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Generation and detection of spin current in the three-terminal quantum dot

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Abstract
We propose a novel device composed of a quantum dot tunneling coupled to ferromagnetic, superconducting, and normal-metal leads. This device can generate, manipulate, and detect pure spin current through the interplay between the spin-polarized quantum transport and the Andreev reflection. The spin current in this device is a well-defined conserved current since there is no need for any spin–orbit coupling. The proposed device is realizable using present nanotechnology.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The generation, manipulation, and detection of spin current in mesoscopic structures are the major challenges for spintronics, which have recently attracted much research interest both experimentally and theoretically. The research can lead to potentially important applications in the spin-based quantum information processing [1]. A pure spin current with spin-up and spin-down electrons flowing in opposite directions can be generated and detected by optical methods. For example, a pure spin current can be generated through a direct optical absorption of circularly polarized light or a quantum interference of two optical beams [2]. The spin accumulation induced by a spin current can also be detected through the Kerr effect [3] and polarized photoluminescence effect [4]. However, the optical methods do not probe the spin current directly, the connection between the spin accumulation on edges and the spin current in bulk depends on many factors such as disorder and edge structures [5]. Moreover, in practice, it is not easy to integrate the optical methods into modern electric circuits. A more convenient method is to directly manipulate spin signals electrically.

Recently, through spin–orbit coupling, the spin Hall effect (SHE) has been proposed as a possible way to generate the pure spin current electrically [6, 7]. There are two kinds of SHE: extrinsic SHE due to the spin-dependent impurity scatterings [7, 8], and intrinsic SHE due to the existence of the spin-split band structure in bulk [6] or mesoscopic [9] semiconductor systems with spin–orbit interactions. Experimentally, both extrinsic and intrinsic SHE have been observed with the help of optical techniques [3, 4], and reciprocal SHE was observed in Al nanowire using electrical measurements [13]. More recently, the time-resolved dynamics of SHE have been measured by using electrically pumped time-resolved Kerr rotation in semiconductors [14]. Theoretically, it is found that the spin current or the intrinsic SHE vanishes in the infinite impure two-dimensional electron system [10], and in recent years many studies have focused on ballistic mesoscopic devices, such as the nanojunctions formed by crossing quasi-one-dimensional quantum wires [11] or rings [12].

However, in a system with spin–orbit coupling, the spin current is not well defined and the SHE itself is weak and sensitive to the impurity scattering [6, 10]. Consequently, it remains a challenge to understand and exploit new physical mechanisms for generating and detecting spin current in solid state devices.

Quantum dots (QDs) with high-precision tunability of quantum transport parameters and long spin relaxation and decoherence times have been fabricated [1, 15], which makes it possible to generate robust spin currents. For example, it has been proposed to generate spin currents based on the spin-pumping principle [16], the use of superconducting leads [17], the microwave radiation on double QDs [18], and the coupling to a quantized cavity field [19]. However, to our knowledge, a device based on QDs which can generate, manipulate and detect spin currents simultaneously has not been proposed.

In this work we propose a three-terminal QD structure, which is composed of a QD coupled to ferromagnetic (FM), superconducting (SC), and normal-metal (NM) leads (see figure 1). We show that this type of device can be used to both generate, manipulate, and detect a pure spin current flowing in NM lead. The underlying physics is the charge and spin conservation law in a QD. Let us consider a spin-polarized current $J^{\uparrow}_{\rm AD} \neq J^{\downarrow}_{\rm AD}$, which is injected from the FM lead A. Since any spin-polarized current ($J^{\uparrow} \neq J^{\downarrow}$) can be decomposed as the summation of a pure charge current $J^{\rm C}$ and a pure spin current $J^{\rm S}$:$J^{\rm C} = J^{\uparrow} + J^{\downarrow}$, $J^{\rm S} = \frac{\hbar}{2e}(J^{\uparrow} - J^{\downarrow})$, we have

$$J^{\rm C}_{\rm AD} + J^{\rm C}_{\rm BD} + J^{\rm C}_{\rm CD} = 0, \tag{1}$$

$$J^{\rm S}_{\rm AD} + J^{\rm S}_{\rm CD} - \frac{\langle S^z\rangle}{\tau_{\rm sp}} = \frac{{\rm d}\langle S^z\rangle}{{\rm d}t}, \tag{2}$$

