QI 2: Quantum Thermodynamics and Open Quantum Systems

Time: Monday 9:30–12:45 Location: H9

Invited Talk QI 2.1 Mon 9:30 H9

Measuring the thermodynamic cost of timekeeping — •Yelena Guryanova — Institute for Quantum Optics and Quantum Information (IQOQI), Austrian Academy of Sciences, Boltzmanngasse 3, 1090 Vienna, Austria

All clocks, in some form or another, use the evolution towards higher entropy states to quantify the passage of time. Because of the statistical nature of the second law and corresponding entropy flows, fluctuations fundamentally limit the performance of any clock. This suggests a deep relation between the increase in entropy and the quality of clock ticks. Indeed, minimal models for autonomous clocks in the quantum realm revealed that a linear relation can be derived, where for a limited regime entropy linearly increases with the accuracy. Does a linear relation persist as we move toward a more classical system? We answer this in the affirmative by presenting the first experimental investigation of this thermodynamic relation in a nanoscale clock. We stochastically drive a nanometer-thick membrane and read out its displacement with a radio-frequency cavity, allowing us to identify the ticks. We show theoretically that the maximum possible accuracy for this classical clock is proportional to the entropy created per tick, similar to the known limit for a weakly coupled quantum clock but with a different proportionality constant. We measure both the accuracy and the entropy. Once non-thermal noise is accounted for, we find that there is also a linear relation between accuracy and entropy.

QI 2.2 Mon 10:00 H9

Thermodynamics of Permutation-Invariant Quantum Many-Body Systems: A Group-Theoretical Framework — •Benjamin Yadin[1], Benjamin Morris[2,3], and Kay Brandner[2,3] — [1]Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Straße 3, 57068 Siegen, Germany — [2]School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD, United Kingdom — [3]Centre for the Mathematics and Theoretical Physics of Quantum Non-equilibrium Systems, University of Nottingham, Nottingham NG7 2RD, United Kingdom

Classical thermodynamics originally described ensembles of many particles controlled collectively without addressing individual particles. However, quantum phenomena such as entanglement may lead to very different collective behaviour. We study non-identical particles that interact identically with their environment and control systems. Such collective dynamics are generally generated by a Hamiltonian invariant under particle permutations.

We develop a general framework for such systems, finding a quantum state space containing additional non-classical degrees of freedom. While the permutation symmetry prevents full thermalisation, we prove that a sufficiently complex bath interaction enables maximum possible thermalisation. For systems initialised out of equilibrium with the bath, we calculate steady-state properties and determine the performance of a heat engine model. Compared with previous models using SU(2) spin interactions, we show that SU(d)-based couplings for d-dimensional particles can lead to thermodynamical advantages.

QI 2.3 Mon 10:15 H9

Geometric structure of thermal cones — •Alexssandre de Oliveira Junior, Jakub Czarkowski, Karol Zyczkowski, and Kamil Korzekwa — Faculty of Physics, Astronomy and Applied Computer Science, Jagiellonian University, 30-348 Kraków, Poland.

The second law of thermodynamics imposes a fundamental asymmetry in the flow of events. The so-called thermodynamic arrow of time introduces an ordering on the space of states that can be distinguished according to the system's evolution as past, incomparable, and future thermal cones. In this work, we analyse the structure of the thermodynamic arrow of time within a resource-theoretic framework, where one investigates the accessibility of quantum state transformations under thermodynamic constraints. Specifically, for a d-dimensional classical state interacting with a heat bath at a fixed temperature T, we found the necessary and sufficient conditions to construct its incomparable and past thermal cones. By introducing a new thermodynamic monotone, the volume of the future thermal cone, we provide a detailed analysis of the behaviour of the thermal cones. In a general context, while the future thermal cone can be seen as a generalisation of the Hardy-Littlewood-Polya theorem, the past and incomparable region can be interpreted as its extensions. Moreover, our results also apply to other majorisation-based resource theories, such as entanglement, since in the limit of infinite temperature, the partial order that emerges is the same (precisely: the opposite) as defined on the set of bipartite pure entangled states by local operations and classical communication

