Nonlocal Andreev reflection with Rashba spin–orbital interaction in a triple-quantum-dot ring*

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We theoretically studied the nonlocal Andreev reflection with Rashba spin–orbital interaction in a triple-quantum-dot (QD) ring, which is introduced as Rashba spin–orbital interaction to act locally on one component quantum dot. It is found that the electronic current and spin current are sensitive to the systematic parameters. The interdot spin-flip term does not play a leading role in causing electronic and spin currents. Otherwise the spin precessing term leads to shift of the peaks of the the spin-up and spin-down electronic currents in different directions and results in the spin current. Moreover, the spin–orbital interaction suppresses the nonlocal Andreev reflection, so we cannot obtain the pure spin current.

Keywords: nonlocal Andreev reflection, Rashba spin–orbital interaction, spin flip, spin precess

PACC: 7430F, 7450, 7320D

1. Introduction

In recent years, one of the main focuses of many researchers has been the mesoscopic normal-metal (NM)/superconductor hybrid systems.[1−8] In these systems the so-called Andreev reflection[9] occurs at the NS interface due to the appearance of a new energy scale: the superconducting (SC) energy gap Δ. This phenomenon indicates that an incoming electron from NM side is reflected as a hole back into NM side, thereby transferring a Cooper pair into the SC condensate. When there are more than two NM leads in NS hybrid systems, it is possible for the reflected hole to transfer either back into the same NM lead or into another spatial-separated NM lead, the former is the normal Andreev reflection and the latter is the so-called nonlocal Andreev reflection.[10−18] Since a hole is just an electron traveling in the opposite direction, the nonlocal Andreev reflection corresponds to the case that a pair of spin-entangled electrons forming the singlet state of a Cooper pair comes from the different NM leads. The study of electron transport in the multi-terminal mesoscopic NS hybrid systems may lead to the realization of solid-state entanglers,[11] which is important to quantum information processing. As known to all, the two electrons forming the singlet state of a Cooper pair must have opposite spin. The intrinsic Rashba spin–orbital (SO)[19−26] interaction can couple the spin degree of freedom of an electron to its orbital motion and destroy the symmetry of space inversion, thereby giving a useful handle for manipulating and controlling the electron spin state feasibly by external electric fields or gate voltages. For this reason, the SO interaction surely will produce an effect on the nonlocal Andreev reflection.

2. Model and formulae

In this paper, we introduce Rashba SO interaction to act locally on one component quantum dot (QD) of a triple-QD ring with two NM leads and one SC lead. Our theoretical investigation indicates that the spin precessing term leads to the difference of the spin-up and spin-down electronic currents. Moreover, the SO interaction suppresses the nonlocal Andreev reflection. The structure that we consider is illustrated in Fig. 1. Two NM leads and an SC lead are coupled to their respective quantum dots to form an Aharonov–Bohm ring. The model Hamiltonian of this system reads[27]

$$H = \sum_{i=1,2} H_{\mathrm{N}i} + H_{\mathrm{S}} + H_0 + H_{\mathrm{c}}, \qquad (1)$$

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where

$$H_{\rm Ni} = \sum_{k\sigma}(\varepsilon_{ik}+qV_i)c^{\dagger}_{ik\sigma}c_{ik\sigma}, \tag{2}$$

$$H_{\rm S} = \sum_{q}\Big[\sum_{\sigma}\varepsilon_q c^{\dagger}_{q\sigma}c_{q\sigma}+\Delta c^{\dagger}_{q\uparrow}c^{\dagger}_{-q\downarrow}+\Delta c_{-q\downarrow}c_{q\uparrow}\Big], \tag{3}$$

$$\begin{aligned} H_0 = & \sum_{\sigma,j=1,2,3}\varepsilon_j d^{\dagger}_{j\sigma}d_{j\sigma} \\ & + \sum_{\sigma,l=1,2}\Big[\Big(t_l {\rm e}^{{\rm i}\varphi/3}-{\rm i}\sigma s_l\Big)d^{\dagger}_{l\sigma}d_{l+1,\sigma} \\ & + r_l\Big(d^{\dagger}_{l\downarrow}d_{l+1,\uparrow}-d^{\dagger}_{l+1,\downarrow}d_{l\uparrow}\Big)+{\rm c.c.}\Big] \\ & + \Big(t_3{\rm e}^{{\rm i}\varphi/3}d^{\dagger}_{3\sigma}d_{1\sigma}+{\rm c.c.}\Big), \end{aligned} \tag{4}$$

$$H_{\rm c} = \sum_{k\sigma,i=1,2}T^{\rm N}_{ik}c^{\dagger}_{ik\sigma}d_{i\sigma}+\sum_{q\sigma}T^{\rm S}_{q}c^{\dagger}_{q\sigma}d_{3\sigma}+{\rm c.c.} \tag{5}$$

