Tunneling resonances and Andreev reflection in transport of electrons through a ferromagnetic metal/quantum dot/superconductor system

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We calculate the transport properties of a ferromagnetic metal/quantum dot/superconductor system by the use of the equivalent single-particle multichannel network that takes into account the interaction in the dot and the pairing potential on the superconducting side. The transport properties are qualitatively different from the nonmagnetic case due to the modification of the Andreev reflection by the exchange field in the ferromagnet. It is found that at finite temperatures the conductance versus the gate voltage exhibits a series of peaks due to the Andreev reflection, depending on the resonances controlled by the charging energy and level spacing of the dot, as well as by the exchange field of the ferromagnet. The zero-bias conductance of the system can either be enhanced or suppressed by the exchange field, depending on the matching condition of the Fermi velocity which is related to the electron occupation in this structure.

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I. INTRODUCTION

The development and refinement in nanotechnology of materials have made it possible to fabricate mesoscopic hybrid systems with various materials and in tunable manner. Spin-polarized transport between ferromagnets (F) and superconductors (S) has become the subject of extensive research because of the potential device applications.[1–4] Recently, some interest has been focused on the transport through the F/S point contacts because it has been shown that the spin polarization of the conduction electrons can be effected by the Andreev reflection.[5–7] In an earlier theoretical work the interplay of the spin-polarized transport and the superconducting pairing was studied and the current-voltage characteristics were calculated for the F/S junction with a conventional superconductor.[8] It was found that the Andreev reflection in this structure is strongly suppressed as the Fermi surface polarization is increased. On the other hand, the resonant tunneling of electrons through a normal quantum dot (QD) with superconducting leads, such as the superconductor/quantum dot/superconductor and the normal metal/quantum dot/superconductor (NQDS) structures, became another extensively studied subject after observing several new phenomena related to the Andreev reflection.[9–11] Due to the electron-electron interaction in the QD the systems can exhibit specific phenomena such as the Coulomb blockade and the Kondo effect which are modified by the competition with the superconducting pairing. As for the NQDS structures, the resonant behavior of the Andreev tunneling has been obtained from theoretical calculations.[12–15] By replacing the normal metal in the NQDS system with a ferromagnetic metal, the splitting of the spin-up and spin-down subbands in the ferromagnetic metal will change the features of the Andreev reflection and may add new physics to such a mesoscopic hybrid system. In a recent paper Zhu *et al.* have investigated the Andreev reflection through a QD coupled with two ferromagnets and a superconductor and derived a general current formula by using nonequilibrium Green function.[16]

In this paper we investigate the spin-dependent transport of electrons through the ferromagnetic metal/quantum dot/superconductor (FQDS) system by the use of the equivalent single-particle multichannel network that takes into account both the interaction in the QD and the pairing potential on the superconducting side. This method has been previously used to investigate the in-phase features of the transport of electrons through a dot in the Coulomb blockade regime with normal leads.[17] Here, the pairing potential on the superconducting side is described with the Bogoliubov–de Genes Hamiltonian. We include the effects of the Coulomb interaction and the multilevel structure of the QD which have not been considered in Ref. 16. From these effects rich features of the Andreev reflection, caused by the interplay among the Coulomb blockade effect in the QD, the Andreev reflection from the superconducting lead, and the exchange interaction on the ferromagnetic side, emerge. At finite temperatures the zero-bias conductance of the system can either be enhanced or suppressed with increasing the exchange field, depending on the matching condition of the Fermi velocity which is related to the electron occupation in this structure.

The paper is organized as follows. In Sec. II we describe the model and the basic formalism. We present the calculated results in Sec. III. In the final section we give brief summary and discussion.

II. THE MODEL AND THE BASIC FORMALISM

The Hamiltonian of the system can be written as

$$H = H_F + H_D + H_S + H_T, \tag{1}$$

where H_F, H_D, H_S, and H_T represent the sub-Hamiltonians of the ferromagnetic lead, the QD, the superconducting wire, and the coupling between the dot and the leads, respectively. In a tight-binding scheme they are expressed as

$$H_F=t_0\sum_{m<-1,\sigma}(c^\dagger_{m,\sigma}c_{m+1,\sigma}+\text{ H.c.})-\sum_{m\leqslant-1,\sigma}\text{sgn}(\sigma)hc^\dagger_{m,\sigma}c_{m,\sigma}, \quad (2)$$