QI 2.4 Mon 10:30 H9

Continuous measurement feedback for adaptive qubit thermometry — •Julia Boeyens and Stefan Nimmrichter — Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Siegen 57068, Germany

Bayesian estimation was recently applied to quantum thermometry since it allows for better estimation accuracy when data is limited and admits adaptive estimation schemes. Here, we apply the Bayesian framework to the setting of continuous temperature measurement. We model a qubit probe, subject to continuous monitoring interacting with a bosonic bath of unknown temperature. The Kushner-Stratonovich equation from classical filtering theory is simulated to find the posterior distribution. Bayesian estimation is then used to infer the temperature from this probability distribution using. This is compared to the discrete analogue, collisional thermometry . An adaptive strategy for improved accuracy is described where Hamiltonian parameters of the qubit can be changed continuously by measurement feedback.

QI 2.5 Mon 10:45 H9

Quantum trajectories beyond weak coupling — •Brecht Donvil[1] and Paolo Muratore Ginanneschi[2] — [1]Institute for Complex Quantum Systems, Albert-Einstein-Allee 11, D-89069, Ulm — [2]University of Helsinki, Department of Mathematics and Statistics P.O. Box 68 FIN-00014, Helsinki, Finland

Master equations are one of the main avenues to study open quantum systems. In situations where the interaction between a dedicated system and its environment is weak, the master equation is of the Lindblad form. In this case, the solution of the master equation can be “unraveled in quantum trajectories” i.e. represented as an average over the realizations of a Markov process in the Hilbert space of the system. Quantum trajectories of this type are both an element of quantum measurement theory as well as a numerical tool for systems in large Hilbert spaces.

In this talk, I show that I show how this procedure can be generalized to arbitrary trace-preserving master equations with time-local dissipation rates. In contrast to the conventional setting, these rates can take also negative values, thus mimicking back-flow of information. Such master equations typically arrive from exactly solvable models or time convoluntionless perturbation theory. The crucial ingredient for our unraveling is to weigh averages by a probability pseudo-measure which we call the “influence martingale”. The influence martingale satisfies a $1d$ stochastic differential equation enslaved to the ones governing the quantum trajectories. The influence martingale thus extends the existing theory without increasing the computational complexity.

15 min. break

Invited Talk QI 2.6 Mon 11:15 H9

Finite-size effects in quantum thermodynamics — •Kamil Korzekwa — Jagiellonian University, Kraków, Poland

The necessity to go beyond classical thermodynamics is usually motivated by the fact that at the nanoscale quantum effects, like coherence and entanglement, start playing an important role. However, in the quantum regime one also deals with systems composed of a finite number n of particles, whereas the theory of thermodynamics is traditionally constrained to the study of macroscopic systems with $n \to \infty$, whose energy fluctuations are negligible compared to their average energy. In this talk I will address this problem and describe recent developments allowing one to go beyond the thermodynamic limit and rigorously investigate thermodynamic transformations of finite-size systems. I will explain why such transformations are generally irreversible and consume free energy, and how this affects the performance of thermodynamic protocols. A new version of the famous fluctuation-dissipation theorem will also be presented, linking the minimal amount of free energy dissipated in the process to the amount of free energy fluctuations present in the initial state of the system.

Moreover, I will discuss a novel resource resonance phenomenon, which allows one to significantly reduce dissipation for transformations between states whose fluctuations are properly tuned. Finally, I will also explain how quantum coherence may bring states closer to resonance effectively decreasing the dissipation of free energy.

QI 2.7 Mon 11:45 H9

Work fluctuations and entanglement in quantum batteries — •Satoya Imai, Otfried Gühne, and Stefan Nimmrichter — Universität Siegen Department Physik Emmy-Noether-Campus Walter-Flex-Straße 3 57068 Siegen Germany

We consider quantum batteries given by composite interacting quantum systems in terms of the thermodynamic work cost of local random unitary processes. We characterize quantum correlations by monitoring the average energy change and its fluctuations in the high-dimensional bipartite systems. We derive a hierarchy of bounds on high-dimensional entanglement (the so-called Schmidt number) from the work fluctuations and thereby show that larger work fluctuations can verify the presence of stronger entanglement in the system. Finally, we develop two-point measurement protocols with noisy detectors that can estimate work fluctuations, showing that the dimensionality of entanglement can be probed in this manner.

