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Magnon-driven quantum dot refrigerators

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ABSTRACT

A new model of refrigerator consisting of a spin-splitting quantum dot coupled with two ferromagnetic reservoirs and a ferromagnetic insulator is proposed. The rate equation is used to calculate the occupation probabilities of the quantum dot. The expressions of the electron and magnon currents are obtained. The region that the system can work in as a refrigerator is determined. The cooling power and coefficient of performance (COP) of the refrigerator are derived. The influences of the magnetic field, applied voltage, and polarization of two leads on the performance are discussed. The performances of two different magnon-driven quantum dot refrigerators are compared.

1. Introduction

The specific low-dimensional structures are attracting much attention due to the advances in techniques for nanostructured materials [1–3]. Of particular interest, since the quantum-dot (QD) refrigerator was presented in 1993 by Edwards et al. [4–7], are the nanothermoelectric setups using the quantum dot system.

Thus far, multi-terminal QD setups have been discussed in several references [8–10] because they allow for the crossed flows of the charge current and heat flow. Sánchez and Büttiker proposed a nano-sized structure consisting of two QDs coupled by the Coulomb interaction without particle exchange [8]. Entin-Wohlman et al. discussed a three-terminal thermoelectric setup composed of a resonant level, two electronic reservoirs, and a phonon source [9]. Li and Jia proposed a particle-exchange heat engine in which three QDs are coupled to two fermionic reservoirs and a bosonic reservoir [10].

The QD coupled to ferromagnetic reservoirs has underlying applications in spintronics, i.e., QD spin valves [11–14]. Strasberg et al. proposed a model of an information driven current through a spin valve with which the Maxwell demon device can be physically realized [15]. Sothmann and Büttiker used two ferromagnetic reservoirs and a ferromagnetic insulator to generate a three-terminal QD setup with only one spin-splitting QD, which can convert part of the heat into an electron current [16]. It gives one type of multi-terminal setup, which can generate a spin-polarized charge current via a thermal gradient. The electron reservoirs of the conventional thermoelectric devices must be kept at different temperatures and chemical potentials [17–20], whereas the magnon-driven QD setups can be operated between two ferromagnetic metals with identical temperature and used to exploit the heat of a ferromagnetic insulator reservoir [10,16]. Based on the model in Ref. [16], we propose a refrigeration model to cool a bosonic reservoir. Note that when the irreversibility is taken into account, the refrigeration model is not the simple reverse operation of the heat engine model described in Ref. [16]. It includes not only the contribution of some crucial parameters such as the magnetic field, which was not discussed in Ref. [16], but also some applications that may be found in micromechanical systems [21,22] and other fields.

In the present paper, the occupation probabilities of the QD are solved by using the model of a magnon-driven quantum dot refrigerator established here and the rate equation. The matter currents are analyzed, and several special cases are discussed. Both the cooling power and coefficient of performance (COP) are optimized by considering the influence of the external magnetic field and applied voltage. The effect of the temperature of the ferromagnetic insulator is considered. The performances of two magnon-driven quantum dot refrigerators with different cooling spaces are analyzed and compared.

2. Quantum dot refrigerator with a ferromagnetic insulator

Fig. 1(a) shows a refrigeration system consisting of a spin-splitting QD embedded in two ferromagnetic metallic leads at temperatures T_L and T_R and chemical potentials μ_L and μ_R and a

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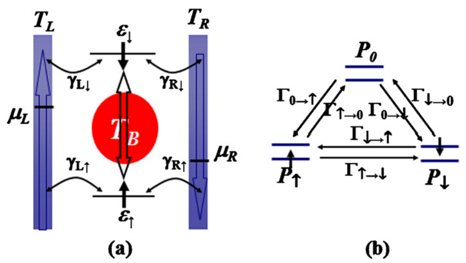

Fig. 1. (a) The energy diagram of the refrigeration system consisting of a spin-splitting QD embedded into two ferromagnetic metallic leads and an additional ferromagnetic insulator. (b) The transition processes among different states.