which are the consequences of charge and spin conservation, where $\tau_{\rm sp}$ is the spin relaxation time in the QD. Here we assume the voltage difference between the QD and SC lead is much smaller than the superconducting gap and the junction is in the Andreev reflection region, where only Cooper pairs instead of single electrons are allowed to tunnel through. Therefore $J^{\rm S}_{\rm BD}$ is always zero and does not appear in equation (2). When the voltage on leads A and C can be tuned so that $J^{\rm C}_{\rm AD} + J^{\rm C}_{\rm BD} = 0$, the charge current injected from the FM lead flows away entirely through the SC lead B and leaves no net charge current in the NM lead C. From equation (2), we can easily obtain $J^{\rm S}_{\rm CD} = \langle S^z\rangle/\tau_{\rm sp} - J^{\rm S}_{\rm AD}$ for the steady state. If the spin–orbit coupling in the QD is weak enough and ignorable, the spin relaxation time $\tau_{\rm spin}$ can be set as infinity and the spin accumulation in the QD can be ignored. Thus a pure spin current will be generated in the NM lead C.

The above device can also detect an external pure spin current injected though the NM lead C. The physics can be understood from the same equations listed above. The external spin current breaks the detail balance of the currents flowing into the QD. In order to maintain the conservation of charge and spin, a voltage change on the FM lead A is automatically induced. Therefore, in this device, the external pure spin current can generate an electric signal, which can be easily measured.

There are two major advantages in the proposed device. First, our device does not involve any spin–orbit coupling. The spin current is a well-defined conserved current. Second, the spin current can be detected in a purely electrical way, which allows us to measure the spin current with very high sensitivity.

2. Model and current formula

In this paper we restrict ourselves exclusively to the generation and detection of spin current originating from the interplay between the effects of sequential electron tunneling and the superconducting Andreev reflection, thus ignoring other factors, such as the impurity effects of the leads, the multiple levels and Coulomb interactions of electrons in the QD, and the low-temperature Kondo effect. Then the Hamiltonian of the system can be written as

$$H = H_{\rm leads} + H_{\rm D} + H_{\rm T}, \tag{3}$$

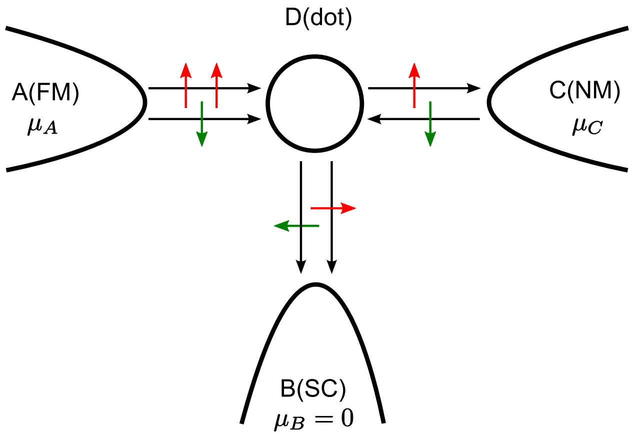

Figure 1. Schematic diagram of the three-terminal QD systems: the central region is a quantum dot with a single energy level, tunneling coupled to FM lead A (with the chemical potential $\mu_{\rm A}$), SC lead B (the chemical potential is set as $\mu_{\rm B} = 0$), and NM lead C (with $\mu_{\rm C}$), respectively. By tuning $\mu_{\rm A}$ and $\mu_{\rm C}$, two equal but opposite spin-resolved currents transport between the QD and the C lead.

where

$$H_{\rm D} = \sum_{\sigma} \epsilon_d d^{\dagger}_{\sigma} d_{\sigma} \tag{4}$$

describes the dot electrons with single energy level ϵ_d, and

$$H_{\rm T} = \sum_{\mathbf{k},\sigma,\eta} V_{\mathbf{k}\sigma\eta} d^{\dagger}_{\sigma} c_{\mathbf{k}\sigma\eta} + {\rm h.c.} \tag{5}$$

describes the tunneling coupling between the QD and leads with the hopping parameter $V_{\mathbf{k}\sigma\eta}$. $c^{\dagger}_{\mathbf{k}\sigma\eta}$ and $d^{\dagger}_{\sigma}$ are creation operators for electrons with the wavevector $\mathbf{k}$ and spin σ in the η lead and in the QD, respectively.

