Contraction of noisy quantum information into relevant subspaces

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Experiments produce more detailed, and often noise-affected, data than the physically meaningful quantities one is interested in. For example, state tomography of a light mode usually estimates the coefficients $\langle n|\tau|m\rangle$ of a quantum state τ in the number basis $\{|n\rangle\}$ for a finite range $n, m = 0, 1, ..., N$. But noise makes estimates of the information $S_{vN}(\tau)$ encoded in τ very poor: For a qubit state $\tau = p_0|0\rangle\langle 0| + (1-p_0)|\alpha\rangle\langle\alpha| + c|0\rangle\langle\alpha| + c^*|\alpha\rangle\langle 0|$, where $|0\rangle$ is the vacuum state, $|\alpha\rangle$ is a fixed (large) coherent state, $0 \leq p_0 \leq 1$ is a variable probability and c is a variable, complex valued coherence, its entropy cannot be larger than $\ln 2$. But the noise-affected data is spread into the larger dimensional number space, increasing the rank of the state estimates, ρ, for the original qubit state, τ. This gives an entropy that is artificially high, i.e. $S_{vN}(\rho) \gg S_{vN}(\tau)$, solely because noise has spread qubit information into a larger space.
Here we introduce a method of mapping a measured large-dimensional noisy quantum state ρ into a qubit state σ that lives in the relevant qubit subspaces associated with $|0\rangle$ and $|\alpha\rangle$, and is a faithful estimate for the qubit state τ. The entropy of σ is a physically meaningful entropy, obtained by "removing" entropic contributions that arise from experimental noise *within* the relevant subspaces. We prove optimality of the mapping and establish entropic properties of the new subspace entropy $S^{sub}_{vN}(\rho) = S_{vN}(\sigma)$.

Control of coherent electron transport and quantum sensing in semiconductors

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The fundamental research of many-body interactions and novel control of coherent transport properties of single particle elementary excitations exploiting strong-light matter interactions[1] is one of the most fascinating problems in physics of nanoscale systems, including NV centers in diamond, having practical scientific relevance for emerging quantum sensing technologies is addressed. The presence of charge carriers and their free movements in doped semiconductor materials as in electric circuits and electric devices is realized by their continuous monitoring via an electromagnetic waves, like in an inelastic light scattering measurement. The impact is revealed by spectral distribution of incoming photons that become imprinted and caused by the motion of the electron oscillators.

[1]B.H. Bairamov**,** V.V. Toporov, F.B. Bayramov, O.B Chakchir, H. Lipsanen, I. Tittonen, M. Kira *Coherent electron transport in metamaterials of integrated semiconductor quantum dots and biomolecules for medical imaging applications*, IEEE Xplore, Procidings of the 12 International Congress on Artificial Materials for Novel Wave Phenomena – Metamaterials 2018, 040-042 (2018).

Optimally correlating unitaries

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Correlations lie at the heart of almost all scientific predictions. It is therefore of interest to ask whether there exist general limitations to the amount of correlations that can be created at a finite amount of invested energy. Within quantum thermodynamics such limitations can be derived from first principles. In particular, it can be shown that establishing correlations between initially uncorrelated systems in a thermal background has an energetic cost. This cost, which depends on the system dimension and the details of the energy-level structure, can be bounded from below but whether these bounds are achievable is an open question. Here, we put forward a framework for studying the process of optimally correlating identical (thermal) quantum systems. The framework is based on decompositions into subspaces that each support only states with diagonal (classical) marginals. Using methods from stochastic majorisation theory, we show that the creation of correlations at minimal energy cost is possible for all pairs of three- and four-dimensional quantum systems. For higher dimensions we provide sufficient conditions for the existence of such optimally correlating operations, which we conjecture to exist in all dimensions.

Photon counting statistics of a microwave cavity

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The development of microwave photon detectors is paving the way for a wide range of quantum technologies and fundamental discoveries involving single photons. Here, we investigate the photon emission from a microwave cavity and find that distribution of photon waiting times contains information about few-photon processes, which cannot easily be extracted from standard correlation measurements. The factorial cumulants of the photon counting statistics are positive at all times, which may be intimately linked with the bosonic quantum nature of the photons. We obtain a simple expression for the rare fluctuations of the photon current, which is helpful in understanding earlier results on heat-transport statistics and measurements of work distributions. Under nonequilibrium conditions, where a small temperature gradient drives a heat current through the cavity, we formulate a fluctuation-dissipation relation for the heat noise spectra. Our work suggests a number of experiments for the near future and it offers theoretical questions for further investigation.

Local vs global master equation of two coupled qubits: a thorough discussion

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Open quantum systems of two coupled qubits are of fundamental importance for the creation of quantum heat engines[1]. Here, we provide a complete derivation of the most general Markovian master equation describing two coupled qubits interacting with common or separate baths, and show how to obtain the solution by exploiting symmetry properties. Then, we explore the differences between the local and global master equation, which are employed to compute the heat current, proving that they intrinsically depend on the way we apply the secular approximation. In spite of the previous literature that claims the failure of the global approach with secular approximation for small coupling constants[2], we show that the global approach with *partial* secular approximation always provides the best choice for the master equation. The full secular approximation may crash in some scenarios, depending not only on the coupling constant[2], but also on the qubit detuning and on the difference between separate and common bath.

[1]Vinjanampathy and Anders, Contemp. Phys. **57**, 545-579 (2016)
[2]Hofer et al., New J. Phys. **19**, 123037 (2017)

Entropy Production in Weakly Measured Quantum Systems

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We study the dynamics and thermodynamics of the continuous weak quantum measurement of a spin with an orientation-independent Hamiltonian. We employ a minimal formalism of two Kraus operators per spin component to evolve the coherence vector within the Bloch sphere. For the measurement of a single spin component the trajectories correspond to evolution towards one of the two eigenstates. For simultaneous measurement of two spin components, the trajectories correspond asymptotically to an exploration of all orientations of the spin, in accordance with Heisenberg uncertainty.
We identify operators that produce general reverse trajectories in the Bloch sphere, and hence evaluate the stochastic entropy production associated with individual realisations of measurement. The stochastic entropy production in the environment is not associated with an exchange of energy with the spin but is instead an intrinsic cost of manipulating uncertainty: quantum entropy production without accompanying heat flow. Averaging over all trajectories demonstrates that a second law holds even while measurement reduces the uncertainty in the quantum state of the spin. The thermodynamics of weak quantum measurement can be treated using tools developed for classical systems [1] and a spin can possess an entropy far in excess of $\ln 2$ when weak measurement reveals its state in finer detail.

