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Triplet pairing states with equal spins in ferromagnet/superconductor heterojunctions for noncollinear magnetizations

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Abstract. Four-component Bogoliubov-de Gennes equations are applied to study tunneling conductance spectra of ferromagnet/ferromagnet/d-wave superconductor ($F_1/F_2/d$-wave S) tunnel junctions and to find out signs of spin-triplet pairing correlations induced in the proximity structure. The pairing correlations with equal spins arises from the novel Andreev reflection (AR), which requires at least three factors: the usual AR at the F_2/S interface, spin flip in the F_2 layer, and superconducting coherence kept up in the F_2 layer. Effects of angle α between magnetizations of the two F layers, polarizations of the F_1 and F_2 layers, the thickness of the F_2 layer, and the orientation of the d-wave S crystal on the tunneling conductance are investigated. A conversion from a zero-bias conductance dip at $\alpha = 0$ to a zero-bias conductance peak at a certain value of α can be seen as a sign of generated spin-triplet correlations.

PACS. 74.45.+c Proximity effects; Andreev effect; SN and SNS junctions – 74.50.+r Tunneling phenomena; point contacts, weak links, Josephson effects – 72.25.-b Spin polarized transport

1 Introduction

The interplay between feromagnetism and superconductivity has been of longstanding research interest, since the competition between these generally mutually exclusive types of order gives rise to a rich variety of phenomena [1–3]. Variety of interesting theoretical predictions, such as the existence of π state superconductivity in F/S multilayer systems [4–6] have been already confirmed experimentally [7,8]. If the F is inhomogeneous magnetization, a long-range spin-triplet pairing [9–17] was predicted as a consequence of the proximity of an inhomogeneous F to a S. It is also shown that spin-triplet pair correlation may also arises in layered structures consisting of superconductors and homogeneous ferromagnets with different magnetization directions [18–22]. For the F/S structures, such a long-range spin-triplet pairing seems to have been observed in experiments [23–25]. Most definite result was obtained by Keizer et al. [25] They reported a Josephson supercurrent through the strong ferromagnetic CrO_2, from which they inferred that it is a spin-triplet supercurrent.

The measurement of tunneling conductance spectroscopy is a direct and sensitive method of studying microscopic characteristics of the superconductor such as the density of quasiparticle states and the symmetry of the superconducting pairing [26–36] Recently, Krivoruchko et al. [26] and D'yachenko et al. [27] investigated the Andreev spectroscopy of point contacts between a low-temperature superconductor and the manganite $La_{0.65}Ca_{0.35}MnO_3$(LCMO). An unusual increase of the conductance and an excess current on the current-voltage characteristic of the contact were found in the region of voltage $e\,|V|$ smaller than the superconducting energy gap. They believed that the unusual results can most reasonably be explained by a long-range proximity effect under the assumption of a conversion from spin-singlet pairs to spin-triplet pairs at the S/LCMO interface. Linder et al. [28] studied the F/I/S structure and found the equal-spin ($S_z = \pm 1$) triplet correlations can be generated if both a spin-flip potential and a spin-active barrier are present. The F/F/S (s-wave or d-wave) structures in the case of collinear magnetization alignments of the two F layers have been widely studied [29,32,33]. Niu and Xing [34] extended the Blonder-Tinkham-Klapwijk (BTK) approach [37] to investigate $F(\alpha)/F(0)/d$-wave S tunnel junctions with arbitrary angle α between the magnetizations of the two Fs. It is found that the noncollinear magnetizations can lead to a novel Andreev reflection (AR) and spin-triplet pairing states near the F/S interface. In the novel AR, the incident electron and the Andreev

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reflected hole come from the same spin subband, forming a triplet pairing with equal spins; while in the usual AR [38], they come from different spin subbands, leading to a singlet pairing with opposite spins. While the idea of the novel AR can be used to explain the long-range proximity effect and related experimental results, its physical picture has not been clearly addressed. Since the BTK approach is suitable only for the clean limit, it is also highly desirable to discuss the factors required for formation of the spin-triplet pairing in the F/F/S junctions.

In this work we study effects of angle α, exchange energies of the F_1 and F_2 layers, and thickness L of the F_2 layer on the tunneling conductance in $F_1(\alpha)/F_2(0)/d$-wave S tunnel junctions. It is found the conductance within the energy gap changes non-monotonically with increasing α, which is attributed to the contribution of the novel AR in the noncollinear magnetization configurations. As a result, a conversion from the zero bias conductance dip (ZBCD) at $\alpha = 0$ to zero bias conductance peak (ZBCP) at a certain value of α is predicted to be a sign of existence of the novel AR and spin-triplet pairing.

