Timetable

Keynote or Invited Talk | Breaks | Discussion Panel | Social Event

Tuesday, 7th of November	8:00–8:50	Registration	
	8:50–9:00	Opening & Welcome	
	9:00–10:00	Thomas Busch	Making statistics work: a quantum engine in the BEC–BCS crossover
	10:00–10:30	Raymon Watson	An interaction driven quantum many-body heat engine enabled by atom-atom correlations
	10:30–11:00	Smoko	
	11:00–11:30	Jayne Thompson	Quantum energetic advantage for agents responding in real-time
	11:30–12:00	Rahul Shastri	Controlling Coherence in Finite Time Quantum Otto Cycle Through Monitoring
	12:00–12:30	Lewis Williamson	Extracting work from coherence in a many-body bosonic system
	12:30–14:00	Lunch	
	14:00–15:00	Varinder Singh	Thermodynamic uncertainty relation in degenerate and nondegenerate maser heat engines
	15:00–15:30	Smoko	
	15:30–16:00	Laraib Niaz (online)	A non-traditional quantum heat engine based on electromagnetically induced transparency
	16:00–16:30	Rose Manakil	Spectroscopy to observe Maxwell's Demon
	16:30–17:00	Discussion Panel	
Wednesday, 8th of November	8:30–9:00	Arrival	
	9:00–10:00	Janet Anders	Strong coupling and coherence in quantum thermodynamics
	10:00–10:30	Nicole Yunger Halpern (online)	What happens to entropy production when conserved quantities fail to commute
	10:30–11:00	Smoko	
	11:00–11:30	Gabriella Gonçalves Damas (online)	Optimizing Three-Qubit Quantum Refrigeration with Fermionic Thermal Baths
	11:30–12:00	Mohamed Boubakour	Dynamical Invariant based Shortcut to Thermalization
	12:00–12:30	Kavan Modi	Multitime detailed balance
	12:30–14:00	Lunch	
	14:00–15:00	Joan Vaccaro	The equilibrium state for quantum systems with long-range interactions
	15:00–15:30	Smoko	
	15:30–16:00	Joshua Foo	Superpositions of thermalisation states in relativistic quantum field theory
	16:00–16:30	Carolyn Wood	Operational models of temperature superpositions
	16:30–17:00	Discussion Panel	

Thursday, 9th of November

8:30–9:00	Arrival	
9:00–9:30	Eric He	Quantum clock precision studied with a superconducting circuit
9:30–10:00	Stefan Zeppetzauer	Implementation of a periodic quantum clock based on coherent feedback
10:00–11:00	Nicole Yunger Halpern (online)	Quantum Steampunk
11:00–11:30	Smoko	
11:30–12:00	Thomás Fogarty	Enhancing many-body quantum batteries through symmetrization
12:00–12:30	Christopher Baker	An optomechanical heat engine based on the superfluid fountain effect
12:30–14:00	Lunch	
14:00–15:00	Michael Jack	Molecular motors: Non-equilibrium statistical mechanics of molecular-scale energy conversion
15:00–15:30	Smoko	
15:30–16:00	Konstantina Koteva	Optimization and Comparison of Energetic Performance for Silicon Spin Qubit Quantum Devices
16:00–16:30	Huang RuoCheng	Engines for predictive work extraction from memoryful quantum stochastic processes
16:30–17:00	Discussion Panel	

18:00–22:00	Conference Dinner

Friday, 10th of November

8:30–9:00	Arrival	
9:00–9:30	Vijit Nautiyal	A finite-time quantum Otto cycle driven by atomic interactions
9:30–10:00	Liam McClelland	A quantum spin heat engine with trapped Yb+ ions
10:00–10:30	Vishnu Muraleedharan Sajitha	Finite-time quantum Otto cycle
10:30–11:00	Smoko	
11:00–11:30	Neil Dowling	Quantum Chaos, Scrambling, and (Operator) Entanglement
11:30–12:00	Tyler Neely	Point vortex thermodynamics realised in Bose-Einstein condensates
12:00–12:30	Matthew Davis	Thermalisation and many-body localisation in a two-dimensional lattice of ultracold polar molecules with disordered filling
12:30–13:00	Wrap Up & Close	
14:00–	Social Activity (TBD)	

Abstracts – Tuesday 7th

Making statistics work: a quantum engine in the BEC–BCS crossover

Thomas Busch
Okinawa Institute of Science and Technology, Japan

Heat engines convert thermal energy into mechanical work and are well studied in the classical and in the quantum regimes. However, in the quantum realm genuine nonclassical forms of energy exist, different from heat, which can also be exploited in cyclic engines to produce useful work.

In this presentation I will introduce the concept of a Pauli engine, a novel quantum many-body engine fuelled by the energy difference between fermionic and bosonic ensembles of ultracold particles that follows from the Pauli exclusion principle. The difference in symmetry between these two systems leads to a change in the population distribution, which can be used to replace the traditional heat strokes in a quantum Otto engine.

I will also show that such a system has been realised by cycling the working medium of the engine between a Bose-Einstein condensate of bosonic molecules and a unitary Fermi gas (and back) through a magnetic field in a system of trapped superfluid 6Li atoms. The experiments obtain a work output of several 10^6 vibrational quanta per cycle with an efficiency of up to 25%, therefore establishing quantum statistics as a useful thermodynamic resource for work production.

