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AGENCIA ESTATAL DE INVESTIGACIÓN

Beating Carnot efficiency with Chiral AC driven Conductors

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Abstract

■ We demonstrate that a chiral conductor driven by AC voltage bias can act as a heat engine with efficiencies much larger than the Carnot limit, and they can also extract work from common temperature baths, violating Kelvin-Planck law.

■ Nevertheless, with a proper definition using information-theoretical approach, entropy production is always positive, and the second law of thermodynamics is preserved.

■ Crucial conditions for achieving efficiency beyond Carnot limit are irreversible entropy production by the photo-assisted electron excitation process due to the AC voltage and the absence of power injection by the AC voltage due to the chirality.

Introduction

■ Quantum thermodynamics is in a second revolution due to the feedback received from other research fields like quantum information and quantum transport.

■ One goal of quantum thermodynamics is to build quantum heat engines or coolers to either produce useful work or to extract heat from reservoirs.

■The efficiency of thermal machines are limited by the positivity of the entropy production, i.e., the second law of thermodynamics.

■ Applying AC potential has a substantial merit for driving the nanoscale system out of equilibrium in a controllable manner. E.g., single electron sources have been recently developed, for Fermionic quantum optics, metrology, and flying qubits.

■ In this study, we suggest that a chiral conductor can act as a thermal machine with efficiency beyond Carnot limit, when it is connected to heat bath driven out of equilibrium by AC voltage.

Setup

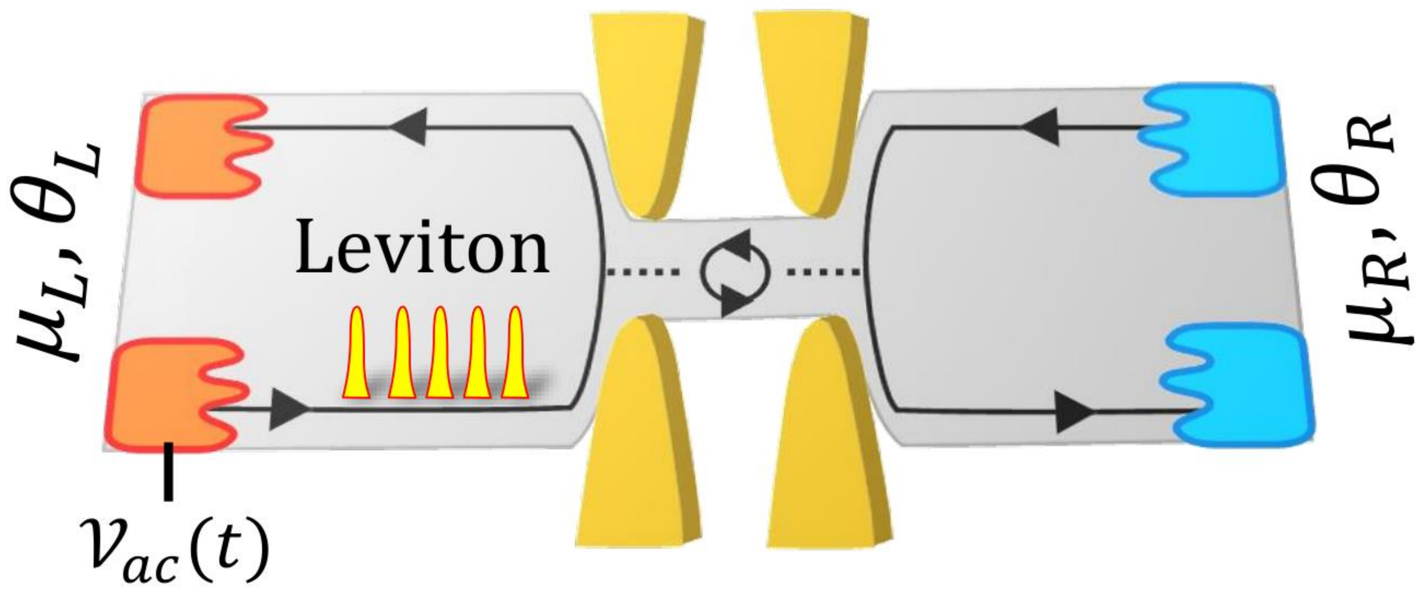
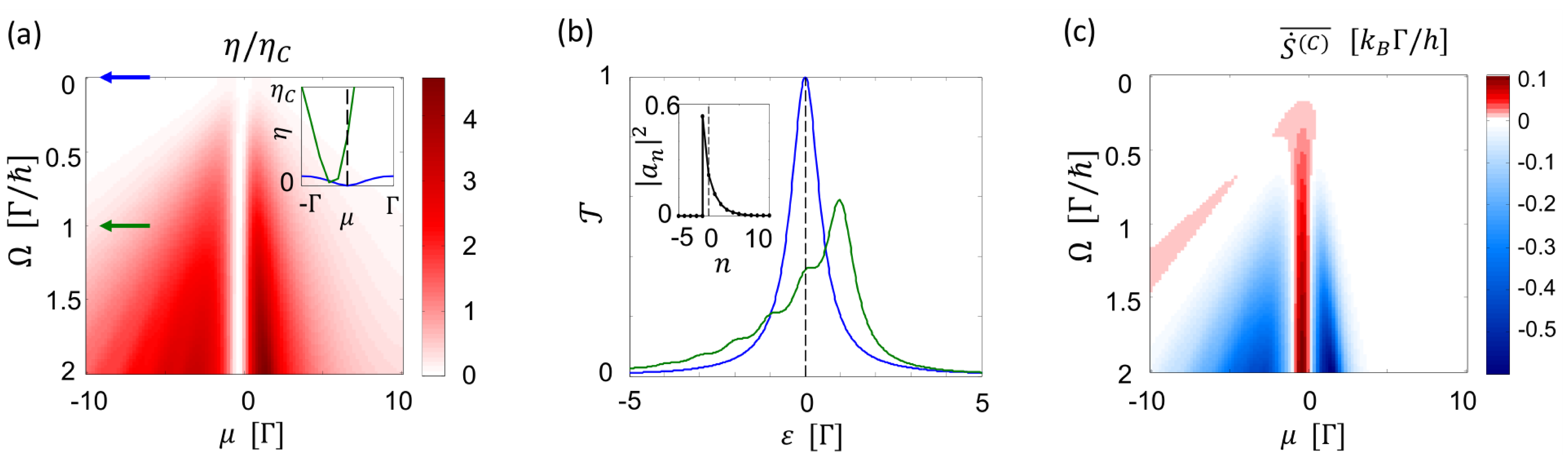