The paper is organized as follows. In Section 2, we extended the BTK approach [37], which was previously used to study differential conductance of normal metal/S junction systems, to calculate wave functions of quasiparticles in the F/F/d-wave S structure. The conductance spectra for arbitrary angle α are given. In Section 3, the calculated results are discussed. Finally in Section 4 we summarize our conclusions.

2 Model and formulation

We consider a two-dimensional F_1/F_2/d-wave S tunnel junction with CuO_2 (a-b) planes of the d-wave S normal to the F_2/S interface. The barrier potential at interfaces is modeled by $U(r) = U_1\delta(x)+U_2\delta(x-L)$ where the x-axis is chosen to be perpendicular to the interface, L is the thickness of the F_2 interlayer, and U_1 (U_2) depends on the product of barrier height and width. Using the four-component wave function $\Psi(\mathbf{r}) = [u_\uparrow(\mathbf{r}), u_\downarrow(\mathbf{r}), v_\uparrow(\mathbf{r}), v_\downarrow(\mathbf{r})]^{\mathrm{T}}$ with $\uparrow$ and $\downarrow$ denoting the spin degree of freedom of the quasiparticle, we write the Bogoliubov-de Gennes (BdG) equation as [39,40]

$$\int d\mathbf{r}' \begin{pmatrix} \widehat{H}(\mathbf{r})\delta(\mathbf{r}-\mathbf{r}') & \Delta(\mathbf{r},\mathbf{r}')i\widehat{\sigma}_2 \\ -\Delta^{+}(\mathbf{r},\mathbf{r}')i\widehat{\sigma}_2 & -\widehat{H}^{*}(\mathbf{r})\delta(\mathbf{r}-\mathbf{r}') \end{pmatrix} \Psi(\mathbf{r}') = E\Psi(\mathbf{r}). \quad (1)$$

Here the 2×2 blocks are given by $\widehat{H}(\mathbf{r}) = \left[-\hbar^2\nabla^2/2m + U(\mathbf{r}) - E_F\right]\widehat{\mathbf{1}} - \mathbf{h}(\mathbf{r})\cdot\widehat{\sigma}$ with σ_i (i = 1, 2, 3) the Pauli matrices and $\widehat{\mathbf{1}}$ the unity matrix, Δ is the superconducting energy-gap function, and E is the quasiparticle energy measured from Fermi energy E_F. $\mathbf{h}(\mathbf{r}) = h_i[0, \sin\alpha(\mathbf{r}), \cos\alpha(\mathbf{r})]$ is the magnetization vector in the F_i layer with h_i the exchange energy and α the angle between $\mathbf{h}$ and the z axis. The magnetization in the middle F_2 layer is assumed along the z axis, i.e., $\alpha(\mathbf{r}) = 0$; while that in the F_1 electrode assumed to orient along the $(0, \sin\alpha, \cos\alpha)$ direction. We wish to point out here that the $F_1(\alpha)/F_2(0)$/S configuration under consideration is equivalent to the $F_1(0)/F_2(\alpha)$/S configuration for any spin-singlet S, because the effective pair potential in the spin-singlet S remains unchanged under rotational transformation of the spin quantization axis [28,39].

Consider a spin-up electron incident on the F_1/F_2 interface at $x = 0$ from the left F_1 at an angle θ to the interface normal. Define $\check{e}_1 = (1,0,0,0)^T$, $\check{e}_2 = (0,1,0,0)^T$, $\check{e}_3 = (0,0,1,0)^T$, and $\check{e}_4 = (0,0,0,1)^T$ as basis wave functions. With general solutions of equation (1), the wave function in the left F_1 is given by

$$\Psi_L = \left(e^{iq_{e+}x} + b_\uparrow e^{-iq_{e+}x}\right)\check{e}_1 + b_\downarrow e^{-iq_{e-}x}\check{e}_2 + a_\uparrow e^{iq_{h+}x}\check{e}_3 + a_\downarrow e^{iq_{h-}x}\check{e}_4, \quad (2)$$

for $x \le 0$. In the middle F_2 and right S regions, we have

$$\Psi_M = \left(f_1 e^{ik_{e+}x} + f_2 e^{-ik_{e+}x}\right)\check{e}_1 + \left(f_3 e^{ik_{e-}x} + f_4 e^{-ik_{e-}x}\right)\check{e}_2 + \left(f_5 e^{ik_{h+}x} + f_6 e^{-ik_{h+}x}\right)\check{e}_3 + \left(f_7 e^{ik_{h-}x} + f_8 e^{-ik_{h-}x}\right)\check{e}_4, \quad (3)$$