[1]R.E. Spinney and I.J. Ford, Phys. Rev. E 85, 051113 (2012)

Many-body correlations as hindrance to approach equilibrium

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Understanding the dynamics of quantum systems out-of-equilibrium is at the core of quantum thermodynamics and of its applications to quantum technologies. In this work we focus on the quantum work probability distribution function P(W) of microscopic many-body systems driven out-of-equilibrium in a finite time process. In this scenario energy fluctuations play an important role. We induce transient currents through finite Hubbard chains, systematically covering all dynamical and interacting regimes: from sudden quench, to near-adiabatic; from non-interacting to strongly correlated. Even not-driven Hubbard chains have a very rich physical behaviour, with many-body interactions inducing a precursor to the metal-Mott insulator quantum phase transition. Here we show that the dynamical driving of the system adds more complexity to this transition, which is captured by P(W). The competition between many-body correlations and dynamical regimes strongly affects, qualitatively and quantitatively, P(W). In particular a strong variation of sign and value of its skewness characterizes the quasi metal-Mott insulator transition, even when the number of degrees of freedom is exponentially increased, and even when we consider a regime which is, for-all-practical-purposes, adiabatic. This emphasises the role that many-body correlations may have in preventing a system from approaching equilibrium.

Characterising Adiabaticity in Many-body Thermal Systems Dynamics

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Characterising adiabaticity is still an open fundamental problem that is vital for understanding adiabatic quantum computing and maximising quantum work among other applications. We recently showed [1] that 'natural' metrics [2] can be used as a simple and graphical method of characterising adiabaticity at zero temperature using the relationship between ground state wavefunctions and densities. Here we consider finite temperatures looking at the distances of the mixed states and of their densities. In principle, at finite temperatures, it is no longer only the ground state which must be considered to characterise an adiabatic dynamics, but the population of all eigenstates. We show how, by using the Bures distance (which extends the natural metrics to finite temperature), we can determine if an evolution is adiabatic without monitoring the eigenstate populations. In contrast, the trace distance, a widely used mixed-state metric, fails to provide such information.
We acknowledge support from the EPSRC.

[1] A. H. Skelt, R. W. Godby and I. D'Amico, Phys. Rev. A 98, 012104 (2018)
[2] I. D'Amico, J. P. Coe, V. V. Franca, and K. Capelle, Phys. Rev. Lett. 106, 050401 (2011)

Unexpected Correlations Between Entropy, Entanglement and Heat in a Bipartite Quantum System

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Research efforts in quantum thermodynamics aim at the understanding of thermodynamic properties such as heat or work in nanoscale systems. This is coupled with the ambition of harnessing quantum effects to improve the efficiency of quantum machines. In this respect, we investigate the thermodynamic role of quantum correlations, with the purpose of exploring their connections with quantum work, heat and entropy production.
We focus on a quantum bipartite system, namely a driven few sites Hubbard chain coupled with an environment formed by a single qubit. We analyse different dynamical regimes – from sudden quench to intermediate regime to adiabatic regime, as well as different many-body correlation strength, from non-interacting all the way to strongly correlated. For different temperatures, we explore the relation between the variation of Von Neumann entropy, the negativity, heat and work and uncover some interesting correlations between these quantities. For example, at finite temperatures, correlations between Von Neumann entropy variation and Negativity are highly dependent on the system initial conditions.
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Efficiency fluctuations of a quantum Otto engine

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We derived the probability distribution of the efficiency of quantum Otto engines. We explicitly compute the quantum efficiency for an analytically solvable example. We analyze the occurrence of values of the stochastic efficiency above unity, in particular at infinity, in the nonadiabatic regime and further determine mean and variance in the case of adiabatic driving. We finally investigate the classical-to-quantum transition as the temperature is lowered.

Transitionless Quantum Driving in a Noisy Quantum Heat Engine

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We look at using transitionless quantum driving (TQD)[1] to improve the performance of a finite-time quantum Otto engine composed of a two level system coupled to two heat baths. Driving an Otto engine in finite-time will typically cause non-adiabatic transitions which act as sources of "friction", decreasing the work output and efficiency of the engine [2]. Increasing the cycle time improves the efficiency and work but of course comes at the cost of decreasing power output. TQD suppresses these non-adiabatic transitions, allowing maximum efficiency in finite-time. We calculate the efficiency, work and power output of the engine in its limit-cycle with and without TQD. We test the robustness of the engine's performance to classical noise in the control fields of the system Hamiltonian, and find that in most parameter regimes the TQD engine outperforms the nonadiabatic engine, but towards the limit of zero cycle-time the TQD engine perfomance is drastically reduced.

[1]M. V. Berry *Transitionless Quantum Driving*, J. Phys. A: Math. Theor. **42**, 365303-9 (2009).
[2]R. Kosloff & T. Feldmann *Discrete four-stroke quantum heat engine exploring the origin of friction*, Phys. Rev. E **65**, 055102 (2002).

Majorana representation of superadiabatic processes

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Shortcuts to adiabaticity are of great importance in finite time experimentally realizable situations. A recent transmon-based experiment benchmarked Stimulated Raman Adiabatic Passage (STIRAP) to achieve the population exchange between the energy levels of a qutrit adiabatically[1]. Superadiabatic(sa)STIRAP is a smart solution which introduces a counter-adiabatic drive to correct for any non-adiabaticity in the dynamics [2]. We perform a quantitative analysis of the tradeoff between operation time and expected fidelity in STIRAP vs saSTIRAP. We also study the corresponding spin-1 dynamics as per Majorana representation, in which a spin-s is represented by $2s$ points on a unit sphere [3]. Contrary to STIRAP pulses, sa-STIRAP pulses confine the single qutrit dynamics to a plane, which is also analogous to the characteristic parametric-evolution of a single-qutrit canonical state on the Majorana sphere [4].

[1]K.S. Kumar, A. Vepsäläinen, S. Danilin, and G.S. Paraoanu *Stimulated Raman adiabatic passage in a three-level superconducting circuit*, Nat. Comms. **7**, 10628 (2016)

[2]A. Vepsäläinen, S. Danilin, and S. Paraoanu *Superadiabatic population transfer in a three-level superconducting circuit*, Sci. Adv. **5**, eaau5999, (2019).

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Hybrid master equations for calorimetric measurements

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I present a mathematical study of an experimental setup proposed by [1] for calorimetric measurements of thermodynamic indicators in an open quantum system. The goal of the experiment is to detect energy quanta exchanged between a driven qubit and thermal bath by measuring changes in the temperature of the bath.
We model the setup as a driven qubit interacting with a large, but finite, thermal bath of electrons, the calorimeter. Under weak-coupling assumptions it is possible to express the evolution of the qubit-calorimeter system as a hybrid master equation for the state of the qubit and the temperature of the calorimeter. In the asymptotic regime of long driving, the hybrid master equation can be reduced to a Fokker-Planck equation for the temperature. From the aforementioned equations, we can obtain numerical information about the temperature behaviour in terms of the intensity of the drive and qubit-calorimeter coupling.

