

Long-Range Spin-Triplet Superconductivity Induced by Magnetic Field in d Wave Superconductor/Ferromagnet Hybrid System

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Abstract We theoretically study the long-range spin-triplet superconductivity in d wave superconductor/ferromagnet/ferromagnet (S/F₁/F₂) trilayer junction, in which the magnetization of F₁ layer could be rotated in the y - z plane by an external magnetic field. The four-component Eilenberger equations were constructed to calculate the superconducting order parameters and density of states (DOS). Near the clean limit, the p wave equal-spin triplet component could be induced when the magnetization directions of F₁/F₂ layers are non-collinear, and the DOS exhibits a split zero-bias conductance peak. The various parameters such as ferromagnetic exchange energy, thickness of ferromagnetic layers, and angles between F₁/F₂ magnetization directions are studied for the effect on inducing triplet superconductivity. By magnetic field controlling the emergence of equal-spin triplet pairings or not, such a tunable S/F₁/F₂ trilayer junction based on long-range spin-triplet superconductivity could be used as a superconducting switch device, which would open up a new view of spintronics.

Keywords Eilenberger equation · Long-range proximity effect · Spin triplet · Spintronics

1 Introduction

Superconductivity and ferromagnetism are two different long-range quantum orders, for which Cooper pairs holding an opposite spin differ from the spins of ferromagnet tending to parallel alignment. Generally, superconductivity and ferromagnetism are hard to coexist in bulk materials except for very few materials such as Sr₂RuO₄, UGe₂, and UPt₃ [1, 2]. That is because ferromagnetic exchange energy (h_0) is commonly several orders of magnitude over than the superconducting energy gap (Δ), dissatisfying the Clogston criterion ($h_0 / \Delta < 0.754$) [3]. However, a superconductor/ferromagnet (S/F) heterostructure provides us a good platform to study the mutual interaction between superconductivity and ferromagnetism [4]. The most striking feature of an S/F heterostructure is the oscillation of the superconducting order parameter on the F side, which has been confirmed by experimental observations of the oscillation of the critical temperature (T_c) of the S/F junction [5, 6] and the transition between 0 and π states [7, 8].

In recent years, some experimental results [9–15] show that the penetration length (L) of Cooper pairs in F layers far exceeds the characteristic length (ξ_F). For instance, a spin-triplet supercurrent was observed by Keizer et al. [11] in the S/F/S junction where F was half-metallic ferromagnet CrO₂. Additionally, Wang et al. [12] reported that zero resistance still can be attained in cobalt nanowires sandwiched between superconducting electrodes with the length of cobalt nanowires in 600 nm. To explain the *long-range* superconducting proximity effect phenomenon, Bergeret et al. [16] proposed the notion of triplet component of superconducting condensate, which could be induced on the F side with a local inhomogeneous magnetization near the S/F interface. The induced triplet Cooper pair has been considered to be odd-frequency s wave in many works [17–21],

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which was first proposed by Berezinskii [22] to account for ^3He superfluid mechanism. However, the exact experimental evidences for the odd-frequency s wave triplet state are still lacking. The usual even-frequency p wave triplet pairing has also been suggested in the S/F junction by experimental and theoretical studies [23]. In this case, the system should not be very dirty and the anisotropic p wave can survive [24].

Besides the observation of a long-range proximity effect on the conventional S/F junction, such effect was also recently observed in the high- T_c cuprate superconductor/manganite ferromagnet junction. For example, in a $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}/\text{La}_{0.7}\text{Ca}_{0.3}\text{MnO}_3$ (YBCO/LCMO) superlattice structure, superconductivity is depressed over a thickness interval of the magnetic layer in the 100 nm range [14, 15]. A few theoretical research works on d wave superconducting proximity effect were reported. Niu and Xing [25] have calculated the d wave S/F junction with the Bogoliubov–de Gennes (BdG) equation and found the induced triplet pairing near the S/F interface with non-collinear magnetizations.