for $0 \le x \le L$, and

$$\Psi_S = \left[c_\uparrow\left(u_+ e^{i\phi_+}\check{e}_1 + v_+\check{e}_4\right) + c_\downarrow\left(u_+ e^{i\phi_+}\check{e}_2 - v_+\check{e}_3\right)\right]e^{ik_+x} + \left[d_\downarrow\left(v_- e^{i\phi_-}\check{e}_1 + u_-\check{e}_4\right) + d_\uparrow\left(u_-\check{e}_3 - v_- e^{i\phi_-}\check{e}_2\right)\right]e^{-ik_-x} \quad (4)$$

for $x \ge L$. Here different spin quantization axes have been taken in the left and middle F layers, which will be considered in matching conditions. Neglecting the self-consistency of spatial distribution of the pair potential in the S [41–43], we take the d-wave pair potential to be $\Delta_\pm = \Delta_0\cos(2\theta_s \mp 2\beta)$ where θ_s is the angle between the F_2/S interface normal and the wavevector of the quasiparticle, β is the angle between the a axis of crystal and the interface normal, and subscripts + and − correspond to the pair potentials for electronlike and holelike quasiparticles, respectively. In equation (4) we have $u_\pm^2 = 1 - v_\pm^2 = (1 + \Omega_\pm/E)/2$ with $\Omega_\pm = \sqrt{E^2 - |\Delta_\pm|^2}$ and $e^{i\phi_\pm} = \cos(2\theta_s \mp 2\beta)/|\cos(2\theta_s \mp 2\beta)|$. Longitudinal components (along the x direction) of the wave vectors for the electron and hole in the S region are $k_\pm = \sqrt{(2m/\hbar^2)(E_F \pm \Omega_\pm) - k_{||}^2}$, and those in the left and middle F layers are $q_{e(h)\pm} = \sqrt{(2m/\hbar^2)[E_F \pm h_1 + (-)E] - k_{||}^2}$ and $k_{e(h)\pm} = \sqrt{(2m/\hbar^2)[E_F \pm h_2 + (-)E] - k_{||}^2}$, respectively, with $k_\| = \sqrt{(2m/\hbar^2)(E_F + h_1 + E)}\sin\theta$ as the parallel component of the wave vector and assumed to be conserved.

All the coefficients $a_{\uparrow(\downarrow)}$, $b_{\uparrow(\downarrow)}$, $c_{\uparrow(\downarrow)}$, $d_{\uparrow(\downarrow)}$, and f_i (i = 1–8) can be determined by the matching conditions at the left and right interfaces. Define $\check{T} = \cos\left(\frac{\alpha}{2}\right)\widehat{\mathbf{1}} \otimes \widehat{\mathbf{1}} + i\sin\left(\frac{\alpha}{2}\right)\hat{\sigma}_3 \otimes \hat{\sigma}_1$ as the transformation matrix for changing the spin quantization axis. The matching conditions for wave functions (2)–(4) are given by

$$\begin{aligned}
&\breve{T}\Psi_L(x=0)=\Psi_M(x=0),\\
&\Psi_M(x=L)=\Psi_S(x=L),\\
&\frac{d\Psi_M(x)}{dx}\Big|_{x=0}=\breve{T}\frac{d\Psi_L(x)}{dx}\Big|_{x=0}+2k_F Z_1\breve{T}\Psi_L(x=0),\\
&\frac{d\Psi_S(x)}{dx}\Big|_{x=L}=\frac{d\Psi_M(x)}{dx}\Big|_{x=L}+2k_F Z_2\Psi_M(x=L), \quad (5)
\end{aligned}$$

where $Z_i = U_i/\hbar v_F$ (i = 1 or 2) is a dimensionless parameter describing the magnitude of interfacial resistance with v_F the Fermi velocity. For a spin-down electron incident on the interface at $x = 0$, coefficients $a_{\uparrow(\downarrow)}$, $b_{\uparrow(\downarrow)}$, $c_{\uparrow(\downarrow)}$, $d_{\uparrow(\downarrow)}$, and f_i (i = 1–8) can be similarly obtained by the BdG equation and matching conditions.