An interaction driven quantum many-body heat engine enabled by atom-atom correlations

Raymon Watson
The University of Queensland, Australia

The field of quantum thermodynamics has seen rapid progress, with quantum heat engines (QHE's) playing a central role in this development. In recent years, there has been growing interest in many-body QHE's, which may be realized experimentally in ultracold atomic gases. Such systems have been shown to be capable of outperforming a single-body QHE operating with the same resources.

We investigate an experimentally realistic QHE that utilizes a one-dimensional (1D) Bose gas as a working fluid, operating under an Otto cycle where a sudden quench of the interaction strength drives the work strokes. Engine performance is explored in the uniform limit, where the system is described by the integrable Lieb-Liniger model, with finite temperature accessible through the Yang-Yang thermodynamic Bethe ansatz. Additionally, by applying a local density approximation, the performance of the engine cycle in a harmonically trapped gas is evaluated. We demonstrate how net work and efficiency may be calculated through experimentally accessible quantities, such as the local two-body correlation function, the total energy of the system, and, in the case of the harmonically trapped gas, the density profile.

Utilizing the various theoretical tools available for the 1D Bose gas, we investigate the operation of the sudden quench Otto cycle across the entire phase space of the model. We emphasize the generality of the formulas presented, and demonstrate that quantum correlations are essential to achieve positive net work. Additionally, we show how, in a harmonically trapped gas, one may enhance operation of such an engine by incorporating finite particle flow from the hot to the cold reservoir through diffusive and thermal contact.

Quantum energetic advantage for agents responding in real-time

Jayne Thompson
A*STAR, Singapore

Agents often execute complex strategies - continually adapting their reactions to input stimuli to synergize with past actions. Consider a card counter playing blackjack, or a predator chasing prey, all such agents contiguously change their output responses, based on current circumstances and what has happened to date. Such agents often need to execute complex strategies, associated with rewarding input-output behaviour. Simultaneously, such agents often benefit from energy efficiency due to limited energetic resources or the need to minimize heat dissipation in temperature-sensitive situations.

Can quantum agents - agents that store and process quantum information—execute complex strategies using less energy than ultimate classical limits?

In this talk, I will first briefly review of information batteries, and outline how it can be integrated within our recent results regarding the memory costs of executing complex adaptive strategies [1]. I describe how these ideas imply that there is a minimal energetic cost for classical agents to execute such an adaptive strategy, such that they must dissipate a certain amount of heat with each decision. I then present our current research showing that quantum agents can reduce this dissipation below classical limits. I then outline the necessary and sufficient conditions on any given strategy to guarantee this quantum energetic advantage, and scenarios where this advantage can diverge without bound. I discuss how the energetic advantage does not require the agent or receive or emit outputs in quantum superposition and thus persists when our quantum agents interact with purely classical environments.

[1] Thomas Elliott, Mile Gu, Andrew Garner, Jayne Thompson. Quantum adaptive agents with efficient long-term memories. Physical Review X, 011007 (2022)

[2] Jayne Thompson, Paul M. Riechers, Andrew Garner, Thomas J. Elliott, and Mile Gu. Quantum energetic advantage for agents responding in real-time, Manuscript in Preparation (draft available on request).

Controlling Coherence in Finite Time Quantum Otto Cycle Through Monitoring

Rahul Shastri
Indian Institute of Technology Gandhinagar, India

We examine the role of diagnostic quantum measurements in determining the work statistics of finite-time cyclic quantum Otto heat engines. We consider multiple kinds of diagnostic measurement schemes carried out by attaching the working substance with a pointer (PRX Quantum 2, 040328). These schemes interpolate between the two extreme limits of completely unmonitored heat engines (energetics determined by the average internal energy change of the working substance) and Otto engine with the two-point projective (TPM) measurement (energetics determined by outcomes of the projective energy measurement at each point of the Otto cycle). In particular we consider situations where the diagnostic measurement is made by measuring the pointer at each point of the cycle (scheme S1), after the completion of each stroke (scheme S2), and only after the completion of the full cycle (scheme S3). These schemes differ in when and how energy measurements are made during the Otto cycle and are hence shown to have varying degrees of coherence retention throughout the Otto cycle. Then for a specific working substance consisting of a two-level system, we find that the average work output corresponding to schemes S1 and S2 approaches the unmonitored and TPM limits by tuning the pointer width from large to small value compared to the system energy gaps. However, coherence in the system leads to deviations from the TPM limit for the S3 scheme. In certain regimes, we show that better average work output is achieved with coherence.

Extracting work from coherence in a many-body bosonic system

Lewis Williamson
The University of Queensland, Australia

One of the defining features of a quantum system is coherence: the ability for a quantum system to exist in superpositions of eigenstates of some observable. Recent work has explored the utility of coherence in engine operation, either to increase power output or to extract work that is not accessible classically. These proposals have either been formal explorations or focussed on two-level or non-interacting systems. In this work we present a protocol to extract work from coherence in a two-mode interacting bosonic system. We show that non-classical work can be extracted from the number-state uncertainty of coherent states. The work is perfectly non-classical at a precise temperature that depends on the detuning and interaction strength between the two bosonic modes. The ratio of non-classical to classical work is reduced at higher or lower temperatures, however this can be mitigated by squeezing the initial state. The work output can be utilised or measured via linear coupling to an external bosonic mode.