$$H_D=\sum_{i=1}^{N}\sum_{\sigma}(\xi_i+V_g)d^\dagger_{i,\sigma}d_{i,\sigma}+\frac{1}{2C}\left(e\sum_{i=1}^{N}\sum_{\sigma}d^\dagger_{i,\sigma}d_{i,\sigma}\right)^2, \quad (3)$$

$$H_S=t_0\sum_{m\geqslant1,\sigma}(c^\dagger_{m,\sigma}c_{m+1,\sigma}+\text{H.c.})-\sum_{m\geqslant1,\sigma}(\Delta c^\dagger_{m,\sigma}c^\dagger_{m,-\sigma}+\text{H.c.}), \quad (4)$$

$$H_T=\sum_{i=1}^{N}\sum_{\sigma}(t^Lc^\dagger_{-1,\sigma}d_{i,\sigma}+t^Rc^\dagger_{1,\sigma}d_{i,\sigma}+\text{H.c.}), \quad (5)$$

where $c_{m,\sigma}$ and $d_{i,\sigma}$ are annihilation operators of electrons in the leads and in the dot, with σ, m, and i being indices of spin, sites and levels, respectively, t^L (t^R) is the hopping matrix element between the left (right) lead and the dot which is assumed to be independent of the dot levels for simplicity, and N is the number of the involved dot levels. The electron states in the closed dot are characterized by level energy ξ_i, dot potential V_g induced by the gate voltage, and charging energy of an effective capacitance C. In the left lead the motion of electrons are described by hopping integral t_0 and exchange field h. The spin indices $\sigma=\uparrow,\downarrow$ correspond to the majority and minority spins in the ferromagnet, respectively. In the right lead Δ is the pairing potential of the Bogoliubov–de Genes Hamiltonian for the superconductivity. In the following we set the Fermi level to be the energy zero and choose t_0 as energy units. For simplicity we suppose that the Fermi level is at the band center if there are no spin polarization and superconducting pairing.

Due to the superconductivity of the right lead, both electrons and holes contribute to the conductance of the system. They are considered as quasiparticles on basis of the Fermi sea. We suppose that the dot has M electrons occupying several levels according to the thermal probability before and after tunneling. Including one electron or one hole in the leads, there are $M\pm1$ electrons in relevant many-body states. To solve the Schrödinger equation we use the following many-body states as the basis wave functions:

$$\Phi^{(e)}_{m,\sigma,D}=c^\dagger_{m\sigma}\left(\prod_{\{i\sigma'\}\in D}d^\dagger_{i\sigma'}\right)|F\rangle,\quad \Phi_{D^{(+)}}=\left(\prod_{\{i\sigma'\}\in D^{(+)}}d^\dagger_{i\sigma'}\right)|F\rangle, \quad (6)$$

$$\Phi^{(h)}_{m,\sigma,D}=c_{m,-\sigma}\left(\prod_{\{i\sigma'\}\in D}d^\dagger_{i\sigma'}\right)|F\rangle,\quad \Phi_{D^{(-)}}=\left(\prod_{\{i\sigma'\}\in D^{(-)}}d^\dagger_{i\sigma'}\right)|F\rangle, \quad (7)$$

where D, $D^{(+)}$, and $D^{(-)}$ denote sets of M, $M+1$, and $M-1$ states in the dot, respectively, and $|F\rangle$ represents the Fermi sea. A wave function that describes the tunneling process can be written as a linear combination of these basis functions

$$\Psi=\sum_{m,\sigma}\sum_{D}p^{(e)}_{m,\sigma,D}\Phi^{(e)}_{m,\sigma,D}+\sum_{D^{(+)}}q_{D^{(+)}}\Phi_{D^{(+)}}+\sum_{m,\sigma}\sum_{D}p^{(h)}_{m,\sigma,D}\Phi^{(h)}_{m,\sigma,D}+\sum_{D^{(+)}}q_{D^{(-)}}\Phi_{D^{(-)}}. \quad (8)$$

By applying the Hamiltonian on Ψ we obtain the following Schrödinger equations for coefficients $p^{(e)}_{m,\sigma,D}$, $p^{(h)}_{m,\sigma,D}$, $q_{D^{(+)}}$, and $q_{D^{(-)}}$:

$$[\chi_D-\text{sgn}(\sigma)h]p^{(e,h)}_{m,\sigma,D}\pm t_0(p^{(e,h)}_{m+1,\sigma,D}+p^{(e,h)}_{m-1,\sigma,D})=Ep^{(e,h)}_{m,\sigma,D},\quad (m<-1), \quad (9)$$