The zero-temperature differential conductance of the present tunnel junction can be obtained as [39,44]

$$G(E)=\frac{1}{2}\int d\theta\bar{G}(E)\cos\theta, \quad (6)$$

with

$$\bar{G}(E)=\frac{2e^2}{h}\sum_{\sigma=\uparrow,\downarrow}P_\sigma(1+A_{\sigma\sigma}+A_{\sigma\bar{\sigma}}-B_{\sigma\sigma}-B_{\sigma\bar{\sigma}}). \quad (7)$$

Here $P_\uparrow = 1-P_\downarrow = \frac{1}{2}(1+P_1)$ with $P_1 = h_1/E_F$ ($h_1 \leq E_F$) as the spin polarization in the F_1 electrode. $A_{\sigma\sigma} = |a_\sigma|^2$, $A_{\sigma\bar{\sigma}} = |a_{\bar{\sigma}}|^2 \frac{q_{h\bar{\sigma}}}{q_{e\sigma}}$, $B_{\sigma\sigma} = |b_\sigma|^2$, and $B_{\sigma\bar{\sigma}} = |b_{\bar{\sigma}}|^2 \frac{q_{e\bar{\sigma}}}{q_{e\sigma}}$ are the probabilities of the novel AR, usual AR, normal reflection, and spin-flip reflection, respectively, with $\bar{\sigma}$ standing for the spin opposite to σ. The integral over θ in equation (6) is over all the incident angles for which the parallel wavevectors can be conservative. $\bar{G}(E)$ in equation (7) can be divided into three parts: the quasiparticle contribution, $P_\uparrow(1-A_{\uparrow\uparrow}-A_{\uparrow\downarrow}-B_{\uparrow\uparrow}-B_{\uparrow\downarrow})+P_\downarrow(1-A_{\downarrow\uparrow}-A_{\downarrow\downarrow}-B_{\downarrow\uparrow}-B_{\downarrow\downarrow})$, the usual AR contribution, $2(P_\uparrow A_{\uparrow\downarrow} + P_\downarrow A_{\downarrow\uparrow})$, and the novel AR contribution, $2(P_\uparrow A_{\uparrow\uparrow} + P_\downarrow A_{\downarrow\downarrow})$.

If the F_1 electrode is half-metallic, i.e., $P_\uparrow = 1$ and $P_\downarrow = 0$, there is neither usual AR nor spin-flip reflection in the left F_1, and the contribution of the minority spin subband to conductance is vanishing. In this case, $A_{\uparrow\downarrow} = 0$ and $B_{\uparrow\downarrow} = 0$ for the spin-up electron incident on the F_1/F_2 interface, so that equation (7) reduces to

$$\bar{G}(E)=\frac{2e^2}{h}[1+A_{\uparrow\uparrow}(E)-B_{\uparrow\uparrow}(E)], \quad (8)$$

in which only the quasiparticle tunneling and novel AR have contributions to the conductance.

3 Results and discussions

In the numerical calculations of equations (6) and (7) we take $\Delta_0/E_F = 0.02$, $Z_1 = 0.5$, $Z_2 = 0$, $\beta = \pi/4$ (the x axis along the {110} direction), and $h_1/E_F = 0.999$, which is very close to the half-metallic case. We first calculate the tunneling conductance spectra with $k_F L = 10$ for parallel (P) and perpendicular alignments of the two Fs' magnetizations. For the left and middle F layers in the P configuration ($\alpha = 0$), from equations (2)–(5) we obtain $b_\downarrow = a_\uparrow = 0$ for $x \leq 0$, $f_i = 0$ (i = 3–6) for $0 \leq x \leq L$, and $c_\downarrow = d_\uparrow = 0$ for $x \geq L$. Since there is no spin flip in the tunneling process, the four-component BdG equation are decoupled into two sets of two-component equations: one for $\breve{e}_1$ and $\breve{e}_4$, and the other for $\breve{e}_2$ and $\breve{e}_3$ In this case, the vanishing $a_\uparrow$ indicates that there is only usual AR process and no spin-triplet correlations with equal spin pairing. For the highly polarized F_1 electrode, the absence of the spin-down electrons makes it impossible to form the spin-singlet Cooper pairs in the F_1 electrode. As a result, the usual AR is completely suppressed and the AR-contributed conductance G_{AR} vanishes. Therefore, the conductance comes only from the quasiparticle-contributed conductance G_{QP} and so a ZBCD forms, as shown by dashed lines in Figure 1. If the magnetization directions of the two F layers are noncollinear (e.g. $\alpha = \pi/2$), the situation is quite different. As shown by solid lines in Figure 1, $G(E)$ within the energy gap has a great increase and exhibits a zero-bias hump (a) or a zero-bias peak (b). In the case of $P_1 = 0.999$, equation (7) can be replaced by equation (8), i.e., $G(E) = G_{QP}(E) + G_{NAR}(E)$ with G_{NAR} the novel AR-contributed conductance. While $G_{QP}(E)$ somewhat decreases with changing α from 0 to $\pi/2$, $G_{NAR}(E)$ gradually plays a dominant part in $G(E)$, as shown by dotted lines in Figure 1. In such a novel AR process, the incident electron and the Andreev-reflected hole come from the same spin subband, resulting in spin-triplet correlations in the $F_1/F_2/S$ structure. The novel AR opens a new transport channel, and has a great influence on the electron transport.