[1]Pekola et al., New J. Phys., 15 (2013)

Maximum Power and Corresponding Efficiency for Two-Level Quantum Heat Engines and Refrigerators

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We study how to achieve the ultimate power in the simplest, yet non trivial, model of a thermal machine, namely a two-level quantum system coupled to two thermal baths. We show that, regardless of the microscopic details and of the operating mode of the thermal machine, the maximum power is achieved through a universal protocol: an Otto cycle in which the controls are rapidly switched between two extremal values. A closed formula for the maximum power is derived, and the experimental feasibility of the protocol is discussed. Our findings extend the analysis done in the literature on the efficiency at maximum power (EMP) to engines operating at the ultimate performance, which is strongly away from the quasi-static regime, and shed new light on the universal role of the EMP. In particular we show that by employing proper energy filters to mediate the system-baths interactions, both the EMP of heat engines and the coefficient of performance at maximum power of refrigerators can approach Carnot's bound with arbitrary accuracy.

Particle in a Contracting/Expanding 1D Box. Canonical Description and Wave Equation for Thermodynamic Evolution.

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The known problem of a particle in an expanding/contracting 1-dimension box is revisited in action-angle like variables having direct translation into thermodynamic quantities.[1 2] An angle dependent potential is proposed to build a non-integrable Hamiltonian which correctly describes the known mechanical behaviour but also yields the thermodynamic evolution -entropy production-. The analogy with the mechanical treatment leads to a Schrodinger like equation. The momentum operator retrieves the entropy related action from its wave solution, and expected values were found to coincide with the corresponding values in the"classical" evolution. The developed formalism, though applied here to a simple model, seems to be a useful approach to deal with quantum thermodynamic systems.

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Open Quantum System Dynamics: recovering positivity of the Bloch-Redfield equation via Partial-Secular Approximation

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We show how to recover complete positivity of the Bloch-Redfield equation via a coarse grain average technique. This is always feasible with a sufficiently large coarse grain time interval which depends on the spectrum of the system and on temperature. The introduction of the coarse grain time scale has also strong impact on the characteristics of the Lamb shift term and implies in general non-commutation between the dissipator and the Hamiltonian. We introduce first the general formalism of the partial secular approximation when the Bloch-Redfield equation is taken as starting point, then we specify the analysis to a two-level system or a quantum harmonic oscillator coupled to a fermionic or bosonic thermal environment via dipole interaction.

Speeding Up the Quantum Refrigerator Cycle via Counter-Diabatic Driving

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Understanding the nonequilibrium dynamics of open quantum systems is essential for controlling small quantum devices and to improve existing quantum information processing technologies. Quantum thermodynamics offers a theoretical framework to achieve this aim, and one can study thermodynamically efficient protocols with low entropy production. In particular, studies of quantum heat engines and refrigerators are important since they can reveal fundamental limits on the conversion between heat and work in the quantum regime. In the presentation, we study a quantum Otto refrigerator based on a superconducting qubit coupled to two RLC circuits[1], and consider applying the shortcuts to adiabaticity via the counter-diabatic driving (CD) technique to enhance its thermodynamic efficiency and power. Originally, the CD is designed to mimic quantum adiabatic dynamics in a finite time in isolated systems. However, we find that it also works effectively in open system dynamics, improving the coherence induced losses of efficiency and power. We find that modeling of dissipation using different classes of the Lindblad master equation results in different performance, either smaller or identical to that of a classical model. We give physical explanations for these findings and discuss related experimental realizations.

[1]B. Karimi and J. P. Pekola, *Otto refrigerator based on a superconducting qubit: classical and quantum performance*, Phys. Rev. B **94,** 184503 (2016).

Platform for unconditional qubit reset based on tunable environments

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Superconducting qubits are initialized by cooling them to very low temperatures and waiting until each qubit has approximately reached the ground state. Here, we present an unconditional reset scheme for superconducting qubits based on voltage-biased superconductor-insulator-normal metal (SIN) junctions. Our theory shows that we can in-situ turn on a dissipation channel with a strength of several hundred MHz resulting in a reset time of the qubit in the nanosecond range. Our method works for transmon qubits and C-shunt flux qubits and can also be applied to superconducting resonators. In our experiments with superconducting resonators[1], we can increase the resonator decay rate by several orders of magnitude in only 3ns. By tuning the resonator coupling strength to the dissipative environment, we are furthermore able to observe a broadband Lamb shift, the generation of incoherent microwave radiation, and optimized heat flow at exceptional points[2].

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[2]M. Silveri, *et al.*, Nat. Phys. (2018); S. Masuda, *et al.*, Sci.Rep. **8**, 3966 (2018); M. Silveri, *et al.*, arXiv:1812.02683

Universal First-Passage-Time Distribution of Non-Gaussian Currents

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We investigate the fluctuations of the time elapsed until the electric charge transferred through a conductor reaches a given threshold value. For this purpose, we measure the distribution of the first-passage times for the net number of electrons transferred between two metallic islands in the Coulomb blockade regime. Our experimental results are in excellent agreement with numerical calculations based on a recent theory describing the exact first-passage-time distributions for any non-equilibrium stationary Markov process. We also derive a simple analytical approximation for the first-passage-time distribution, which takes into account the non-Gaussian statistics of the electron transport, and show that it describes the experimental distributions with high accuracy. This universal approximation describes a wide class of stochastic processes, and can be used beyond the context of mesoscopic charge transport. In addition, we verify experimentally a fluctuation relation between the first-passage-time distributions for positive and negative thresholds.

Interpolated Collision Models

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Collision models are often used in quantum thermodynamics to model interactions with an environment, often to model thermalization. These models treat the environment as being composed of many non-interacting quantum systems, called ancillas, which interact with the system of interest one at a time. A natural example is an atom in an ideal gas. Collision models have a natural formulation in terms of discrete time steps, $t = n\,\delta t$, which must be processed if one wants a continuous time description. A common method of doing this is to take the *continuum limit*, $\delta t \to 0$, often while increasing the system-ancilla interaction strength, g, such that $g^2 \delta t$ is constant. In this poster we will discuss a novel method of deriving a master equation from a Collision model. Our method leaves δt and g finite and constructs the unique Markovian interpolation scheme between time points $t = n\,\delta t$. As we will discuss, this interpolative approach is more general; taking the continuum limit within it recovers the prior approach. Moreover, with this approach it is easy to consider a system interacting with a variety of ancillas via a variety of couplings, for a variety of different durations, all chosen stochastically at each interaction. This approach can also be adapted for continuous variable systems (boson or fermionic) in the context of Gaussian quantum mechanics, allowing for non-perturbative treatment of many situations. We will present examples of this formalism used to study purification, thermalization, and energy transfer/friction.

Spectroscopy of the two superconducting resonators coupled via transmon type qubit and heat transport

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We study heat transport in a system formed by a qubit coupled to two resonators, each terminated by mesoscopic normal-metal reservoirs acting as a both source and drain (dissipative) thermal baths, such as the recently demonstrated quantum heat valve [1], in both the equal and unequal resonators regimes.