$H_{\rm leads}$ describes the electrons in three different leads. For the noninteracting electrons in the A and C leads,

$$H_{\rm A(C)} = \sum_{\mathbf{k},\sigma} \epsilon_{\mathbf{k}\sigma{\rm A(C)}} c^{\dagger}_{\mathbf{k}\sigma{\rm A(C)}} c_{\mathbf{k}\sigma{\rm A(C)}}. \tag{6}$$

Ferromagnetism on the A lead may be represented by a spin-dependent density of states (DOS) $\rho_{\sigma\eta}(\omega)$, which results in a spin-dependent hybridization parameter $\Gamma_{\sigma\eta}(\omega) \equiv \pi\sum_{\mathbf{k}} |V_{\mathbf{k}\sigma\eta}|^2 \delta(\omega - \epsilon_{\mathbf{k}\sigma\eta})$. In the wide-band limit, we neglect the energy dependence of $\Gamma_{\sigma\eta}(\omega)$, evaluating it at the Fermi energy. The spin polarization at the FM lead can be defined as $P_{\rm A} = (\Gamma_{\uparrow{\rm A}} - \Gamma_{\downarrow{\rm A}})/(\Gamma_{\uparrow{\rm A}} + \Gamma_{\downarrow{\rm A}})$ with $-1 \leqslant P_{\rm A} \leqslant 1$. For electrons in the SC B lead,

$$H_{\rm B} = \sum_{\mathbf{k},\sigma} \epsilon_{\mathbf{k}\sigma{\rm B}} c^{\dagger}_{\mathbf{k}\sigma{\rm B}} c_{\mathbf{k}\sigma{\rm B}} + \sum_{\mathbf{k}} (\Delta' c_{\mathbf{k}\downarrow{\rm B}} c_{-\mathbf{k}\uparrow{\rm B}} + {\rm h.c.}), \tag{7}$$

where $\Delta' = \Delta\exp({\rm i}\phi)$ is the complex SC order parameter with Δ the energy gap and ϕ the phase.

The tunneling current can be expressed in terms of the distribution functions of leads and the local properties of the QD by using the Keldysh nonequilibrium Green function technique [20]. In the Nambu representation, the Green functions of QDs are defined as $\mathbf{G}^{\rm r}(t,t') = -{\rm i}\Theta(t -$

$t')\langle\{\Psi(t),\Psi^\dagger(t')\}\rangle$ and $\mathbf{G}^<(t,t') = \mathrm{i}\langle\Psi^\dagger(t')\Psi(t)\rangle$, where the operator $\Psi = (d_\uparrow^\dagger, d_\downarrow)^\dagger$. For the A (or C) lead, the result is

$$J^\sigma_{\mathrm{A(C)D}} = \mathrm{i}\frac{e}{\hbar}\int\frac{\mathrm{d}\omega}{2\pi}\Gamma_{\sigma\mathrm{A(C)}}[f_{\mathrm{A(C)}}(\omega)(\mathbf{G}^\mathrm{r}-\mathbf{G}^\mathrm{a})_{11} + \mathbf{G}^<_{11}], \quad (8)$$

where $f_{\mathrm{A(C)}}(\omega) = 1/[\exp((\omega-\mu_{\mathrm{A(C)}})/k_\mathrm{B}T)+1]$ is the Fermi distribution function of the A (or C) lead.