$$[\chi_D-\text{sgn}(\sigma)h]p^{(e,h)}_{-1,\sigma,D}\pm t_0p^{(e,h)}_{-2,\sigma,D}\pm\sum_i t^Lq_{D^{(+,-)}(i,\sigma)}=Ep^{(e,h)}_{-1,\sigma,D}, \quad (10)$$

$$\chi_{D^{(+,-)}(i,\sigma)}q_{D^{(+,-)}(i,\sigma)}\pm t^{L*}p^{(e,h)}_{-1,\sigma,D}\pm t^{R*}p^{(e,h)}_{1,\sigma,D}=Eq_{D^{(+,-)}(i,\sigma)}, \quad (11)$$

$$\chi_Dp^{(e,h)}_{1,\sigma,D}\pm t_0p^{(e,h)}_{2,\sigma,D}\pm\sum_i t^Rq_{D^{(+)}(i,\sigma)}+\Delta p^{(h,e)}_{1,\sigma,D}=Ep^{(e,h)}_{1,\sigma,D}, \quad (12)$$

$$\chi_Dp^{(e,h)}_{m,\sigma,D}\pm t_0(p^{(e,h)}_{m+1,\sigma,D}+p^{(e,h)}_{m-1,\sigma,D})+\Delta p^{(h,e)}_{m,\sigma,D}=Ep^{(e,h)}_{m,\sigma,D},\quad (m>1), \quad (13)$$

where E is the total energy of the $M\pm1$ particles, $D^{(+)}(i,\sigma)$ $[D^{(-)}(i,\sigma)]$ is a set of dot states obtained from D by adding (subtracting) state $\{i\sigma\}$, the sum for i is over all possible sets $D^{(+)}(i,\sigma)$ $[D^{(-)}(i,\sigma)]$ for a given D, and

$$\chi_D=\frac{e^2M^2}{2C}+MV_g+\sum_{i\in D}\xi_i, \quad (14)$$

$$\chi_{D^{(+,-)}(i,\sigma)}=\frac{e^2(M\pm1)^2}{2C}+(M\pm1)V_g+\sum_{i\in D^{(+,-)}(i,\sigma)}\xi_i. \quad (15)$$

In Eqs. (9)–(13) the plus sign in $\pm$ corresponds to the first index in the superscript of coefficient p which refers to electron (e) or hole (h).

In the following calculations we will include four discrete levels with equal level spacing for the dot. From the above

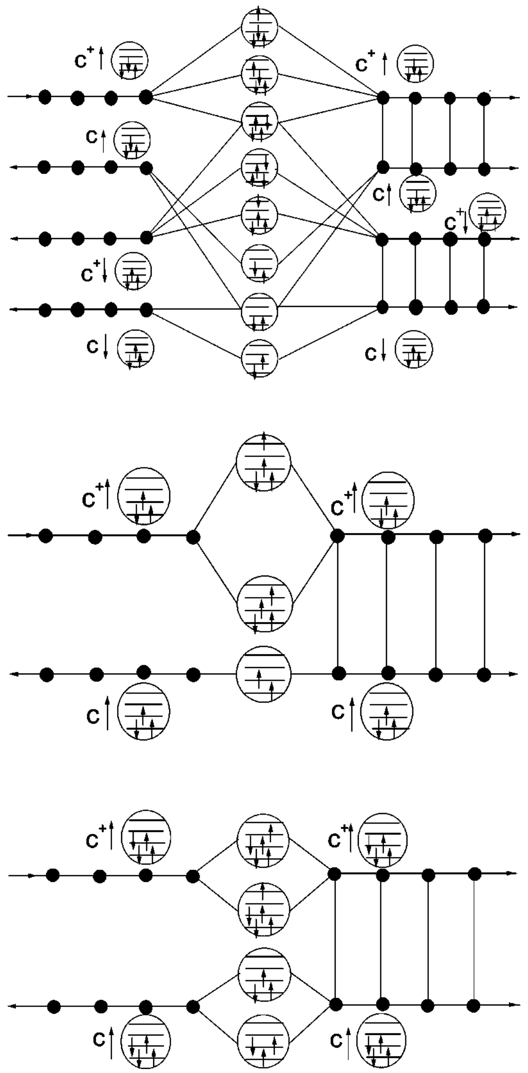

FIG. 1. Illustration of the equivalent single-particle networks for electron tunneling through a ferromagnetic metal/quantum dot/superconductor system. Four energy levels in the dots are included. The ferromagnet is described with a one-dimensional tight-binding lattice. There are three electrons in the dot for (a) and (b), four electrons for (c), before and after tunneling. The states of the dot are described in cycles. The position and spin of the tunneling electron are represented by the lattice sites and ↑ or ↓ signs, respectively. $c^{\dagger}$ (c) stands for electron (hole) channels.

