies in a doubly-periodic square box. We then extract the distribution of vortex-antivortex distances, or dipole lengths, and evolve this using a Fokker-Planck equation. For comparison, we also model the same system using a dissipative point vortex model that traces the dynamics of all vortices and antivortices over time, prior to finding the dipole length distribution.

On the influence of two-level systems on very low temperature nanomechanical resonators

Thomas Antolin[1], Jonas Glatthard[1], Andrew Armour[1]
[1]University of Nottingham

Defects can be found in almost all top-down fabricated quantum devices. Such defects can be modelled as two-level systems (TLSs) and have been proven to be the source of significant noise and decoherence in their host systems. We study the effect that a distribution of TLSs has on a hosting nanomechanical resonator at very low temperatures. Using a linear response approach, we calculate the effect of TLSs on the frequency of the resonator, taking into account broadening of the mechanical resonance due to other sources of damping. Including interactions between TLSs leads to frequency fluctuations which increase as the temperature is lowered.

Session 2 – Abstracts

Long-lived entanglement and spin-1 dynamics of molecules in magic-wavelength optical tweezers

Daniel Ruttley[1], Tom Hepworth[1], Fritz von Gierke[1], Philip Gregory[1], Alexander Guttridge[1], Simon Cornish[1]
[1]Department of Physics, Durham University

Realising quantum control and entanglement of particles is crucial for advancing both quantum technologies and fundamental science. Significant developments in this domain have been achieved in a variety of systems. In this context, ultracold polar molecules offer new and unique opportunities due to their more complex internal structure associated with vibration and rotation, coupled to the existence of long-range interactions. However, the same properties make molecules highly sensitive to their environment, impacting their coherence and utility in some applications.

In this talk, I will describe how we engineer a pristine environment for individually trapped ultracold molecules using magic-wavelength optical tweezers. These decouple the molecules' internal states from their environment, allowing for long-lived coherence between multiple rotational states. Furthermore, in these traps, we can create long-lived entanglement between pairs of molecules using hertz-scale interactions. I will describe how we achieved the highest reported fidelity to date for the preparation of a two-molecule Bell state and present the first realisation of a microwave-driven entangling gate between two molecules. This work opens new avenues for quantum-enhanced metrology, ultracold chemistry, and the use of rotational states for quantum simulation, quantum computation, and as quantum memories. The extension of precise quantum control to complex molecular systems will allow their additional degrees of freedom to be exploited across many domains of quantum science.

The Onset of Quantum Turbulence for a Levitating Sphere in Helium II

Manuel Arrayás[2], Jacob Clothier[1], Omar El Buckley[1], **Courtney C. E. Elmy**[1], Šimon Midlik[1,3], Roch Schanen[1], José Trueba[2], Carlos Uriarte[2], Dmitry Zmeev[1]
[1]Lancaster University, [2]Universidad Rey Juan Carlos, [3]Charles University

We have engineered a versatile device to investigate the properties of helium superfluids through the diamagnetic levitation and manoeuvring of a superconducting sphere of lead (r = 1 mm). Numerous motion patterns have been achieved, most notably the free decay of oscillatory motion, uniform motion, and the free decay of circular motion. The latter facilitates a multitude of new approaches to researching quantum turbulence.

The sphere can be successfully detected through an inductive circuit, the signal from which is translated into position using a map generated from finite element analysis. This allows future research to take place inside a dilution refrigerator. We analyse the transition between laminar and turbulent flow in helium II at temperatures between 4.2 and 1.5 K and detail the future stages of research.

Session 3 – Abstracts

QUEST-DMC: A superfluid bolometer for a direct dark matter search

Miss Tineke Salmon[1], QUEST Collaboration[1,2,3,4,5]
[1]Lancaster University, [2]Royal Holloway University of London, [3]University of Oxford, [4]University of Sussex, [5]University of Liverpool

The QUEST-DMC project, QUantum Enhanced Superfluid Technologies for Dark Matter and Cosmology, is conducting a low mass sub-GeV direct dark matter search using superfluid ^{3}He-B as a target.
The detector is a superfluid bolometer comprising of a sub-cm^3 copper box filled and surrounded by ^{3}He-B, containing a vibrating wire resonator thermometer and heater. It is cooled using a custom nuclear demagnetisation refrigerator. The design and construction of the experiment will be discussed, including sensitivity considerations such as materials choices and characteristics of the vibrating wire probes.
Calibration runs and proof-of-concept searches have been carried out at pressures between 0 and 29 bar and superfluid temperatures around 0.15 Tc. A summary of these results will be presented. Using a transformer readout, we have achieved an energy threshold of 3.5 keV and hope to improve on this with the upcoming run utilising SQUIDs and working at lower temperatures around 0.13 Tc.