Here $H_{\rm Ni}$ is the Hamiltonian of the i-th NM lead, in which $c^{\dagger}_{ik\sigma}\,(c_{ik\sigma})$ is the electron creation (annihilation) operator. $H_{\rm S}$ describes the Hamiltonian of the SC lead with Δ being the superconductor energy gap. Note that the bias voltage V is applied to the NM lead 1 and zero chemical potential is kept at the SC lead and NM lead 2. What we are interested in is the nonlocal Andreev reflection process, so we assume that the bias voltage V is lesser than the SC energy gap Δ. H_0 stands for the Hamiltonian for the triple-QD ring with the magnetic flux φ, and the discrete bare energy levels ε_j are well controlled by the corresponding gate voltages. Here t_l is the usual interdot hopping amplitude irrelevant to the Rashba SO interaction, ${\rm i}\sigma s_l$ ($\sigma=\pm1$ for spin-up and spin-down electrons) indicates the strength of spin precessing term, and r_l is the strength of interdot spin flip term, the latter two arise from the SO interaction. We can set $t_1=t_2=t_3=t$, $s_1=s_2=s$, $r_1=-r_2=r$ when the three QDs are positioned on a circle equidistantly.[27] $H_{\rm c}$ is the Hamiltonian which stands for the couplings between the QDs and three leads. For simplicity, we have assumed that the hopping matrix elements are independent of the spin index.

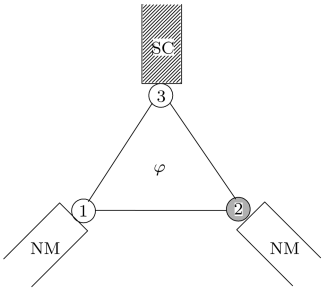


Fig. 1. Schematic diagram of a triple-QD ring structure with the local Rashba SO interaction on QD-2 (shaded one).

We now calculate the spin-up electronic current passing through the NM lead 2, which is defined as

$$I_{\rm N2\uparrow} = e\left\langle\frac{{\rm d}\hat{N}_{\rm N2\uparrow}}{{\rm d}t}\right\rangle \tag{6}$$

with $\hat{N}_{\rm N2\uparrow}=\sum_{k\sigma}c^{\dagger}_{2k\uparrow}c_{2k\uparrow}$. From Heisenberg equation of motion, the spin-up electronic current can be rewritten as ($\hbar=1$)

$$I_{\rm N2\uparrow}(t) = -e\sum_{k}[T_{k\rm N1}G^{<}_{d2\uparrow k\uparrow}(t,t)+{\rm c.c.}], \tag{7}$$

where $G^{<}_{d2\uparrow k\uparrow}(t,t')={\rm i}\left\langle c^{\dagger}_{k\uparrow}(t')\,d_{2\uparrow}(t)\right\rangle$ is the lesser Green's function. Using the theorem of analytic continuation,[28] we have

$$\begin{aligned} & I_{\rm N2\uparrow}(t) \\ = & -e\int{\rm d}t_1[G^{\rm r}(t,t_1)\Sigma^{<}_1(t_1,t) \\ & + G^{<}(t,t_1)\Sigma^{\rm a}_1(t_1,t)]_{55}+{\rm c.c.}, \end{aligned} \tag{8}$$

$$= -e\int{\rm d}t_1[(G^{\rm r}-G^{\rm a})\Sigma^{<}_1+G^{<}(\Sigma^{\rm a}_1-\Sigma^{\rm r}_1)]_{55}, \tag{9}$$

in which $\Sigma^{\gamma={\rm r,a,<}}_i=\sum_k T^{*}_{k\rm Ni}g^{\gamma}_{k\rm Ni}T_{k\rm Ni}$.

