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Spin and charge Nernst effect in a four-terminal double-dot interferometer

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ABSTRACT

We investigate the spin and charge Nernst effect of a four-terminal Aharonov–Bohm interferometer with Rashba spin–orbit interaction (RSOI). It is shown that a pure spin Nernst effect or a fully spin-polarized Nernst effect can be obtained by modulating the magnetic flux phase ϕ and the RSOI induced phase φ. It is also demonstrated that some windows of ϕ (or φ) for maintaining an almost fully spin-polarized Nernst effect exist and their width is under the control of the other phase. Moreover, for the charge Nernst coefficient N_c and spin Nernst coefficient N_s the relationship $N_c(\phi,\varphi) = -N_s(\varphi,\phi)$ always holds. These results suggest that our proposal may act as a controllable thermospin generator.

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1. Introduction

One of the major goals of spin caloritronics [1,2] is to explore spin-dependent thermoelectric effects due to potential applications in the development of spin-based electronic devices driven by thermal gradients. To date, spin-dependent thermoelectric effects in various materials and nanostructures have been investigated such as the spin Seebeck effect in magnetic materials [3,4] and heterojunctions [5–8], the anomalous Nernst effect in low dimensional systems [9–13], the giant magnetothermoelectric effect in a magnetic tunnel junction [14], the thermospin effect in quantum dot (QD) systems [15–20], and the spin-dependent Seebeck effect in Aharonov–Bohm interferometers [21–26]. For instance, Yang and Liu [18] proposed that a serially coupled double dot with an applied magnetic field can be used as a pure-spin-current thermal generator. This effect originates from a mirror symmetry configuration held by the two spin components of the electron transmission probability relative to chemical potentials. Recently, tremendous research interest about another spin-dependent thermoelectric effect called the spin Nernst effect [27–30] which refers to that a transverse spin current is created when the four-terminal system is subjected to a longitudinal thermal gradient has also arisen. The spin Nernst effect has been theoretically studied in a four-terminal cross-bar device [27]. The results show that the existence of RSOI leads to the appearance of the spin Nernst effect and the spin

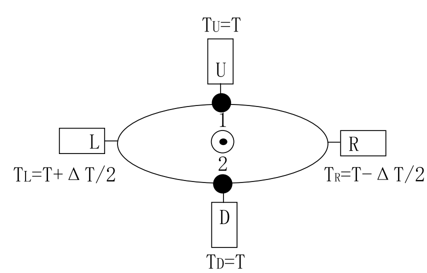

Fig. 1. Schematic plot of the four-terminal double-dot interferometer with a longitudinal temperature difference ΔT applied between lead-L and lead-R. A magnetic flux may be enclosed by the ring-shaped system.

Nernst effect is more sensitive to the disorder strength than the charge one. Though there has been some work on the spin Nernst effect, the study on the spin Nernst effect of QD systems is yet sparse in literatures.

In this work, we focus on a four-terminal double-dot interferometer with RSOI and a perpendicular magnetic flux. As depicted in Fig. 1, the temperature of lead-U and lead-D is set as the system equilibrium temperature T. A longitudinal temperature difference ΔT is applied between lead-L and lead-R, so that $T_L = T + \Delta T/2$ and $T_R = T - \Delta T/2$. By the calculations based on the nonequilibrium Green's function method and the Landauer–Buttiker (LB) formula, we will explore the influences of the dot energy level, the RSOI and the magnetic flux on the spin and charge Nernst effect in this system.

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2. Theoretical model

In the investigated device, the leads are all nonmagnetic and the RSOI only exists in the QDs, so the Hamiltonian of such a four-terminal double-dot interferometer reads as

$$H = \sum_{k\sigma\alpha} \varepsilon_{k\alpha} C^{\dagger}_{k\alpha\sigma} C_{k\alpha\sigma} + \sum_{i\sigma} \varepsilon_i d^{\dagger}_{i\sigma} d_{i\sigma} + \sum_{k\sigma i\beta=L,R} (t_{\beta i\sigma} C^{\dagger}_{k\beta\sigma} d_{i\sigma} + h.c.) + (t_{U1\sigma} C^{\dagger}_{kU\sigma} d_{1\sigma} + t_{D2\sigma} C^{\dagger}_{kD\sigma} d_{2\sigma} + h.c.), \quad (1)$$