The spin-up current from the SC B lead is

$$J^\uparrow_{\mathrm{BD}} = \mathrm{i}\frac{e}{\hbar}\Gamma_{\uparrow\mathrm{B}}\int\frac{\mathrm{d}\omega}{2\pi}\widetilde{\rho}_{SB}(\omega) \times [f(\omega)(\mathbf{G}^\mathrm{r}-\mathbf{G}^\mathrm{a})_{11} + \mathbf{G}^<_{11}] + \frac{e}{\hbar}\Gamma_{\uparrow\mathrm{B},\downarrow\mathrm{B}}\int\frac{\mathrm{d}\omega}{2\pi}\left(\frac{\Delta}{\omega}\right) \times \mathrm{Im}\{\mathrm{e}^{\mathrm{i}\phi}[2\widetilde{\rho}_{SB}(\omega)f(\omega)\mathbf{G}^\mathrm{r}_{12} + \rho^*_{SB}(\omega)\mathbf{G}^<_{12}]\}. \quad (9)$$

Exchanging the spin indices $\uparrow\leftrightarrow\downarrow$ gives the result for the spin-down current. $\rho^*_{SB}(\omega) = [\rho_{SB}(\omega)]^*$, where $\rho_{SB}(\omega) = |\omega|/\sqrt{\omega^2-\Delta^2}$ when $|\omega| > \Delta$, and $\rho_{SB}(\omega) = \omega/\mathrm{i}\sqrt{\Delta^2-\omega^2}$ when $|\omega| < \Delta$. The dimensionless Bardeen–Cooper–Schrieffer (BCS) density of states is defined as $\widetilde{\rho}_{SB}(\omega) = \Theta(|\omega|-\Delta)|\omega|/\sqrt{\omega^2-\Delta^2}$, which is the ratio of superconducting density of states to the normal density of states ρ_{NB}. The tunneling couplings between the B lead and the QD are $\Gamma_{\uparrow\mathrm{B}} = 2\pi\rho_{NB}|V_{\uparrow\mathrm{B}}|^2$ and $\Gamma_{\uparrow B,\downarrow B} = 2\pi\rho_{NB}V_{\uparrow\mathrm{B}}V_{\downarrow\mathrm{B}} = \sqrt{\Gamma_{\uparrow\mathrm{B}}\Gamma_{\downarrow\mathrm{B}}}$. In evaluating the above current formula, the chemical potential of the SC lead is set as $\mu_\mathrm{B} = 0$, so $f(\omega) = 1/[\exp(\omega/k_\mathrm{B}T)+1]$.

By using the equation-of-motion approach, the retarded Green functions shown in equations (8) and (9) are

$$\mathbf{G}^\mathrm{r} = \frac{1}{D(\omega)}\begin{bmatrix} \omega+\epsilon_d+\frac{\mathrm{i}\Gamma_{\downarrow\mathrm{A}}}{2}+\frac{\mathrm{i}\Gamma_{\downarrow\mathrm{C}}}{2}+\frac{\mathrm{i}\Gamma_{\downarrow\mathrm{B}}\rho_{SB}(\omega)}{2} & \frac{\mathrm{i}}{2}\Gamma_{\uparrow\mathrm{B},\downarrow\mathrm{B}}\mathrm{e}^{\mathrm{i}\phi}\left(\frac{\Delta}{\omega}\right)\rho_{SB}(\omega) \\ \frac{\mathrm{i}}{2}\Gamma_{\uparrow\mathrm{B},\downarrow\mathrm{B}}\mathrm{e}^{-\mathrm{i}\phi}\left(\frac{\Delta}{\omega}\right)\rho_{SB}(\omega) & \omega-\epsilon_d+\frac{\mathrm{i}\Gamma_{\uparrow\mathrm{A}}}{2}+\frac{\mathrm{i}\Gamma_{\uparrow\mathrm{C}}}{2}+\frac{\mathrm{i}\Gamma_{\uparrow\mathrm{B}}\rho_{SB}(\omega)}{2} \end{bmatrix}, \quad (10)$$

where $D(\omega)$ is the determinant of the matrix. By using the Keldysh operational rules for the contour Green function, we obtain the lesser Green function shown in equations (8) and (9) as $\mathbf{G}^< = \mathbf{G}^\mathrm{r}\mathbf{\Sigma}^<\mathbf{G}^\mathrm{a}$ with the lesser self-energy