equations the problem of the transmission through the FQDS system reduces to a single-particle picture of a multichannel network. In Figs. 1(a) and 1(b) we partially show possible networks for a dot with three (odd) electrons before and after tunneling. Symbols $c^{\dagger}$ and c denote the electron and hole channels in the leads, respectively. The states of the dot are represented by the occupation status of levels shown in the circles. To keep a stationary current, the outgoing channels should have the same status of the level occupation as that of the incoming channels, but the spin of electron in the dot may be flipped. Figure 1(b) shows the spin-flip process in the tunneling. In Fig. 1(c), we display the tunneling process in the case of even electrons in the dot. In the intermediate states the tunneling electron goes to an empty level, while the hole from the superconducting side goes to an occupied level, creating a Cooper pair in the superconducting lead. There are other independent networks which are not shown.

If an electronic plane wave with unit amplitude is incident from the ferromagnet, there appear reflected waves in both the electron and hole channels of the left lead, and the coefficients $p^{(e,h)}_{m,\sigma,D}$ can be written as

$$p^{(e)}_{m,\sigma,D}=e^{ik^{(e)}_{\sigma}m}+r^{(e)}_{\sigma,D}e^{-ik^{(e)}_{\sigma}m},\qquad \text{for}\quad m<0, \tag{16}$$

$$p^{(h)}_{m,\sigma,D}=r^{(h)}_{\sigma,D}e^{-ik^{(h)}_{\sigma}m},\qquad \text{for}\quad m<0, \tag{17}$$

where $r^{e,h}_{\sigma,D}$ and $k^{(e,h)}_{\sigma}$ are, respectively, the reflection amplitude and the wave vector in the corresponding channels. The wave vectors satisfy $\epsilon=2t_0\cos k^{(e)}_{\sigma}-\mathrm{sgn}(\sigma)h-eV_b$ and $\epsilon=-2t_0\cos(-k^{(h)}_{\sigma})-\mathrm{sgn}(\sigma)h+eV_b$, where $\epsilon=E-\chi_D$ is energy of the electron or hole in the lead and V_b is the bias voltage. We can calculate the reflection amplitudes $r^{(e,h)}_{\sigma,D}$ for all channels in network l by solving the Schrödinger equations. By virtue of the current conservation, at low temperatures the conductance can be evaluated on the ferromagnet side and expressed as[8,18,19]

$$G=-\frac{e^2}{h}\int_{-\infty}^{\infty}d\epsilon\sum_{l}\frac{\partial f_0(\epsilon)}{\partial\epsilon}F_l(T)[N^{(e)}_l-\mathrm{Tr}(\hat{R}^{(e)\dagger}_l\hat{R}^{(e)}_l)+\mathrm{Tr}(\hat{R}^{(h)\dagger}_l\hat{R}^{(h)}_l)], \tag{18}$$

where l is the index of the independent networks, $\hat{R}^{(e)}_l$ and $\hat{R}^{(h)}_l$ are reflection matrices for, respectively, electron and hole channels on the ferromagnet side, $N^{(e)}_l$ is the number of electron channels, $f_0(\epsilon,T)$ is the standard Fermi distribution of electrons, and $F_l(T)$ is the thermal probability of the dot states in network l,

$$F_l(T)=\frac{1}{\mathcal{N}}\exp\left(-\frac{\chi_{D_l}}{k_BT}\right),\quad \text{with}\ \mathcal{N}=\sum_l\exp\left(-\frac{\chi_{D_l}}{k_BT}\right). \tag{19}$$

The contribution of the Andreev reflection to the conductance is included by the term of $\hat{R}^{(h)}_l$ in Eq. (18). By sweeping the gate voltage V_g, the occupation number in the dot is sequentially changed, corresponding to a series of resonant conductance peaks. The spacing between peaks is determined by both the charging energy and the level spacing. The calculation of the current at a finite bias voltage is similar but the difference in the chemical potential between two leads should be taken into account.