Second, we study effects of the polarization of the middle F_2 layer on the tunneling spectra. For the nonmagnetic metallic interlayer (N) of $h_2 = 0$, we find that the novel AR is zero and the conductance spectra are very similar to the dashed line in Figure 1, independent of angle α. This is because the $F_1(\alpha)$/N/S configuration is equivalent to the $F_1(0)$/N/S one [28,39], as has been mentioned in Section 2, so that no spin flip occurs in the transport process. For finite h_2 and noncollinear magnetization, the spin-flip effect always exists in the $F_1(\alpha)/F_2(0)/S$ junction or equivalent $F_1(0)/F_2(\alpha)/S$ junction. As an incident electron with spin up tunnels via the F_1/F_2 interface into the F_2 layer, owing to the change of spin quantization axes, it is split up into two coherent electronic states: $(e,\uparrow)$ and $(e,\downarrow)$. Because of the usual AR at the F_2/S interface, both of them are transformed into coherent hole states: $(h,\uparrow)$ and $(h,\downarrow)$. Finally, the coherent holes in spin-up and spin-down channels in the F_2 interlayer may partly enter the spin-up subband of the left F_1 electrode, giving rise to a novel AR. This mechanism is very similar to that discussed previously by Kadigrobov et al. [10], in which a magnetically inhomogeneous ferromagnet was regarded as a spin splitter. As a result, the novel AR is a joint effect of the usual AR at the F_2/S interface and the spin flip in the middle F_2 layer. With increasing h_2, the usual AR

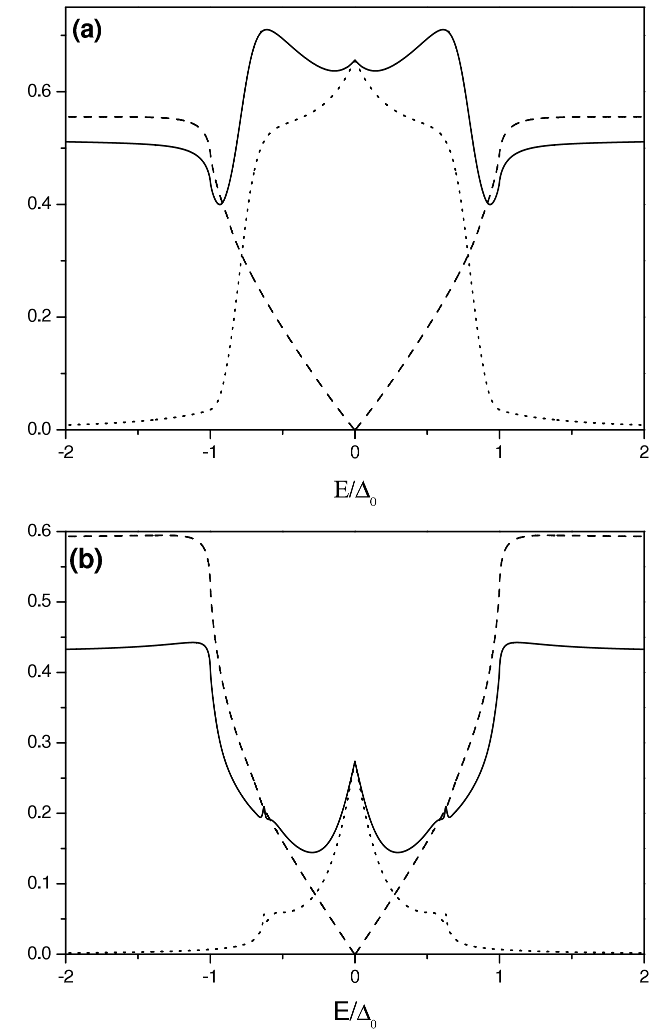

Fig. 1. Total tunneling conductance G (solid line), novel AR-contributed conductance G_{NAR} (dotted line), and quasiparticle-contributed conductance G_{QP} (dashed line) as a function of energy with $h_2/E_F = 0.2$ (a) and $h_2/E_F = 0.8$ (b).

