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Thermal rectification in the nonequilibrium quantum-dots-system

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HIGHLIGHTS

- We study the nonequilibrium two-quantum-dots system with the DM interaction.
- We can control the thermal rectification of the two-quantum-dots through modulating the DM interaction strength or changing the external magnetic field.
- Large thermal rectification value can be obtained in this two-quantum-dots system.
- This two-quantum-dots system has an application as a direction-controllable thermal diode.

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ABSTRACT

We study thermal rectification of a two-quantum-dots system with Dzyaloshinskii–Moriya (DM) interaction and coupling to two bosonic reservoirs. Compared with other proposals (Zhang et al., 2009 [9]), our model can offer larger rectification efficiency through different modulations in small size systems ($N=2$).

1. Introduction

Thermal diode is a very important thermal device [1–3] which has extensive applications in phonon information [4–7]. The heat current flow can be induced in a unidirectional way, and can be regarded as the basic part in controlling the large-scale heat flow. So far, many proposals have been raised to design thermal diode models, such as Frenkel–Kontorova lattice, spin chains and quantum dots [2,8–12]. In all these designs, the lattice size will influence the heat current flow significantly between the two reservoirs. In the spin chain model, the polarity of the thermal diode can be controlled by modulating the spin energy gap at different sites or by changing the anisotropic interaction strength between the adjacent spins. The efficiency of the thermal diode model can be measured by thermal rectification $\mathcal{R}$. In the six-spins-chain system, the thermal rectification $\mathcal{R}$ can reach the value from -0.5 to 0.3. However, as studied in Ref. [8], it is not likely to control the $\mathcal{R}$ value in small systems with the spin number $N \le 4$. Another proposal uses two capacitive coupling quantum dots. It can control heat flow between two fermionic reservoirs [10,13]. The asymmetric Coulomb blockade configuration is the origin of the diode effect. Using the gate voltage to modulate the tunneling energy E_{an}, the rectification $\mathcal{R}$ can reach the value 0.9.

Recently, the problems of the interaction between a quantum-dot system and its thermal environment have attracted a lot of attention [14–17]; the quantum-dot system has advantages in scalability and long coherence time [14]. Due to the quantum tunneling effect in the quantum-dot system, the spin–spin interaction and the spin–orbit interaction play an important role [15,18]. Moreover, when the material has reversal asymmetry, the coexistence of the superexchange interaction and the spin–orbit interaction will induce a new interaction, the so-called Dzyaloshinskii–Moriya (DM) interaction [19–23]. It has been verified [19,20] that DM interaction can result in the change of the spin

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alignment, and many other effects, such as thermal entanglement, spin wave and spin current, magnon Hall effect [15,16,18,24,25].

In this paper, we study the heat transport problem in a two-quantum-dots system containing the DM interaction. We calculate the heat current in the steady state limit and analyze the heat current contributions of the different system states. We propose a direction-controllable thermal diode between two bosonic reservoirs and study the thermal rectification of this diode model. We find that, in this two-quantum-dots system, thermal rectification $\mathcal{R}$ can reach the value from −0.3 to 0.35, through changing the DM interaction strength. Compared with the six-spins-chain proposal, thermal rectification $\mathcal{R}$ in our proposal is larger.

2. Model

We consider a two-quantum-dots system and two thermal reservoirs as shown in Fig. 1. The left quantum dot interacts with the left reservoir only, and the right quantum dot interacts with the right reservoir only. The total Hamiltonian is [15,16]

$$H_{tot} = H_s + H_{BL} + H_{BR} + H_{SBL} + H_{SBR}. \tag{1}$$

Here, H_s is the two-quantum-dots system Hamiltonian, H_{B_ν} is the νth (ν=L, R) reservoir Hamiltonian, and H_{SB_ν} is the interaction between the νth reservoir and the system. We consider the anisotropic interaction and the DM interaction in this two-quantum-dots system, and neglect the second-order spin–orbit interaction. Under these conditions, the system Hamiltonian H_s can be written as [15]

$$H_s = J\chi(\sigma_L^+\sigma_R^+ + \sigma_L^-\sigma_R^-) + J(1+iD)\sigma_L^+\sigma_R^- + J(1-iD)\sigma_L^-\sigma_R^+ + \frac{B+b}{2}\sigma_L^z + \frac{B-b}{2}\sigma_R^z. \tag{2}$$

where the parameter χ describes the anisotropy strength in the spin xy plane, the parameter D stands for the DM interaction in the two-quantum-dots system, and the energy gaps of the left spin and the right spin are $\frac{B+b}{2}$ and $\frac{B-b}{2}$, respectively.