Fig. 1. Chiral conductor with a localized energy level. To one of the electronic contacts, a time-dependent AC voltage $V_{\rm ac}(t)$ is applied. Edge channels from left and right are tunnel coupled to the localized state with a tunnel rate Γ. The left (right) reservoirs have temperature $\theta_{L(R)}$ and chemical potential $\mu_{L(R)}$.

Efficiency enhancement by AC voltage driving



Parameters: $\theta_L - \theta_R$= 0.1θ, $k_B\theta$= 0.25 Γ. The AC voltage profile is periodic Lorentzian pulses carrying an electron charge per period, with vertical offset. The temporal width of each pulse is 0.05×2π/Ω. DC potential bias is chosen for maximal power generation.

Fig. 2. Efficiency enhancement beyond Carnot limit by AC voltage driving.
(a) Efficiency when tuning the AC frequency Ω and the average chemical potential μ. Inset: Plot near μ = 0 for Ω = 0 (blue) and Ω = Γ/ℏ (green), showing a photo-assisted thermo-electric heat engine.
(b) Photo-assisted transmission probability $\mathcal{T}$ of an electron of energy ε incoming from the left reservoir for Ω = 0 (blue) and Ω = Γ/ ℏ (green). Inset: the photo-assisted transition probabilities $|a_n|^2$, whose asymmetry induces electron-hole asymmetry.
(c) The entropy production rate defined by Clausius $\bar{\dot S}^{(C)}$, i.e., sum of heat current into the reservoirs divided by their temperatures. It is negative when the efficiency is larger than the Carnot efficiency.

Entropy production defined by shannon entropy flow

■ We find that the entropy production $\dot{S}$ defined by information-theoretical approach is always non-negative.

$$\bar{\dot S} = \frac{k_B}{h}\sum_{\alpha=L,R}\int d\mathcal{E}\left[-\sigma[f_\alpha(\mathcal{E})]+\sigma[f_\alpha^{(\rm out)}(\mathcal{E})]\right]$$

