Work and cooling bounds in quantum thermodynamics

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In traditional thermodynamics the Carnot cycle yields the ideal performance bound of heat engines and refrigerators. We propose and analyze a minimal model of a heat machine that can play a similar role in quantum regimes. The minimal model consists of a single two-level system with periodically modulated energy splitting that is permanently, weakly, coupled to two spectrally-separated heat baths at different temperatures. The equation of motion allows to compute the stationary power and heat currents in the machine consistently with the second-law of thermodynamics. This dual-purpose machine can act as either an engine or a refrigerator (heat pump) depending on the modulation rate. In both modes of operation the maximal Carnot efficiency is reached at zero power. We study the conditions for finite-time optimal performance for several variants of the model. Possible realizations of the model are discussed. A minimal model of a quantum refrigerator (QR), i.e. a periodically phase-flipped two-level system permanently coupled to a finite-capacity bath (cold bath) and an infinite heat dump (hot bath), is introduced and used to investigate the cooling of the cold bath towards the absolute zero (T=0). Remarkably, the temperature scaling of the cold-bath cooling rate reveals that it does not vanish as T→0 for certain realistic quantized baths, e.g. phonons in strongly disordered media (fractons) or quantized spin-waves in ferromagnets (magnons). This result challenges Nernst's third-law formulation known as the unattainability principle.

Work extraction from a heat engine in a cycle by a quantum mechanical device (quantum "piston") and its efficiency bound are shown to crucially depend on the capacity of the quantum state of the piston to accumulate useful work. Energy gain (e.g. in lasing) is shown to drastically differ from work gain. These general results are applied to atoms in a cavity where one mode serves as the piston.

[1] M.Kolar, D. Gelbwasser, R. Alicki and G.Kurizki, Quantum bath refrigeration towards absolute zero: Challenging the unattainability principle, Phys. Letters 109 090601 (2012)

[2] D. Gelbwasser, R. Alicki and G. Kurizki, Minimal universal quantum heat machine Phys. Rev. E 012140 (2013)