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Performance analysis of an interacting quantum dot heat engine with an external applied magnetic field

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HIGHLIGHTS

- A general model of the quantum dot heat engine is proposed.
- The effects of Coulomb and magnetic fields are considered.
- The maximum power output and efficiency are determined.
- Suitable region of the external applied magnetic field is given.
- Several models adopted recently in literature are unified.

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ABSTRACT

A general model of a single orbital interacting quantum dot embed into two metal leads is established, in which an external applied magnetic field is considered and a linear fade of the Coulomb energy resulting from the energy level splitting is introduced. The occupation probabilities of quantum states are determined by the master equation under the steady state condition. The expressions of matter fluxes, heat fluxes, power output, and efficiency are derived. The effects of both the magnetic field and energy level on the performance are discussed. The maximum power output and efficiency are calculated. The optimal regions of the energy level and magnetic field are determined. Some important conclusions in literature can be directly deduced under the different extreme conditions of the present model.

1. Introduction

In recent years, due to the synthesis techniques and advances in material processing, nanoscale structures have attracted great attention. Nanothermoelectric heat engines can reach the Carnot efficiency by using a sharply tuned energy filter between the two reservoirs at different chemical potentials and temperatures [1]. One type of nanothermoelectric heat engines is quantum dot heat engines [2–4].

Electron transport through a quantum dot has recently received considerable attention in theoretical [5–11] and experimental [12–19] researches. The master equation is one kind of the methods to solve quantum dot problems [20–22]. Esposito et al. used the quantum master equation to describe the exchange of electrons between the spin non-degenerate quantum dot and the leads, revealing the operation condition and calculating the efficiency at the maximum power output [23]. Muralidharan and Grifoni used nonequilibrium currents of the steady state to evaluate the performance of a thermoelectric setup through a single orbital interacting quantum dot, in which the Coulomb interaction was taken into account [24].

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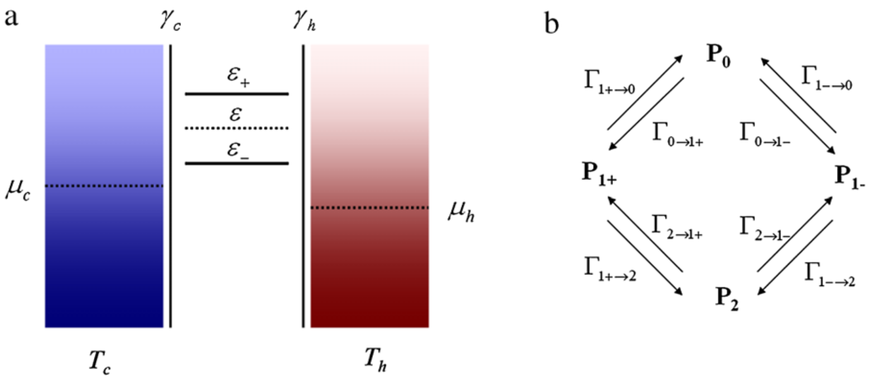

Fig. 1. (a) The energy diagram with splitting levels available for tunneling. (b) The schematic diagram of available transition processes.

Zhang et al. used the master equation to evaluate a spin degenerate quantum dot refrigerator in which the influence of the Coulomb interaction was considered as well [25]. Wang et al. studied a quantum dot engine with two discrete energy levels, in which the Coulomb energy between the electrons in one energy level was neglected, revealing the effects of the energy level and energy space on the performance of the engine [26]. Sothmann and Büttiker investigated the performance of multi-terminal setups consisting of a single spin-split level quantum dot coupled two ferromagnetic metallic reservoirs and a ferromagnetic insulator, in which the Coulomb energy between two electrons is infinitely large so that the double occupation is forbidden [27]. Kuo and Chang used multilevel Anderson model to simulate a multiple quantum dot junction system in the Coulomb regime [28]. Sierra and Sánchez used the Coulomb-blockaded quantum dot model to investigate the nonlinear regime of the charge and energy transport [29]. Besides, Liu et al. proposed a thermoelectric device composed of two serially connected quantum dots and considered the strong intradot and interdot Coulomb interaction [30]. Wierzbicki and Świrkowicz investigated the power output and efficiency of a quantum dot attached to ferromagnetic electrodes which results in the spin-dependent transmission of electrons [31].

In the present paper, a general thermoelectric engine consisting of a spin-degenerate quantum dot embed into two leads is proposed. By using the master equation, the occupation probabilities of the quantum dot can be solved. Both the power output and efficiency are optimized by considering the influence of the Zeeman split and Coulomb energy. The results obtained are of general significance and can be directly used to derive some important conclusions appearing recently in literature.

2. Quantum dot heat engine in an external magnetic field

The system under consideration is composed of a spin-degenerate quantum dot coupled to two metal leads, as shown in Fig. 1(a), which is similar to the unpolarized case in Ref. [31]. The quantum dot interacts with two leads at different chemical potentials and temperatures. The energy level ε is near the Fermi levels of two reservoirs, while other levels in the quantum dot have no contribute to processes. μ_c and μ_h are the chemical potentials of cold and hot reservoirs. When an external magnetic field is applied, two spin states split into two energy levels ε^+ and ε^-. The quantum dot of the system is described by the following one-site Hubbard Hamiltonian [24,27,32], i.e.,

$$H_{dot} = \sum_{\sigma} \varepsilon_\sigma a_\sigma^\dagger a_\sigma + (U - \lambda\alpha) a_\uparrow^\dagger a_\uparrow a_\downarrow^\dagger a_\downarrow, \qquad (1)$$

where $\varepsilon_\sigma = \varepsilon \pm \alpha$ denotes the energies of the spin-split levels, U is the Coulomb energy produced by the two electrons occupied the quantum dot at the same time, $\alpha = g\mu_B\mu_0 H/2$, H is the external applied magnetic field, g is the Lande factor, μ_B is the Bohr magneton, μ_0 is the vacuum permeability, $a_\sigma^\dagger$ (a_σ) is the creation (annihilation) operator of the electron with spin σ, and λ is a constant ranging from 0 to 1. In the present paper, the Boltzmann constant k_B is set to be equal to 1. It is well known that the larger the magnetic field is, the more obvious the Zeeman splitting. As a result, the Coulomb energy is reduced. In Eq. (1), a linear fade of the Coulomb energy is introduced. Eq. (1) results in four Fock-space energy levels denoted by their energies: 0, $\varepsilon_\uparrow$, $\varepsilon_\downarrow$, $\varepsilon_\uparrow + \varepsilon_\downarrow + U$. In the limit of weak contact coupling, it is accessible for exchanging one electron during a tunneling process.

The occupation probability of finding the system in state $|i, j\rangle$ at time t is denoted by $P_{i,j}(t)$, where i is the electron number in the energy level $\varepsilon_\uparrow$ and j is that in the energy level $\varepsilon_\downarrow$. By using the quantum master equation, the evolution of the occupation probability is described as [20–23,25–27]

$$\frac{\mathrm{d}P_{i,j}(t)}{\mathrm{d}t} = \sum_{(i',j')} [\Gamma_{(i',j')\to(i,j)} P_{i',j'}(t) - \Gamma_{(i,j)\to(i',j')} P_{i,j}(t)], \qquad (2)$$