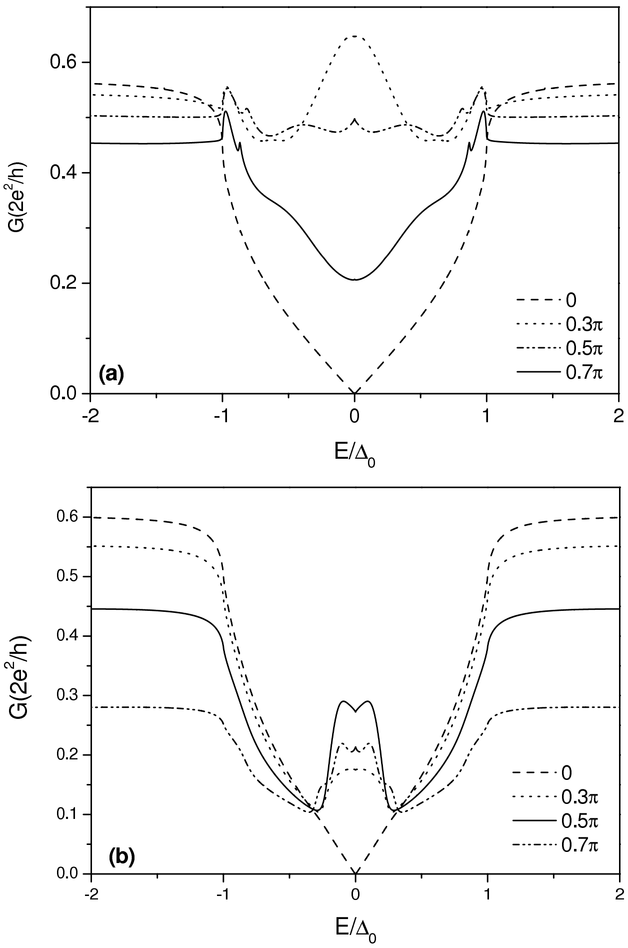

Fig. 2. Tunneling conductance spectra for several α indicated, with $h_2/E_F = 0.3$ (a) and $h_2/E_F = 0.9$ (b). The other parameters are the same as in Figure 1.

is suppressed but the spin-flip effect is enhanced. As a result, $G(E)$ exhibits a nonmonotonous change with the polarization of the middle F_2 layer, exhibiting a zero-bias conductance hump for $P = 0.2$ and a zero-bias conductance peak (ZBCP) for $P = 0.8$, respectively, shown in Figures 1a and 1b.

Third, we study the effect of angle α on the tunneling spectra in the $F_1/F_2/d$-wave S junction with $k_F L = 10$. If one wants to observe the novel AR effect, the exchange energy h_2 can not be zero. Figure 2 shows tunneling conductance spectra for different angle α by taking $h_2/E_F = 0.3$ (a) and 0.9 (b). For $\alpha = 0$, the conductance comes only from the quasiparticle contribution G_{Qp}, and exhibits a ZBCD. With increasing α, $G(E)$ with $|E| > \Delta_0$ always decreases, indicating a monotonous decrease of G_{Qp}. Within the energy gap, however, the change of $G(E)$ with α is not monotonous; it first increases and then decreases, exhibiting the maximal ZBCP at a certain value of α. For a highly-polarized F electrode, the usual AR process is completely suppressed and the novel AR process plays a key role in $G(E)$ for $|E| < \Delta_0$, resulting in a nonmonotonous evolution of $G(E)$ from ZBCD to ZBCP behavior.

Next, we discuss the effect of the F_2 layer thickness L on the conductance spectra. For $\alpha = 0$, it is found [33] that $G(E)$ oscillates with L due to quantum interference effects within the middle F_2 layer, and have two oscillation components with different periods, respectively, arising from the usual AR and normal reflection. For finite α, the present calculations indicate that zero-bias conductance has the similar oscillating behavior, as shown in Figure 3. In this case, for an incident electron with spin up from the F_1 electrode to the F_2 layer there are eight coherent wave functions: $(e,\uparrow)$, $(e,\downarrow)$, $(h,\downarrow)$, and $(h,\uparrow)$ with moving to the right and left due to the AR and normal reflections. Their interference effects give rise to the oscillations of $G(E)$ with L. However, the present theoretical approach and calculated results are tenable only in the clean limit, in which the electron and the Andreev-reflected hole remain coherent. To guarantee such a superconducting coherence,

