Energy conversion at the nanoscale: exploiting non-thermal resources

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Nanoscale engines - such as on-chip thermoelectric devices - are increasingly used to transduce energy and particles between reservoirs for *useful* tasks like cooling. Unlike macroscopic engines, these systems often operate under conditions where environmental reservoirs are constantly out-of-equilibrium and cannot be described by well-defined thermal distributions. Consequently, temperature and chemical potential lose their meaning, and fluctuations in energy and particle flows become significant. Rather than treating this non-thermal nature as a limitation, we exploit it as a *resource* to design devices that can even outperform traditional engines in performance. We investigate a prototype quantum thermoelectric device operating between a non-thermal and thermal reservoir, analyzing energy and particle flows in the coherent transport regime via scattering theory [1]. Our approach seeks to optimize the device's performance based on the efficiency, precision, or a trade-off between the two at a given output cooling current while the usual heat-work distinction breaks down. We introduce entropy currents as resources and exploit a Lagrange multiplier method to optimize the particle transmission characteristics to achieve the optimal performance. We find that the resulting optimal transmission filters are directly shaped by the non-thermal distribution. Our work provides a framework for characterizing and leveraging non-thermal resources, opening pathways for unconventional energy conversion strategies in quantum thermodynamics and nanoscale physics.

[1] E. Danielsson, H. Kirchberg, J. Splettstoesser, Phys. Rev. B 112, 195434 (2025)