Thermodynamic uncertainty relation in degenerate and nondegenerate maser heat engines

Varinder Singh
Center for Theoretical Physics of Complex Systems, Institute for Basic Science, South Korea

We investigate the thermodynamic uncertainty relation (TUR), i.e., a trade-off between entropy production rate and relative power fluctuations, for nondegenerate three-level and degenerate four-level maser heat engines. In the nondegenerate case, we consider two slightly different configurations of three-level maser heat engine and contrast their degree of violation of standard TUR. We associate their different violating properties of TUR to the phenomenon of spontaneous emission which gives rise to an asymmetry between them. Furthermore, in the high-temperature limit, we show that standard TUR relation is always violated for both configurations. For the degenerate four-level engine, we study the effects of noise-induced coherence on TUR. We show that depending on the parametric regime of operation, noise-induced coherence can either suppress or amplify the relative power fluctuations.

A non-traditional quantum heat engine based on electromagnetically induced transparency

Laraib Niaz
COMSATS University, Pakistan

We present a scheme to realize a gain-assisted quantum heat engine (QHE) based on electromagnetically induced transparency (EIT). We consider a three-level Λ-type atomic system that interacts with two thermal reservoirs and a coupling field. The gain is induced in the system via spontaneously generated coherence (SGC) between two lower levels. To generate SGC, our system must maintain some rigorous conditions, but its effect on the system's dynamics is significant. The SGC can enhance the emission cross-section and spectral brightness of the QHE. We also investigate the role of the relative phase between the control and probe field on the emission cross-section and spectral brightness.

Spectroscopy to observe Maxwell's Demon

Rose Manakil
Griffith University, Queensland, Australia

In the middle of the 19th century successful implementation of steam engines encouraged systematic investigations into heat, work, and energy in physical systems, leading to the development of classical thermodynamics and statistical mechanics. Heat engines convert thermal energy into useful work by leveraging the flow of heat across a temperature gradient. Unfortunately, some of the energy is lost in exhausted waste heat due to practical limits related to the materials and substances involved. A principal limiting factor is typically the 'cold' reservoir temperature available in the environment.

In the Maxwell's Demon thought experiment information about the particle's location can be used to cool the particle, demonstrating the interplay between energy and information. As a result of this we can consider using two spin reservoirs and a single thermal reservoir to achieve 100% energy conversion from heat to work while not violating the second law of thermodynamics as we are separating out the energy from the entropy in the heat.

In our planned proof of concept experiment we will detect the emission spectrum of near-resonant spontaneous Raman scattered 370nm photons by a trapped 171Yb+ ion in the Lambe-Dicke regime with a secular frequency on the order of 1-2MHz. The motional energy of the ion is quantised, and this will enable us to resolve conversion of motional thermal energy into increased photon energy. Detecting this small shift in energy from single scattered photons requires the development of a free-space narrow-linewidth ($<$300 kHz) Fabry-Perot cavity with high-finesse ($\approx$ 1000) and high absolute transmission ($>$10%). We report on progress towards the development of this high-resolution ultraviolet spectrometer.

Abstracts – Wednesday 9th

Strong coupling and coherence in quantum thermodynamics

Janet Anders
University of Exeter, United Kingdom

The interaction of nanoscale and quantum systems with their environment can be relatively strong, and alter the equilibrium state. For open quantum systems, explicit expressions of these so-called mean force (MF) equilibrium states have been missing. In this talk I will report on useful analytic expressions of these states, valid for a general quantum system in contact with a bosonic bath [1]. The results are illustrated with the well-known spin-boson model, for which we provide the first classification of coupling regimes, from weak to ultrastrong, and for both the quantum and classical setting [2].

In the second part of the talk, I will briefly comment on quantum signatures that arise in thermodynamic processes due to the presence of coherences (superposition states). For example, the work distribution of time-varying quantum systems violates the corresponding classical fluctuation-dissipation relation for slowly driven processes [3]. This result implies that quantum fluctuations prohibit finding slow protocols that minimize both, dissipation and fluctuations simultaneously. A geometric framework is proposed to find optimal trade-offs. Another example is that coherences give rise to a second, quantum, kind of irreversibility. We unravel how this irreversibility manifests itself in energetic exchanges that differ from those in the classical regime [4].

[1] Weak and Ultrastrong Coupling Limits of the Quantum Mean Force Gibbs State, J. Cresser, J. Anders, PRL 127, 250601 (2021)

[2] Quantum-classical correspondence in spin-boson equilibrium states at arbitrary coupling, F. Cerisola, et al arXiv:2204.10874

[3] Work Fluctuations in Slow Processes: Quantum Signatures and Optimal Control, H. Miller, M. Scandi, J. Anders, M. Perarnau-Llobet, PRL 123, 230603 (2019)

[4] Energetic footprints of irreversibility in the quantum regime, H. Mohammady, A. Auffeves, J. Anders, Comm. Phys. 3, 1 (2020)

What happens to entropy production when conserved quantities fail to commute

Nicole Yunger Halpern
NIST, QuICS, and University of Maryland, USA

I will extend entropy production to a deeply quantum regime involving noncommuting conserved quantities. Consider a unitary transporting conserved quantities ("charges") between two systems initialized to thermal states. Three common formulae model the entropy produced. They respectively cast entropy as an extensive thermodynamic variable, as an informationtheoretic uncertainty measure, and as a quantifier of irreversibility. Often, the charges are assumed to commute with each other (e.g., energy and particle number). Yet quantum charges can fail to commute. Noncommutation invites generalizations of the three formulae, which I will posit and justify. Charges' noncommutation breaks the three formulae's equivalence. Furthermore, different formulae quantify different physical effects of charges' noncommutation on entropy production. For instance, entropy production can signal contextuality—true nonclassicality—by becoming nonreal. This work opens up stochastic thermodynamics to noncommuting charges—particularly quantum thermodynamics.

