Quasistatic and quantum-adiabatic Otto engine for 2-D material: the case of a graphene quantum dot

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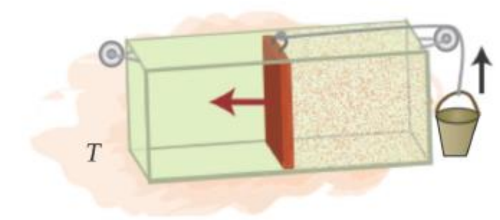
ABSTRACT

In this work, we study the performance of classical and quantum magnetic Otto cycles with a working substance composed of a single graphene quantum dot modeled by the continuum approach with the use of the zigzag boundary condition. Modulating an external/perpendicular magnetic field, in the classical approach, we found a constant behavior in the total work extracted that is not present in the quantum formulation. We find that, in the classical approach, the engine yielded a greater performance in terms of total work extracted and efficiency as compared with its quantum counterpart. In the classical case, this is due to the working substance being in thermal equilibrium at each point of the cycle, maximizing the energy extracted in the adiabatic strokes.

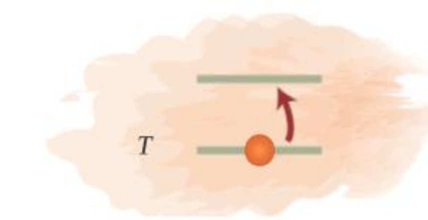
INTRODUCTION

The concept of quantum heat engines (QHEs) was introduced by Scovil and Schultz-Dubois in [1], in which they demonstrate that a three-level energy maser can be described as a heat engine operating under a Carnot cycle. This important research gave way to the study of quantum systems implemented as the working substances of heat machines oriented in search of efficient nanoscale devices. These devices are characterized by the structure of their working substance, the thermodynamic cycle of operation, and the dynamics that govern the cycle.

Classical



Quantum



System

We consider the Dirac-Weyl Hamiltonian for low energy electron states in graphene under the presence of external perpendicular magnetic field and a mass related potential given by

$$H = v_F\left(\mathbf{p}+e\mathbf{A}\right)\cdot\boldsymbol{\sigma} + V(r)\sigma_z, \quad (1)$$

where, $v_f \sim 10^6 m/s$ is the Fermi velocity, **A** is the vector potential and $\boldsymbol{\sigma}=(\sigma_x,\sigma_y)$ are Pauli's spin matrices.

We take the model treated in the Refs. [2,3] where the authors assume that the carriers are confined to a circular area of radius **R**, which is modeled by a potential of the form

$$V(r) = \begin{cases} 0 & \text{if } r < R, \\ \infty & \text{if } r \geq R, \end{cases} \quad (2)$$

where r is the radial coordinate of the cylindrical coordinates.

The are two different boundary conditions that can be applied to treat the potential form of Eq. (1), the zigzag boundary conditions (ZZBC) and the infinite mass boundary conditions (IMBC).

IMBC

$$\frac{\psi_1(\rho^*,\phi)}{\psi_2(\rho^*,\phi)} = i\tau e^{i\phi}$$

$$\frac{\tau\varepsilon}{2}\,{}_1\widetilde{F}_1\left(m+1-\frac{\varepsilon^2}{4\beta}, m+2, \beta\right) - {}_1\widetilde{F}_1\left(m+1-\frac{\varepsilon^2}{4\beta}, m+2, \beta\right) = 0.$$