References:
[1] QUEST-DMC collaboration, QUEST-DMC superfluid He-3 detector for sub-GeV dark matter, Eur. Phys. J. C **84**, 248 (2024).
[2] QUEST-DMC collaboration, QUEST-DMC: Background Modelling and Resulting Heat Deposit for a Superfluid Helium-3 Bolometer, J. Low Temp. Phys. **215**, 465-476 (2024).

Distinguishing between Direct and Parametric Driving in Nanomechanics using a Vibrating Carbon Nanotube

Sam Dicker[1]
[1]Lancaster University

Carbon nanotube resonators are sensitive devices which can be used in ultrasensitive force detection, and in radio frequency signal processing. Carbon nanotubes could be the advantageous for these applications as they are stiff and lightweight, have high quality factors, and can be made with few defects using chemical vapor deposition.

The mechanical resonances of a suspended carbon nanotube are typically measured via a change in the electrical current through it when it is driven by an oscillating electric force. However, this method often reveals more resonances than expected, indicating the presence of parametric resonances which obscure or overlap with the directly driven resonances. Whereas direct driving arises from an electrostatic force acting at the mechanical resonance frequency, parametric driving arises from the modulation of the spring constant via an alternating gate voltage at integer multiples of the resonance

frequency. Measuring the direct current does not distinguish between these two types of resonance and thus makes it difficult to identify the underlying mechanical spectrum and exploit it for force sensing.

Here, we show how to distinguish direct and parametric driving. We use a suspended carbon nanotube stamped between a source and drain contact over a gate creating a transistor. The device is measured in a dilution refrigerator, cooled to 10mk, and connected to RF lines and a traveling wave parametric amplifier (TWPA). The vibrations of the nanotube, driven by an oscillating gate voltage, give rise to an output voltage that depends on their underlying mechanical frequency. Through this we distinguish experimentally between directly driven resonances (in which the response is at the same frequency as the drive) and parametrically driven resonances (in which the response is at a sub-harmonic frequency). This is true even for resonances that look similar when measured using electrical current alone.

Session 4 – Abstracts

Two-dimensional superfluidity and the A-B phase transition in helium-3

Samuli Autti[1], Richard Haley[1], Adam Mayer[1], Alex Thomson[1], **Luke Whitehead**[1], Dmitry Zmeev[1]
[1]Lancaster University

Previous work at Lancaster has examined the behaviour of superfluid helium-3 at container boundaries, where it forms an independent, two-dimensional system, with implications for our understanding of thermalisation of quasiparticles in the superfluid. We show the design and operation of an experimental cell to continue this work, probing the surface states using a large, low-frequency oscillator. Alongside this, as part of the QUEST-DMC collaboration, we investigate the first order phase transition between the A and B-phases of superfluid 3He, with potential to further our understanding of the early universe. Using a magnet to create a bubble of isolated B-phase within bulk A-phase, we can remove the effects of walls on the nucleation to test the mechanisms that trigger it.

Phase slip activation and free energy barrier characterisation in boron-doped nanocrystalline diamond

Jake Bennett[1], Yehya Megmmi[1], Soumen Mandal[1], Oliver Williams[1], Sean Giblin[1], Georgina Klemencic[1]
[1]School of Physics and Astronomy, Cardiff University, Queen's Building, The Parade, Cardiff, CF24 3AA, UK

Phase slips are a superconducting phenomenon often seen in materials that are 1D or 2D with respect to the coherence length. A phase slip is a local fluctuation of the order parameter to zero, resulting in a finite resistance below the critical temperature, Tc. These fluctuations are typically probabilistic and it is easy to view them as a nuisance. If, however, phase slip activation is deterministic it can serve as a mechanism for developing low-temperature memory devices [1, 2]. Phase slips have recently been realised in Boron-doped nanocrystalline diamond (BNCD) microbridges, while also demonstrating deterministic activation [3], despite these structures being 3D with respect to the coherence length. These relatively large structures reduce fabrication complexity and may provide an easier alternative to developing low-temperature memory storage.

While phase slips have been observed in BNCD, the temperature-dependent activation mechanisms and energy required for these events have not been characterised. Close to Tc, the phase slip energy barrier can be overcome with thermal activation, but as the temperature reduces the barrier can bypassed via quantum tunnelling. By fitting to R(T) data it is possible to determine these temperature regimes and calculate the energy barrier.

Here, we present R(T) measurements and analysis of BNCD microbridges of various widths (2 – 10 μm). The grain structure is believed to be responsible for phase slips in BNCD, so we also compare microbridges with different average grain sizes (~ 60 – 100 nm). The phase slip activation mechanism and free energy barrier are evaluated and compared with theory. This work develops our understanding of phase slips in BNCD for a more accessible route for low-temperature computing applications.

