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REBUILDING QUANTUM THERMODYNAMICS ON QUANTUM MEASUREMENT

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ABSTRACT

Classical thermodynamics (Fig.1a) was initially developed to build engines [1]: The goal was to exploit the cyclic transformations of some working fluid, to efficiently extract heat from thermal baths and convert it into work stored in batteries. This initially applied area of physics gave rise to fundamental concepts like thermodynamic time arrow, i.e. thermodynamic irreversibility: Namely, time has a preferred direction, which can be measured by entropy production [2,3]. Irreversibility has a thermal imprint, which affects work extraction: If an engine is run irreversibly (too fast), its efficiency drops down. This paradigm has important consequences for information technologies, which can be seen if the working fluid is replaced by a two-level system encoding one bit of information. Cooling down such an elementary "working agent" actually corresponds to the erasure of an elementary memory as evidenced by Landauer, and sets the ultimate energetic bound for classical computation [4]. With the rise of stochastic thermodynamics, it has become obvious that both time arrow and work extraction deeply rely on a source of randomness, here on the presence of thermal fluctuations. Thermal fluctuations indeed provide the stochastic energy source that feeds heat engines. On the other hand, thermal fluctuations induce random perturbations of the system's classical trajectory, breaking the reversibility of the system's evolution [5,6].

Since a few decades, quantum thermodynamics aims to extend the results of classical thermodynamics, taking into account that the working fluids, baths and batteries actually are quantum systems. A first important motivation is to explore if quantum coherences has some energetic counterpart. The topics of "Coherence as a resource" leads to investigate energetic aspects of quantum computation [7,8,9,10] but also specific mechanisms of work extraction in quantum heat engines [11,12,13,14]. A second fundamental question deals with the nature of time arrow at the quantum scale, and how to characterize it [15,16,17]. As it appears in (Fig.1b), in quantum thermodynamics the bath has kept a central role: Namely, the bath is the stochastic source of energy and irreversibility. Oddly enough, so far quantum measurement has mostly been treated as a practical step in protocols aimed to extract information on the system state, as in Maxwell's demon experiments [13, 14], or to define stochastic thermodynamic quantities [15,16].

However, quantum measurement can also be seen as an ultimate source of randomness [18], inducing fluctuations of completely different nature than thermal fluctuations. Here we provide a new approach for quantum thermodynamics, based on such measurement-induced randomness (*Measurement based thermodynamics*). In this view, the measuring apparatus plays unusual roles, i.e. becomes a source of irreversibility and energy of purely quantum nature. We then evidence a new kind of quantum engines, for which work is extracted from the measurement channel in the absence of any bath (*Measurement powered quantum engines*)

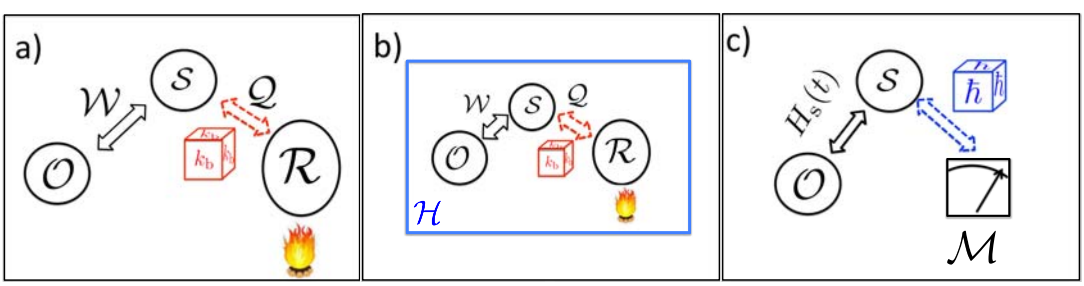

Figure 1: The sceneries of thermodynamics. a) Classical thermodynamics. A system S (usually called a working fluid) exchanges work with an external operator (= a battery), and heat with a stochastic entity, which is a thermal reservoir (dice k_B). This paradigm describes both the work extraction and the reset of classical heat engines, the thermodynamic time arrow, and ultimate bounds for classical computing (if the "working fluid" is a two-level system). b) Current framework for quantum thermodynamics. The system now pertains to a Hilbert space, therefore its state can carry coherences which are expected to have an energetic counterpart. This counterpart can enhance the performances of quantum engines, or reciprocally, set the energetic cost of a given quantum task when it is performed at finite temperature. c) Suggested alternative framework for quantum thermodynamics. The stochastic entity is now a measuring device (dice hbar), which is a source of ultimate randomness and genuinely quantum irreversibility. Energetic quantum fluctuations induced by the measurement are identified to a genuinely quantum component to heat exchanges, i.e. "Quantum heat". This quantum heat can be exploited to run engines, and reciprocally, sets the energetic cost of a quantum task when it is performed in the presence of decoherence.

