Mathematical foundations of quantum thermodynamics

6-9 December 2016, Smolenice, Slovakia

BOOK OF ABSTRACTS

INVITED TALKS

Tuesday, 18:00-18:45

Christian Gogolin (ICFO, Spain)

Pure state quantum statistical mechanics

This seminar constitutes a basic introduction into modern quantum statistical mechanics and in particular recent developments concerning equilibration and thermalization in closed quantum many-body systems. We will see how equilibration and thermalization can be defined in unitarily evolving and finite dimensional quantum systems, and under what conditions they can be proved to happen. I will mainly concentrate on analytical results, but also relate to recent experiments, touch on the large numerical literature on the topic, and point our some open problems.

Wednesday, 09:00-09:45

David Reeb (Leibniz University Hannover, Germany)

Fundamental energy cost for quantum measurement

Measurements and feedback are essential in the control of any device operating at the quantum scale and exploiting the features of quantum physics. As the number of quantum components grows, it becomes imperative to consider the energetic expense of such elementary operations. Here we determine the fundamental energy requirements for physical implementations of any general quantum measurement. We show that the exact costs for projective measurements depend on the outcome probabilities only, causing more severe constraints on error correction and control protocols than previously known. In contrast, energy can be extracted from certain measurement processes even if their outcome is recorded. Our results constitute fundamental physical limitations against which to benchmark implementations of future quantum devices as they grow in complexity. (arXiv:1609.06981, joint work with Kais Abdelkhalek and Yoshifumi Nakata)

Wednesday, 11:00-11:45

Yelena Guryanova (IQOQI, Vienna, Austria)

Thermodynamics of multiple conserved quantities

We consider a generalisation of thermodynamics that deals with multiple conserved quantities at the level of individual quantum systems. Each conserved quantity, can be extracted and stored in its own battery. Unlike in standard thermodynamics, where the second law places a constraint on how much of the conserved quantity (energy) that can be extracted, here, on the contrary, there is no limit on how much of any individual conserved quantity that can be extracted. However, other conserved quantities must be supplied, and the second law constrains the combination of extractable quantities and the trade-offs between them which are allowed. We present explicit protocols which allow us to perform arbitrarily good trade-offs and extract arbitrary conserved quantities from individual systems.

Wednesday, 14:00 - 14:45

Lidia del Rio (ETH Zurich, Switzerland)

Currencies and agents in resource theories

How may we quantify the value of physical resources, such as entangled quantum states, heat baths or lasers? Existing resource theories give us partial answers; however, these rely on idealizations, like the concept of perfectly independent copies of states used to derive conversion rates. As these idealizations are impossible to implement in practice, such results may be of little consequence for experimentalists.

In the first part of this talk I introduce the general tool of currencies [arXiv:1605.01064, arXiv:1511.08818] to quantify realistic descriptions of resources, applicable in experimental settings when we do not have perfect control over a physical system, when only the neighbourhood of a state or some of its properties are known, or when there is no obvious way to decompose a global space into subsystems. Currencies are a special set of resources chosen to quantify all others - like Bell pairs in LOCC or a lifted weight in thermodynamics. We will see that from very weak assumptions on the theory we can already find useful currencies that give us both necessary and sufficient conditions for resource conversion, and we can build up more results as we impose further structure.

In the second part of the talk I will explore how we can model the knowledge that agents may have of a physical state, beyond the density operator formalism. We will see how to relate theories that differ in the language used to describe resources, like micro and macroscopic thermodynamics. Finally, we take a top-down approach to locality, in which a subsystem structure is derived from a global theory rather than assumed.

Thursday 11:00-11:45

Stefan Wolf & Veronika Baumann (Università della Svizzera italiana, Lugano, Swizzerland)

From Quantum to Classical

CONTRIBUTED TALKS

Tuesday, 18:45-19:10

M. Hamed Mohammady (University of Exeter, United Kingdom)

Quantum refrigeration using many body systems

The reduced state of a many body system that conserves the total local energy will be a mixture of the energy eigenstates, provided certain initial conditions are met. Recent numerical results with a Heisenberg spin chain suggest that if the initial state of the chain is that of a collection of local thermal states of temperature less than T, then the reduced states will always be thermal with a temperature smaller than T. If this can be proven to be necessarily true for all times, it will follow that such a system can be used as a refrigerator, by swapping one of the qubits in the chain with a thermal qubit of temperature T than we wish to cool.