[1]A. Ronzani et al., Nat. Phys. **14**, 991 (2018).

Measurement Induced Charging of Quantum Batteries

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Quantum batteries [1], defined as physical systems capable of storing and exchanging their energy with the environment, have become a matter of interest in the field of quantum thermodynamics in recent years. In our work we explore the charging process of battery by means of quantum measurement application with regard to its final coherence (for the sake of strengthening quantum properties). Initially, our simplified model of battery consists of a pair of identical two-level systems (TLS) with low probability of excited states. We study the charging process, realized by an application of an energy eigenstate projector and its orthogonal complement, resulting in two outcomes of measurement: successful and failed, respectively. In the case of former the system is able to jointly increase its initial energy and coherence, quantified by well-established measure [2], in the region of small TLS excitation probabilities. Our approach is probabilistic, i.e. it is successfully carried out only for a subset of realizations. The effect of partial purity of the initial TLS state on the charging procedure and generalization for the case of battery, consisting of many copies of TLS are explored. We show that a similar charging procedure for the case of using a generalized measurement strategy (POVM) instead of projective measurement leads to an improvement of the results.

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[2] T. Baumgratz et al. *Quantifying coherence*, Phys. Rev. Lett. **113**, 140401 (2014)

Quantum correlations and thermodynamic performances of two-qubit engines with local and common baths

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In this contribution we investigate heat engines whose working substance is made of two coupled qubits performing a generalised Otto cycle by varying their applied magnetic field or their interaction strength during the compression and expansion strokes. We look into the possibility of generating quantum correlations at the steady state when using local and common jump operators, noting along the way the difference between the steady state of the master equation with local operators and the thermal state of the working substance. We then utilise these local and common environments, that are not necessarily at equilibrium, during the heating and cooling strokes. We also take into account the effect of measurements which are necessary for a consistent definition of thermodynamic work in a quantum setting. Contrary to the local cases studied we find instances of quantum engines coupled to nonequilibrium common environments exhibiting non-trivial connections to quantum correlations as witnessed by a monotonic dependence of the work produced on quantum discord and entanglement. These connections vary from case to case implying that this is a model dependent phenomenon

Autonomous thermal motors: quantum soloists and quantum duets

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I will discuss how directed transport can emerge in two-temperature autonomous motors as a consequence of the broken thermal equilibrium and of the broken spatial symmetry. I will first consider a minimal model of a quantum rotator composed of a single particle confined in an asymmetric harmonic potential and driven by two temperature-biased heat reservoirs. the particle exhibits a finite angular momentum, corresponding to a directed rotary motion [1]. At variance with the classical case, the thermal fluctuations in the baths give rise to a non-vanishing average torque contribution. I will then consider the case of two particles kept at different temperatures and moving on shifted periodic potentials. The model exhibits a non vanishing center-of-mass average velocity, as a consequence of the temperature gradient and of the broken spatial symmetry (A. Imparato *in prepar.*). This model represents the extension to the two-temperature case of the *Quantum Brownian motion in a periodic potential* considered in M. P. A. Fisher and W. Zwerger, Phys. Rev. B 32, 6190 (1985). This model can be made discrete, when one considers the case of two rotators interacting with the clock model Hamiltonian (discrete XY-model): such a discrete ratchet [2] displays several novel quantum effects, such as tunnelling-induced current inversion.

[1]H. Fogedby, A. Imparato, EPL 122: 10006 (2018)
[2]K. V. Hovhannisyan and A. Imparato, arXiv:1806.08779

Signature of the transition to a bound state in thermoelectric quantum transport

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We study a quantum dot coupled to two semiconducting reservoirs, when the dot level and the electrochemical potential are both close to a band edge in the reservoirs. This is modelled with an exactly solvable Hamiltonian without interactions (the Fano-Anderson model). The model is known to show an abrupt transition as the dot-reservoir coupling is increased into the strong-coupling regime, if the band's density of states goes to zero at the band edge. This transition involves an infinite-lifetime bound state appearing in the band gap. We find a signature of this transition in a discontinuous behaviour of the dot's transmission function. This can result in the steady-state DC electric and thermoelectric responses having a very strong dependence on coupling close to critical coupling. We give examples where the conductances and thermoelectric power factor exhibit huge peaks at critical coupling, while the figure of merit ZT grows as the coupling approaches critical coupling, with a small dip at critical coupling.

Bolometry with graphene Josephson junction

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A bolometer detects electromagnetic radiation by absorbing it and measuring the resulting temperature increase in the absorbing element. Graphene is a promising candidate for the absorber material due to its true 2D nature, allowing the fabrication of an absorber with extremely small volume. Thus, even a single microwave photon incident on the small graphene absorber can increase its temperature substantially. Properties of graphene can also be modified with an electric field which in turn allows tuning the properties of the bolometer *in situ*. Furthermore, a Josephson junction is an attractive choice for the temperature sensor since its critical current has roughly exponential dependence on the temperature. For these reasons, we have experimentally studied a graphene-Josephson-junction-based bolometer. Our preliminary results suggest the noise equivalent power of 50 zW/rtHz. Together with a thermal time constant of 0.5 μs this implies energy resolution below h$\times$50 GHz, bringing the detection of single microwave photon with thermal detectors a step closer to reality.

Quantum Thermalization in a Closed Many-Body Quantum System

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Ergodic and chaotic motion in phase space were identified by Boltzmann to be the key prerequisite to attain thermal equilibrium in classical many-body systems. The transcription of this notion to the realm of quantum mechanics has remained a matter of lively debate. Does an isolated quantum many-body system initially prepared in a non-stationary state thermalize and, if so, what are the signatures and time scales for the approach to equilibrium? Moreover, can the notion of classical-quantum correspondence be extended to statistical mechanics of non-equilibrium systems? Is the breakdown of quantum integrability and the appearance of quantum chaos as signified by universality classes of level statistics necessary to attain thermalization? We investigate the interplay between quantum chaos and thermalization for a closed polarized Fermi-Hubbard model with an impurity and tunable interaction parameters. Such systems have become realizable in experiments with ultracold atoms in optical lattices. By varying the interaction parameters, the system smoothly evolves from a completely quantum integrable to a quantum chaotic system featuring a GOE level statistics. We probe the state of thermalization by recording the time-dependent reduced one-particle density matrix (1RDM) of the impurity embedded in the polarized Fermi-Hubbard system. Employing an exact diagonalization and calculating the time-evolution of the N-particle state, we address the question as to whether and when the 1RDM of the test particle converges to the 1RDM of the canonical ensemble taken to be the hallmark of thermalization.