$$\mathbf{\Sigma}^< = \mathrm{i}\begin{bmatrix} \Gamma_{\uparrow\mathrm{A}}f_\mathrm{A}(\omega)+\Gamma_{\uparrow\mathrm{C}}f_\mathrm{C}(\omega)+\Gamma_{\uparrow\mathrm{B}}f(\omega)\widetilde{\rho}_{SB}(\omega) & -\Gamma_{\uparrow\mathrm{B},\downarrow\mathrm{B}}\mathrm{e}^{\mathrm{i}\phi}\left(\frac{\Delta}{\omega}\right)\widetilde{\rho}_{SB}(\omega) \\ -\Gamma_{\uparrow\mathrm{B},\downarrow\mathrm{B}}\mathrm{e}^{-\mathrm{i}\phi}\left(\frac{\Delta}{\omega}\right)\widetilde{\rho}_{SB}(\omega) & \Gamma_{\downarrow\mathrm{A}}\overline{f}_\mathrm{A}(\omega)+\Gamma_{\downarrow\mathrm{C}}\overline{f}_\mathrm{C}(\omega)+\Gamma_{\downarrow\mathrm{B}}f(\omega)\widetilde{\rho}_{SB}(\omega) \end{bmatrix}, \quad (11)$$

where $\overline{f}_{\mathrm{A(C)}}$ is the Fermi distribution function of holes in the A (or C) lead: $\overline{f}_{\mathrm{A(C)}}(\omega) = 1 - f_{\mathrm{A(C)}}(-\omega)$.

In the Andreev reflection region, i.e. $\mu_\mathrm{A}, \mu_\mathrm{C} < |\Delta|$, the spin-up currents from the FM A lead and SC B lead are

$$J^\uparrow_{\mathrm{AD}} = \frac{e}{\hbar}\int\frac{\mathrm{d}\omega}{2\pi}|\mathbf{G}^\mathrm{r}_{11}|^2\Gamma_{\uparrow\mathrm{A}}\Gamma_{\uparrow\mathrm{C}}(f_\mathrm{A}-f_\mathrm{C}) + \frac{e}{\hbar}\int\frac{\mathrm{d}\omega}{2\pi}|\mathbf{G}^\mathrm{r}_{12}|^2\Gamma_{\uparrow\mathrm{A}}[\Gamma_{\downarrow\mathrm{A}}(f_\mathrm{A}-\overline{f}_\mathrm{A}) + \Gamma_{\downarrow\mathrm{C}}(f_\mathrm{A}-\overline{f}_\mathrm{C})]. \quad (12)$$

and

$$J^\uparrow_{\mathrm{BD}} = -\frac{e}{\hbar}\int\frac{\mathrm{d}\omega}{2\pi}|\mathbf{G}^\mathrm{r}_{12}|^2[\Gamma_{\downarrow\mathrm{A}}\Gamma_{\uparrow\mathrm{A}}(f_\mathrm{A}-\overline{f}_\mathrm{A}) + \Gamma_{\uparrow\mathrm{A}}\Gamma_{\downarrow\mathrm{C}}(f_\mathrm{A}-\overline{f}_\mathrm{C}) + \Gamma_{\downarrow\mathrm{A}}\Gamma_{\uparrow\mathrm{C}}(f_\mathrm{C}-\overline{f}_\mathrm{A}) + \Gamma_{\uparrow\mathrm{C}}\Gamma_{\downarrow\mathrm{C}}(f_\mathrm{C}-\overline{f}_\mathrm{C})], \quad (13)$$

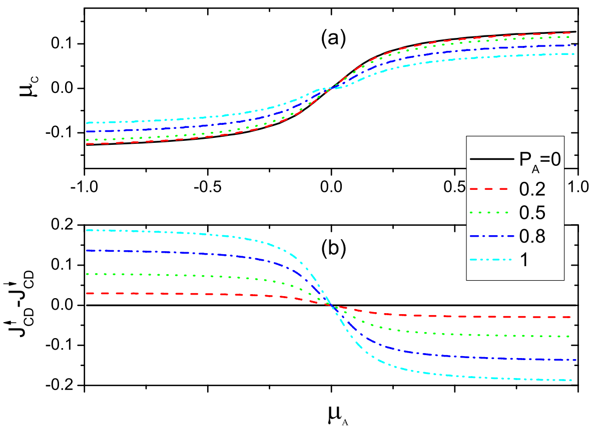

Figure 2. (a) The chemical potential μ_C of the NM lead versus the chemical potential μ_A of the FM lead for generating the pure spin current in the NM lead; (b) the corresponding pure spin current as a function of μ_A for different spin polarization of the FM lead. The parameters are $\Delta = 1$, $\epsilon_d = 0$, and $\Gamma = 0.1$.

respectively. One can easily show that $J^\uparrow_{\mathrm{BD}} = J^\downarrow_{\mathrm{BD}}$, where the Cooper-pair tunnels between the QD and the SC lead.