In order to further understand the d wave superconducting proximity effect and the inducing process of triplet component, in this work, we constructed the d wave S/ F_1 / F_2 trilayer structure, which is shown in Fig. 1. In this structure, the magnetization direction of soft magnet layer F_1 can be controlled by an external magnetic field, while the magnetization direction of hard magnet layer F_2 is undisturbed. We have extended four-component Eilenberger equations to suit for our system, which contains not only singlet but also triplet pairing components. We consider the possible p wave pairing correlation in the F layer, which is close to the clean limit. We find that equal-spin triplet component can be induced as the magnetization directions of F_1 / F_2 layers are non-collinear, and gets maximum when the angle of two magnetizations of F_1 / F_2 layers approximate $2/3\pi$. Furthermore, other parameters are also studied in the induced effect on triplet pairing. Our proposed magnetic field tunable S/ F_1 / F_2 trilayer junction could be used as a superconducting switch device, opening up a new view of spintronics.

2 The Model and Method

We construct the S/ F_1 / F_2 trilayer junction as shown in Fig. 1. Here, S represents the d wave superconductor, e.g., $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ with CuO_2 (a – b) planes perpendicular to the S/F interface. F_1 denotes a thin soft magnetic material, e.g., $\text{La}_{0.7}\text{Ca}_{0.3}\text{MnO}_3/\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$, of which the magnetization could be rotated in y – z plane by an external magnetic field, and F_2 stands for a hard magnetic material, e.g., $\text{La}_{0.7}\text{Sr}_{0.3}\text{CoO}_3/\text{CoFe}_2\text{O}_4$, whose magnetization is assumed to be along the z -axis and hardly be changed by

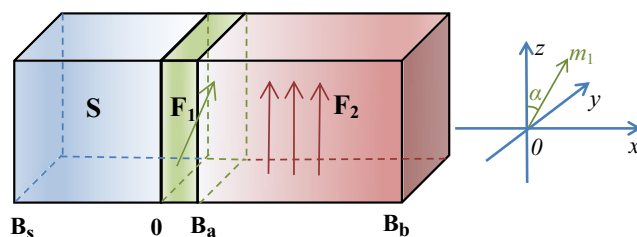


Fig. 1 Schematic illustration of a multi-layer junction structure. S represents the d wave superconductor. F_1 is a soft magnetic material of which the magnetization could be rotated in the y – z plane by an external magnetic field, and F_2 is a hard magnetic material whose magnetization is assumed to be along the z -axis

an external magnetic field. For the above junction structure, when applying the external magnetic field to alter F_1 magnetization, non-collinear magnetization emerges and gives rise to a local inhomogeneous magnetization near the F_1 / F_2 interface, which could induce equal-spin triplet pairing component on F_2 sides.

Instead of using the Usadel equation which is attained approximately in the dirty limit and considering the real system between dirty and clean limits, we start from the Eilenberger equation. Near T_c , the Eilenberger equation for anomalous Green's function takes the following form [26, 27]:

$$\left(\varpi \pm i\hbar - \frac{1}{2}\mathbf{v}\frac{\partial}{\partial\mathbf{R}}\right)f_{\pm}(\omega, \mathbf{R}, \mathbf{v}) = \tilde{\Delta}_{\pm}(\omega, \mathbf{R}, \mathbf{v}) \quad (1)$$

where $\tilde{\Delta}_{\pm}(\omega, \mathbf{R}, \mathbf{v}) = \Delta + \frac{1}{2\tau_1} \int \frac{d\Omega'}{4\pi} f_{\pm}(\omega, \mathbf{R}, \mathbf{v}') + \frac{3}{2\tau_{so}} \int \frac{d\Omega'}{4\pi} f_{\mp}(\omega, \mathbf{R}, \mathbf{v}') \sin^2(\theta - \theta')$ and $\varpi = \omega + \frac{1}{2\tau_1} + \frac{1}{\tau_{so}}$ (ω is the Matsubara frequency, $\mathbf{R}$ is the center of the mass coordinate of paired particles, $\mathbf{v}$ is the Fermi velocity, τ_{so} is the spin orbit scattering time, and τ_1 is the elastic scattering time). $f_{\pm}(\omega, \mathbf{R}, \mathbf{v})$ is the anomalous Green's function $\begin{pmatrix} f_{\uparrow\downarrow} & f_{\uparrow\uparrow} \\ f_{\downarrow\downarrow} & f_{\downarrow\uparrow} \end{pmatrix}$, which contains not only the opposite-spin component ($f_{\uparrow\downarrow}(\downarrow\uparrow)$) but also the equal spin component ($f_{\uparrow\uparrow}(\downarrow\downarrow)$).