Measuring Effective Temperatures of Qubits Using Correlations

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Superconducting circuits are typically thermalised to the lowest temperature stage of a dilution refrigerator. However effective temperature of a qubit T_{eff} might be much different from the reading T_{base} of a base stage temperature sensor due to stray radiation, improper thermalisation and other reasons. Being able to measure the effective T of qubits helps to identify unwanted thermal links as well as pinpointing the sources of qubit's noise and decoherence. In this work we develop a new method of measuring T_{eff}, which does not rely on high signal-to-noise ratio (ability to read out the state of the system in single-shot regime) or excitation of higher energy levels. Based on correlations between the results of consecutive measurements, it is applicable to any quantum two-level system where a QND measurement can be realised.
We experimentally realise the method and demonstrate its consistency with other available methods. We repeat the systematic study of the excited-state population in a 3D Transmon qubit and find it consistent with a Maxwell-Boltzmann distribution with a constant offset of residual e-state population, which we attribute to hot nonequilibrium quasiparticles. Our result is consistent with recent studies of hot non-equilibrium quasiparticles and their dependence on the environment temperature.

Weakly coherent collisional models

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Collisional models describe the open dynamics of a quantum system as a series of sequential interactions with independently prepared environmental ancillas. This generates a stroboscopic dynamics which, in the short time limit, can be cast in the form of a master equation. These models have recently been reconciled with thermodynamics,[1] placing the entire framework on much firmer grounds. In most collisional models, however, the ancillas are assumed to be thermal. In this talk we present a formulation of a collisional model where the ancillas have thermal populations, but also a certain amount of coherences.[2] We first show that in order to obtain a well behaved continuous time limit, the magnitude of the coherences must scale as the square-root of the interaction time. Hence, in the short time limit, even weak coherences suffice to obtain a non-negligible effect. Next we discuss the thermodynamics of this model, including the first and second laws. It is found that the coherences in the ancilla are processed in a non-trivial way, effectively leading to a work-like contribution to the system, even if no actual work is performed.

[1]G. De Chiara, *et. al.*, New Journal of Physics, **20**, 113024 (2018).
[2]F. L. Rodrigues Jr., M. Paternostro, G. De Chiara, G. T. Landi, *in preparation* (2019).

Two-step evaporation to fabricate SIS junctions in superconducting qubits

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Josephson junctions are the key elements of almost all kinds of superconducting qubits. The reproducibility and accuracy of fabricating Josephson junctions remains one of the technical challenges ahead for building scalable quantum computers. Traditionally, $Al/AlO_x/Al$ tunnel junctions are fabricated by shadow evaporation enabled by double-layer resist, which is not suitable for wafer-size fabrication and sensitive to e-beam lithography parameters. Here we present the progress we have made in fabricating $Al/AlO_x/Al$ tunnel junctions by two-step evaporation: the two overlapping electrodes are defined and evaporated in two separate e-beam lithography and evaporation steps respectively. Before evaporating the second electrode, the native oxide layer on the first electrodes needs to be removed by in-situ Ar ion milling, and a thinner oxide layer is formed in a controlled atmosphere. In such a two-step evaporation process, the edges of the electrodes are much straighter than those fabricated using shadow evaporation. The room-temperature resistance of the junctions can be well controlled by the Ar ion milling strength, allowing us to predict the qubit frequency at low temperature.

Fundamental limitations of the step quantum heat engine

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The model of a step quantum heat engine (SQHE) is defined as a working body, given by the two-level system (TLS), acting separately (i.e. in steps) with the heat baths and the energy storage system (a battery). A single step of the engine is defined as the unitary and energy conserving operation. For the general SQHE we prove the fundamental attainable efficiency, given as a function of a cold and hot temperature, which is below the Carnot efficiency. The reason is that the engine is quasi-autonomous, i.e. there is no extra external control like fields commonly used in a non-autonomous setting, but in contrary the SQHE is realised by a unique physical process of the TLS population inversion via a strong coupling with the heat bath. For our model of the SQHE we additionally discuss the problem of the work definition for the fully quantum systems. So far the only reasonable definition of the work (consistent with the fluctuation theorems) is given by the change in a mean energy of the battery which has additionally a translational symmetry, i.e. these changes do not depend on how much energy is currently stored in the battery. However, this symmetry impose a nonphysical property that the battery cannot have a ground state. We solve this problem showing that the battery with a ground state can be used as a proper energy storage system only if the work is defined as a change of the ergotropy instead of a mean energy.

Coherence and asymmetry cannot be broadcast

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In the presence of conservation laws, most notably energy conservation, superpositions of eigenstates of the corresponding conserved quantities cannot be generated by quantum dynamics. Thus, any such coherence represents a potentially valuable resource of asymmetry, which can be used, for example, to enhance the precision of quantum metrology or to enable state transitions in quantum thermodynamics. Here we ask if such superpositions, already present in a reference system, can be broadcast to other systems, thereby distributing coherence indefinitely. We prove a no-go theorem showing that this is forbidden by quantum mechanics in every finite-dimensional system, with implications for the sharing of timing information of a clock and the possibility of catalysis in quantum thermodynamics. We also prove that even weaker forms of broadcasting, of which Åberg's 'catalytic coherence' is a particular example, can only occur in the presence of infinite-dimensional reference systems, with implications for protocols extracting work from energetic coherence.[1]

[1]arXiv: 1812.08214

Efficiency fluctuations in microscopic machines

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Nanoscale machines are strongly influenced by thermal fluctuations, contrary to their macroscopic counterparts. As a consequence, even the efficiency of such microscopic machines becomes a fluctuating random variable. Using geometric properties and the fluctuation theorem for the total entropy production, a 'universal theory of efficiency fluctuations' at long times, for machines with a finite state space, was developed in [Verley *et al.*, Nat. Commun. **5**, 4721 (2014); Phys. Rev. E **90**, 052145 (2014)]. We extend this theory to machines with an arbitrary state space. Thereby, we work out more detailed prerequisites for the 'universal features' and explain under which circumstances deviations can occur. We also illustrate our findings with exact results for two non-trivial models of colloidal engines.

Nonequilibrium phonons and quasiparticles in single-electron transistors

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Quasiparticle excitations are detrimental to the operation of various superconducting devices. The density of quasiparticles should be exponentially suppressed at low temperatures, but commonly a quasiparticle density many orders of magnitude larger than the thermal expectation is observed. Phonons with energy greater than twice the superconducting gap can break Cooper pairs to form quasiparticles, and conversely two quasiparticles recombining to form a Cooper pair will emit such phonons. In our experiment, we demonstrate how the superconducting island of a single-electron transistor is poisoned with quasiparticles when another heated superconducting island is used as an emitter of nonequilibrium phonons, while a thermal phonon emitter, a similarly heated normal metal island, creates much fewer quasiparticles.