Using the self-energy of the i-th NM lead and taking Fourier transformation, we have

$$\begin{aligned} I_{\rm N2\uparrow} = & -{\rm i}e\int\frac{{\rm d}E}{2\pi}\Gamma_{\rm N1}\{[G^{\rm r}(E)-G^{\rm a}(E)]\,f_{\rm N1}(E) \\ & + G^{<}(E)t\}_{55}, \end{aligned} \tag{10}$$

and similarly

$$\begin{aligned} I_{\rm N2\downarrow} = & {\rm i}e\int\frac{{\rm d}E}{2\pi}\Gamma_{\rm N1}\{[G^{\rm r}(E)-G^{\rm a}(E)]\,f_{\rm N1}(E) \\ & + G^{<}(E)\}_{77}, \end{aligned} \tag{11}$$

where $f(E)=1/({\rm e}^{\beta E}+1)$ is the Fermi distribution function, $\Gamma_{\rm Ni}=2\pi\sum_k|T_{k\rm Ni}|^2\,\delta(E-\varepsilon_{ki})$ is the linewidth matrix function of the i-th NM lead which describes the coupling strength between the NM lead and the corresponding QD. $G^{\rm r,a,<}$ are the retarded, advanced, and lesser Green's functions for the triple-QD ring in 12×12 Nambu$\otimes$spin representation[6]

$$G^{\rm r}(t,t') = -{\rm i}\theta(t-t')\langle\{\Psi(t),\Psi^{\dagger}(t')\}\rangle \tag{12}$$

with row vector $\Psi^{\dagger}=(d^{\dagger}_{1\uparrow},\ d_{1\downarrow},\ d^{\dagger}_{1\downarrow},\ d_{1\uparrow},\ d^{\dagger}_{2\uparrow},\ d_{2\downarrow},\ d^{\dagger}_{2\downarrow},\ d_{2\uparrow},\ d^{\dagger}_{3\uparrow},\ d_{3\downarrow}\ d^{\dagger}_{3\downarrow},\ d_{3\uparrow})$. In order to obtain the electronic current, one must know expressions of the retarded and lesser Green's functions for the triple-QD ring. The retarded Green's function can be in principle obtained from the equation of motion approach,

but the calculation process is tedious. The most convenient way to calculate the retarded Green's function is the Dyson equation, which is given by

$$G^{\rm r}(E) = \frac{1}{E - H_0 - \Sigma^{\rm r}(E)}, \tag{13}$$

where H_0 is the matrix for Hamiltonian of the the triple-QD ring without the external coupling, and $\Sigma^{\rm r}(E) = \Sigma_1^{\rm r}(E) + \Sigma_2^{\rm r}(E)$ is the total self-energy. As for the lesser Green's function $G^<(E)$ we use the Keldysh equation

$$G^<(E) = G^{\rm r}(E)\Sigma^<(E)G^{\rm a}(E) \tag{14}$$

with the lesser self-energy $\Sigma^<(E) = \Sigma_1^<(E) + \Sigma_2^<(E)$.

Here we focus on the case of $eV < \Delta$. Using the above relation, we can obtain the general expressions for the spin-up and spin-down electronic currents

$$I_{\rm N2\uparrow} = e\Gamma_{\rm N1}\Gamma_{\rm N2}\int \frac{{\rm d}E}{2\pi}\left\{\left(|G_{51}^{\rm r}|^2 + |G_{53}^{\rm r}|^2\right)\left[f^-(E) - f(E)\right] + \left(|G_{52}^{\rm r}|^2 + |G_{54}^{\rm r}|^2\right)\left[f^+(E) - f(E)\right]\right\}, \tag{15}$$

$$I_{\rm N2\downarrow} = -e\Gamma_{\rm N1}\Gamma_{\rm N2}\int \frac{{\rm d}E}{2\pi}\left\{\left(|G_{72}^{\rm r}|^2 + |G_{74}^{\rm r}|^2\right)\left[f^+(E) - f(E)\right] + \left(|G_{71}^{\rm r}|^2 + |G_{73}^{\rm r}|^2\right)\left[f^-(E) - f(E)\right]\right\}. \tag{16}$$

Here $f^{\pm}(E) = f(E \pm V) = 1/(\,{\rm e}^{\beta(E\pm eV)} + 1)$.