where $C^{\dagger}_{k\alpha\sigma}(C_{k\alpha\sigma})$ is the creation (annihilation) operator of an electron with the spin index σ ($\sigma = \uparrow, \downarrow$ or $\pm$) and energy $\varepsilon_{k\alpha}$ in lead-α ($\alpha = L, R, U, D$). $d^{\dagger}_{i\sigma}(d_{i\sigma})$ represents the creation (annihilation) of an electron with energy ε_i in QDi ($i = 1, 2$). $t_{\alpha i\sigma}$ describes the coupling between lead-α and QDi. Considering the RSOI in the two dots and the enclosed magnetic flux, the tunnel matrix elements are written as $t_{L1\sigma} = te^{i\phi/4}e^{-i\sigma\varphi_1/2}$, $t_{L2\sigma} = te^{-i\phi/4}e^{-i\sigma\varphi_2/2}$, $t_{R1\sigma} = te^{-i\phi/4}e^{i\sigma\varphi_1/2}$, $t_{R2\sigma} = te^{i\phi/4}e^{i\sigma\varphi_2/2}$, $t_{U1\sigma} = t$ and $t_{D2\sigma} = t$ where we only consider the symmetric coupling case and t is the common magnitude of the tunnel matrix elements. In the tunnel matrix elements, ϕ is the magnetic flux phase which relates to the magnetic flux Φ by the relation $\phi = 2\pi\Phi/\Phi_0$ with Φ_0 being the flux quantum and φ_i is the phase caused by the RSOI in QDi [31].

Employing the nonequilibrium Green's function method, the spin-dependent electric current in lead-α $J_{\alpha\sigma}$ ($e = \hbar = k_B = 1$) can be derived as the LB formula form [32–35]

$$J_{\alpha\sigma} = \sum_{\beta\neq\alpha} \int \frac{d\varepsilon}{2\pi} T_{\alpha\beta\sigma}(\varepsilon)[f_\alpha(\varepsilon) - f_\beta(\varepsilon)], \quad (2)$$

where $f_\alpha(\varepsilon) = [e^{(\varepsilon-\mu_\alpha)/T_\alpha} + 1]^{-1}$ is the Fermi–Dirac distribution function in lead-α with μ_α and T_α being the chemical potential and temperature of lead-α. $T_{\alpha\beta\sigma}(\varepsilon) = Tr[\Gamma^{\alpha}_{\sigma} G^{r}_{\sigma}(\varepsilon)\Gamma^{\beta}_{\sigma} G^{a}_{\sigma}(\varepsilon)]$ is the transmission function which describes the ability of an electron with the spin index σ and the incident energy ε tunneling between lead-α and lead-β. Here Γ^{α}_{σ} represents the line width function contributed by lead-α. In local basis, it is a 4×4 matrix whose matrix elements are defined as $\Gamma^{\alpha}_{ij\sigma} = 2\pi t_{\alpha i\sigma} t^{*}_{\alpha j\sigma} \rho_\alpha(\varepsilon)$ where $\rho_\alpha(\varepsilon)$ denotes the density of electron states in lead-α. Within the wide-band approximation [36], $\rho_\alpha(\varepsilon)$ is usually taken as a constant. For simplicity, the four leads are supposed to be made of the same material. Then by defining $\Gamma = 2\pi t^2\rho$ with ρ being the common density of electron states in the four leads, the line width functions can be expressed as

$$\Gamma^{L}_{\sigma} = \Gamma \begin{pmatrix} 1 & e^{i\varphi_\sigma} \\ e^{-i\varphi_\sigma} & 1 \end{pmatrix}, \quad (3)$$

$$\Gamma^{R}_{\sigma} = \Gamma \begin{pmatrix} 1 & e^{-i\varphi_\sigma} \\ e^{i\varphi_\sigma} & 1 \end{pmatrix}, \quad (4)$$

$$\Gamma^{U}_{\sigma} = \Gamma \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \quad (5)$$

and

$$\Gamma^{D}_{\sigma} = \Gamma \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \quad (6)$$

with $\varphi_\sigma = \frac{\phi - \sigma\varphi}{2}$ and $\varphi = \varphi_1 - \varphi_2$. In the expression of the transmission function, G^{r}_{σ} and G^{a}_{σ} are respectively the retarded and advanced Green's function of the central scattering region in spectrum space. According to the Dyson equation, they can be calculated as