References

[1] Upadhyaya, Braasch, Landi, and NYH, arXiv:2305.15480 (2023).

[2] Majidy, Braasch, Lasek, Upadhyaya, Kalev, and NYH, arXiv:2306.00054 (2023).

Optimizing Three-Qubit Quantum Refrigeration with Fermionic Thermal Baths

Gabriella Gonçalves Damas
Universidade Federal de Goiás, Brazil

The use of quantum reservoirs plays a crucial role in open-quantum systems theory, particularly in the context of quantum refrigeration. While bosonic reservoirs, modeled by quantum harmonic oscillators, have been extensively studied, recent attention has been drawn to fermionic reservoirs composed of two-level systems. Unlike bosonic reservoirs, fermionic reservoirs possess a finite number of energy levels, offering unique advantages in various applications, including heat machines. In this study, we conduct a comprehensive investigation of a quantum refrigerator operating in the presence of both bosonic and fermionic thermal reservoirs. Our aim is to explore and highlight the advantages offered by fermionic baths over their bosonic counterparts. Through rigorous simulations and analysis, we demonstrate the enhanced performance and efficiency achieved when utilizing fermionic thermal reservoirs.

Dynamical Invariant based Shortcut to Thermalization

Mohamed Boubakour
Okinawa Institute of Science and Technology, Japan

Shortcut to thermalization (STT) refers to techniques that allow to speed up the thermalization of an open quantum system [1]. STT are relevant in order to boost Quantum Heat Engine performances, where thermal stokes are by default slow and limit the power output. In particular the isothermal stroke, has to be driven sufficiently slowly during all the process to remain at equilibrium.

However realizing a shortcut for the isothermal stroke can be complicated due to the challenge of describing the dynamics of an Open Quantum System with a time-dependent Hamiltonian. Indeed, in the frame of the Master Equation, the calculation of the operators acting on the system in the interaction picture can be complicated when the time-evolution operator is given with a time-dependent Hamiltonian. This issue can be solved by using dynamical invariants (DI). DI were introduced first by Lewis and Riesenfeld to solve the time-dependent Schrodinger Equation [2]. They have interesting algebraic properties, in particular its eigenstates are solution of the time-dependent Schrodinger Equation and can be used to calculate the time-evolution operator.

In our work, we use DI to realize a shortcut for the isothermal stroke. We focus on the Quantum Brownian Motion described by the Caldeira-Leggett model [3] where the Brownian particle is trapped in a time-dependent harmonic potential. We derive the corresponding Master Equation by using the DI of the harmonic oscillator. We then realize the Shortcut by doing reverse engineering: we assume the state of the particle to be Gaussian and combined with the driven Master Equation we can determine the profile of the trap frequency. We also show how the Markovian nature of the bath can limit the Shortcut performance and how coherence can be important for the particle to equilibrate at finite time.

[1] R. Dann, A. Tobalina, and R. Kosloff, Shortcut to Equilibration of an Open Quantum System, Phys. Rev. Lett. 122, 250402 (2019).

[2] H. R. Lewis and W. B. Riesenfeld, An Exact Quantum Theory of the Time-Dependent Harmonic Oscillator and of a Charged Particle in a Time-Dependent Electromagnetic Field, Journal of Mathematical Physics 10, 1458–1473 (1969).

[3] A. Caldeira and A. Leggett, Quantum tunnelling in a dissipative system, Annals of Physics 149, 374–456 (1983).

Multitime detailed balance

Kavan Modi
Monash University, Victoria, and Transport for New South Wales, Australia

Detailed balance is a fundamental requirement for equilibrium phenomena, especially for thermal states. We give a new operational interpretation for the quantum notion of detailed balance and extended it to the multitime setting. This leads to an operational understanding for non-equilbrium steady state (NESS), which play central role in phenomena of transport. We will conclude with some applications of the extended detailed balance.