In the zero temperature limit we have

$$I_{\rm N2\uparrow} = \frac{e^2V}{2\pi}\Gamma_{\rm N1}\Gamma_{\rm N2}\left[\left(|G_{51}^{\rm r}|^2 + |G_{53}^{\rm r}|^2\right) - \left(|G_{52}^{\rm r}|^2 + |G_{54}^{\rm r}|^2\right)\right] = \frac{e^2V}{2\pi}T_{\rm N2\uparrow}, \tag{17}$$

$$I_{\rm N2\downarrow} = \frac{e^2V}{2\pi}\Gamma_{\rm N1}\Gamma_{\rm N2}\left[\left(|G_{71}^{\rm r}|^2 + |G_{73}^{\rm r}|^2\right) - \left(|G_{72}^{\rm r}|^2 + |G_{74}^{\rm r}|^2\right)\right] = \frac{e^2V}{2\pi}T_{\rm N2\downarrow}. \tag{18}$$

Using the spin-dependent electronic current, the total electronic and spin currents are given by

$$I_{\rm N2} = I_{\rm N2\uparrow} + I_{\rm N2\downarrow}, \tag{19}$$

$$I_{\rm N2s} = \left(I_{\rm N2\uparrow} - I_{\rm N2\downarrow}\right)/2e. \tag{20}$$

3. Results and discussion

Equations (15)–(20) are the central results of this paper. Equation (15) shows that the spin-up electronic current of the NM lead 2 comes from two different conducting processes: (A) $\Gamma_{\rm N1}\Gamma_{\rm N2}\left(|G_{51}^{\rm r}|^2 + |G_{53}^{\rm r}|^2\right)[f^-(E) - f(E)]$. It represents the spin-up quasiparticle current due to the applied bias V between the NM leads 1 and 2, which can be judged by the thermal factor $f^-(E) - f(E)$. We can find that the transmission probability of quasiparticles can be divided into two subprocesses, in which (i) $\Gamma_{\rm N1}\Gamma_{\rm N2}\,|G_{51}^{\rm r}|^2$ illuminates the process that the electron with up spin incident from the NM lead 1 tunnels into the NM lead 2; (ii) $\Gamma_{\rm N1}\Gamma_{\rm N2}\,|G_{53}^{\rm r}|^2$ is the process that an electron with down spin incident from the NM lead 1 first flips its spin in the ring, then tunnels into NM lead 2. (B) $\Gamma_{\rm N1}\Gamma_{\rm N2}\left(|G_{52}^{\rm r}|^2 + |G_{54}^{\rm r}|^2\right)[f^+(E) - f(E)]$. It is the most interesting nonlocal Andreev process: an electron in the NM lead 1 is reflected as a hole into the NM lead 2, which can be judged by the thermal factor $f^+(E) - f(E)$. We can find that the probability of nonlocal Andreev reflection process also has two terms, in which (i) $\Gamma_{\rm N1}\Gamma_{\rm N2}\,|G_{52}^{\rm r}|^2$ is for an electron with down spin coming from NM lead 1 is Andreev reflected into a hole with up spin in the NM lead 2, but it includes two different subprocesses, one is that both the incident electron and the reflected hole remain their spins when they travel through the ring, however, the other is that they both flip their spins; (ii) $\Gamma_{\rm N1}\Gamma_{\rm N2}\,|G_{54}^{\rm r}|^2$ for an electron with up spin is Andreev reflected into a hole with up spin, it also includes two different subprocesses: one is for an electron with up spin which first flips its spin in a ring (so when the electron arrives at the SC interface, its spin is down), then is Andreev reflected into a hole with up spin. The other is that an electron with up spin is Andreev reflected into a hole with down spin, and the reflected hole flips its spin in a ring, then tunnels into NM lead 2. Equation (16) can be analysed similarly.

In the following we numerically investigate how the transport changes with the systematic parameters. Here we focus on the case of zero temperature. We have set the $e^2V/2\pi$ as the current unit and $eV/2\pi$ as the spin current unit. First, we analyse the electronic

current with different spin influenced by the SO interaction. In order to analyse distinctly, we discuss the case in the absence of the spin precessing term or the spin-flip term respectively. In Fig. 2 we plot the spectra of the spin-dependent electronic current as a function of the magnetic flux φ in the absence of the spin precessing term (i.e., $s = 0$). We set the system's parameters as follows: $t = 1$, $\Gamma_{\rm N1} = \Gamma_{\rm N2} = 0.1$, $\Gamma_{\rm S} = 0.3$, $\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = 0$. It is found that the spin-up and spin-down currents coincide with each other whenever $r = 0$ or $r = 0.3$, and they reaches the maximum at the same magnetic flux, which means the spin-flip term cannot lead to the spin current. At the same time, we find that the electronic currents in the case of different spin-flip strengths ($r = 0$ and $r = 0.3$) have a small variation. So we conclude that the spin-flip term arising from the SO interaction does not play a major role in causing the spin and electronic currents. Figure 3 shows the spin-up and spin-down electronic currents without the interdot spin-flip term (i.e., $r = 0$) varying with the magnetic flux φ. Other parameters are chosen to be the same as those in Fig. 2. We can observe that the peaks of $s = 0$ spin-up and spin-down currents shift at the same magnetic flux apart in different directions when the spin precessing term ($s = 0.3$) is present, which illustrates that the spin precessing term leads to the spin current. The physical reason of the above phenomena can be analysed from the Hamiltonian: The spin precessing term is $-{\rm i}s$ for spin-up electron and ${\rm i}s$ for spin-down electron, so the SO interaction destroys the symmetry of the spin-up and spin-down electrons and brings a spin-dependent phase factor $\sigma\phi$ ($\phi = \tan^{-1}(s/t)$), which results in the split of the spin-up and spin-down electronic currents, and also leads to their peaks moving the same magnetic flux in different directions.