III. RESULTS AND DISCUSSION

On the basis of the Schrödinger equations, we carry out numerical calculations on transport properties of the FQDS system. In the case of $|\epsilon|<\Delta$, only the Andreev reflection makes contribution to the current. In the numerical calculations, we use the following parameters: the level spacing of dot is $\delta\xi=0.04$, the first level is at $\xi_1=0.0$, the electron-electron interaction in the dot is represented by $e^2/2C=0.015$, the temperature is set to be $K_BT=0.005$, the super-

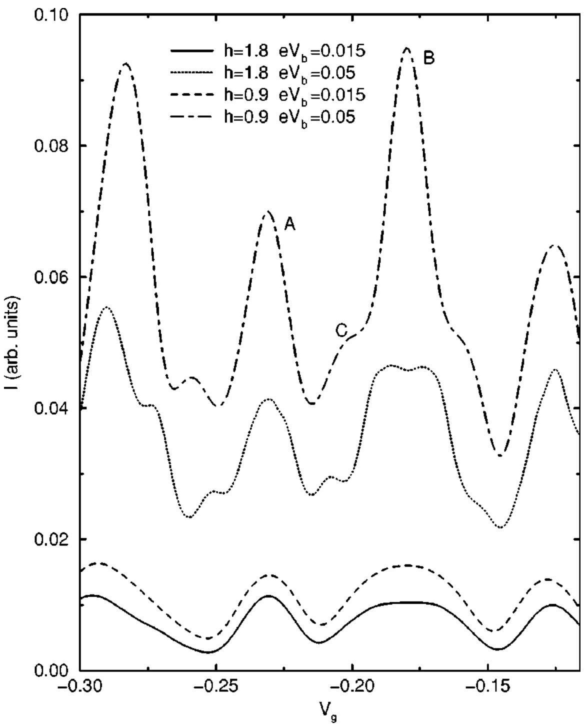

FIG. 2. Current I versus gate voltage V_g for different exchange fields and bias voltages.

conducting energy gap is assumed to be $\Delta=0.15$, and the coupling strength is taken as $t_l=t_r=0.10$. These parameters are structure dependent and may vary from sample to sample. Figure 2 shows the current I as a function of the gate voltage V_g at small bias voltage and various exchange fields.

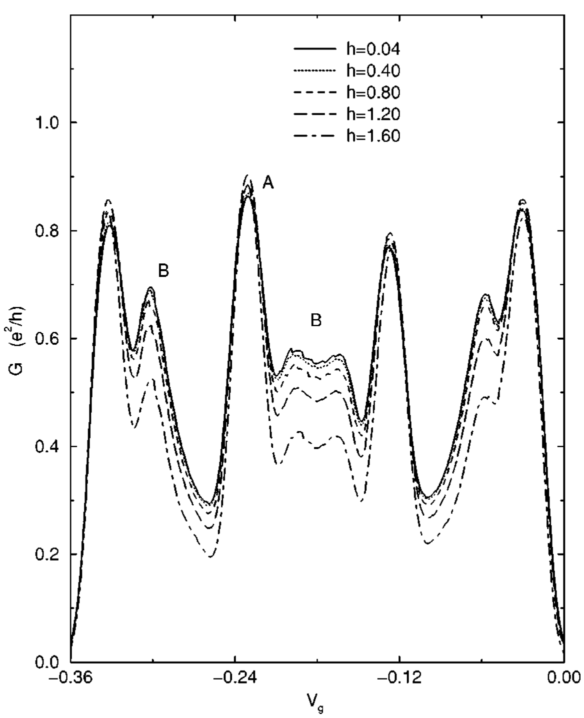

FIG. 3. Conductance G versus gate voltage V_g for different exchange fields.