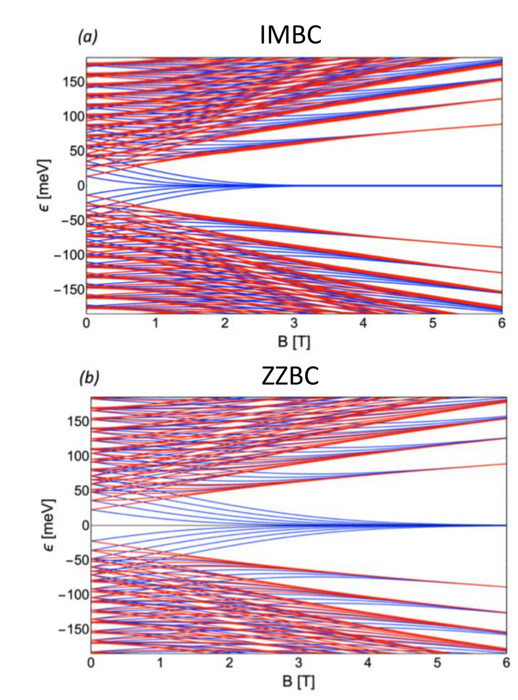
ZZBC

$$\psi(\rho^*,\phi) = 0 \rightarrow \chi_1(\rho^*) = 0.$$

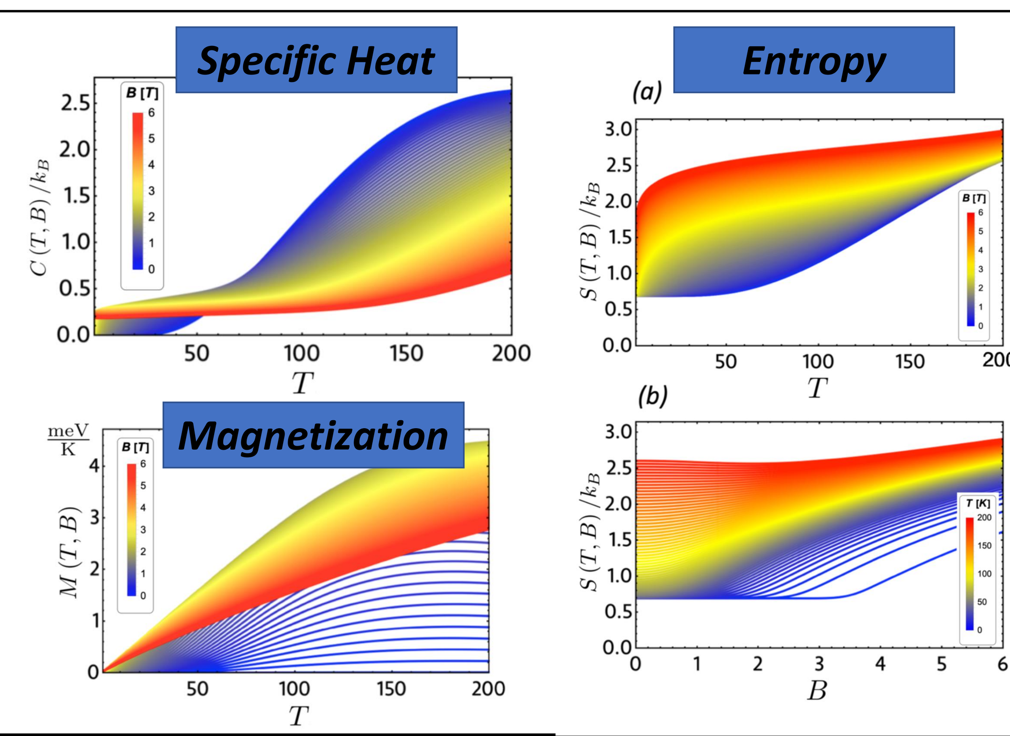
$${}_1\widetilde{F}_1\left(m+\frac{1}{2}+\frac{k}{2}-\frac{\varepsilon^2}{4\beta}, m+1, \beta\right) = 0.$$

Important notation: the index τ is used as valley index for the case of IMBC and the index k in the case of ZZBC.