The equilibrium state for quantum systems with long-range interactions

Joan Vaccaro
Griffith University, Queensland, Australia

The standard formulation of thermodynamics, being based on the Boltzmann distribution and the Gibbs-Shannon entropy, describes idealized systems with short-range interactions. However, many physical systems have been found to exhibit probability distributions that depart from the Boltzmann distribution and so they lack description by this standard formulation. Three decades ago Tsallis argued that to describe these aberrant systems the Gibbs-Shannon entropy needs to be replaced by a new entropy function (Tsallis entropy) to generalise thermodynamics as q-thermostatistics. Unfortunately, the success of the approach relies on an arbitrary fitting parameter q, Tsallis entropy lacks a consistent interpretation in terms of information, and its use in developing resource theories is limited. I will discuss an alternative approach developed with my colleagues (Phys. Rev. E 101, 060101 (2020). We use the fundamental principles of ergodicity (via Liouville's theorem), the self-similarity of correlations, and the existence of the thermodynamic limit to derive generalised forms of the equilibrium distribution for long-range-interacting systems. Significantly, our formalism provides a justification for q-thermostatistics which it includes as a special case. We also give the complementary maximum entropy derivation of the same distributions by constrained maximisation of the Gibbs-Shannon entropy. The consistency between the ergodic and maximum entropy approaches clarifies the use of the latter in the study of correlations and nonextensive thermodynamics. I will also discuss the quest to turn long-range interactions under equilibrium conditions into a quantum resource.

Superpositions of thermalisation states in relativistic quantum field theory

Joshua Foo
Stevens Institute of Technology, NJ, USA

Recent results in relativistic quantum information and quantum thermodynamics have shown that probe systems interacting with superpositions of thermalisation states (for example, the states associated with two spatially translated Rindler wedges) do not thermalise, even if the temperature associated with each state is identical. Here, we provide a concrete explanation of these results and unveil a connection between different approaches using the framework of quantum field theory in relativistic noninertial reference frames. We show how a probe that accelerates in a superposition of spatially translated Rindler wedges interacts with two different sets of field modes, whose inequivalent decompositions with respect to the Minkowski modes leads to complex correlations–that is, interference–between them. This interference perturbs the particle statistics measured by the probe away from the expected Planck distribution. The same holds for probes in a superposition of displaced localised trajectories within causal diamonds. In special cases where the modes are orthogonal (for example, when the Rindler wedges are translated in a direction orthogonal to the plane of motion), thermalisation does indeed result. Our approach draws a connection between quantum information, relativity, and the thermodynamic properties of quantum fields.

Operational models of temperature superpositions

Carolyn Wood
The University of Queensland, Australia

When a quantum system interacts with a thermal bath we say the two can reach thermal equilibrium, and the system acquires the same temperature as the. But how does a delocalised quantum system thermalise with a bath whose local temperature varies, as, for example, in the Tolman-Ehrenfest effect?

Here we formulate two scenarios in which the notion of a "superposition of temperatures" may arise. First: a probe interacting with two different baths dependent on the state of another quantum system (the control). Second: a probe interacting with a single bath whose purified state is itself a superposition of states corresponding to different temperatures. We show that the two scenarios are fundamentally different and can be operationally distinguished. Moreover, we show that the probe does not in general thermalise even when the involved temperatures are equal, and that the final probe state is sensitive to the specific realisation of the thermalising channels. Our models may be applied to scenarios involving joint quantum, gravitational, and thermodynamic phenomena, and explain some recent results found in quantum interference of relativistic probes thermalising with Unruh or Hawking radiation. Finally, we show that our results are reproduced in partial and pre-thermalisation processes, and thus our approach and conclusions hold beyond the idealised scenarios, where thermalisation is incomplete.

[1] Wood, Verma, Costa & Zych (2021), arXiv:2112.07860

Abstracts – Thursday 9th

Quantum clock precision studied with a superconducting circuit

Eric He
The University of Queensland, Australia

We theoretically and experimentally study the precision of a quantum clock near zero temperature, explicitly accounting for the effect of continuous measurement. The clock is created by a superconducting transmon qubit dispersively coupled to an open co-planar resonator. The cavity and qubit are driven by coherent fields, and the cavity output is monitored with a quantum noise-limited amplifier. When the continuous measurement is weak, it induces persistent coherent oscillations (with fluctuating periods) in the conditional moments of the qubit, which are manifest in the output of the resonator. On the other hand, strong continuous measurement leads to an incoherent cycle of quantum jumps. In each regime, we find an equality for the precision of the clock by deriving approximate equations of motion. Furthermore, using these results, we derive and verify a kinetic uncertainty relation for the precision of the clock, thus making an explicit link between the (kinetic) thermodynamic behaviour of the clock and it's precision. Both theory and experiment show enhanced precision in the oscillatory regime over the jump regime, suggesting that in certain situations, quantum coherence may provide a fundamental advantage for time-keeping.

Implementation of a periodic quantum clock based on coherent feedback

Stefan Zeppetzauer
The University of Queensland, Australia

Clocks play an integral part in a variety of applications but have recently drawn interest in the context of fundamental questions such as the connection between time and thermodynamics and the limits of timekeeping. From a thermodynamic point of view, a clock is a nonlinear dissipative system that relies on the increase in entropy to keep track of time. It was recently shown that the resolution of a periodic clock is directly proportional to the energy dissipated per cycle. Therefore, a good clock, both classical and quantum, necessitates a high energy dissipation rate. We realise a new type of periodic quantum clock based on coherent feedback between two coupled resonators. As the feedback is not done via readout, there is no measurement-induced noise, allowing for the characterisation of the system's inherent quantum noise and its effects on the clock's thermodynamical and metrological properties.

We implement the coherent feedback clock on a superconducting circuit consisting of two coupled high-Q coplanar resonators, where one is rendered nonlinear by a Josephson junction embedded in the centre conductor. This provides the nonlinearity necessary for a periodic clock. We show the existence of limit cycles in the quantum regime, where quantum fluctuations become the dominant noise source, and demonstrate the system's applicability as a new type of quantum clock. Specifically, we show the relation between dissipated energy and clock resolution, and how quantum fluctuations in the feedback cycle affect the clock tick accuracy.