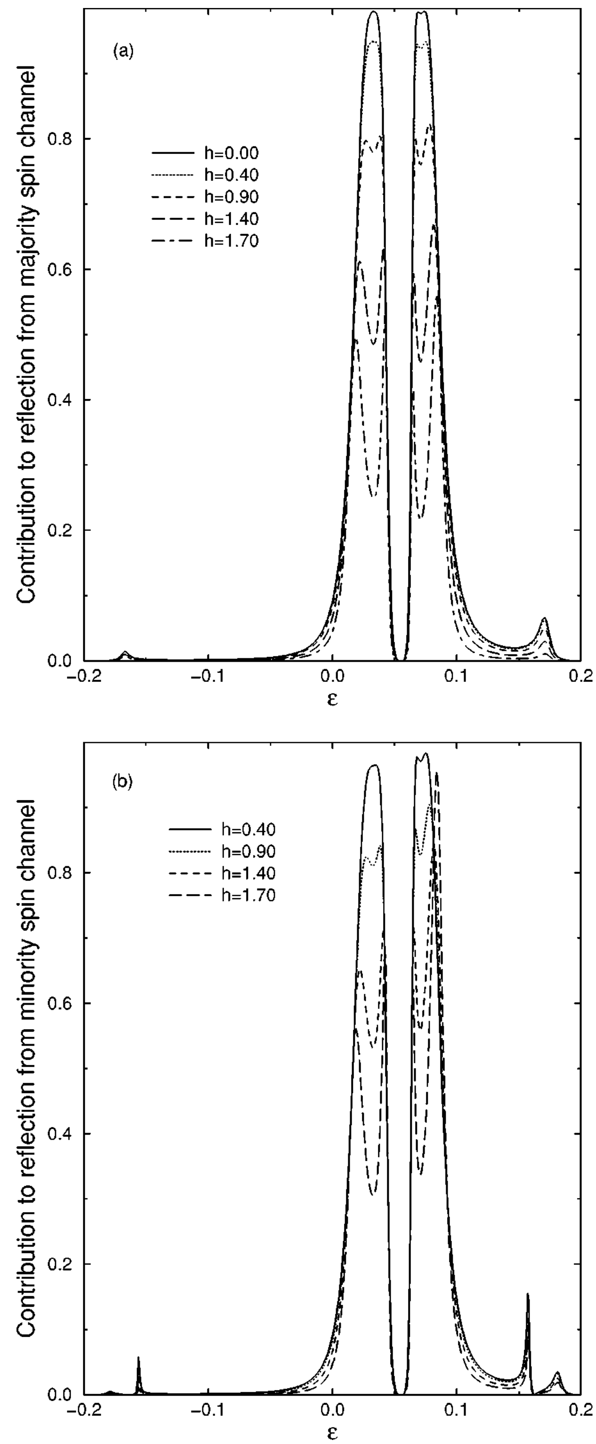

FIG. 4. The contributions to the Andreev reflection from (a) the majority spin channel and (b) the minority spin channel versus the energy of the tunneling electron for different exchange fields. The corresponding dot state has the maximum thermal probability at gate voltage $V_g=-0.18$.

At first, due to the interplay of the Coulomb blockade and the Andreev reflection, a series of peaks emerges in the I-V_g curves, and they can be classified into A, B, and C types. The A and B types correspond to the odd and even occupations of the dot, respectively. If the bias is larger than the interval of levels, the C-type peaks begin to appear. The features of the