Measurement based quantum thermodynamics

Our purpose is to propose a radically new perspective on quantum thermodynamics, by replacing the bath (i.e. the thermal source of stochasticity, Fig. 1b) by a measuring apparatus (i.e. a genuinely quantum source of stochasticity, Fig. 1c). Doing so, we are brought back to a textbook situation of quantum mechanics, namely a quantum system driven by a Hamiltonian H(t), coupled to a projective measuring apparatus.

Firstly, this scenery enables to define a quantum trajectory. Let us suppose that the system is initially in a pure state, continuously driven, and measured at discrete times t_k in arbitrary bases $M(t_k)$. If the measurement outcomes are read, the system remains in a pure state $|\psi(t)>$ at any time. $|\psi(t)>$ can be fully reconstructed from the knowledge of the measurement outcomes and the applied Hamiltonian. It consists in a sequence of continuous evolutions (between the measurement steps) and stochastic, measurement induced quantum jumps (Fig.2). Such stochastic quantum trajectories are analogous of the stochastic trajectories of classical thermodynamics, but here the primary cause of stochasticity is quantum measurement.

Quantum trajectories are extremely useful to evidence that quantum measurement is a source of irreversibility. When a quantum system is successively measured in two non-orthogonal bases, measuring it again in the initial basis will not necessarily give the same initial result: It gives rise to a genuinely quantum term in entropy production $\Delta_i S$, which can be related to the increase of the system's Von Neumann entropy [Cyril, Parrondo]. Less expectedly, quantum measurement can also provide energy: In what follows we focus on this original aspect.

Quantum trajectories bring new definitions for thermodynamic quantities Since the pioneering works in quantum stochastic thermodynamics [15,16], it was taken great care to define *operational* thermodynamic quantities (internal energy, work, and heat). Most often, this led to fully identify these thermodynamic quantities with energy measurement outcomes. These are restrictive definitions, which prevent in particular from attributing an internal energy to a coherent superposition of energy eigenstates. We have recently suggested [17] to define the system's internal energy as the expectation value of the Hamiltonian $U(t)=<\psi(t)|H(t)|\psi(t)>$ where $|\psi(t)>$ is the quantum state of the system. Though our choice of definition is not based on energy measurements, it is still fully operational as it relies on the knowledge of the system's quantum trajectory $|\psi(t)>$, which is experimentally accessible [19,20]. With our definition, the system's internal energy is defined at any time, independently of any measurement, and for any quantum state.

Based on this definition for the internal energy, we define the work increment $\delta W(t) = <\psi(t)|dH(t)|\psi(t)>$, that corresponds to the deterministic energy change due to the action of the driving entity. The heat increment $\delta Q(t)=dU-\delta W(t)$ quantifies the stochastic energy change induced by the measurement. This heat has no classical equivalent, such that we have called it *Quantum heat* (Fig.2). If the measured observable commutes with the system's Hamiltonian, the quantum heat distribution averages to 0 over all measurement outcomes. This is not the case otherwise: This corresponds to some mean energy exchange between the measuring device and the quantum system, which can be used to design quantum engines (See Fig.3 in the case of a Qubit and below).

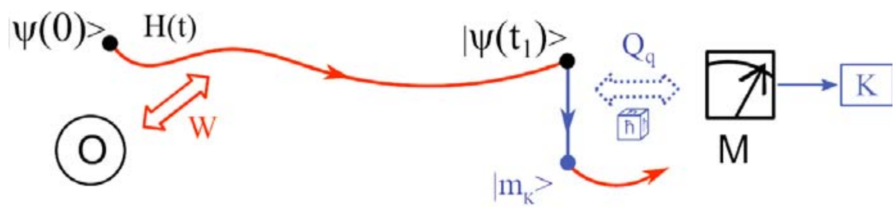

Figure 2: Ideal 2-points quantum trajectory. The system is initially prepared in the state $|\psi(0)>$ with internal energy U_0 and driven by the operator O through the Hamiltonian H(t). During the deterministic Hamiltonian evolution, the system receives the work $W(t) = < \psi(t)|H(t)| \psi(t)> -U_0$. At $t=t_1$ the system is measured by the classical device M with the stochastic outcome K. The system's state is thus projected on the state $|m_k>$. During the quantum jump, the system receives the quantum heat $Q_q = < m_k|H(t_1)| m_k> -< \psi(t_1)|H(t_1)| \psi(t_1)>$.