The Hamiltonian of the νth reservoir H_{B_ν} and the system–reservoir interaction Hamiltonian H_{SB_ν} can be written as [15]

$$H_{B_\nu} = \sum_n \omega_n b_{n\nu}^+ b_{n\nu}, \tag{3a}$$

$$H_{SB_\nu} = S_\nu B_\nu = (\sigma_\nu^+ + \sigma_\nu^-)\left(\sum_n g_n^{(\nu)} b_{n\nu} + g_n^{(\nu)*} b_{n\nu}^+\right). \tag{3b}$$

Here, the reservoir consists of a collection of non-interacting oscillators. The parameter ω_n labels different oscillator frequencies. The system–reservoir interaction strength g_n^ν describes the interaction between the νth spin and the oscillator of frequency ω_n in the νth reservoir. The eigenvalues and the corresponding eigenvectors of the system Hamiltonian H_s are [15]

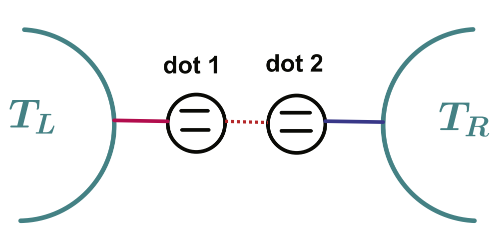

Fig. 1. A schematic representation of the two-quantum-dot system containing DM interaction. The two quantum dots interact with the thermal reservoirs at different temperatures T_L and T_R.

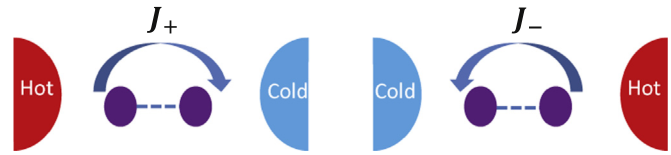

Fig. 2. A schematic representation of the forward heat current J_+ and the backward heat current J_-.

$$|\varepsilon_1\rangle = N^+\left(\left(\frac{b+\xi}{J(1-iD)}\right)|01\rangle + |10\rangle\right), \quad E_1 = +\xi; \tag{4a}$$

$$|\varepsilon_2\rangle = N^-\left(\left(\frac{b-\xi}{J(1-iD)}\right)|01\rangle + |10\rangle\right), \quad E_2 = -\xi; \tag{4b}$$

$$|\varepsilon_3\rangle = M^+\left(\left(\frac{B+\eta}{J\chi}\right)|00\rangle + |11\rangle\right), \quad E_3 = +\eta; \tag{4c}$$

$$|\varepsilon_4\rangle = M^-\left(\left(\frac{B-\eta}{J\chi}\right)|00\rangle + |11\rangle\right), \quad E_4 = -\eta, \tag{4d}$$

where the states $|0\rangle$ and $|1\rangle$ are the excited state and the ground state of a quantum dot, respectively. The coefficients $N^\pm$, $M^\pm$, ξ, and η satisfy the relation $N^\pm = (1 + \frac{(b\pm\xi)}{J^2+(JD)^2})^{-1/2}$, $M^\pm = (1 + (\frac{B\pm\eta}{J\chi})^2)^{-1/2}$, $\xi = (b^2 + J^2 + (JD)^2)^{1/2}$, and $\eta = (B^2 + (J\chi)^2)^{1/2}$. We now reformulate the system components in the system–reservoir interaction Hamiltonian H_{SB_ν} in the new basis $\{|\varepsilon_1\rangle, |\varepsilon_2\rangle, |\varepsilon_3\rangle, |\varepsilon_4\rangle\}$

$$\sigma_L^x = S_{3,1}^L|\varepsilon_3\rangle\langle\varepsilon_1| + S_{4,1}^L|\varepsilon_4\rangle\langle\varepsilon_1| + S_{3,2}^L|\varepsilon_3\rangle\langle\varepsilon_2| + S_{4,2}^L|\varepsilon_4\rangle\langle\varepsilon_2| + H.C., \tag{5a}$$

$$\sigma_R^x = S_{3,1}^R|\varepsilon_3\rangle\langle\varepsilon_1| + S_{4,1}^R|\varepsilon_4\rangle\langle\varepsilon_1| + S_{3,2}^R|\varepsilon_3\rangle\langle\varepsilon_2| + S_{4,2}^R|\varepsilon_4\rangle\langle\varepsilon_2| + H.C. \tag{5b}$$

The parameters $|S_{m,n}^\nu|$ are set as $|S_{3,1}^L|^2 = |S_{4,2}^L|^2 = \frac{\eta\xi - Bb}{2\eta\xi} + \frac{J^2\chi}{2\eta\xi}$, $|S_{4,1}^L|^2 = |S_{3,2}^L|^2 = \frac{\eta\xi + Bb}{2\eta\xi} - \frac{J^2\chi}{2\eta\xi}$, $|S_{3,1}^R|^2 = |S_{4,2}^R|^2 = \frac{\eta\xi + Bb}{2\eta\xi} + \frac{J^2\chi}{2\eta\xi}$, $|S_{4,1}^R|^2 = |S_{3,2}^R|^2 = \frac{\eta\xi - Bb}{2\eta\xi} - \frac{J^2\chi}{2\eta\xi}$.

3. Solutions and results

We apply the master equation method to solve the system dynamics. The time evolution of the two-quantum-dots system ρ can be obtained with the second-order approximation in the interaction picture [26,27]

$$\frac{d\rho_{m,n}}{dt} = -i[H_{SBj}(t), \rho(0)]_{m,n} - \int_0^t d\tau[H_{SBj}(t), [H_{SBj}(\tau), \rho(\tau)]]_{m,n}. \tag{6}$$

In our calculation, we assume the weak interaction between the system and the reservoirs. The Markovian approximation is applied, and the reservoirs keep in its thermal equilibrium during the evolution. Considering the system behavior in the steady state, we can neglect the coherence term of the system. So we obtain the Pauli master equation associated with the system state population ρ_{nn} (n=1, 2, 3, 4) as