Wednesday, 9:45-10:10

Fabio Anza (University of Oxford, United Kingdom)

Observable thermalisation

A crucial point in statistical mechanics is the definition of thermal equilibrium, which is given as the state that maximises the von Neumann entropy, under the validity of some constraints. Arguing that such a definition can never be experimentally probed, in this paper we propose a new way to define thermal equilibrium, focused on observables rather than on the full state of the quantum system. We characterise such notion of thermal equilibrium, for an arbitrary observable, via the maximisation of its Shannon entropy and we bring to light the thermal properties that such a principle heralds.

Wednesday, 10:10-10:35

Senaida Hernández Santana (ICFO, Barcelona, Spain)

Decay of correlations in long-range interacting systems at non-zero temperature

While the locality of correlation functions has been widely studied for 1D systems with short-range interactions, little is known about long-range interacting systems. In this work, we study how correlations behave in a system with long-range interactions at thermal equilibrium from analytical and numerical perspectives. We analytically prove that correlations between anticommutative operators decay at least as a power-law at finite temperature for fermionic and two-site long-range interacting Hamiltonians. We also study the density-density correlations for a specific model and demonstrate that they decay asymptotically as a power-law, which is in great agreement with our analytical findings. In addition, we observe that our bound is actually tight, as it is satured in the numerical study.

Wednesday, 11:45-12:10

Nicolai Friis (University of Innsbruck, Austria)

Passivity and practical work extraction using Gaussian operations

Quantum states that can yield work in a cyclical Hamiltonian process form one of the primary resources in the context of quantum thermodynamics. Conversely, states whose average energy cannot be lowered by unitary transformations are called passive. However, while work may be extracted from non-passive states using arbitrary unitaries, the latter may be hard to realize in practice. It is therefore pertinent to consider the passivity of states under restricted classes of operations that can be feasibly implemented. We ask how restrictive the class of Gaussian unitaries is for work extraction. We investigate the notion of Gaussian passivity, i.e., we present necessary and sufficient criteria identifying all states whose energy cannot be lowered by Gaussian unitaries. (see arXiv:1608.04977)

Wednesday, 12:10-12:35

Rodrigo Gallego (Freie Universitat Berlin, Germany)

Thermodynamics with local control

We investigate the limitations in thermodynamics resulting from having local control over the components of the machine. These limitations are specially relevant for machines composed of strongly interacting many-body systems, where results from the theory of Quantum Control are incorporated. This provides a restricted set of operations and new bounds for the performance of engines. Our findings show that those control limitations make in general impossible to reach Carnot efficiency and in many realistic models, even forbid to reach a finite efficiency or work per particle. We focus on spin-chains as a case study, for which we show that in the limit of strong interactions the ferromagnetic case becomes useless for work extraction, while the anti-ferromagnetic reaches Carnot efficiency.

Wednesday, 14:45-15:10

Raam Uzdin (The Hebrew University of Jerusalem, Israel)

Generalized Clausius inequalities

We use the Bregman divergence to derive families of generalized Clausius inequalities (gCI). These gCI relate changes in higher moments of the energy to information measures. The Bregman divergence has an appealing geometrical, and operational thermodynamic meaning that reveals an interesting mathematical structure. We find cases where the standard second law does not provide any information but the gCI do. It is also used to set a tighter efficiency bound on irreversible heat machines. Yet, there are many new challenges, e.g., to fully map the regime of validity of the new gCI, and to formulate their quantum extension (preliminary results will be shown). Time permitting generalized “Global” second law will be discussed as well.

Thursday, 9:20-9:45

Jonatan Bohr Brask (University of Geneva, Switzerland)

Multiple environments and the quantum master equation

For an open quantum system, one is often interested in an effective description of the dynamics, averaging over external noise. A quantum master equation provides such a description and can be derived from a microscopic model of the system and bath and their interaction, by tracing over the bath and applying appropriate approximations. Care needs to be taken when several noise processes act simultaneously or the Hamiltonian evolution of the system is modified. Simultaneous coupling to multiple baths does not generally correspond to simple addition of master equation generators. We demonstrate that addition of the generators can in fact lead to master equations that are not physically valid, and discuss conditions under which direct addition at the master equation level is justified.