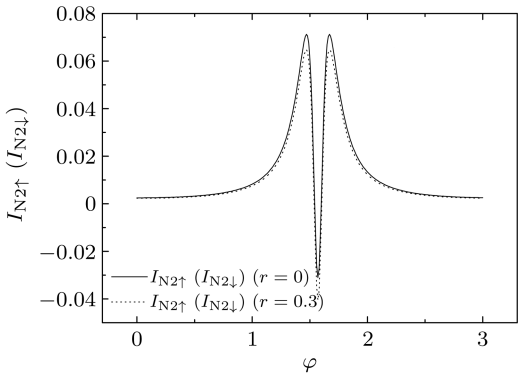


Fig. 2. The spin-up and spin-down currents versus the external magnetic flux φ at different spin-flip strengths in the absence of the spin precessing term: $r = 0$ (solid line), $r = 0.3$ (dotted line). The symmetric parameters are set: $s = 0, t = 1$, $\Gamma_{\rm N1} = \Gamma_{\rm N2} = 0.1$, $\Gamma_{\rm S} = 0.3$ and $\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = 0$.

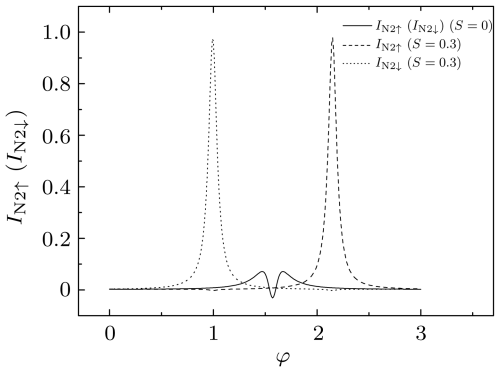


Fig. 3. The spin-up and spin-down currents versus the external magnetic flux φ at different spin precessing strengths in the absence of the spin-flip term: $s = 0$ (solid lines), $s = 0.3$ (dashed and dotted line). The spin-flip strength is chosen to be zero and other parameters are the same as those in Fig. 2.

Next, we discuss the nonlocal Andreev reflection with the SO interaction. In Fig. 4, we depict the spin-up nonlocal Andreev reflection current versus external magnetic flux φ for different r and s. Other parameters are chosen to be the same as those in Fig. 2. It is found that the spin-up nonlocal Andreev reflection current oscillates with φ and decreases much when $s \neq 0$, which means that the spin precessing term suppresses the nonlocal Andreev reflection. From Eq. (15) we see that the total spin-up current in NM lead 2 results from two processes: the nonlocal Andreev reflection and direct transmission of spin-up electron from NM lead 1 to NM lead 2 under small bias voltage. These two processes contribute to the opposite signs and therefore the total electronic current depends on a competition between the normal transmission and the nonlocal Andreev reflection. Since the nonlocal Andreev reflection is suppressed, the normal quasiparticle current plays a leading role in the spin-up electronic current, the total spin-up electronic current increases much, which can explain the spin-up current being bigger when $s = 0.3$ than the case of $s = 0$ (see

Fig. 3). A similar argument applies to the spin-down nonlocal Andreev reflection and spin-down electronic current.

Finally, we study how the electronic current and spin current change with the system's parameters. In Fig. 5, we depict the total electronic current and the spin current as functions of the magnetic flux φ at different SO strengths. Other parameters are chosen to be the same as those in Fig. 2.

