Extending the Laws of Thermodynamics for Arbitrary Autonomous Quantum Systems

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Recent formulations of the law of thermodynamics encompass the case of single quantum systems coupled to macroscopic energy sources. The latter are generally treated either as ideal work sources (treated as a classical entity via a time-dependent Hamiltonian of the system) or assumed to be pure heat sources starting in a thermal equilibrium state. In contrast, implementations show multiple examples of hybrid sources of work and heat. One can also wonder to which extent one can formulate constraints about the energy exchanges between arbitrary quantum systems starting out of equilibrium, under the form of the laws of thermodynamics.
In [1], we address these questions by considering any quantum system as source of both work and heat. Based on the system's entropy, we identify an effective temperature and the fraction of its energy which is of thermal nature. We show that the variation of this thermal energy plays the same role as heat in a universal microscopic formulation of the second law. The latter is valid for an arbitrary set of quantum systems, initially in any quantum state. On the other hand, we identify general resources stored in the quantum states that differ from thermal equilibrium states. The consumption of these resources is equivalent to work, and allows one e.g. to decrease entropy or to induce heat flows against thermal biases. We use these microscopic notions of work and heat to recover known ideal limits of quantum thermodynamics, but also to explore nanoscale quantum machines where even the energy sources can be single quantum systems.
Our results open perspectives to understand and optimize the energetic performances of autonomous quantum setups, from quantum batteries to in-situ refrigerators.

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