Thursday, 9:45-10:10
Mark Mitchison (Universität Ulm, Germany)
Non-equilibrium steady states of autonomous thermal machines
I will introduce and discuss the long-standing open problem of how to correctly model the non-equilibrium steady state of a quantum network using a Lindblad master equation. This old question has gained renewed attention in recent years because it is directly applicable to the theory of autonomous thermal machines. The difficulties are associated with the secular approximation, which on the one hand is necessary to ensure consistency with basic thermodynamic laws, but on the other hand guarantees an energy-diagonal steady state, such that intra-system energy currents vanish identically even far from thermal equilibrium. We illustrate the physical context of this mathematical problem in quantum thermodynamics, and discuss possible resolutions of the apparent paradox.

Thursday, 10:10-10:35
Ralph Silva (University of Geneva, Switzerland)
Autonomous quantum machines and finite sized clocks
Recent quantum thermodynamic resource theories and derivations of the second law in the quantum regime are predicated upon the unitary operation as a basic building block. The unitary itself is usually described by external observer that manipulates an interaction. Including this control into a fully quantum description, a so-called “quantum clock”, is thus a critical step to placing quantum protocols on a firm footing. Here we present a quantum clock that performs a general energy-preserving unitary with an error that is exponentially small in both the dimension and the energy of the clock. This has implications for the validity of resource theories, and is both a benchmark for future implementations, a as well as a conjecture on the fundamental limitations of clocks. arXiv:1607.04591

Thursday, 11:45-12:10
Paul Erker (Uni della Svizzera Italiana, Switzerland / Uni Autonoma de Barcelona, Spain)
Autonomous quantum clocks: how thermodynamics limits our ability to measure time
We discuss the fundamental limitations and resources for measuring time. A prerequisite for any system to function as a clock is it being out of equilibrium. We thus introduce the concept of autonomous quantum clocks using only the minimal out-of-equilibrium resources, i.e. two thermal baths at different temperatures. We find a fundamental trade-off between the amount of heat dissipated and the performance of the clock in terms of accuracy and resolution. We present both universal arguments as well as a detailed simulation illustrating these behaviors. This shows that the amount of entropy increase according to the second law is a resource for timekeeping.

Thursday, 12:10-12:35

Harry Miller (University of Exeter, United Kingdom)

Time-reversal symmetric work distributions for closed quantum dynamics in the histories framework

A central topic in the emerging field of quantum thermodynamics is the definition of thermodynamic work in the quantum regime. One widely used solution is to define work for a closed system undergoing non-equilibrium dynamics according to the two-point energy measurement scheme. However, due to the invasive nature of measurement the two-point quantum work probability distribution leads to inconsistencies with two pillars of thermodynamics: it breaks the first law and the time-reversal symmetry expected for closed dynamics. We here introduce the quantum histories framework as a method to characterise the thermodynamic properties of the unmeasured, closed dynamics. Extending the classical phase space trajectories to continuous power operator trajectories allows us to derive an alternative quantum work distribution for closed quantum dynamics that fulfils the first law and is time-reversal symmetric. We find that the work distribution of the unmeasured dynamics leads to deviations from the classical Jarzynski equality and can have negative values highlighting distinctly non-classical features of quantum work.

Friday, 9:30-9:55

Philipp Kammerlander (ETH Zürich, Switzerland)

An operational formulation of thermodynamics makes the zeroth law obsolete

We introduce a new operational mathematical framework for classical phenomenological thermodynamics inspired by (quantum) information theory. By formulating a minimal set of operational assumptions we are able to rederive the theory’s statements along standard lines. While doing so, we prove a central theorem of phenomenological thermodynamics, Carnot's theorem on the effciency of classical reversible cyclic thermal machines. We follow the standard proof of Carnot's theorem and, interestingly, do not have to refer to the 0th law of thermodynamics in the course of doing so. In this talk I will focus on the specific findings which question the status of the thought-to-be fundamental 0th law in the standard derivation of thermodynamics as it is often encountered in textbooks.

Friday, 9:55-10:20

Henrik Wilming (Freie Universität Berlin, Germany)

Low-temperature cooling with finite non-equilibrium resources

The unattainability principle states that exact ground-state cooling requires infinite resources. We argue that ground-state cooling using non-equilibrium resources with respect to a heat bath is essentially controlled by a single function, which we call “vacancy”. We show for a large class of resource states, namely certain thermal states out of equilibrium with respect to the available heat bath, that the vacancy provides the exact (non-asymptotic) necessary and sufficient condition to prepare a state close to a ground-state. The vacancy also controls the asymptotic limit for arbitrary resource states, for which we give a new proof.

