Entropy production and thermodynamic power of the squeezed thermal reservoir

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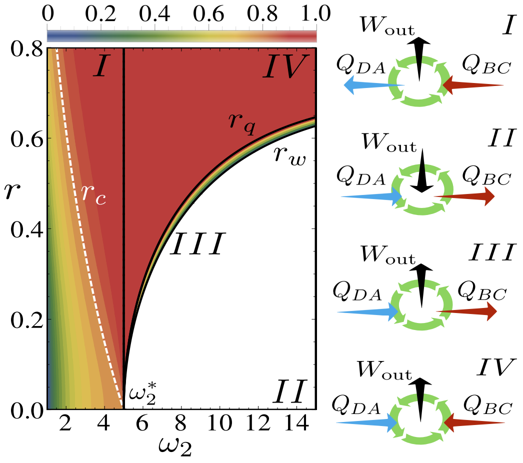
Thermodynamic theory was developed from the analysis of real heat engines, such as the steam engine along the 19th century [1]. Those macroscopic engines have quantum analogues, whose analysis constitute an important branch of research in quantum thermodynamics [2]. Clarifying the impact of quantumness in the operation and properties of thermal machines represents a major challenge. Quantum effects can arise in the working sustance and environment and, from the pionering proposal of M. O. Scully *et. al.* [3], there have been different works in the literature pointing that nonequilibrium quantum reservoirs may be used to increase both power and efficiency of quantum machines. Nevertheless, a solid understanding of these enhancements and their optimization has remained elusive, as it requires a precise formulation of the second law of thermodynamics in such nonequilibrium situations.

Using recent proposals in quantum fluctuation theorems [4], we analyze the entropy production and the maximal extractable work from a squeezed thermal reservoir. The quantum nature of the reservoir induces genuine nonequilibrium features such as an entropy transfer with a coherent contribution. These nonequilibrium features allow for work extraction from a single reservoir, and are the responsible of power and efficiency enhancements for quantum heat engines operating with this kind of reservoirs. Here we consider in detail a heat engine performing a (modified) quantum Otto cycle [2, 5], optimize it, and discuss its many striking consequences, like the appearance of multi-task regimes in which the heat engine may extract work and refrigerate a cold reservoir at the same time [6]. Moreover, we show how our approach leads to the introduction of a *thermodynamic efficiency* based on the concept of nonequilibrium free energy, which naturally accounts for the performance of both classical and quantum thermodynamic resources. Our results hint at possible applications like squeezing-fueled batteries, multi-task thermal machines, or erasure devices operating below Landauer's limit.

In the Figure, we show a phase diagram with the four regimes of operation of the Otto cycle (I, II, III, IV) as a function of the working substance frequency modulation during the isentropic strokes, $\omega_1 \to \omega_2$, and the squeezing parameter $r \geq 0$. The color scale corresponds to the *energetic* efficiency of the cycle $\eta = W_{\text{out}}/Q_{\text{in}}$ as a heat engine, for inverse temperatures in the reservoirs $\beta_2 = 0.2\beta_1$, yielding a Carnot efficiency $\eta_c = 0.8$ (white dashed curve). In the right side the direction of the arrows represents the sign of the energy fluxes for each regime.



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