Measurement powered quantum engines

Quantum Heat Engines are currently investigated in the standard framework (Fig1b), where energy is extracted from some eventually engineered bath. A tremendous question is related to the enhancement of the engine's performance, because of the presence of coherences in the system or in the bath [8,9,21]. In the standard framework, this topics of "Coherence as energetic resource" carries big conceptual problems related to a conflict of timescales: In classical thermodynamics indeed, optimal work extraction requires to operate in a quasi-static way; or the other hand, extracting work from coherence requires to operate faster than decoherence.

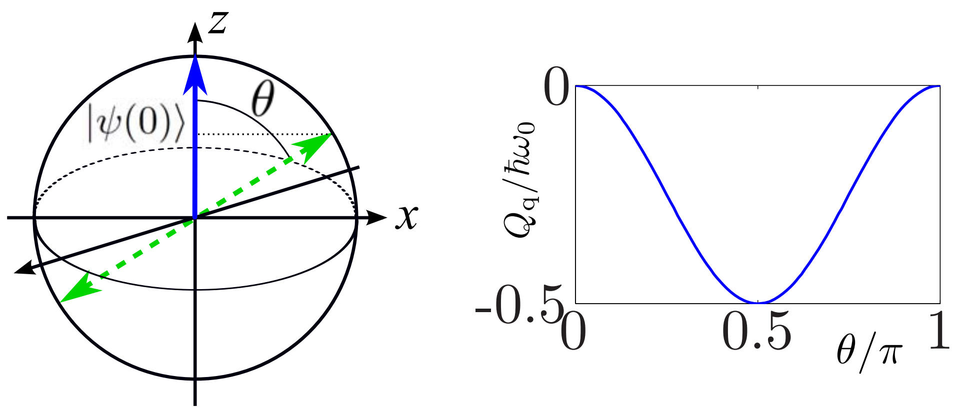

Figure 3: Mean transfer of energy between a Qubit of free Hamiltonian H=hω$_0$ (|e><e| - |g><g|) and a measuring apparatus. Left: The Qubit is initially prepared in $|\psi_i\rangle = |e\rangle$ and measured in the basis $\{|+_\theta\rangle;|-_\theta\rangle\}$, with $|+/-_\theta\rangle = (+/-)\cos(\theta/2)|e\rangle + \sin(\theta/2)|g\rangle$. After the measurement the Qubit is projected in $|\psi_f\rangle$. As the measurement basis does not commute with the Qubit's energy basis, the measurement process does not conserve the mean Qubit's internal energy, defined as $U = \langle\psi|H|\psi\rangle$. For this transformation the energy balance reads $\Delta U=U_f-U_i=Q_q$, where Q_q is the quantum heat. Left: Mean quantum heat exchange Q_q (in unit of the Qubit's energy) as a function of the measurement's basis angle θ. If θ=0 or π, the measurement does not perturb the Qubit's state, no entropy is created and the quantum heat vanishes. Reciprocally, θ=π/2 corresponds to a maximal entropy production and maximal transfer of quantum heat.

To provide a fresh perspective on the problem, we have filtered a genuinely quantum work extraction mechanism, and considered the new framework of Fig1c, where energy is now solely provided by the measuring apparatus. This defines a new device with no classical equivalent, e.g. a measurement-powered engine (MPE). A special case of interest is provided by the "Zeno regime", where the driven system is continuously measured. It can therefore be frozen by Zeno effect in any state. In particular, in the specifically quantum situation where the Hamiltonian basis and the measurement basis do not commute, the frozen state will be a non-stationary state of the Hamiltonian. It can be thus be chosen such that between two close measurements, the system provides energy (work) to the driving operator. This energy is recovered by the system during the measurement step, under the form of quantum heat. Such work extraction mechanism is clearly sensitive to the phase of the measurement basis, and has no classical equivalent.

We are currently working on a realistic proposal for such engine [22], in the framework of circuit Quantum ElectroDynamics. The system is a superconducting Qubit, resonantly driven by an input microwave classical field and undergoing repeated QND measurements in arbitrary bases. By properly choosing the frozen state, work is extracted such that the output power overcomes the input power.
We expect the MPE to provide new tools to analyse any kind of quantum heat engine, in particular those involving some engineered bath. In this new perspective, we expect the bath not only to play the role of a stochastic energy source, but also the role of a measuring device, that projects the quantum system on interesting states for work extraction (active states [21]).

Conclusion

Measurement based thermodynamics provides a new paradigm enabling to clarify "what is quantum in quantum thermodynamics". It evidences the existence of a genuinely quantum entropy production, due to the stochasticity of quantum measurement. New mechanisms of work extraction appear, where the fuel is the quantum heat, ie the energy transferred by the measurement channel. In the future, this new paradigm will bring new tools to quantitatively investigate energetics aspects of quantum processing, for which decoherence and measurements performed by the environment are bigger enemies than relaxation in thermal baths.

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