POSTERS

Veronika Baumann (Università della Svizzera italiana, Lugano, Swizzerland)

The measurement problem is the measurement problem is the measurement problem

Recently, it has been stated that single-world interpretations of quantum theory (QT) are logically inconsistent. The claim is derived from contradicting statements of agents in a setup combining two Wigner's-friend experiments. Those statements stem from applying the measurement-update rule subjectively, i.e., only for the respective agent's own measurement. We argue that the contradiction expresses the incompatibility of collapse and unitarity - resulting in different formal descriptions of a measurement - and does not allow to dismiss any specific interpretation of QT.

Paul Boes (Freie Universitat Berlin, Germany)

Thermal operations under partial information - an operational Jaynes Principle for energy

Thermal operations have been a useful conceptual tool in recent studies of quantum thermodynamics. Here, we model coarse operational control by studying the setting of thermal operations under partial information: Instead of the initial state, only the expectation values m_i with respect to a set of observables M are known. We find that, without suitable catalysts, this problem admits a linear characterisation. In the presence of suitable catalysts and for M being the system Hamiltonian, the thermal state is the only state that can be prepared having only this information without any average work. This provides an operational derivation of Jaynes' Principle for this special setting. We discuss for which systems this becomes a deterministic statement in the thermodynamic limit.

Roman Krčmár (RCQI, Bratislava, Slovakia)

von Neuman entropy in classical statistical models

Entanglement is a property of the quantum system. It expresses correlations between various parts of the quantum system. For two partite division von Neumann entropy can be used as a measure of the entanglement. Correlations are enhanced around the phase transition point and therefore Von Neumann entropy can be used for detection of quantum phase transitions, it has logarithmic divergences around them. Using Suzuki-Trotter transformation we can map one-dimensional quantum model to two-dimensional classical statistical model. Using this mapping we can define classical analogue of von Neumann entropy. Expecting the same qualities, we can use this quantity for detecting positions of classical phase transition.

Jiří Maryška (FNSPE CTU, Prague, Czechia)

Gibbs-like states

We present a framework which allows us to analytically describe the asymptotic dynamics of a wide class of finite open quantum systems generated by Lindblad operator L. With the help of this framework we show that there exists a neat relation between the set of integrals of motion and stationary states corresponding to the system. This relation and the properties of the set of integrals of motion then imply that the stationary states take form which resembles often used generalized Gibbs states. These so-called Gibbs-like states follow a principle, which can be seen as a generalization of well known maximal entropy principle.

Harry Miller (University of Exeter, United Kingdom)

Leggett-Garg inequalities for quantum fluctuating work

A set of Leggett-Garg inequalities for the statistics of fluctuating work done on a system driven out of equilibrium are derived. It is shown that quantum systems can violate these inequalities, demonstrating that fluctuations in work in the quantum regime exhibit non-classical features that cannot be replicated through any classical non-equilibrium process. This clarifies that the fluctuating work cannot generally be interpreted as a classical stochastic variable due to violations of so-called macrorealism at the quantum level. Our work helps to elucidate the influence of temporal correlations on work extraction within quantum non-equilibrium thermodynamics.

Daniel Nagaj (RCQI, Bratislava, Slovakia)

Fighting dispersion in continuous time quantum walks

Continuous-time quantum walks (CTQW) on graphs are a universal tool in quantum computation, for examplie in a space efficient construction with qubits encoded as multiple wavepackets with precise momenta on dual rails. These scatter on a graph, including a δ-function interaction.

We need to be careful about the tradeoff between the packet width (momentum precision) and the required computational time/space. First, because individual scattering graph components do not perfectly transmit momenta near the desired one. Second, because the packet motion on long lines between components of the graph introduces dispersion errors.

We find a method for fighting dispersion, increasing the coherence time scaling with the packet width L. The trick is adding a small anti-dispersion gadget after each constant line segment. We get control over the error in translation for distances/times O(L^3), compared to o(L^2) for free evolution.