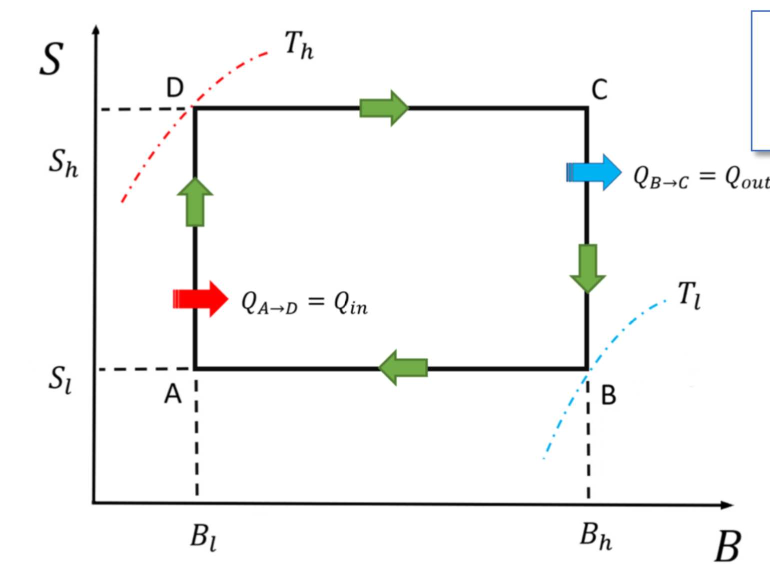
Energy Spectrum



Thermodynamic



Otto Cycle



Classical Work

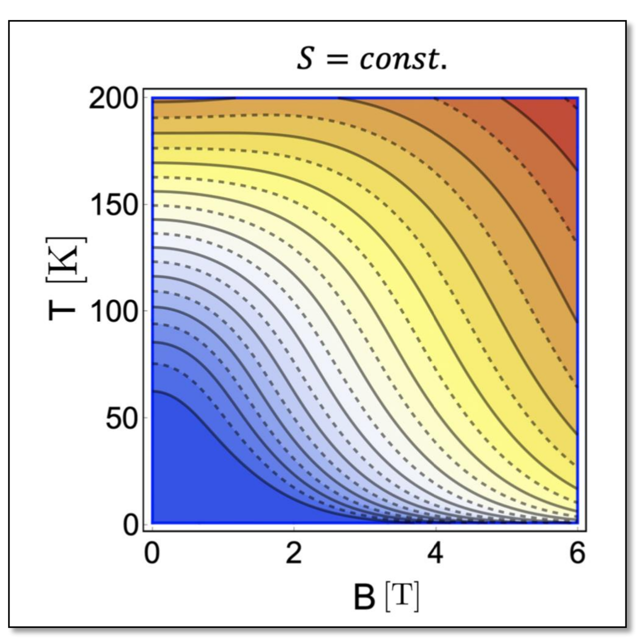
$$\mathcal{W}^c = U_D(T_h, B_l) - U_A(T_A, B_l) + U_B(T_l, B_h) - U_C(T_C, B_h).$$