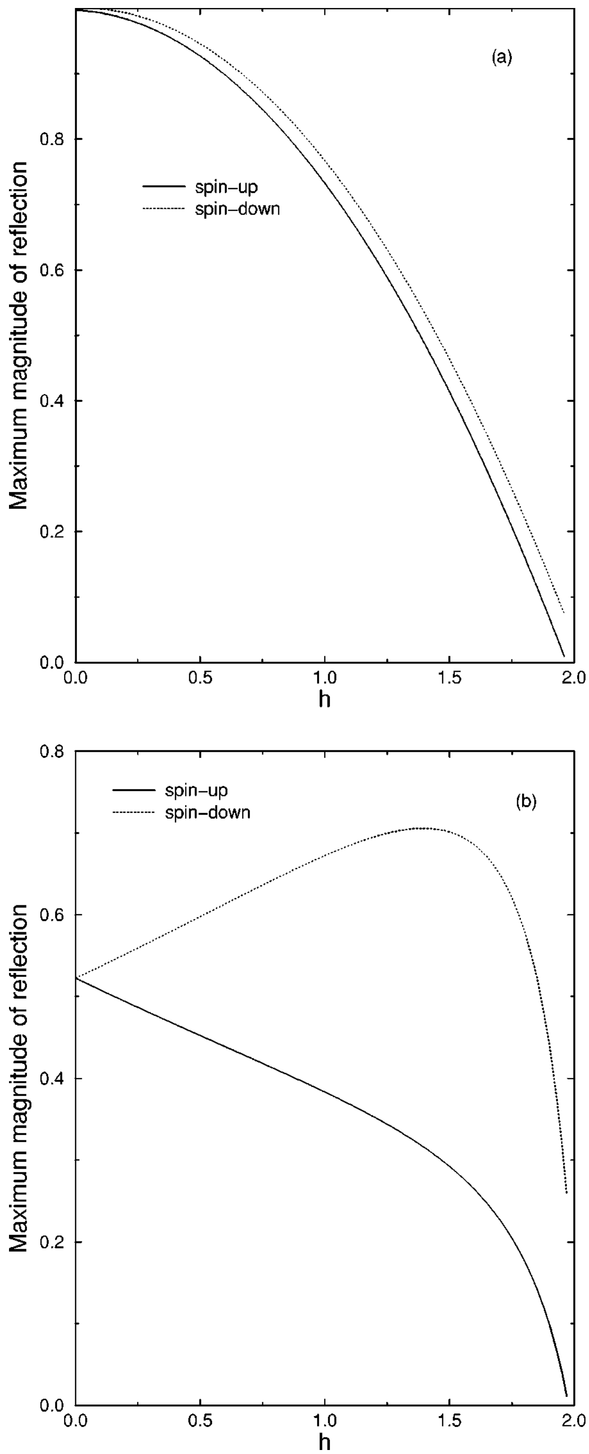

FIG. 5. The maximum magnitudes of the Andreev reflection in spin-up and spin-down channels as functions of exchange energy h for spin-up incident electron. Panels (a) and (b) correspond to networks shown in Fig. 1(c) with $\epsilon=0.033$ and Fig. 1(a) with $\epsilon=0.023$, respectively.

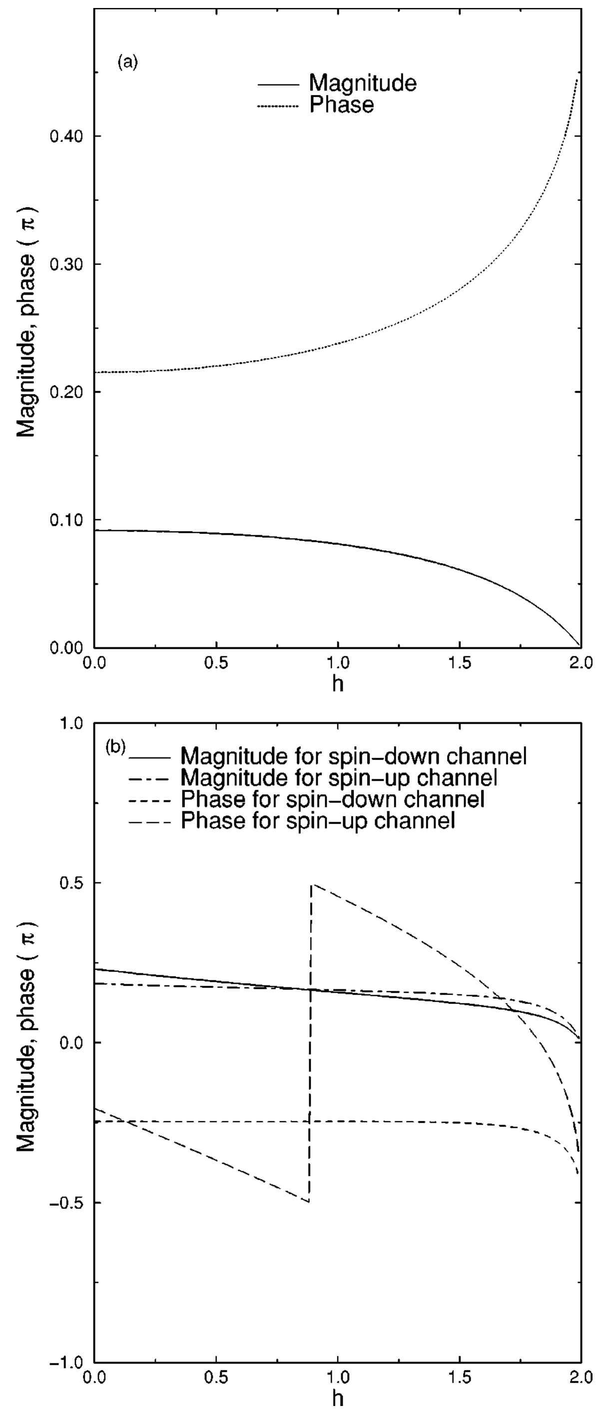

FIG. 6. The magnitude and phase of the Andreev reflection as functions of exchange energy h for networks shown in (a) Fig. 1(c) and in (b) Fig. 1(a) with $\epsilon=0.0$. For panel (a) the contributions from the spin-up and spin-down channels are almost the same.

types are similar to those in an NQDS system.[15] Secondly, due to the existence of the ferromagnetism in the system, the Andreev reflection is modified by the exchange interaction on the ferromagnetic side. As can be seen from Fig. 2, the current is suppressed with increasing the exchange field because of the reduction of the Andreev reflection. For small exchange interaction, the B-type peaks are more discernible, reflecting the favor of the even occupation in the dot for the Andreev reflection. However, the B-type peaks are more sensitive to the increase of the exchange interaction on the ferromagnetic side.