Squeezed Thermal Reservoir as a Generalized Equilibrium Reservoir

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We explore the perspective of considering the squeezed thermal reservoir as an equilibrium reservoir in a generalized Gibbs ensemble with two noncommuting conserved quantities. We outline the main properties of such a reservoir in terms of the exchange of energy, both heat and work, and entropy, giving some key examples to clarify its physical interpretation. This allows for a correct and insightful interpretation of all thermodynamical features of the squeezed thermal reservoir, as well as other similar nonthermal reservoirs, including the characterization of reversibility and the first and second laws of thermodynamics.[1]

[1]G. Manzano, Phys. Rev. E **98**, 042123 (2018). [arXiv:1806.07448]

Detailed Balance and Fluctuation Relations in Open Quantum Systems

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Quantum detailed balance and quantum fluctuation relations are two important concepts in the dynamics of open quantum systems: both concern how such systems thermalize while interacting with their environment. Based on the results presented in Ref.[1] I will show that, for thermalizing quantum dynamics, quantum detailed balance implies the validity of a quantum fluctuation relation (where only forward-time dynamics is considered). However, the converse is not necessarily true; indeed, there are cases of thermalizing dynamics which feature the quantum fluctuation relation without satisfying detailed balance. I will discuss explicit examples in order to clarify the main results.

[1]M. Ramezani et al., *Quantum detailed balance conditions and fluctuation relations for thermalizing quantum dynamics*, Phys. Rev. E **98**, 052104 (2018).

Improvement of the current quantization in SINIS turnstile by quasiparticle extraction through biased SIS junctions

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We have enhanced the performance of superconductor-insulator-normal metal-insulator-superconductor (SINIS) single-electron turnstiles by lowering the (effective) temperature of one of its leads. This is done by extracting quasiparticles from one superconducting lead using biased SIS junctions. We show that it is possible to tune the accuracy of the turnstile without modifying its physical structure. As a result an improvement on the current quantization due to this bias is possible even in gate signal frequencies as high as 160 MHz, for which we reached low quasiparticle densities. We estimate the quasiparticle density approximating the (effective) temperature of the lead by means of sequential tunnelling and Andreev reflection numerical models, finally we illustrate generally how the lead temperature varies with the bias voltage of the SIS junction.

Second Law of Thermodynamics for Batteries with Vacuum State

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We study the implications of introducing vacuum state of the battery for arbitrary thermodynamic processes. Using the framework of thermal operations we derive a form of the second law which holds for batteries with bounded energy spectrum. In this form the second law gains corrections which vanish when battery is initialized far from the bottom of its spectrum. Furthermore, by studying a paradigmatic example of Landauer erasure we show that the existence of battery ground state leads to a thermodynamic behaviour which cannot be realized using an ideal weight. Surprisingly, this remains true even when battery operates far from its bottom.

Two-Stroke Optimization Scheme for Mesoscopic Refrigerators

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Refrigerators use a thermodynamic cycle to move thermal energy from a cold reservoir to a hot one. Implementing this operation principle with mesoscopic components has recently emerged as a promising strategy to control heat currents in micro and nano systems for quantum technological applications. Here, we combine concepts from stochastic and quantum thermodynamics with advanced methods of optimal control theory to develop a universal optimization scheme for such small-scale refrigerators. Covering both the classical and the quantum regime, our theoretical framework provides a rigorous procedure to determine the periodic driving protocols that maximize either cooling power or efficiency. As a main technical tool, we decompose the cooling cycle into two strokes, which can be optimized one by one. In the regimes of slow or fast driving, we show how this procedure can be simplified significantly by invoking suitable approximations. To demonstrate the practical viability of our scheme, we determine the exact optimal driving protocols for a quantum microcooler, which can be realized experimentally with current technology. Our work provides a powerful tool to develop optimal design strategies for engineered cooling devices and it creates a versatile framework for theoretical investigations exploring the fundamental performance limits of mesoscopic thermal machines.[1]

[1]P. Menczel, T. Pyhäranta, C. Flindt, and K. Brandner, *Two-Stroke Optimization Scheme for Mesoscopic Refrigerators*, arXiv:1903.10845 [cond-mat.mes-hall] (2019).

Quantum fluctuation theorem beyond two-point measurements

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We derive a quantum fluctuation theorem for heat exchange in a bipartite system based on quantum process tomography. Contrary to the usual two-projective-energy-measurement scheme that destroys quantum features, this novel fluctuation theorem fully captures quantum coherences and quantum correlations. We show that the latter contributions each satisfy a fluctuation theorem on their own.

Energy-temperature uncertainty relation in quantum thermodynamics

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It is known that temperature estimates of macroscopic systems in equilibrium are most precise when their energy fluctuations are large. However, for nanoscale systems deviations from standard thermodynamics arise due to their interactions with the environment. Here we include such interactions and, using quantum estimation theory, derive a generalised thermodynamic uncertainty relation valid for classical and quantum systems at all coupling strengths. We show that the non-commutativity between the system's state and its effective energy operator gives rise to quantum fluctuations that increase the temperature uncertainty. Surprisingly, these additional fluctuations are described by the average Wigner-Yanase-Dyson skew information. We demonstrate that the temperature's signal-to-noise ratio is constrained by the heat capacity plus a dissipative term arising from the non-negligible interactions. These findings shed light on the interplay between classical and non-classical fluctuations in quantum thermodynamics and will inform the design of optimal nanoscale thermometers.

Assisted Work Distillation

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We study the process of assisted work distillation. This scenario arises when two parties share a bipartite quantum state ρ^{AB} and their task is to locally distil the optimal amount of work when one party is restricted to thermal operations whereas the other can perform general quantum operations and they are allowed to communicate classically. We demonstrate that this question is intimately related to the distillation of classical/quantum correlations. In particular, we show that the advantage of one party performing global measurements over many copies of ρ^{AB} is related to the non-additivity of the entanglement of formation. We also show that there may exist work bound in the quantum correlations of the state that is only extractable under the wider class of local Gibbs-preserving operations.

Concepts of Work in Autonomous Quantum Heat Engines

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One of the fundamental questions in quantum thermodynamics concerns the separation of energetic changes into heat and work. Contrary to the classical case the entropy change of the piston cannot be neglected in the quantum domain. We illustrate that the concept of work ultimately depends on the desired task and the implied capabilities of an agent that seeks to make use of the work generated by an engine. This provides a unified perspective on quantum work and we illustrate that each quantifier—from non-equilibrium free energy to ergotropy—has well defined operational interpretations. We analyse the different concepts of work in a heat-pumped three-level maser and derive the respective engine efficiencies. Finally, we show that in the classical limit of strong maser intensities the engine efficiency converges towards the Scovil–Schulz-DuBois maser efficiency, irrespective of the work quantifier.