3. Generating the pure spin current

With the help of the current formula, we can evaluate the condition for generating the pure spin current: $J^\uparrow_{\mathrm{AD}} + J^\downarrow_{\mathrm{AD}} = -2J^\uparrow_{\mathrm{BD}}$ in the Andreev reflection region at zero temperature. In figure 2, we show μ_C of the NM lead as a function of μ_A of the FM lead for generating a pure spin current flowing between the NM lead and QD for different spin polarization cases in the FM lead, and the corresponding pure spin current $J^\uparrow_{\mathrm{CD}} - J^\downarrow_{\mathrm{CD}}$ as a function of μ_A. Without losing the physics we are considering here, we assume that the tunneling couplings between QD and leads are symmetric: $\Gamma_{\uparrow\mathrm{A}} = \Gamma_{\downarrow\mathrm{A}} = \Gamma_{\uparrow B} = \Gamma_{\downarrow\mathrm{B}} = \Gamma_{\uparrow\mathrm{B},\downarrow\mathrm{B}} = \Gamma_{\uparrow\mathrm{C}} = \Gamma_{\downarrow\mathrm{C}} = \Gamma$ at $P_\mathrm{A} = 0$, and $\Gamma_{\uparrow\mathrm{A}} = (1-P_\mathrm{A})\Gamma$, $\Gamma_{\downarrow\mathrm{A}} = (1+P_\mathrm{A})\Gamma$ at finite P_A. In the case of a nonmagnetic lead, i.e. $P_\mathrm{A} = 0$, the tunneling couplings between leads and QD are symmetric for spin-up and spin-down electrons ($\Gamma_{\uparrow\eta} = \Gamma_{\downarrow\eta}$) and the whole system is symmetric under the spin reversal, and then there is zero spin current flowing between the QD and the NM lead, i.e. $J^\uparrow_{\mathrm{CD}} = J^\downarrow_{\mathrm{CD}}$. For the finite spin polarization case, i.e. $P_\mathrm{A} \neq 0$, the dot-FM-lead tunneling coupling strength becomes spin dependent due to the spin-dependent density of states in the FM lead. Figure 2(b) shows a finite pure spin current generated between the QD and NM lead when tuning μ_A and μ_C shown in figure 2(a). The magnitude of the pure spin current is enhanced when increasing the value of the spin polarization of the FM lead. In the small bias case, i.e. $\mu_\mathrm{A}, \mu_\mathrm{C} \ll |\Delta|$, simple algebra shows that the relation of the chemical potentials of FM and NM leads becomes $\mu_\mathrm{C}/\mu_\mathrm{A} = 3(1-P_\mathrm{A}^2)/(7-3P_\mathrm{A}^2)$ for generating the pure spin currents, which results in a narrow plateau in the μ_A–μ_C plot when $P_\mathrm{A} = 1$, as shown in figure 2(a), and the slope of μ_C over μ_A increases with decreasing P_A for small bias.

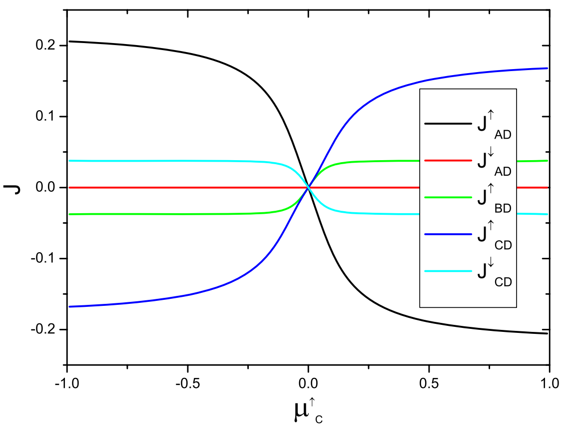

Figure 3. The current between each lead and QD versus the chemical potential $\mu^{\uparrow}_{\mathrm{C}}$ $(= -\mu^{\downarrow}_{\mathrm{C}})$ of the C lead. The parameters are $\mu_{\mathrm{A}} = \mu_{\mathrm{B}} = 0$, $P_{\mathrm{A}} = 1$, $\Delta = 1$, $\epsilon_d = 0$, and $\Gamma = 0.1$.