Quantum Work

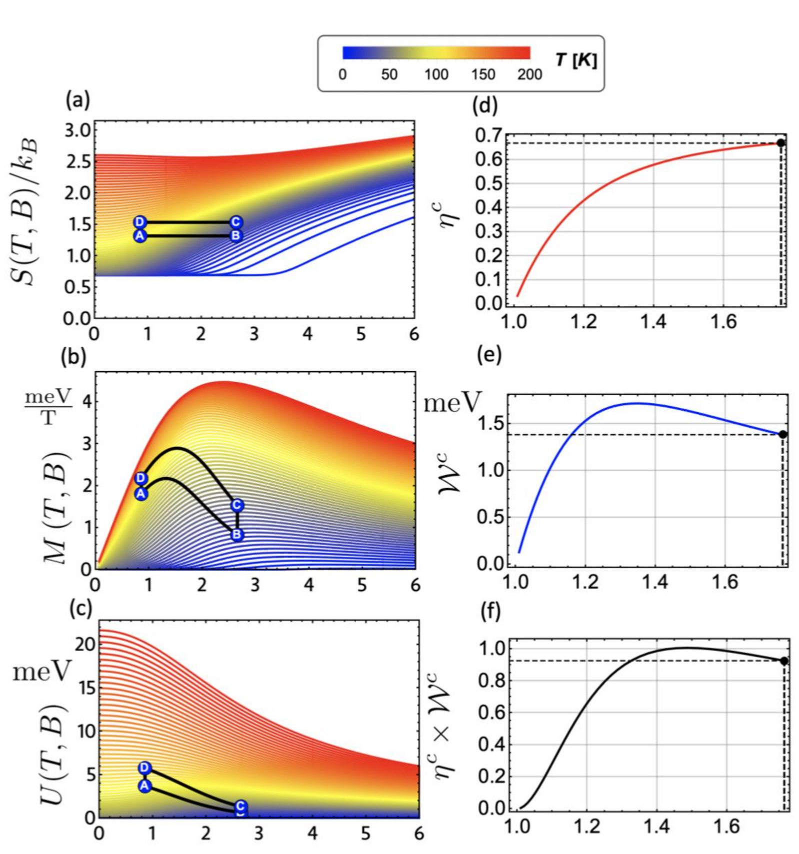
$$\mathcal{W}^q = \sum_m\sum_\tau \left(E^l_{m,\tau} - E^h_{m,\tau}\right) \times \left[P_{m,\tau}(T_h, B_l) - P_{m,\tau}(T_l, B_h)\right]$$

RESULTS

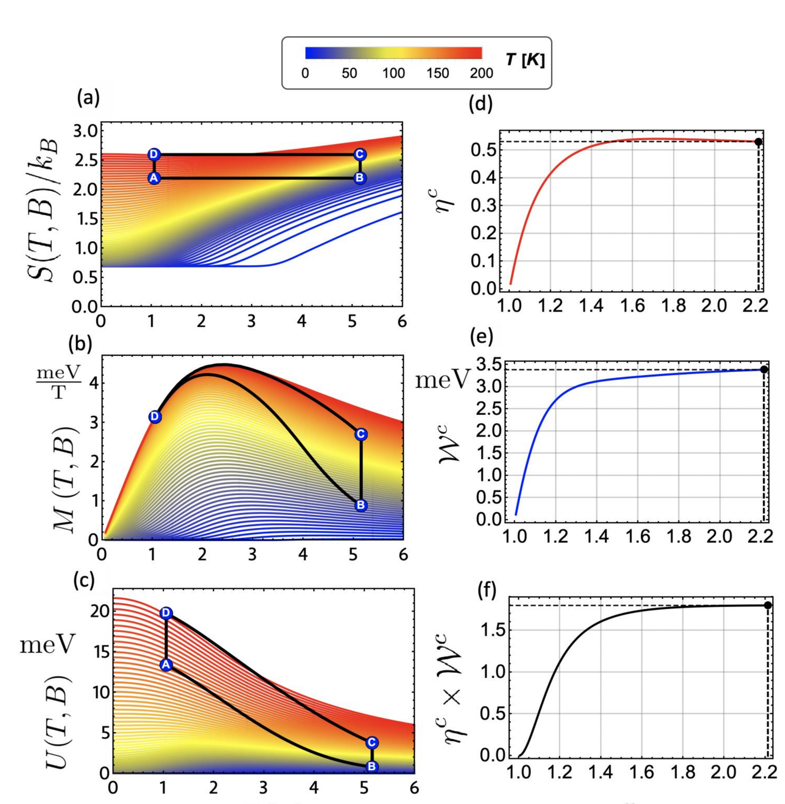
Classical



The behavior of temperature (vertical axis) versus external magnetic field (horizontal axis) for a classical isentropic stroke. The contour plot shows the different levels curves (constant entropy values) exhibit a constant temperature behavior for low magnetic fields. As the field increases, temperature diminishes to keep the entropy constant.