Daniel Reitzner, Michal Sedlák, Mário Ziman (RCQI, Bratislava, Slovakia)

Incompatible measurements on quantum causal networks

We extend the notion of incompatibility from measurements that test preparations to measurements that test dynamical processes. Such measurements, known as testers, consist of the preparation of an input state, the application of the tested process, and a measurement on the output. Mathematically, testers are described by a suitable generalization of the notion of positive operator-valued measure (POVM). Unlike in the case of POVMs, however, testers that commute are not necessarily compatible, and testers that are compatible do not necessarily commute. All our results can be extended to testers of quantum processes consisting of multiple time steps.

Tomáš Rybár, Mário Ziman (RCQI, Bratislava, Slovakia)

Simulation of channels and dynamical maps

We investigate the possibility of stroboscopically simulating quantum channels and dynamical maps via collision models.

Michal Sedlák (RCQI, Bratislava, Slovakia)

Efficient characterization of linear optical quantum Toffoli gate

We report on a detailed characterization of three-qubit linear optical quantum Toffoli gate. The first method provides a bound on quantum process fidelity that is determined by average output state fidelities for three partially conjugate product bases. A distinct advantage of this approach is that only fidelities with product states need to be measured while keeping the number of measurements much smaller than for other methods (192 two-photon coincidences suffice). For the second method we measured 4032 different two-photon coincidences which allow us to estimate the fidelity of the gate to be 90%. Although these data are not tomographically complete, we show that they are sufficient for a reliable reconstruction.

Marcus Huber, Lidia del Rio, Christian Gogolin (quantum-journal.org)

Executing Quantum

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Quantum is non-profit and community-run: an effort by researchers and for researchers to make science more open and publishing more transparent and efficient.

WORKSHOP PROGRAM

TUESDAY 06/12/2016

14:30 - 17:00 conference bus (from Vienna Airport)
17:00 - 18:00 refreshment, registration and accommodation
18:00 - 18:45 **Christian Gogolin:** Pure state quantum statistical mechanics
18:45 - 19:10 **M. Hamed Mohammady:** Quantum refrigeration using many body systems
19:15 - 20:00 welcome dinner

WEDNESDAY 07/12/2016

08:00 - 09:00 breakfast
09:00 - 09:45 **David Reeb:** Fundamental energy cost for quantum measurement
09:45 - 10:10 **Fabio Anza:** Observable thermalisation
10:10 - 10:35 **Senaida Santana:** Decay of correlations at non-zero temperature
10:35 - 11:00 break and refreshment
11:00 - 11:45 **Yelena Guryanova:** Thermodynamics of multiple conserved quantities
11:45 - 12:10 **Nicolai Friis:** Passivity and practical work extraction using Gaussian operations
12:10 - 12:35 **Rodrigo Gallego:** Thermodynamics with local control
12:45 - 13:30 lunch
14:00 - 14:45 **Lidia del Rio:** tba
14:45 - 16:10 **Raam Uzdin:** Generalized Clausius inequalities
15:35 - 16:00 break and refreshment
16:00 - 18:30 focused group activities
19:00 - 21:00 working dinner

THURSDAY 08/12/2016

08:00 - 09:00 breakfast
09:20 - 09:45 **Jonatan Bohr Brask:** Multiple environments and the quantum master equation
09:45 - 10:05 **Mark Mitchison:** Non-equilibrium steady states of autonomous thermal machines
10:10 - 10:35 **Ralph Silva:** Autonomous quantum machines and finite sized clocks
10:35 - 11:00 break and refreshment
11:00 - 11:45 **Stefan Wolf & Veronika Baumann:** From Quantum to Classical
11:45 - 12:10 **Paul Erker:** Does thermodynamics limit our ability to measure time?
12:10 - 12:35 **Harry Miller:** Time-reversal symmetric work distributions for closed quantum dynamics in the histories framework
12:45 - 13:30 lunch
14:00 - 16:00 focused group activities
16:00 - 16:30 break and refreshment
16:30 - 18:30 group reports and discussions
19:00 - 21:00 conference dinner

FRIDAY 09/12/2016

08:00 - 09:00 breakfast
09:30 - 09:55 **Philipp Kammerlander:** An operational formulation makes the zeroth law obsolete
09:55 - 10:20 **Henrik Wilming:** Low-temperature cooling with finite non-equilibrium resources
10:20 - 11:00 refreshment
11:00 - 13:30 conference bus (ends at Vienna Airport)