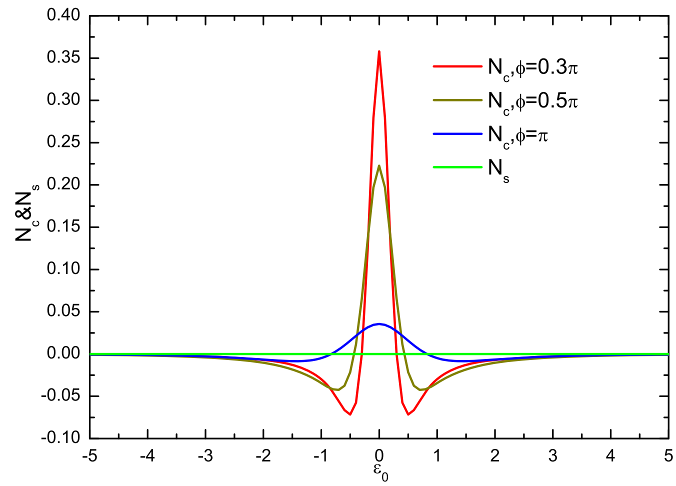

Fig. 2. (Color online.) The charge Nernst coefficient N_c and spin Nernst coefficient N_s versus the dot energy level ε_0 for different ϕ with the parameter $\varphi = 0$.

$$G^{r}_{\sigma} = [G^{a}_{\sigma}]^{\dagger} = \begin{pmatrix} \varepsilon - \varepsilon_1 + \frac{i}{2}\Gamma_{11\sigma} & \frac{i}{2}\Gamma_{12\sigma} \\ \frac{i}{2}\Gamma_{21\sigma} & \varepsilon - \varepsilon_2 + \frac{i}{2}\Gamma_{22\sigma} \end{pmatrix}^{-1}, \quad (7)$$

with $\Gamma_\sigma = \sum_\alpha \Gamma^{\alpha}_{\sigma}$.

In the case of zero electric biases, i.e., $\mu_L = \mu_R = \mu_U = \mu_D = \mu$, we can define the spin-dependent Nernst coefficient $N_\sigma = J_{U\sigma}/\Delta T$ to measure the ability to induce a transverse electric current with the spin index σ by the longitudinal temperature difference ΔT. In the linear response regime, the temperature difference is very small. So after the Taylor expansion of the Fermi–Dirac distribution function to the first order in ΔT, the spin-dependent Nernst coefficient N_σ can be obtained as

$$N_\sigma = \frac{1}{4\pi} \int d\varepsilon (T_{UR\sigma} - T_{UL\sigma}) \frac{\varepsilon - \mu}{T^2} f(1-f), \quad (8)$$

where f is the Fermi–Dirac distribution function at zero bias and zero thermal gradient. Based on Eqs. (2)–(7), we arrive at

$$T_{UR\sigma} - T_{UL\sigma} = \frac{8Y\Gamma^3(\sin\varphi_\sigma + \sin 2\varphi_\sigma)}{Z_\sigma}, \quad (9)$$

in which $Z_\sigma = [2XY - 3\Gamma^2 + \Gamma^2(2\cos\varphi_\sigma + \cos 2\varphi_\sigma)]^2 + 9(X + Y)^2\Gamma^2$, $X = \varepsilon - \varepsilon_1$ and $Y = \varepsilon - \varepsilon_2$. Combining Eq. (8) with Eq. (9), the spin-dependent Nernst coefficient N_σ can be evaluated. Finally, the spin (charge) Nernst coefficient can be defined as $N_s = N_\uparrow - N_\downarrow$ ($N_c = N_\uparrow + N_\downarrow$), which is the measurement of the ability to generate a transverse spin (charge) current in response to the longitudinal thermal gradient.

3. Numerical results and discussions

In the numerical calculations, we set $\Gamma = 1$ as the energy unit and the equilibrium system temperature $T = 0.1$. The dot energy levels of the two QDs are assumed to be identical ($\varepsilon_1 = \varepsilon_2 = \varepsilon_0$). The chemical potential of the leads at zero bias μ is fixed to be zero throughout this paper. From Eqs. (8) and (9), we can easily find that $T_{UR\sigma} - T_{UL\sigma}$ (N_σ) is generally dependent on electron spin. This spin dependence can be ascribed to the RSOI induced spin-dependent phase participates in the quantum interference among different Feynman paths for electron tunneling from lead-L(R) to lead-U and thus makes the quantum interference effect be spin-resolved, which indicates that the presence of the RSOI is a key factor for the occurrence of the spin Nernst effect in the present device. Therefore, as shown in Fig. 2 the spin Nernst coefficient remains zero with the change of ε_0 due to the absence

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