We can apply $\hat{f} = \begin{pmatrix} f_{\uparrow\downarrow} & f_{\uparrow\uparrow} \\ f_{\downarrow\downarrow} & f_{\downarrow\uparrow} \end{pmatrix} = f_0\hat{\sigma}_0 + f_1\hat{\sigma}_1 + f_3\hat{\sigma}_3$ ($\hat{\sigma}_0$ and $\hat{\sigma}_{i=1,2,3}$ are the unit and Pauli matrix, respectively, $\hat{f}_{\text{sing}} = f_3\hat{\sigma}_3$ and $\hat{f}_{\text{trip}} = f_0\hat{\sigma}_0 + f_1\hat{\sigma}_1$) to generalize Eq. 1 in the Pauli space. Here, we omit the whole mathematical process of simplifying Eq. 1, which has been introduced minutely in [23]. We reserve all the information of parameters without any approximation, and the simplified diffusive equation for the F layer can be written as follows:

$$-iD\frac{\partial^2}{\partial x^2}\hat{f} + 2\tilde{e}\hat{f} + \{\hat{V}, \hat{h}, \hat{f}\} + i4/\tau_{so}(1 - i\varepsilon \cdot 2\tau_1) \cdot \hat{f}_{\text{sing}} = 0 \quad (2)$$

Here, we use energy ($\varepsilon = i\omega$) to substitute the Matsubara frequency (ω), $\tilde{\varepsilon} = \varepsilon(1 - i2\tau_t\varepsilon) - i2\tau_t h^2$, $\tilde{h} \cdot \hat{f} = \sum_{i=0,1,3} h_i f_i \sigma_i$ with $h_{0,1} = h(1 - i4\tau_t\varepsilon)$ and $h_3 = h(1 - i4\tau_t\varepsilon + 4\frac{\tau_t}{\tau_{so}})$. The matrix ($\hat{V}_{l=1,2}$) contains the magnetization direction message (in our model, the matrix $\hat{V}_1$ for the F_1 layer is $\hat{\sigma}_3 \cos \alpha + \hat{\sigma}_2 \sin \alpha$, where α is the angle between $h(x)$ and z -axis, and the matrix $\hat{V}_2$ for the F_2 layer will degenerate to $\hat{\sigma}_3$). $\{\cdot\cdot\}$ is the anticommutator. The modified Eilenberger equations suited to our trilayer junction are given by as follows:

$$-iD_S \frac{\partial^2}{\partial x^2} \hat{f}_S + 2\varepsilon \hat{f}_S - 2\Delta \hat{\sigma}_3 = 0, \quad B_s < x < 0 \quad (3)$$

$$\begin{aligned} & -iD_F \frac{\partial^2}{\partial x^2} \hat{f}_{F1} + 2\varepsilon \hat{f}_{F1} + \{\hat{V}_1, \tilde{h} \cdot \hat{f}_{F1}\} \\ & + i4/\tau_{so}(1 - i\varepsilon \cdot 2\tau_t) \cdot \hat{f}_{F1}^{\text{sing}} = 0, \quad 0 < x < B_a \end{aligned} \quad (4)$$

$$\begin{aligned} & -iD_F \frac{\partial^2}{\partial x^2} \hat{f}_{F2} + 2\varepsilon \hat{f}_{F2} + \{\hat{V}_2, \tilde{h} \cdot \hat{f}_{F2}\} \\ & + i4/\tau_{so}(1 - i\varepsilon \cdot 2\tau_t) \cdot \hat{f}_{F2}^{\text{sing}} = 0, \quad B_a < x < B_b \end{aligned} \quad (5)$$

Supplementing the above Eilenberger equations with proper boundary conditions,

$$\left. \frac{d\hat{f}_S}{dx} \right|_{x=-B_s} = 0, \quad \xi_S \left. \frac{d\hat{f}_S}{dx} \right|_{x=0^-} = \gamma \xi_F \left. \frac{d\hat{f}_{F1}}{dx} \right|_{x=0^+}, \quad \gamma = \rho_S \xi_S / \rho_F \xi_F \quad (6)$$

$$\xi_S \frac{\gamma_b}{\gamma} \left. \frac{d\hat{f}_{F1}}{dx} \right|_{x=0^+} = \hat{f}_S - \hat{f}_{F1}, \quad \hat{f}_{F1} \Big|_{x=B_a^-} = \hat{f}_{F2} \Big|_{x=B_a^+}, \quad \gamma_b = R_b A / \rho_F \xi_F \quad (7)$$

$$\left. \frac{d\hat{f}_{F1}}{dx} \right|_{x=B_a^-} = \left. \frac{d\hat{f}_{F2}}{dx} \right|_{x=B_a^+}, \quad \left. \frac{d\hat{f}_{F2}}{dx} \right|_{x=B_b} = 0 \quad (8)$$