References:
[1] J. Buh *et al.* Nat. Commun. **6**, 10250 (2015).
[2] N. Ligato *et al.* Nat. Commun. **12**, 5200 (2021).
[3] G.M. Klemencic *et al*. Carbon, **175**, 43-49 (2021).

Characterisation of an Aluminium Cylindrical Cavity at Low Temperatures

Joshoua Esmenda[1], Edward Laird[1], Ian Bailey[1], Trevor Gamble[2], Paul Smith[2], Ed Daw[2], Yuri Pashkin[1]
[1]Lancaster University, [2]Sheffield University

Superconducting microwave cavities have found applications in many areas including quantum computing, particle accelerators, and dark matter search. Their extremely high-quality factors translate to very narrow bandwidth, which makes them key components of sensitive detectors. In this study, we aim to understand the loss mechanisms of an aluminium cavity and how they undergo changes as the cavity material transitions from the superconducting to normal state. We found that at temperatures not much lower than the transition temperature (Tc), losses are dominated by quasiparticle excitations and are well described by the BCS theory. The exponential decrease of quasiparticle excitations below Tc results in the 1000-fold increase of the quality factor, as well as the shift of the resonance frequency due to the change of the kinetic inductance of the superconductor. At very low temperatures, losses due to two-level systems begin to dominate giving a peak in the quality factor of about 27 million at 200 mK. Understanding the loss mechanisms is invaluable as wherever area this technology is applied, the working temperature may vary.

Wednesday, January 8, 2025

11:30—12:00	**Arrivals**
12:00—12:30	**Lunch**
12:40—12:45	**Welcome and housekeeping** Prof. Sean Giblin (Cardiff University) and Dr Ryan Doran (Newcastle University)
12:45—13:15	**Superfluid Helium probed by micro-resonators** Dr Simon Midlik (Lancaster University and Charles University in Prague)
13:15—13:45	**The State of the art in ultra-cold atomic BECs** Dr Kali Wilson (University of Strathclyde)
13:45—15:00	**Contributed Talks from Early Career Researchers**
	Quantum paraelectricity in search of dark matter Deepanjan Das (Lancaster University)
	Vortex Avalanches and Collective Motions in Neutron Stars Dr Gary Liu (Newcastle University)
	Kinetic Theory of Confined Soliton Gas Michael Armstrong (Northumbria University)
	Out of Equilibrium Behaviour of Quantum vortices: A Comparison of Point Vortex Dynamics and Fokker-Planck Evolution Richard Tattersall (Newcastle University)
	On the Influence of two-level systems on very low temperature nanomechanical resonators Thomas Antolin (University of Nottingham)
15:00—15:15	**Tea and Coffee Break**
15:15—15:45	**Contributed Talks from Early Career Researchers**
	Long-lived entanglement and spin-1 dynamics of molecules in magic-wavelength optical tweezers Daniel Ruttley (Durham University)
	The Onset of Quantum Turbulence for a Levitating Sphere in Helium II Cortney C. E. Elmy (Lancaster University)
15:45—16:45	**Embedding EDI in Research** Dr Vi Parker (Newcastle University)
17:00—18:00	**Plenary Talk** Dr Anna Marchant (RAL Space)
18:00 –	**Free Time**

Thursday, January 9, 2025

09:00—09:15	**Matthew Lovell, IoP Member Ops Manager**
09:15—09:45	**A Coherent approach to career** Scott Manifold (Oxford Quantum Circuits)
09:45—11:00	**Essential Skills for ECRs** Dr Paul Branch, Ogden Trust Outreach Fellow (Newcastle University)
11:00—11:30	**Contributed Talks from Early Career Researchers**
	QUEST-DMC: A superfluid bolometer for a direct dark matter search Tineke Salmon (Lancaster University)
	Distinguishing between Direct and Parametric Driving in Nanomechanics using a Vibrating Carbon Nanotube Sam Dicker (Lancaster University)
11:30—11:45	**Tea and Coffee Break**
11:45—12:30	**Contributed Talks from Early Career Researchers**
	Two-dimensional superfluidity and the A-B phase transition in helium-3 Luke Whitehead (Lancaster University)
	Phase slip activation and free energy barrier characterisation in boron-doped nanocrystalline diamond Jake Bennett (Cardiff University)
	Characterisation of an Aluminium Cylindrical Cavity at Low Temperatures Joshoua Esmenda (Lancaster University)
12:30—13:00	**Ultra-cold molecules** Dr Phil Gregory, IoP Bates Prize Winner (Durham University)
13:00—13:10	**Closing remarks** Prof. Sean Giblin (Cardiff University)
13:10 –	**Lunch and departure**