Collisional quantum thermometry

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We introduce a general framework for thermometry based on collisional models, where ancillas probe the temperature of the environment through an intermediary system. This allows for the generation of correlated ancillas even if they are initially independent. Using tools from parameter estimation theory, we show through a minimal qubit model that individual ancillas can already outperform the thermal Cramer-Rao bound. In addition, when probed collectively, these ancillas may exhibit superlinear scalings of the Fisher information, especially for weak system-ancilla interactions. Our approach sets forth the notion of metrology in a sequential interactions setting, and may inspire further advances in quantum thermometry.

Quantum Calculation of the Nonequilibrium Heat Capacity in the Resonant Level Transport

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Using the so-called thermomechanical field method[1] enabling fully quantum mechanical treatment of nonequilibrium systems with time-dependent thermodynamical (non-Hamiltonian) parameters such as temperature or chemical potential we study the nonequilibrium heat capacity of a single resonant level. This work thus generalizes similar previous classical study[2] to the fully quantum regime. We identify various contributions to the quantum result, in particular the "boundary terms" due to the finite coupling to the electronic leads, and inspect their influence on the final behavior. Eventually, we single out the term which is a direct quantum counterpart of the classical result and thoroughly analyze its behavior with various model parameters contrasting it with the classical result. We also formulate our method for more complicated multilevel cases with potentially significant quantum interference contributions.

[1]M. Hasegawa and T. Kato, Journal of the Physical Society of Japan **86**, 024710 (2017)
[2]E. Boksenbojm, C. Maes, K. Netocny, and J. Pesek, Europhys. Lett. **96**, 40001 (2011)

Thermodynamic properties of linear and branched polyethylenimine

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Polyethylenimine (PEI) or polyaziridine is a biopolymer is a non-viral gene vector used in gene delivery, containing a sequence of amino and methylene groups arranged in linear or in branched forms. Polyethylenimine, both in linear and branched configurations, with a different range of polymerization, having between 3 and 25 mers for linear configuration and between 3 to 18 mers for branched arrangement, have been studied, in terms of thermodynamic stability, by means of three functions of state: internal energy (E), enthalpy (H) and Gibbs free energy (G) at the DFT PBEPBE 6-311G (d,p) level of theory, using the Gaussian 09W software. Preliminary results show that the stability of the linear polymers decreases with their degree of polymerization, with the increasing of their chain length and is less influenced by the ramification range in the case of branched PEI. The values of internal energy equal the values enthalpy and the values of Gibbs free energy for the molecules studied. Key words: thermodynamics, functions of state, polymers, polyethylenimine, linear, branched.

Quantum Thermodynamics in non-Markovian Settings Using the TEMPO Algorithm

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In order to simulate quantum systems strongly coupled to an environment, we use an exact numerical approach that describes the non-Markovian time evolution of the system. The method we use is called the Time-Evolving Matrix Product Operator, or TEMPO [1]. TEMPO exploits the Augmented Density Tensor (ADT) in order to represent the time evolution of the system in terms of tensors. The aim of this project is to apply the TEMPO method in order to understand how the laws of thermodynamics generalize to arbitrary quantum systems both at and away from equilibrium, and in both Markovian and non-Markovian settings. In particular we are updating the algorithm to compute the quantum heat statistics by means of counting fields.

[1]A. Strathearn, P. Kirton, D. Kilda, J. Keeling, and B. W. Lovett, *Efficient non-Markovian quantum dynamics using time-evolving matrix product operators*, Nat. Comm. **9**, 3322 (2018).

Irreversible Work Cycles

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Work, in the context of thermodynamic processes, is a random variable. We are interested in looking at possible ways of engineering irreversible work cycles in the finite-size regime that could possibly exhibit the phenomenon of *resonance*, as seen in a recent work by Korzekwa et. al.[1] Under the resource-theoretic framework, the authors find that for certain pairs of temperatures the error introduced by finite-size effects in resource inter-conversion can be suppressed. We are looking for ways of modifying the Carnot cycle— one needs a non-trivial modification that encapsulates an apparatus for *resonance*. Under the physical constraint of having access to fixed temperature baths, a first question is: "Can one tune the interaction with the given bath such that one is able to, at least, approximately simulate an isothermal process at a lower temperature?" To this end, we define something called *partial thermalization*, and following the mathematical framework of Åberg[2], we are currently exploring this avenue.

[1]K. Korzekwa, C. T. Chubb, and M. Tomamichel, *Avoiding Irreversibility: Engineering Resonant Conversions of Quantum Resources*, Phys. Rev. Lett. 122, 110403.
[2]J. Åberg, *Truly work-like work extraction via a single-shot analysis*, Nat. Comm. **4**, 1925(2013).

Electronic and transport properties of amorphous and superhard nanocomposite films obtained from C_{60} ion beam

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The study of electronic and transport properties of amorphous and nanocomposite superhard carbon films deposited from the mass-separated beam of accelerated C_{60} ions with an energy of 5 keV onto a substrate with different temperatures (Ts) is present. The change of the Ts from 373K to 673K leads to transition structure of the films from amorphous state with sp2 2D clusters to superhard nanocomposites with 3D graphite nanocrystals. Measurement of the electrical conductivity of films at low temperatures showed a gradual transition from hopping conductivity with variable length of jump in amorphous films (373-473K) to the tunnel one with power-law dependence from temperature for the nanocomposite (573-673K) and further to the percolation conductivity at direct contact of graphite nanocrystals. [1] The role of intergranular insulator at tunneling conductivity of nanocomposite is acted by amorphous carbon matrix which has an electronic structure close to amorphous diamod.

[1]V.E. Pukha, V.L. Karbovskii, S.O. Rudchenko. *Electronic and optical properties of superhard nanocomposite flms obtained from C60 ion beam*, Materials Research Express **1, 3**, 035049-1-035049-11 (2014).

Almost Thermal Operations: Inhomogeneous Reservoirs

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The resource theory of thermal operations explains the state transformations that are possible in a very specific thermodynamic setting: there is only one thermal bath, auxiliary systems can only be in the corresponding thermal state (free states), and the interaction must commute with the free Hamiltonian (free operation). In this paper, with the help of a toy collisional model, we study the mildest deviation: the reservoir particles are subject to inhomogeneities, either in the local temperature (introducing resource states) or in the local Hamiltonian (generating a resource operation). For small inhomogeneities, the two models generate the same channel and thus the same state transformations. However, their thermodynamics is significantly different when it comes to work generation or to the interpretation of the "second laws of thermal operations". In terms of work generation, we obtain a distribution of the work with resource operations whereas none is generated with resource states. As for the second laws, we find that $\Delta F_\alpha \leq W$ holds only for $\alpha \leq 1$ and is violated for $\alpha > 1$ for resource operations. With resource states, we provide the ε such that $\Delta F_\alpha^\varepsilon < 0$ holds. (`https://arxiv.org/abs/1904.08736.`)

A Cheap but Accurate Approximation for Many-body Quantum Thermodynamic Properties

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Quantum Thermodynamics strives to understand quantum fluctuations at the nanoscale, with particular importance being given to the determination of thermodynamic properties in out-of-equilibrium systems. This in itself is a challenging task, but when many-body interactions give rise to strongly correlated systems, the challenge increases exponentially. Here we study the work extraction and entropy production in the epitome of the strongly-correlated systems, the Hubbard model, for chains up to 6 sites. Strikingly, we show that, even considering a completely non-interacting approximation for the evolution operator, just starting from the exact initial thermal state is sufficient to recover most of the accuracy. Our results demonstrate that this is the case in any dynamical regime – sudden quench to quasi-adiabatic – as well as for any temperature, including low temperatures where a non interacting approximation would be clearly a poor choice.