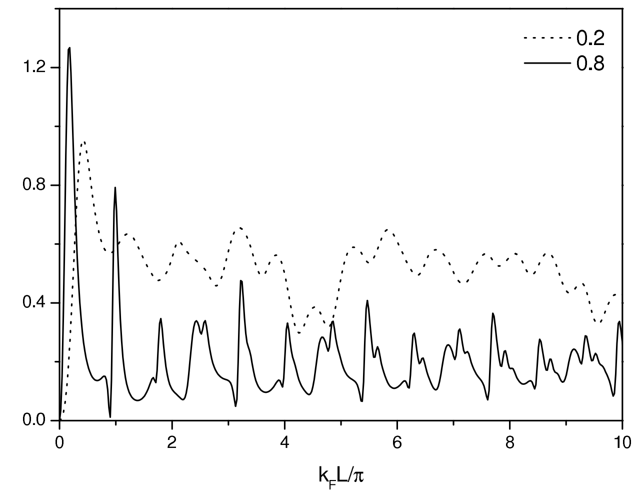

Fig. 3. Zero-bias conductance as a function of thickness L of the F_2 interlayer. The other parameters are same as in Figure 1.

the thickness of the F_2 layer is limited to be of the order of the coherence length, which decreases with h_2 increased. As a result, the appearance of spin-triplet pairing correlations requires at least three factors: the AR at the F_2/S interface, spin flip in the F_2 layer, and superconducting coherence kept up in the F_2 layer. In the present structure there are two interfaces correlated to each other. At an isolated F_1/F_2 interface, there are spin-conservated and spin-flip quasiparticle reflections, but no AR; while at the isolated F_2/S interface there is usual AR, but no novel AR. However, if the F_2 layer is thin enough, the incident electron and Andreev-reflected hole can remain coherent in the whole F_2 layer. In the present approach the F_1/F_2 and F_2/S interfaces together with the thin F_2 layer with noncollinear magnetization can be regarded as an effective interface, at which the novel AR effect occurs. To realize the conversion from the spin-singlet pairing correlation at the F_2/S interface into the spin-triplet one at the F_1/F_2 interface, the former must travel coherently through middle F_2 layer. Therefore if L is much greater than the coherence length of the F_2 layer, the novel AR will be completely suppressed.

We wish to propose a relatively realistic experimental system, $F_1/F_2(\alpha)/d$-wave S, for the observation of the effect of spin triplet correlations on the conductance spectra. Here F_1 is chosen to be highly polarized and close to a half metal; at the same time, it has a high coercive field or its magnetization is pinned by an antiferromagnetic layer. As an example, CrO_2 with high polarization $P_1 = 0.96$ is a good candidate for the F_1 [45,46]. F_2 is chosen to be low polarized and its thickness to be shorter than the coherence length; at the same time, α is easily adjusted by an applied magnetic field. On this condition, the magnetization direction of F_1 is fixed and that of the weakly ferromagnetic F_2 can change continuously. In Figure 4a we plot the tunneling conductance spectra for $k_F L = 8$, $h_1/E_F = 0.96$, and $h_2/E_F = 0.1$. Similar to Figure 2, $G(E)$ within the superconducting energy gap has a non-