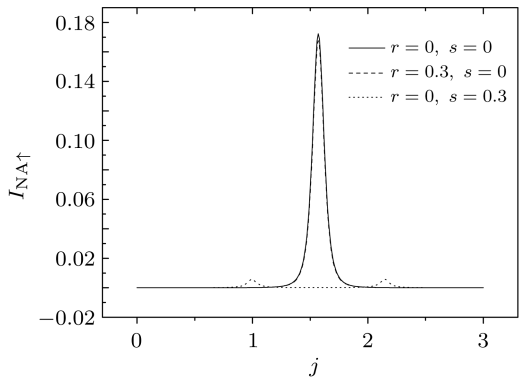


Fig. 4. The nonlocal Andreev reflection current versus the external magnetic flux φ at different SO strengths: $r = 0$, $s = 0$ (solid line), $r = 0.3$, $s = 0$ (dashed line), $r = 0$, $s = 0.3$ (dotted line). Other parameters are the same as those in Fig. 2.

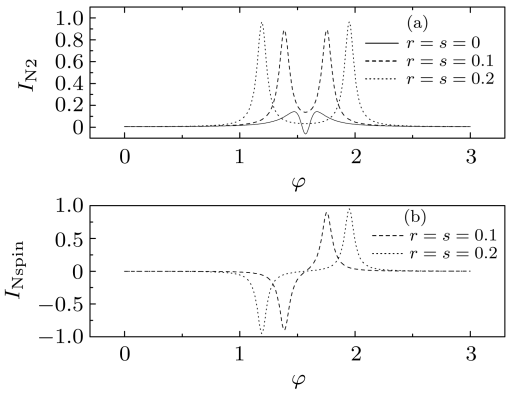


Fig. 5. The total electronic current (a) and the spin current (b) in NM lead 2 versus the external magnetic flux φ at different SO strengths: $r = s = 0$ (solid line), $r = s = 0.1$ (dashed line), $r = s = 0.2$ (dotted line). Other parameters are the same as those in Fig. 2.

Theoretically, because of the competition between the normal quasiparticle current and nonlocal Andreev reflection current, the electronic current can be positive or negative (see Fig. 2). But the spin precessing term strongly suppresses the nonlocal Andreev reflection, so the electronic current is also positive and the pure spin current cannot appear (Fig. 5(a)). Additionally, the amplitude of the spin current increases as the SO interaction strength increases (Fig. 5(b)), which also prove that the SO coupling plays the important role in the appearance of the spin current. In Fig. 6, we show the electronic current and spin current vary with energy level ε_1 of QD 1 at the different SO strengths. We also find that the electronic current keeps a positive value when energy level ε_1 varies (Fig. 6(a)), and find that the electronic current and spin current (Fig. 6(b)) are sensitive to the energy level of QD 1, so we can conveniently control the electronic and spin current by the gate voltage from the experimental point of view.

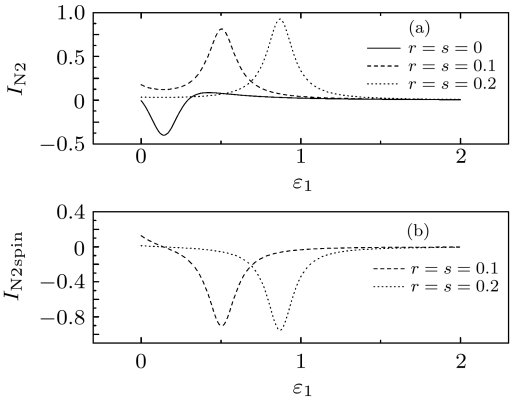


Fig. 6. The total electronic current (a) and the spin current (b) in NM lead 2 versus QD energy level ε_1 with the arbitrarily chosen magnetic flux $\varphi = -1.5$ at different SO strengths: $r = s = 0$ (solid line), $r = s = 0.1$ (dashed line), $r = s = 0.2$ (dotted line). Other parameters are the same as those in Fig. 2.

4. summary

We have theoretically investigated the variation of nonlocal Andreev reflection with Rashba SO interaction in a triple-QD ring, and found that the nonlocal Andreev reflection can be modulated by the system's parameters, such as bias voltages, gate voltages and external magnetic fluxes. By introducing the Rashba SO interaction to act locally on one component QD, we observed that the spin precessing term leads to shift of the peaks of the electronic current with different spins apart from the same magnetic flux in different directions. Moreover, the SO interaction suppresses the nonlocal Andreev reflection, and thus we cannot obtain the pure spin current. These conclusions can be used to increase or decrease the SO interaction strength for its own needs by external electric fields or gate voltages since our proposed system is within the reach of the present nano-technology.

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