Metrotropy, or Maximal energy extraction via quantum measurement

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We study the maximal amount of energy that can be extracted from a finite quantum system by means of projective measurements. For this quantity we coin the expression "metrotropy" $\mathcal{M}$, in analogy with "ergotropy" $\mathcal{W}$, which is the maximal amount of energy that can be extracted by means of unitary operations. The study is restricted to the case when the system is initially in a stationary state, and the ergotropy is accordingly achieved by means of a permutation of the energy eigenstates. We show that i) the metrotropy is achieved by means of an even combination of the identity and an involution permutation; ii) it is $\mathcal{M} \leq \mathcal{W}/2$, with the bound being saturated when the permutation that achieves the ergotropy is an involution.

Mesoscopic effects in the heat conductance of SNS and NS junctions

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Heat conductance in superconducting junctions plays a crucial role in coherent caloritronics and for quasi-particle cooling. Here we analyze this heat conductance for single-channel junctions with arbitrary transmission as well as diffusive connectors and show the influence of the superconducting gaps and phases of the contacts[1]. If the junction is *diffusive*, these effects are completely quenched on average. This full suppression of phase- and gap dependence of the heat conductance can have severe consequences for applications. However, we find that the influence of both the gap and the phase difference persists in weak-localization corrections and conductance fluctuations. While these statistical properties strongly deviate from the well-known analogues for the charge conductance, we demonstrate that the heat conductance fluctuations maintain a close to universal behavior. We find a generalized Wiedemann-Franz law for Josephson junctions with equal gaps and vanishing phase difference.

[1]F. Hajiloo, F. Hassler, and J. Splettstoesser, arXiv:1901.11402 (2019)

Steady State Entanglement beyond Thermal Limits

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Classical engines turn thermal resources into work, which is maximized for reversible operations. The quantum realm has expanded the range of useful operations beyond energy conversion, and incoherent resources beyond thermal reservoirs. This is for example the case of entanglement generation in a driven-dissipative protocol. In this work,[1] we propose a device which is able to generate a significant amount of steady state entanglement without the need for a coherent driving field, thus proving that entanglement creation could be practically implemented relying only on disordered energy sources. We provide a description of the structure and behavior of the proposed set-up in terms of effective temperatures and effective thermal baths, thus revealing explicitly its possible interpretation as a nanoscale thermal machine. Maximal concurrence and entropy production are reached for the hot reservoir being at negative effective temperature, beating the limits set by purely thermal operations on an equivalent system. A practical implementation is discussed in a quantum optical model of a pair of incoherently driven non-interacting qubits resonantly coupled to a quantized and strongly dissipative cavity mode.

[1]F. Tacchino, A. Auffèves, M.F. Santos and D. Gerace, *Steady State Entanglement beyond Thermal Limits*, Phys. Rev. Lett. **120**, 063604 (2018).

Supremacy of incoherent sudden cycles

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In quantum thermodynamics, one of the interesting and timely questions is about the role of the quantum features such as coherence and entanglement on the performance of quantum heat engines and refrigerators. In this regard, we investigate theoretically a four-step Otto refrigerator based on a two-level system (TLS) coupled alternately to two different heat baths[1]. Modulation of the coupling is achieved by tuning the level spacing of the TLS by an external control, for example, by varying the magnetic flux. We find that the TLS, which avoids quantum coherences, acts as a refrigerator with finite cooling power even in the limit of infinite operation frequency. On the other hand, the cycles that create quantum coherence in the sudden expansions and compressions lead to heating of both the baths. Further, to suppress the creation of coherence, we propose a driving method that keeps the energy eigenstates time-independent and thus restores the refrigeration cycle. We also discuss a physical realization of the cycle based on a superconducting qubit coupled to dissipative LC-resonators.

[1]J. P. Pekola, B. Karimi, G. Thomas, and D. V. Averin, *Supremacy of incoherent sudden cycles*, arXiv:1812.10933 [quant-ph] (2018).

Effect of the External Control on the Performance of a Shortcut to Adiabaticity Quantum Engine.

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We assess the energy cost of implementing Shortcut to Adiabatic expansion/compression of a quantum harmonic oscillator, which constitute the power strokes of an specific model of quantum Otto engine. We identify two different, yet not contradictory, definitions of work applicable to compute the energy consumed or produced by and externally driven quantum process. We demonstrate that considering the system whose configuration dictates the force that drives the quantum working medium, exemplified in our model by a Paul trap, is necessary for a fair assessment of the performance of the engine. On one hand, it fixes the specific gauge for the quantum system, resulting in a counterintuitive evolution of its internal energy. On the other, it allows us to identify the rate dependent losses present in the process, which in fact constitute the cost of the STA and make the efficiency of the device effectively zero.

Crossover between electron-phonon and boundary resistance limited thermal relaxation in copper films

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We observe a crossover from electron-phonon (ep) coupling limited energy relaxation to that governed by thermal boundary resistance (pp) in copper films at sub-kelvin temperatures. Our measurement yields a quantitative picture of heat currents, in terms of temperature dependences and magnitudes, in both ep and pp limited regimes, respectively. We show that by adding a third layer in between the copper film and the substrate, the thermal boundary resistance is increased fourfold, consistent with an assumed series connection of thermal resistances.

Fundamental limitations to local energy extraction in quantum systems

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We examine when it is possible to locally extract energy from a bipartite quantum system in the presence of strong coupling and entanglement, thus exploring a type of "passivity" that differs from the usual notion regarding energy extraction under unitary maps. Using techniques from semidefinite programming previously used in the context of quantum state discrimination, we find necessary and sufficient conditions for such extraction to be impossible, fully characterizing this distinct notion of passivity. We also show a physically-relevant quantitative bound on the threshold temperature at which this passivity appears, which explicitly shows how entanglement in the ground state of a multipartite system is a possible cause for this phenomenon. Furthermore, we show how this no-go result also holds for thermal states in the thermodynamic limit, provided that the spatial correlations decay sufficiently fast, and we give a number of numerical examples. This type of passivity, as we argue, is only of fundamental importance in quantum scenarios, and it may impose constraints on the operation of quantum thermal machines at strong coupling.