In addition, our clock is a natural candidate for the implementation of spiking neural networks, a novel deep learning model that mimics the behaviour of biological neurons and shows promising advantages in dynamic learning tasks compared to conventional perceptron models.

Quantum Steampunk

Nicole Yunger Halpern
QuICS and University of Maryland, USA

Steampunk is a genre of literature, art, and film that juxtaposes futuristic technologies with Victorian settings. This fantasy has become a reality in quantum thermodynamics. On the one hand, Victorians and their contemporaries developed thermodynamics to understand the steam engines that powered the Industrial Revolution. On the other hand, quantum information science is partially cuttingedge and partially futuristic. Quantum thermodynamics therefore shares its aesthetic—its spirit—with steampunk. To celebrate and share our field, I published the nonfiction book Quantum Steampunk: The Physics of Yesterday's Tomorrow for the general public with Johns Hopkins University Press last year. This talk will consist of a Q&A about the book-creation experience.

Reference: https://quantumsteampunk.umiacs.io/book/

Enhancing many-body quantum batteries through symmetrization

Thomás Fogarty
Okinawa Institute of Science and Technology, Japan

It has been shown that batteries with inherently quantum properties such as coherence have improved performance over their classical counterparts. This has motivated the continued study of quantum batteries in which quantum correlations can be used to enhance energy extraction. In this work we investigate many-body batteries comprised of cold-atomic gases, specifically focussing on the role of particle statistics in the operation of these devices. To this end we consider the non-interacting Fermi gas and its bosonic counterpart the strongly interacting Tonks-Girardeau (TG) gas. These two systems are intrinsically linked via the Bose-Fermi mapping theorem which ensures that local properties, such as the charging capacity, are identical. However, the maximum energy that can be extracted from the batteries, known as the ergotropy, is distinct due to the contrasting coherence properties of both systems as a result of their different exchange symmetry. These unique properties allow to clearly evince the role that symmetrization plays in work extraction from quantum devices which have equal charge. In this work we show that the intrinsic coherence of the TG gas can allow for greater energy extraction due to the presence of strong interactions, however this is heavily dependent on the non-equilibrium dynamics induced by the charging process. We explore this by considering sudden quenches in different trapping potentials, namely harmonic and quartic traps. The former allows to take advantage of self-similar many-body dynamics to preserve coherence, however has unstable charge, while the latter saturates to a stable non-equilibrium steady state but is sensitive to decoherence effects from particle collisions. This allows us to discern different operational regimes where bosonic batteries can outperform their fermionic counterparts, showing how we can take advantage of symmetrization to improve the performance of quantum devices.

An optomechanical heat engine based on the superfluid fountain effect

Christopher Baker
The University of Queensland, Australia

The mutual coupling between optical and mechanical degrees of freedom in a cavity optomechanical system enables important processes, such as laser cooling and amplification of mechanical motion, and applications ranging from precision sensors to quantum memories and interfaces. This coupling is typically mediated by radiation pressure forces. However, the magnitude of radiation pressure forces is constrained by the energy mismatch between photons and phonons. In this talk, I will show how it is possible to overcome this barrier using entropic forces arising from the absorption of light [1]. We have recently shown that entropic forces can exceed the radiation pressure force by eight orders of magnitude and demonstrate this using a superfluid helium-coated microsphere. The microsphere's optical whispering gallery mode is coupled to superfluid waves on the surface of the device, which are driven by the superfluid fountain effect.

In this system, the optomechanical gain provided by as little as 0.2 intracavity photons is sufficient to exceed the superfluid acoustic losses, reaching the threshold of regenerative oscillations, i.e., phonon lasing, at a laser power of only a few picowatts, a factor of 2000 lower than has been shown before. This phonon laser can be viewed as a microscale thermodynamic heat engine converting heat into mechanical work, with the superfluid film acting as the working medium, the cryostat acting as the cold reservoir, and the heated region of the microsphere acting as the hot reservoir. We show that its efficiency—while low due to the small temperature differential introduced by photon absorption—is nonetheless around a hundred times higher than previous nanomechanical heat engines and could be increased above 10% in purpose-designed devices.

[1] A. Sawadsky, R. A. Harrison, G. I. Harris, W. W. Wasserman, Y. L. Sfendla, W. P. Bowen, and C. G. Baker, Engineered Entropic Forces Allow Ultrastrong Dynamical Backaction, Science Advances 9, eade3591 (2023).

Molecular motors: Non-equilibrium statistical mechanics of molecular-scale energy conversion

Michael Jack
Department of Physics, University of Otago, Dunedin, New Zealand

Motion at the molecular scale is often governed by overdamped Brownian motion on a free-energy potential landscape. In this talk we survey the use of this framework to describe the non-equilibrium energy conversion behavior of artificial and biological molecular scale devices (often called molecular or protein motors). Combining the Brownian framework with Shannon entropy, it is possible to develop a thermodynamically-consistent description of energy conversion between chemical and mechanical degrees of freedom (as occurs in biological proteins) and of microscopic heat engine concepts, such as, the Feynman ratchet. We also show how this description relates to the so called "thermodynamic uncertainty relation". Finally, we discuss the generalization of this framework to treating many interacting molecular motors.