In Fig. 3 we plot the linear conductance versus the gate voltage at different exchange fields. It can be seen that the

B-type peaks are strongly suppressed at zero bias and the C-type peaks completely disappear. This is because at zero bias the tunneling processes involving more than one levels in the dot or two spin states in the ferromagnetic lead can occur only via the thermal excitations. When the exchange field increases, the B-type peaks are suppressed. However, the A-type peaks are first increased slightly and then decreased. This complicated behavior is due to the four types of processes involved in the A-type tunneling which are shown in Fig. 1(a). The quantum interference originated from the different wave vectors of the spin states may lead to the complicated behavior of the A-type peaks. In the sense of the proximity effect the Andreev reflection of the FQDS system is similar to that in a F/S junction, but in the former the level structure and the interaction strength within the dot can also influence the results.

In order to study the Andreev reflection in more details, we investigate the behavior of contributions from the channels of the majority and minority spins in the injection lead. The contributions to the Andreev reflection from the majority and minority spin channels versus the energy of the incident electron for the dot state with the maximum thermal probability are, respectively, plotted in Figs. 4(a) and 4(b) for various values of the exchange energy. The reflection takes place in an energy range corresponding to the superconducting gap, while the peak structure reflects the energy levels in the dot. By increasing the exchange energy on the ferromagnetic side, the peaks are lowered and split, implying the suppression of the exchange field on the Andreev reflection and the splitting of energy of the two spin states. From the comparison between these two figures it can be seen that the difference in the shape of curves is rather small. The reason is that the process of the Andreev reflection involves both spin states.

In Figs. 5(a) and 5(b) the magnitude of the Andreev reflection as a function of the exchange energy for the spin-up incident electron at energy corresponding to the peak in the case of $h=0$ is plotted. In the case without spin-flip processes, the Andreev reflection decreases monotonously with increasing the exchange energy, as expected from its suppression effect. However, for the spin-flip tunneling process, the Andreev reflection may increase with increasing h, as shown by the dotted line in Fig. 5(b). Similar behavior is obtained and discussed for F/S junctions and FQDS systems and is attributed to the exchange-energy dependence of the matching condition for the Fermi velocities.[1,4,16] In the present case the magnitude of the Andreev reflection depends on the parameters of the QD and on the Fermi velocities in the incoming and outgoing channels. Thus, the matching condition becomes more complicated. Especially, the outgoing channels are different for the non-spin-flip and spin-flip processes, leading to evident difference in the matching condition. This is reflected in Fig. 5 which shows the different behavior for the non-spin-flip [curves in Fig. 5(a) and solid line in Fig. 5(b)] and the spin-flip [dotted curve in Fig. 5(b)] cases.

It is also interesting to investigate the variation of the phase in the Andreev reflection. In Figs. 6(a) and 6(b) we show the magnitude and phase of the Andreev reflection as functions of the exchange energy for the contributions from the networks shown in Fig. 1(c) and Fig. 1(a), respectively. As one can see, in Fig. 6(a), the magnitude of the Andreev reflection decreases monotonously, while the phase increases, with increasing the exchange field. In Fig. 6(b), due to the existence of the spin-flip process, in the curve for the spin-up incident wave the phase changes abruptly by π at a value of h. It is worthy to note that this point coincides with the value of h where the magnitudes of the Andreev reflection for the spin-up and spin-down incident waves become equal.

IV. SUMMARY

We have investigated the transport of electrons through a quantum dot coupled to a ferromagnetic lead and a superconducting lead by taking into account the pairing potential on the superconducting side, the exchange energy on the ferromagnetic side, and the Coulomb interaction and level structure of the dot. The tunneling current measured on the ferromagnetic side is mainly from contributions of the Andreev reflection. The obtained results lead to the following conclusions. (1) Both the intensity and the phase of the Andreev reflection can be controlled by the resonant tunneling through the dot which can be tuned with varying the gate voltage. (2) For even occupations of the dot, the resonant tunneling involves two dot levels, one empty and the other occupied, to create or destroy Cooper pairs on the superconducting side. (3) The tunneling spectrum depends on the exchange energy of the ferromagnetic lead, the Coulomb interaction and the level spacing of the dot. Their combined effect leads to complicated structure of peaks. (4) For odd occupations of the dot, the spin-flip processes occur in the tunneling. In this case the magnitude of the resonant Andreev reflection can either be enhanced or suppressed with increasing the exchange field. The above conclusions are from detailed calculations based on the equivalent single-particle networks which can account for the Coulomb interaction, the level structure, the pairing potential, and the exchange energy on an equal footing.

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