QI 2.8 Mon 12:00 H9

Large fluctuations of qubit decoherence under $1/f$ noise of a sparse bath of two-level fluctuators — •Mohammad Mehmandoost and Viatcheslav Dobrovitski — QuTech and Kavli Institute of Nanoscience, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands

We theoretically study the qubit decoherence caused by $1/f$ noise of a sparse bath of Two-Level Fluctuators (TLFs) in the Ramsey and Hahn echo experiments. We focus on the role of bath density d, defined as the ratio of the number of TLFs n to the logarithmic frequency range $\ln(\gamma_M/\gamma_m)$, on the qubit decoherence. The first spectral density of $1/f$ noise produced by sparse bath samples, small d, are roughly similar. The qubit decoherence in this regime is, however, not fully characterized by the noise first spectral density. We therefore use the exact expressions describing the qubit decoherence coupled to a sample TLF bath. Using Monte Carlo simulations, we show that the qubit decoherence is subject to large sample-to-sample fluctuations in sparse baths of fixed density d. This highlights the necessity to adopt a statistical approach to characterize the qubit decoherence in this regime. We also found that the qubit decoherence under $1/f$ noise of sparse TLF baths is governed by only a few TLFs. We show that if these TLFs are removed, the coherence times are substantially improved. We hope the latter finding opens up a way to improve the coherence times of the state-of-the-art qubits affected by $1/f$ noise.

QI 2.9 Mon 12:15 H9

Entanglement Preservation in Open Quantum System — •Mei Yu, Stefan Nimmrichter, and Otfried Gühne — Universität Siegen, Siegen, Germany

It's widely known that the entanglement will decay when system is exposed to the environment. In this paper, we study how to keep the entanglement against destructive effect from environment at different temperatures. Within the spin gases model, we firstly investigate the entangling ability of two-qubit gate in Markovian and non-Markovian dephasing environment. Then, we implement the specific reset operation on two-qubit system at stochastic times in order to keep entanglement in steady state. The steady-state entanglement behavior is analysed in both cases of Markvovian and non-Markovian dephasing noise with different temperatures. Excepting for considerable entanglement value, the difference between Markovian and non-Markovian effect can be observed directly.

QI 2.10 Mon 12:30 H9

Quantum thermodynamics of rare earth spin ensembles embedded into Y_2SiO_5 — Andreas Meyer[1,2], Rudolf Gross[1,2,3], and •Nadezhda P. Kukharchyk[1,3] — [1]Walther-Meissner-Institut, Bavarian Academy of Sciences, Garching, Germany — [2]Physics Department, Technical University of Munich, Garching, Germany — [3]Munich Center for Quantum Science and Technologies, Munich, Germany

Interest in the field of quantum thermodynamic has emerged recently supported by advances in quantum information field. While quantum systems themselves require an optimized approach for characterisation of entropy and work, also the temperature range at which such systems operate is highly sensitive to even small excitation. The rare earth spin ensembles belong to those systems, which are in the focus of quantum thermodynamics. When these ensembles are cooled down to millikelvin temperatures, even short controlling pulses result in a strong perturbation of thermal equilibrium in the host crystal, which reveals itself in the observed dynamics of the excited spin ensemble [1]. In this talk, we will discuss the dynamics of the non-equilibrium state within the Y_2SiO_5 crystal, as well as its impact on the relaxation and decoherence processes within the rare earth spin ensembles. The analytical modelling of the heat dynamics will be compared to the experimental finding of the coherence study of $^{167}Er:Y_2SiO_5$ at millikelvin temperatures.

1. N. Kukharchyk et al, "Enhancement of optical coherence in $^{167}Er:Y_2SiO_5$ crystal at millikelvin temperatures", arXiv: 1910.03096