4. Detecting the spin current

It is interesting to find that the spin current flowing from one lead can be detected by using the same mesoscopic QD system. When a nonequilibrium spin current flows from one lead (say the C lead in figure 1), we can treat the two spin components of electrons in the C lead as two independent electron reservoirs, which are characterized by the Fermi distribution functions with different spin-dependent electrochemical potentials [21], i.e. $\mu_{\mathrm{C}\uparrow} \neq \mu_{\mathrm{C}\downarrow}$. Without loss of generality, by setting the reference energy as $\mu_{\mathrm{A}} = \mu_{\mathrm{B}} = 0$, the spin-dependent chemical potential of the C lead is chosen as $\mu_{\mathrm{C}\uparrow} = -\mu_{\mathrm{C}\downarrow}$. In figure 3 we plot the currents between the QD and different leads as a function of spin-dependent chemical potential $\mu_{\mathrm{C}\uparrow}$ $(= -\mu_{\mathrm{C}\downarrow})$ for the spin polarization of the FM lead as $P_{\mathrm{A}} = 1$. Figure 3 shows that when the electrochemical potentials of the C lead are spin dependent, there is a spin current transport between the C lead and the QD, i.e. the spin-up current flowing in the opposite direction to the spin-down current but with a different magnitude in this case. Finite $\mu_{\mathrm{C}\uparrow}$ $(= -\mu_{\mathrm{C}\downarrow})$ in the C lead induces nonzero current transport between the QD and the A and B leads. The spin current or spin accumulation induced by recent experimental technology is very weak. For small $\mu^{\uparrow}_{\mathrm{C}}(= -\mu^{\downarrow}_{\mathrm{C}}) \ll \Gamma_{\mathrm{A,B,C}}$, we can deduce analytical relations among the currents in different leads. When choosing the symmetric tunneling coupling case and setting the dot resonant level as $\epsilon_d = 0$, the charge and spin currents from the C lead to the QD can be found as $J^{\mathrm{C}}_{\mathrm{CD}} = J^{\uparrow}_{\mathrm{CD}} + J^{\downarrow}_{\mathrm{CD}} = -(J^{\mathrm{C}}_{\mathrm{AD}} + J^{\mathrm{C}}_{\mathrm{BD}})$ and $J^{\mathrm{S}}_{\mathrm{CD}} = J^{\uparrow}_{\mathrm{CD}} - J^{\downarrow}_{\mathrm{CD}} = -[(5 - 3P^2_{\mathrm{A}})/(P_{\mathrm{A}}(1 + P^2_{\mathrm{A}}))]J^{\mathrm{C}}_{\mathrm{AD}}$ for finite spin polarization $P_{\mathrm{A}} \neq 0$, respectively. Therefore, measuring the currents flowing between the QD and the A and B leads can give the result of spin current flowing between the QD and the C lead.

5. Conclusions

A device for spin current generation and detection without time-dependent field being involved has been proposed based on the interplay of spin-polarized quantum transport and Andreev reflection in a three-terminal QD coupled to FM, SC, and NM leads. We found that a pure spin current can be generated in the NM lead, which can be conveniently controlled and tuned by the bias voltages. The magnitude of pure spin current is enhanced when increasing the spin polarization of the FM lead. Most importantly, we showed that the same device can be used to measure the spin current. The experimental realization of the proposed device is not difficult. The main experimental challenges are in connecting the FM and SC leads to the device. Recently, FM and SC leads have been successfully fabricated to couple carbon nanotubes [22], single molecules [23], nanowire structures [24], and self-assembled QDs [25]. Another possible realization would be the use of spin-polarized scanning tunneling microscopy [26], where the spin-polarized current can be injected from the tip to the sample. We believe that it should be possible to fabricate the proposed device using present nanotechnology.

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