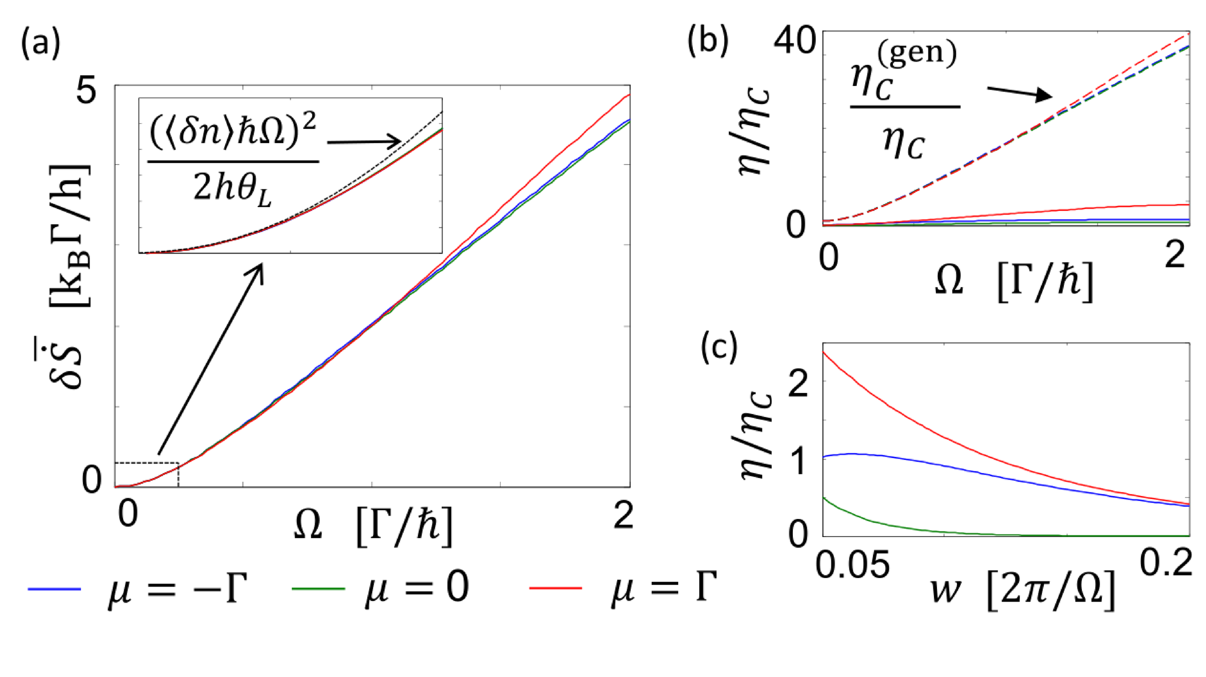


Fig. 3. **(a)** Difference of entropy productions $\delta\bar{\dot S} \equiv \bar{\dot S} - \bar{\dot S}^{(C)}$, in the situation of Fig. 2. Inset: Enlargement for the slow-driving regime, $\Omega \in [0, k_B\theta/\hbar]$, showing that the difference is determined by the photon numer uncertainty $\langle\delta n\rangle$ (dashed line). **(b)** Efficiency in comparison with a new upper bound determined by positivity of entropy production $\bar{\dot S}$ (dashed lines). **(c)** Efficiency when tuning the temporal width w of the Lorentzian pulses, while fixing $\Omega = \Gamma/\hbar$. The more the pulses are squeezed, the more the efficiency is enhanced, due to larger photon number uncertainty.

Work extraction from single temperature

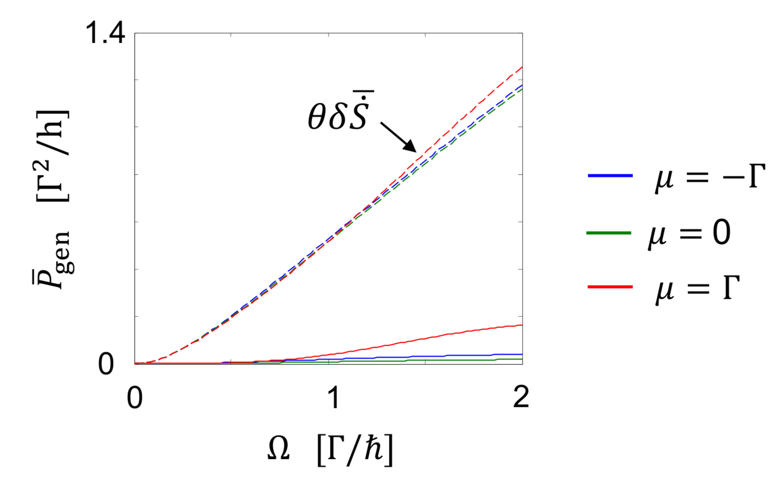


Fig. 4. Generated power when the two reservoirs have the same temperature θ. The power generation is allowed upto $\theta\delta\bar{\dot S}$ (dashed lines) when the AC driving induces additional entropy production, $\delta\bar{\dot S}$ > 0. Here, $k_B\theta = 0.25\Gamma$.

Conclusion

■ We demonstrated photo-assisted thermoelectric engine, extracting work even beyond Carnot limit.
■ The entropy production defined by information-theoretical approach is always non-negative, while one defined by Clausius is not.
■ The difference between the two entropy productions was determined by photon number uncertainty in the low frequency and linear regime.
■ The ac voltage plays a role of the nonequilibrium demon recently suggested, which only induce nonequilibrium without energy injection.
■ Our system have a merit that it does not need a fine tuning, as the energy injection is always zero regardless to ac voltage profile.

Reference: Sungguen Ryu, Rosa López, Llorenç Serra, and David Sánchez. In preparation.