QI 38: Quantum Thermodynamics

Time: Friday 11:00–13:15 Location: HS IX

QI 38.1 Fri 11:00 HS IX

Understanding System-Meter Correlation Time in Quantum Information Engines — •Rasmus Hagman, Janine Splettstösser, and Henning Kirchberg — Department of Microtechnology and Nanoscience (MC2), Chalmers University of Technology, S-412 96 Göteborg, Sweden

We examine a quantum information engine (QIE) with a finite cycle time, operating between two thermal reservoirs. The engine utilizes information transfer between a working system, modeled as a quantum two-level system, and a meter, modeled as a quantum harmonic oscillator, to convert heat into work.The time-dependent information transfer is linked to the correlation time between the system and meter, which is a crucial resource for the QIE, as the cycle time is lower bounded by this correlation time. Our study accounts for the energetic costs of quantum measurement and the information acquisition process in a comprehensive framework that includes finite-time operations. In this framework, the QIE can reach a Zeno limit at very short correlation times, enabling the extraction of net positive work from a single heat bath where the acquired information needs to be considered to fulfill the second law. We also analyze work and heat as functions of the system's and meter's temperatures, and find that the QIE work in different regimes: as heat engine, heat pump or refrigerator, as well as a "true" information engine, producing net positive work by extracting heat from the colder bath. We optimize power output at given efficiency by analyzing Pareto fronts. Our QIE model could be tested in cavity quantum electrodynamics experiments for empirical validation.

QI 38.2 Fri 11:15 HS IX

The laws of thermodynamics in a 3D scattering environment — •Michael Gaida, Giulio Gasbarri, and Stefan Nimmrichter — Universität Siegen, Deutschland

The laws of thermodynamics, fundamental to physics, are well-established for macroscopic systems but need to be refined in the microscopic and quantum regimes, where the dynamics exhibits strong fluctuations out of equilibrium. In such cases, stochastic models are used, but their thermodynamic consistency must be scrutinized. Collision models for example, which treat the environment as a sequence of unitarily interacting ancillae, rely on precise timing, tailored ancilla resonances, or external work sources to maintain consistency [1]. In contrast, a dilute thermal gas environment gives rise to random, off-resonant scattering events that exchange energy between internal and motional degrees of freedom. Here we consider the dynamics and equilibration of an open system with both motional and internal degrees of freedom of a gas, extending previous results in one dimension [2]. We consider the case of a thermal reservoir and of a non equilibrium work reservoir in which the external and internal temperature of the gas particles differs.

[1] P. Strasberg, G. Schaller, T. Brandes, and M. Esposito, Quantum and information thermodynamics: A uni- fying framework based on repeated interactions, Phys. Rev. X 7, 021003 (2017). [2] S. L. Jacob, M. Esposito, J. M. Parrondo, and F. Barra, Thermalization induced by quantum scattering, PRX Quantum 2, 020312 (2021).

QI 38.3 Fri 11:30 HS IX

An autonomous engine converting particle-exchange to mechanical motion — •Sofia Sevitz[1], Federico Cerisola[2], and Janet Anders[1,2] — [1]University of Potsdam, Institute of Physics and Astronomy, Karl-Liebknecht-Str. 24-25, 14476 Potsdam, Germany — [2]Physics and Astronomy, University of Exeter, Exeter EX4 4QL, United Kingdom

We study the platform consisting of a quantum dot coupled to a mechanical resonator. By coupling the dot (medium of the particle-exchange engine) to the resonator (work load), the produced work is stored in the displacement (which functions as a battery) and can be directly measured. We develop a thermodynamics framework to quantify heat and particle flows between system and reservoirs. In this way, we are able to estimate the mechanical energy stored in the displacement of the resonator. By computing the Husimi distribution we show that as the energy transfer increases, the state of the resonator approaches a coherent state, resulting in the emergence of measurable self-sustained oscillations. The device considered here provides a promising platform for the study of work extraction and storage in the nanoscale with experimentally feasible capabilities.

QI 38.4 Fri 11:45 HS IX

Consistent Clausius inequality and its typical positivity for pure states — •Philipp Strasberg — Instituto de Física de Cantabria (IFCA), Santander, Spain

I show how to consistently derive Clausius inequality, in unison with textbook thermodynamics but in conflict with some recent suggestions in quantum thermodynamics, using a microscopic notion of entropy and temperature. While its strict non-negativity can only be established for a specific initial ensemble, I also show how dynamical typicality ensures that the overwhelming majority of pure states behaves like said ensemble. While the talk focuses on the archetypal example of two systems exchanging heat, the results are general and applicable to a much wider range of scenarios.

QI 38.5 Fri 12:00 HS IX

Boyle's Law in Single-Particle Quantum Systems — •Anton Kantz, Jonathan Brugger, Anja Kuhnhold, and Andreas Buchleitner — Physikalisches Institut der Albert-Ludwigs-Unversität Freiburg, Hermann-Herder-Str. 3, D-79014 Freiburg

We examine properties of statistically defined pressure in a single-particle quantum system. Previous work [1] has shown that isotropic pressure can be achieved if the corresponding classical system is chaotic, or through averaging over many high-energy quantum states of an integrable system.

An important property of a classical gas is Boyle's law, which states that pressure is inversely proportional to volume. We investigate Boyle's law for a single quantum particle moving in a two-dimensional domain. In analogy to the ideal gas law, we aim to define a temperature using the product of pressure - derived directly from the microscopic spectral structure - and volume.

We first consider a two-dimensional rectangular box, which exhibits integrable dynamics, and investigate Boyle's law under various microscopic definitions of pressure. We then transition to a Sinai billiard, which generates classically chaotic dynamics, and investigate to which extent the structure of the billiard's eigenstates makes Boyle's law emerge.