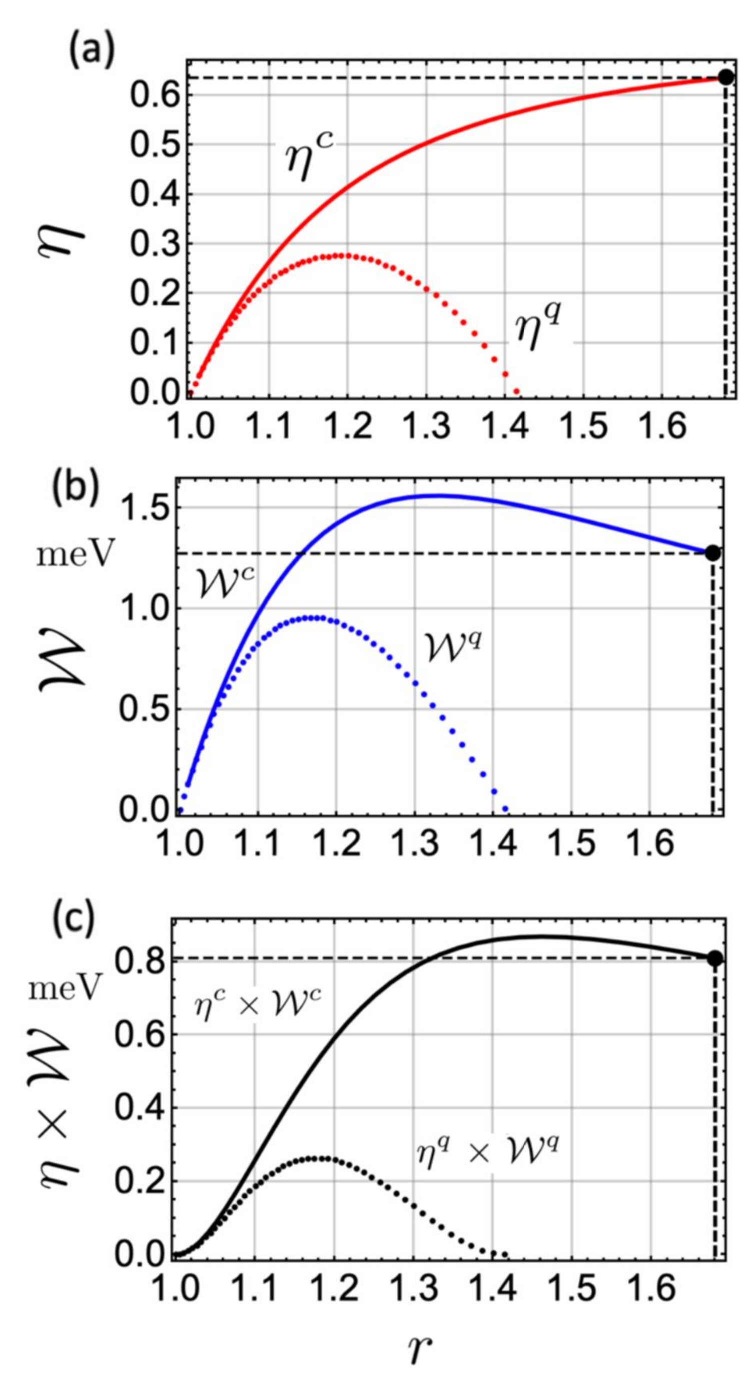
Parameters: $T_l = 29.9\ K$, $T_h = 119.5\ K$, $B_h = 2.65\ T$ and B_l up to $0.85\ T$.