ferromagnetic insulator at temperature T_B. The two splitting levels are denoted as $\varepsilon_\uparrow$ and $\varepsilon_\downarrow$. In Fig. 1(a), $\gamma_{r\sigma}$ is the spin-dependent tunnel coupling strength between the ferromagnetic metallic lead r ($r = L, R$) and the QD with spin σ. The density of state $\rho_{r\sigma}$ of the ferromagnetic metallic lead is spin-dependent. In this model, a polarization p_r is introduced, defined as $p_r = (\rho_{r\uparrow} - \rho_{r\downarrow})/(\rho_{r\uparrow} + \rho_{r\downarrow})$. Three special cases, i.e., $p_r = \pm 1$ and $p_r = 0$, represent completely polarized and unpolarized leads, respectively.

The QD in the system is described by the following one-site Hubbard Hamiltonian [16,23,24]

$$H_{dot} = \sum_\sigma \varepsilon_\sigma d_\sigma^\dagger d_\sigma + U d_\uparrow^\dagger d_\uparrow d_\downarrow^\dagger d_\downarrow, \tag{1}$$

where $\varepsilon_\sigma = \varepsilon \mp \alpha/2$, the symbol "$\mp$" corresponds to the cases of the energy levels $\varepsilon_\uparrow$ and $\varepsilon_\downarrow$, $\alpha = \mu_g g B$, B denotes the magnetic field, μ_g is the Bohr magneton, g is the Lande factor, $d_\sigma^\dagger (d_\sigma)$ is the creation (annihilation) operator, and U is the Coulomb energy resulting from the double occupancy of the QD, which is assumed to be infinitely large in the following discussion. The Boltzmann constant k_B and electron charge e are set as 1 in the following discussion. The energy exchange between the QD and ferromagnetic metals occurs via electron tunneling, and the occupation of the electron states in the reservoir is given by the Fermi distribution. However, the coupling between the QD and the ferromagnetic insulator described by the Bose distribution is achieved through an exchange interaction. In contrast to the tunnel coupling strengths, the coupling strength γ_B between the QD and the insulator will have, in general, nontrivial energy dependence. However, as for the following discussion, this energy dependence is irrelevant [10,16]. The tunnel coupling strength between the ferromagnetic metallic lead r and the QD can be expressed as $\gamma_{r\uparrow} = \gamma_r \frac{1+p_r}{2}$ and $\gamma_{r\downarrow} = \gamma_r \frac{1-p_r}{2}$, where $\gamma_r = \gamma_{r\uparrow} + \gamma_{r\downarrow}$.

In sequential tunneling approximation, continuous tunneling of a single electron is defined and the broadening of energy levels can be neglected. Moreover, the collinear magnetizations are taken into account [16]. According to the model illustrated in Fig. 1(b), Eq. (1) results in three quantum states $|i\rangle$ $(i = 0, \uparrow, \downarrow)$. The occupation probability of finding the system in a state at time t is denoted as $P_i(t)$ and the energy level is denoted by ε_i. The evolution of the occupation probability can be written as the rate equation [5,16,17,25–28]

$$\frac{dP_i(t)}{dt} = \sum_{i'} \left[\Gamma_{i' \to i} P_{i'}(t) - \Gamma_{i \to i'} P_i(t) \right], \tag{2}$$

where $\Gamma_{i \to i'}$ is the transition rate from state $|i\rangle$ to $|i'\rangle$. In the limit of the weak contact coupling, only one electron is permitted to exchange during the transition process between the QD and the ferromagnetic metallic leads or the exchange of one magnon changes the spin state of the QD and the ferromagnetic insulator.