Optimization and Comparison of Energetic Performance for Silicon Spin Qubit Quantum Devices

Konstantina Koteva
Institut Néel, CNRS Grenoble, France

The excitement surrounding quantum computing and its potential for fast and effcient calculations faces the reality of multiple engineering challenges and limited physical resources. While multiple platforms have demonstrated high performing qubits at small scale, noise and increasing cooling costs limit the performance of intermediate and large scale quantum devices. Exploring the nature of these limitations has the potential to unveil hidden ineffciencies in design or experimental settings that could steer researchers towards practical optimisation.

To benefit from the intrinsic relationship between resource cost and success of computation, a model relating noise to physical and computation variables is necessary. To this end, we present a full-stack model of a quantum computer based on experimental data from the silicon spin qubit platform. In particular, we investigate two types of spin qubits in silicon, the electric dipole spin resonance (EDSR) and the electron spin resonance (ESR), each coupled to an electric or magnetic feld, respectively. In this study, we relate microscopic variables such as the duration of a single qubit gate to macroscopic variables like the power consumption of the cryostat. Their connection is established through a noise model based on current technological capabilities and realistic experimental settings. To achieve a full-stack approach, energetics of individual gates, qubit measurement, heat conduction of the cables as well as cryogenic power is all taken into account and related to the fidelity of the computation. To compare the energetic efficiency of the two spin qubit platforms we estimate their energy consumption for the implementation of 2-, 4- and 8-qubit variational quantum eigensolver (VQE) with the same success probability. Finally, using the Metric-Noise-Resource (MNR) methodology, we optimise the power consumption of the two setups to discover optimal qubit temperature and driving frequency as a function of the success of the computation.

Engines for predictive work extraction from memoryful quantum stochastic processes

Huang RuoCheng
Nanyang Technological University, Singapore

Quantum information-processing techniques enable work extraction from a system's inherently quantum features, in addition to the classical free energy it contains. Meanwhile, the science of computational mechanics affords tools for the predictive modelling of non-Markovian classical and quantum stochastic processes.

We combine tools from these two sciences to develop a theoretical prototype for a predictive quantum engine: a machine that charges a battery by feeding on a multipartite quantum system whose parts are temporally correlated via a classical stochastic process. In other words, the engine's fuel is a classical stochastic process with quantum outputs. We also test the engine on simple models to benchmark the performance of our engine against various alternatives, including one without coherent quantum information-processing and one without predictive functionality; our predictive quantum engine is shown to outperform these alternatives in terms of work output.

Finally, we evaluate the engine's performance on fuel processes with different degrees of temporal correlations and find the work yield to increase with such correlations. Additionally, our results suggest that there exists a phase boundary in parameter space where memory of past observations can enhance the work extraction. Our work opens the prospect of machines that harness environmental free energy in an essentially quantum, essentially time-varying form.

Abstracts – Friday 10th

A finite-time quantum Otto cycle driven by atomic interactions

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Quantum heat engines (QHEs) have been studied extensively in recent years due to two main reasons. Firstly, they provide a well-developed theoretical framework to study the fundamental theories of thermodynamics in the quantum regime. Secondly, they have the potential to leverage truly quantum features, allowing for the development of quantum thermal machines that surpass the performance of their classical counterparts. QHEs with a many-body working fluid allows us to explore ways in which we can exploit many-body effects such as quantum entanglement and quantum correlations to gain the quantum advantage. One-dimensional (1D) Bose gases are regularly realised in experiments with high degree of control over their internal properties. This makes them an ideal platform to study many-body QHEs.

In this work, we propose a many-body QHE driven by atomic interactions in a weakly interacting 1D Bose gas or a quasicondensate. We use theoretical tools to numerically simulate the entire finite-time quantum Otto cycle in an experimentally realisable scenario. In the interaction-induced work strokes of the Otto cycle, the working fluid is treated as an isolated quantum many-body system. Whereas in the heat transfer strokes, the working medium is treated like an open quantum system that is in thermal and diffusive contact with a reservoir. To simulate the heat transfer strokes with a finite-size reservoir, we use the tunnel-coupled model of two quasicondensates with an initial temperature and chemical imbalance. The simulation of finite-time cycle allows us to evaluate the practicality of such engines by calculating the power output. Additionally, we propose a protocol that involves performing additional chemical work on the system during the heat transfer strokes to boost the performance. We also compare the classical-field results with the theory of generalised hydrodynamics.