[1] C. Wulf, Microscopic Models of Pressure, Bachelor thesis, Albert-Ludwigs-Universität Freiburg, 2024

QI 38.6 Fri 12:15 HS IX

Non-Markovian Noise Driving a Single-Atom Heat Engine — •Moritz Göb[1], Bo Deng[1,2], Milton Aguilar[3], Max Masuhr[1,2], Daqing Wang[1,2], Eric Lutz[3], and Kilian Singer[1] — [1]Experimental Physics I, Institute of Physics, University of Kassel, Heinrich-Plett-Straße 40, 34132 Kassel — [2]Institute of Applied Physics, University of Bonn, Wegelerstraße 8, 53115 Bonn — [3]Institute for Theoretical Physics I, University of Stuttgart, Pfaffenwaldring 57, 70550 Stuttgart

We present a Paul trap with a tapered geometry [1]. The radio frequency electrodes are angled in axial direction. This configuration yields a coupling of the motional radial and axial degrees of freedom, allowing for the implementation of a single-atom heat engine [2] and duffing-like oscillator [3]. In this contribution, we present the design, implementation, and characterization of such an ion trap. Furthermore, we present first results of using non-Markovian noise to drive a heat engine.

[1] B. Deng, M. Göb, M. Masuhr, J. Roßnagel, G. Jacob, D. Wang and K. Singer, Quantum Sci. Technol. 10 015017 (2025).
[2] J. Roßnagel, S. T. Dawkins, K. N. Tolazzi, O. Abah, E. Lutz, F. Schmidt-Kaler, and K. Singer, Science 352, 325 (2016).
[3] B. Deng, M. Göb, B. A. Stickler, M. Masuhr, K. Singer and D. Wang, PRL 131, 153601 (2023).

QI 38.7 Fri 12:30 HS IX

Nonequilibrium quantum thermodynamics without detailed balance — •Irene Ada Picatoste[1] and Heinz-Peter Breuer[1,2] — [1]Physikalisches Institut, Universität Freiburg, Hermann-Herder-Straße 3, D-79104 Freiburg, Germany — [2]EUCOR Centre for Quantum Science and Quantum Computing, University of Freiburg, Hermann-Herder-Straße 3, D-79104 Freiburg, Germany

We study quantum Brownian motion through the paradigmatic Caldeira-Leggett model describing a central mode coupled to a thermal bath of modes. Starting from the microscopic solution, we construct an exact, time-convolutionless master equation for the reduced state of the central mode [1] and, using a recently developed approach to nonequilibrium quantum thermodynamics [2], we find an effective energy operator using the principle of minimal dissipation. We then examine the instantaneous fixed point of the dynamics and use its jump operators to understand the mechanisms governing the dynamics. We identify two different processes: a particle exchange generator in the detailed balance form that drives the system towards a Gibbs state [3] and, due to the absence of the rotating wave approximation, an additional squeezing generator.

[1] I. A. Picatoste, A. Colla, and H.-P. Breuer, Phys. Rev. Research 6, 013258 (2024).
[2] A. Colla and H.-P. Breuer, Phys. Rev. A 105, 052216 (2022).
[3] A. Colla and H.-P. Breuer, arXiv preprint 2408.00649 (2024).

QI 38.8 Fri 12:45 HS IX

Quantum Thermodynamics in Strongly Coupled Open Systems: Additivity of Multiple Baths Scenarios — •Tim Alhäuser[1] and Heinz-Peter Breuer[1,2] — [1]Institute of Physics, University of Freiburg, Hermann-Herder-Straße 3, D-79104 Freiburg, Germany — [2]EUCOR Centre for Quantum Science and Quantum Computing, University of Freiburg, Hermann-Herder-Straße 3, D-79104 Freiburg, Germany

Employing the framework of Dynamically Emergent Quantum Thermodynamics [1], an open system approach to non-equilibrium quantum thermodynamics, we discuss the definitions of heat, work and renormalized temperature in strongly coupled and structured environments beyond the Born approximation. Using the Fano-Anderson model [2] we investigate heat and energy transfer in quantum systems. A comparison is made between exact solutions of this model [3] and those obtained through the expansion of the time-convolutionless (TCL) master equation at second and fourth order in both single- and multi-baths cases, demonstrating the performance of the TCL approach. This leads to a unique splitting of the master equation's dissipator into contributions from individual baths, based on appropriate conditions for the heat currents and bath temperatures.

[1] A. Colla and H.-P. Breuer, Phys. Rev. A **105**, 052216 (2022).
[2] A. Colla and H.-P. Breuer, arXiv: 2408.00649 [quant-ph](2024).
[3] I. A. Picatoste, A. Colla, and H.-P. Breuer, Phys. Rev. Res. **6**, 013258 (2024).

QI 38.9 Fri 13:00 HS IX

Coherence Manipulation in Asymmetry and Thermodynamics — •Tulja Varun Kondra — Heinrich Heine University Dusseldorf

In the classical regime, thermodynamic state transformations are governed by the free energy. This is also called as the second law of thermodynamics. Previous works showed that, access to a catalytic system allows us to restore the second law in the quantum regime when we ignore coherence. However, in the quantum regime, coherence and free energy are two independent resources. Therefore, coherence places additional nontrivial restrictions on the state transformations that remain elusive. In order to close this gap, we isolate and study the nature of coherence, i.e., we assume access to a source of free energy. We show that allowing catalysis along with a source of free energy allows us to amplify any quantum coherence present in the quantum state arbitrarily. Additionally, any correlations between the system and the catalyst can be suppressed arbitrarily. Therefore, our results provide a key step in formulating a fully general law of quantum thermodynamics.