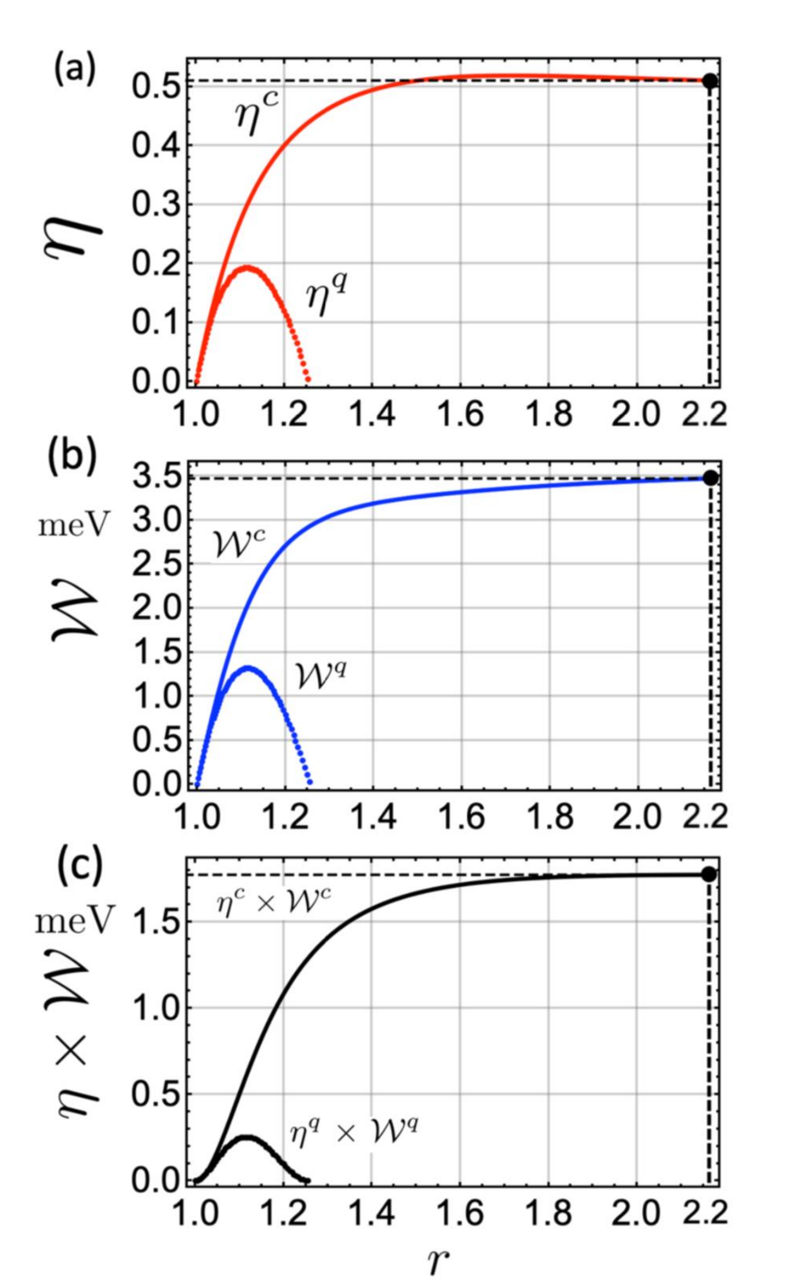
Parameters: $T_l = 39.15\ K$, $T_h = 200\ K$, $B_h = 5.15\ T$ and B_l up to $1.05\ T$.

Quantum

Dotted lines : Quanutm results. Solid lines : Classical results.



Parameters: $T_l = 29.9\ K$, $T_h = 119.5\ K$, $B_h = 2.65\ T$ and B_l up to $0.85\ T$.



Parameters: $T_l = 39.15\ K$, $T_h = 200\ K$, $B_h = 5.15\ T$ and B_l up to $1.05\ T$.

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[1] H. E. D. Scovil, and E. O. Schulz-DuBois, Phys. Rev. Lett. 2, 262 (1959).
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CONCLUSIONS

- We report a less work extraction for the quantum case compares to the classical approach because in the quantum case the system only thermalizes in the isochoric stages while for the classical case the system goes through for four equilibrium states. Hence, because of the principle of minimum energy, the system is allowed to extract more energy when the adiabatic strokes can lead to states that are in thermal equilibrium, which is only possible in the classical case.

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