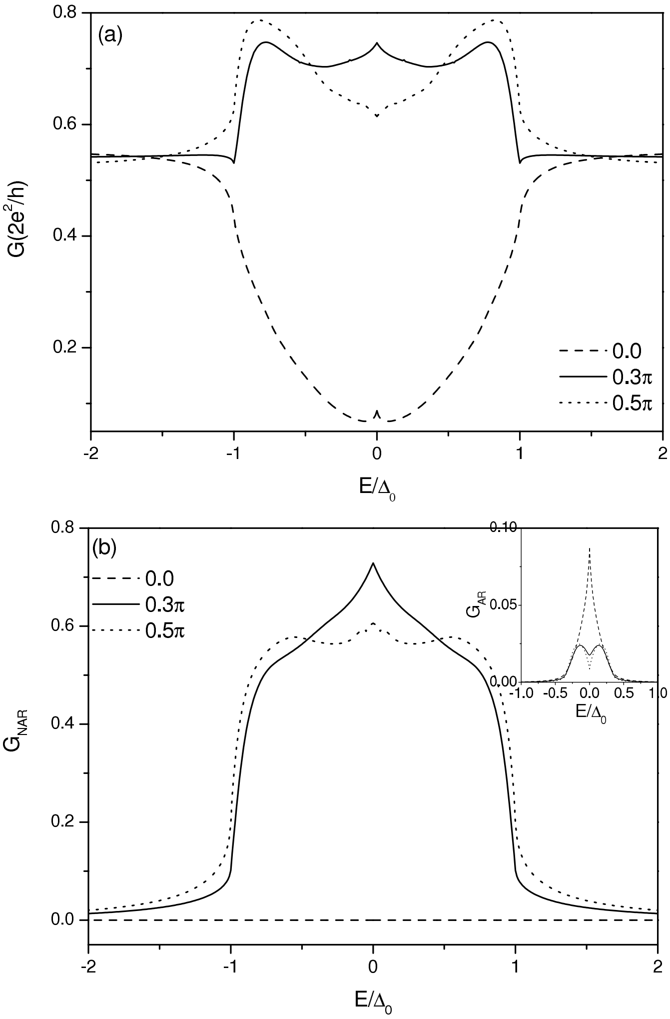

Fig. 4. Total tunneling conductance G (a), G_{NAR} and G_{AR} (b) as a function of energy for several α indicated. The other parameters are given in text.

monotonous change with α, exhibiting a ZBCD at $\alpha = 0$ and a ZBCP at a certain value of $\alpha = \alpha_c$. Such a change of $G(E)$ with α can be seen as a sign of generated spin-triplet correlations in this system. $G(E)$ is the sum of three parts of contributions: $G_{NAR}(E)$, $G_{AR}(E)$, and $G_{QP}(E)$. The novel AR and usual AR contributions to the conductance are plotted in Figure 4b and in its inset, respectively. At $\alpha = 0$, $G_{NAR} = 0$ and nonzero G_{AR} exhibits maximal due to $P < 1$. With increasing α from 0 to α_c, G_{NAR} increases and G_{AR} decreases. Owing to existence of a small spin minority subband, G_{AR} is not zero but very small, so that G_{NAR} plays a dominant part in the zero-bias conductance. If one wants to avoid the effect of G_{AR} on the conductance, a half-metallic electrode ($P = 1$) needs to be used.

Finally, it is pointed out that the anisotropic orientation of the d-wave S crystal is of secondary importance for the results obtained here, provided that the F_1 electrode is highly polarized or half metallic. In all the calculations

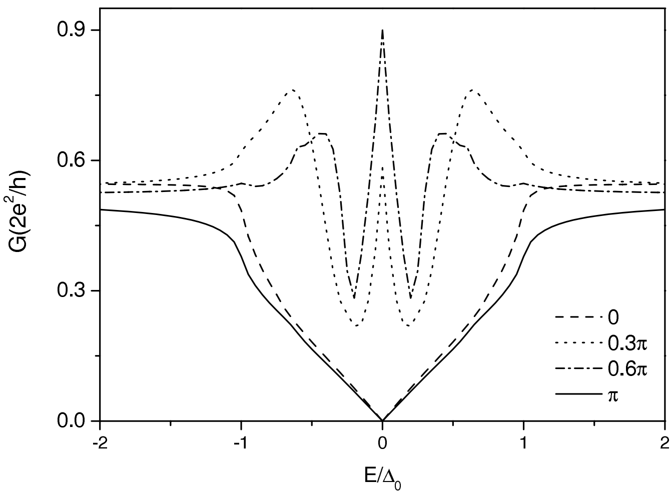

Fig. 5. Tunneling conductance spectra for several α indicated, with $\beta = 0$, $h_1/E_F = 0.999$, $h_2/E_F = 0.1$, and $k_F L = 10$.

above, $\beta = \pi/4$ is used, i.e. the interface normal is aimed at one node of the d-wave pair potential. If $\beta = 0$ is taken, the calculated results shown in Figure 5 are somewhat similar to those in Figure 2 with $\beta = \pi/4$. With changing α from collinear to noncollinear, the zero-bias $G(E)$ still exhibits a conversion from the ZBCD to ZBCP behavior.

4 Conclusions

By use of the BdG equations and BTK approach we have studied the conductance spectra of $F_1(\alpha)/F_2(0)/d$-wave S tunnel junctions with different magnetization configurations. Effects of angle α between magnetizations of the two F layers, polarizations of the F_1 and F_2 layers, the thickness of the F_2 layer, the orientation of the d-wave S crystal on the tunneling conductance are investigated. To observe the effect of spin triplet correlations on the conductance spectra, we propose a more realistic experimental system, $F_1/F_2(\alpha)/d$-wave S, with highly polarized (or half-metallic) F_1 electrode and thin F_2 interlayer with relatively low polarization, which satisfies three factors: the usual AR at the F_2/S interface, spin flip in the F_2 layer, and superconducting coherence kept up in the F_2 layer. In such a system, with changing α there may be a conversion from the ZBCD at $\alpha = 0$ to ZBCP at a certain value of α. This conversion or appearance of the ZBCP comes from the novel AR, and can be regarded as a sign of generated spin-triplet pairing correlations.

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