According to Eq. (2), the occupy probabilities in the steady state can be solved as

$$P_0 = \frac{1}{\Omega}(\Gamma_{\uparrow\to 0}\Gamma_{\downarrow\to 0} + \Gamma_{\uparrow\to\downarrow}\Gamma_{\downarrow\to 0} + \Gamma_{\downarrow\to\uparrow}\Gamma_{\uparrow\to 0}), \tag{3}$$

$$P_\uparrow = \frac{1}{\Omega}(\Gamma_{0\to\uparrow}\Gamma_{\downarrow\to\uparrow} + \Gamma_{0\to\downarrow}\Gamma_{\downarrow\to\uparrow} + \Gamma_{\downarrow\to 0}\Gamma_{0\to\uparrow}), \tag{4}$$

and

$$P_\downarrow = \frac{1}{\Omega}(\Gamma_{0\to\downarrow}\Gamma_{\uparrow\to\downarrow} + \Gamma_{0\to\uparrow}\Gamma_{\uparrow\to\downarrow} + \Gamma_{\uparrow\to 0}\Gamma_{0\to\downarrow}), \tag{5}$$

where Ω is the normalizing factor.

In the symmetric condition, i.e., $p_L = -p_R = p$, $\gamma_L = \gamma_R = \gamma_B = \gamma$, and $\mu_L = -\mu_R = V/2$, the average matter flux entering the QD from the right reservoir can be obtained as

$$I_M^R = I_M^{R\downarrow} + I_M^{R\uparrow} = \gamma_{R\downarrow}\left[P_0 f_R^- - P_\uparrow(1 - f_R^-)\right] + \gamma_{R\uparrow}\left[P_0 f_R^+ - P_\downarrow(1 - f_R^+)\right], \tag{6}$$

where $I_M^{r\sigma}$ is the spin-resolved electron current of lead r with spin σ and $f_r^\mp = [1 + \exp(\frac{\varepsilon \mp \alpha/2 - \mu_r}{T_r})]^{-1}$. The magnitude of the matter flux entering the QD from the right reservoir is equal to that entering the left reservoir from the QD, but their directions are opposite, i.e., $I_M^R = -I_M^L$. Below, we will focus on the case of $p > 0$. In the absence of a bias voltage, spin-up electrons preferably leave the left reservoir and spin-down ones preferably enter the right one.

Although there is no electron exchange between the ferromagnetic insulator and the QD, a magnon current exists due to the exchange interaction between the insulator and the QD. The magnon current can be analytically obtained as

$$I_M^B = \frac{\gamma}{2} n P_\uparrow - \frac{\gamma}{2}(1 + n) P_\downarrow, \tag{7}$$

where $n = [\exp(\alpha/T_B) - 1]^{-1}$.

The heat flows extracted from the three reservoirs are written as

$$J_Q^L = (\varepsilon_\uparrow - \mu_L)\frac{1+p}{2}\gamma\left[P_0 f_L^- - P_\uparrow(1 - f_L^-)\right] + (\varepsilon_\downarrow - \mu_L)\frac{1-p}{2}\gamma\left[P_0 f_L^+ - P_\downarrow(1 - f_L^+)\right], \tag{8}$$

$$J_Q^R = (\varepsilon_\uparrow - \mu_R)\frac{1-p}{2}\gamma\left[P_0 f_R^- - P_\uparrow(1 - f_R^-)\right] + (\varepsilon_\downarrow - \mu_R)\frac{1+p}{2}\gamma\left[P_0 f_R^+ - P_\downarrow(1 - f_R^+)\right], \tag{9}$$

and

$$J_Q^B = \frac{\alpha}{2}\gamma\left[n P_\uparrow - (1 + n) P_\downarrow\right]. \tag{10}$$

The external input power is given by

$$P = (\mu_R - \mu_L) I_M^R. \tag{11}$$

In the condition of $T_B < T_E$ $(T_L = T_R = T_E)$, the heat is absorbed from the ferromagnetic insulator and released to the two ferromagnetic leads. The cooling space is the ferromagnetic insulator. The cooling power and COP are given by

$$\dot{Q}_C = J_Q^B \tag{12}$$

and

$$\eta_C = \frac{\dot{Q}_C}{P}. \tag{13}$$

When $T_B > T_E$, the heat is absorbed from the two ferromagnetic leads and released to the ferromagnetic insulator. The cooling space is changed to be two ferromagnetic leads. Thus, the cooling power is given by

$$\dot{Q}_C = J_Q^L + J_Q^R, \tag{14}$$

while the expression of the COP is the same as Eq. (13).