A quantum spin heat engine with trapped Yb+ ions

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Heat engines convert the energy in heat into usable work. Classical heat engines are limited by the Carnot efficiency, which is a limit imposed by classical thermodynamics. The recent proposal of entirely quantum heat engines could exhibit efficiencies surpassing this classical limit by leveraging entropy transfer from a thermal bath into a spin reservoir. To realise a demonstration quantum heat engine, we intend to use a trapped 171Yb+ ion which acts as a transducer between thermal and spin reservoirs. Stimulated anti-Stokes Raman scattering between Zeeman sub-levels has previously been shown to cool the ion below the Doppler limit. Raman transitions transfer the energy from the motional state by increasing the energy of the emitted photon with respect to the absorbed photon. This process can be stimulated with a second laser beam or the emitted photon can be scattered spontaneously. In the latter case the "work" photon whose energy has been increased can be distinguished from the background beam using sub-MHz precision spectroscopy. The process of reducing the motional quanta through the emission of a work photon increases the entropy in the atom's internal state, which can then be reset using either deterministic quantum gate operations or probabilistically through collisions with a suitable spin reservoir. This process is not a coherent spin exchange mechanism, so investigation into self-induced Zeeman coherence could offer an alternative for resetting the ion's spin. Experimentally, the vibrational modes rethermalise continuously under the influence of the surrounding environment and anharmonic trap interactions. As a first step in this project, we present measurements of the rethermalisation rate of the crystal's vibrational modes returning to a Maxwell-Boltzmann distribution after a single extraction, and the optimisation of Raman detunings and laser beam spot sizes to balance speed against fidelity.

Finite-time quantum Otto cycle

Vishnu Muraleedharan Sajitha
The University of Queensland, Australia

Most work on many-body quantum heat engines has focused on the adiabatic regime, with much less known about engine operation in finite time cycles. Finite-time operation is necessary to achieve finite power output, but this usually reduces efficiency due to quantum friction. In this talk, I will discuss non-adiabatic effects in the operation of an interacting spin-chain engine. I will first analyze different regimes of operation for the system, which can function as both an engine and a refrigerator depending on the reservoir temperatures. Focusing on the engine regime, I will present results on finite-time performance, quantifying frictional effects and how these manifest in the work fluctuations. I will then study ways to optimize the driving protocol to minimize friction and, hence, maximize engine performance.

Quantum Chaos, Scrambling, and (Operator) Entanglement

Neil Dowling
Monash University, Victoria, Australia

Chaotic systems are highly sensitive to a small perturbation, and are ubiquitous throughout biological sciences, physical sciences and even social sciences. In contrast to chaos in classical mechanics, quantum chaos is a opaque concept, admitting a wide range of definitions across different fields. Taking sensitivity to perturbation as the underlying principle, we identify an operational notion for quantum chaos. Namely, we demand that the future state of a many-body, isolated quantum system is sensitive to past multitime operations on a small subpart of that system. By 'sensitive', we mean that the resultant states from two different perturbations cannot easily be transformed into each other. That is, the pertinent quantity is the complexity of the effect of the perturbation, within the final state. From this intuitive metric, which we call the Butterfly Flutter Fidelity, we use the language of multitime quantum processes to identify a series of operational conditions on chaos. Our operational criterion already contains the routine notions, as well as the well-known diagnostics for quantum chaos.

From these, Local-Operator Entanglement turns out to be a specific case of the Butterfly Flutter Fidelity. The scaling of this well studied signature is equivalent to the classical simulability of a dynamics, and from a range of evidence is conjectured to also measure integrability. We show further that scrambling, as measured by out-of-time-order correlators (OTOCs), probes the scaling of this quantity. We showcase this result through a class of analytically tractable Floquet model of dynamics, which encompasses both (interacting) integrable and non-integrable models.

Our framework therefore unifies existing diagnostics within a single structure, spells out the properties of the underlying process tensor encoding the dynamics, and identifies the exact connection to information scrambling. This paves the way to systematically study other many-body dynamical phenomena like many-body localization, measurement-induced phase transitions, and Eigenstate Thermalization.

Point vortex thermodynamics realised in Bose-Einstein condensates

Tyler Neely
The University of Queensland, Australia

The point vortex approximation for two-dimensional fluid flows describes "vortex matter", where the constituent particles are the locally swirling elements of the fluid – point vortices. These systems exhibit complex dynamics, and like normal matter, have solid, liquid, and gas phases. However, long-range interactions and a bounded phase space lead to exotic high-energy equilibrium states, described by absolute negative Boltzmann temperatures.

I will describe our ongoing experiments on the phases of 2D vortex matter. By using a uniform disc-shaped Bose-Einstein condensate, we experimentally realise a system of point vortices isolated from the external environment, with precise experimental control of the initial energy and angular momentum of the vortex ensemble. By initialising the vortices in highly non-equilibrium configurations, we demonstrate thermalisation on experimental timescales. Furthermore, we explore low-energy configurations under systematic heating, by engineering a point vortex ground state. While of fundamental interest to quantum turbulence, vortex matter may be a resource for studying the thermodynamics of small systems or towards engineering reservoirs with unusual thermodynamic properties.

Thermalisation and many-body localisation in a two-dimensional lattice of ultracold polar molecules with disordered filling

Matthew Davis
The University of Queensland, Australia

We perform exact simulations of the dynamics of ultracold polar molecules confined to a two-dimensional optical lattice with disordered filling. The physics of these systems is described by a dipolar spin-1/2 Hamiltonian, with effective on-site disorder arising from the dilute, randomised configurations of molecules in the lattice. We study the relaxation of local spin observables, growth of bipartite entanglement entropy and level-spacing statistics in lattices containing up to N=16 molecules at 50% filling. We observe several key signatures of many-body localisation as the relative strength of the spin-density interactions is increased. Our proposal paves the way for studies of many-body localisation in higher-dimensional dipolar spin models and highlights the potential for quantum simulation of non-equilibrium dynamics in current state-of-the-art ultracold polar molecule platforms.