Here, we assume F_1 and F_2 have the same parameter and there is no resistance at the F_1/F_2 interface. $D_{S(F)}$ is the diffusion coefficient, $\xi_{S(F)} = \sqrt{D_{S(F)}/2\pi T_{cs}}$ is the coherence length, and $\rho_{S(F)}$ is the resistivity for superconducting and ferromagnetic layers, respectively. R_b is the interface resistance at $x = 0$, and A is its area. The pair potential for the d wave superconductor takes the form $\Delta = \Delta_0 \cos(2\theta_s \mp 2\beta)$ [28], where θ_s is the angle between the momentum of the quasiparticle and x -axis and β is the angle of the crystal a -axis and x -axis, and we assume it to be zero. The density of states (DOS) can be obtained by calculating with $N(x, \varepsilon) = N_0 \int d\theta \text{Re}\{\sqrt{1 - f(x, \varepsilon, \theta)} f^\dagger(x, \varepsilon, \theta)\}$, where N_0 denotes local DOS of normal state at the Fermi energy, and the relevant numerical results are discussed below.

3 Results and Analysis

3.1 $\alpha = 0$ Situation

Firstly, we consider the case that the magnetization directions of F_1 and F_2 are parallel, which degenerates to the simple S/F model. Using this model, we can check the efficiency of calculation by our theoretical method. Here, we calculate the superconducting wave function with reasonable parameters ($\Delta_0 = 10$ meV, $\xi_S = \xi_F = 5$ nm, $\gamma = 0.2$, $\gamma_b = 0.1$, $h/\Delta = 8$). The calculated wave function amplitudes ($|f|$) for each possible component are shown in Fig. 2a [the red line stands for singlet component (f_3), and green and blue lines denote opposite-spin and equal-spin triplet components (f_0/f_1), respectively]. As expected,

Fig. 2 **a** Superconducting wave function amplitude ($|f|$) for singlet component (f_3) (red line), $m_z = 0$ opposite-spin triplet component (f_0) (green line), and $m_z = \pm 1$ equal-spin triplet component (f_1) (blue line). **b** Normalized DOS for the F layer with two different thicknesses. **c** Energy gap ($\Delta(x)$) for the whole junction

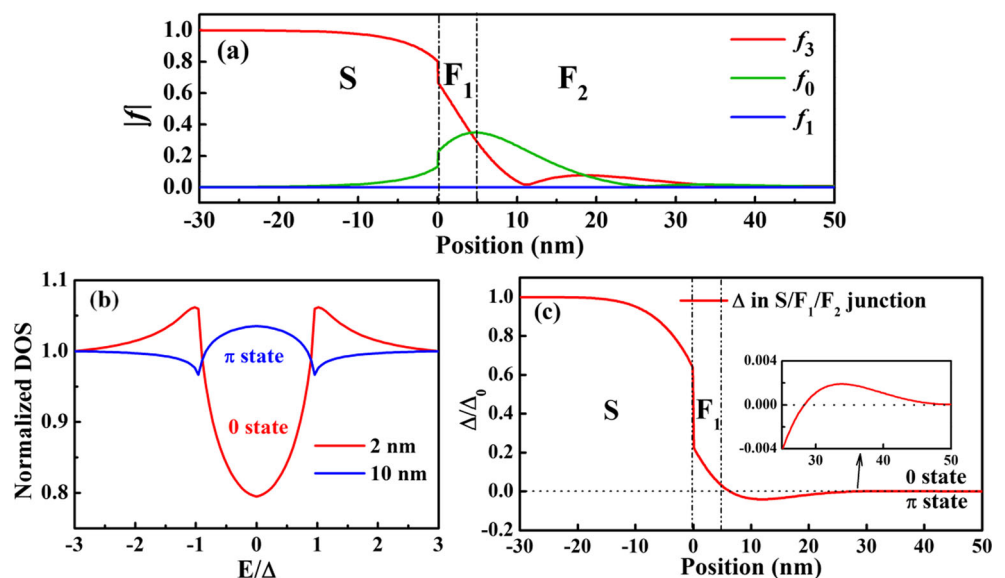
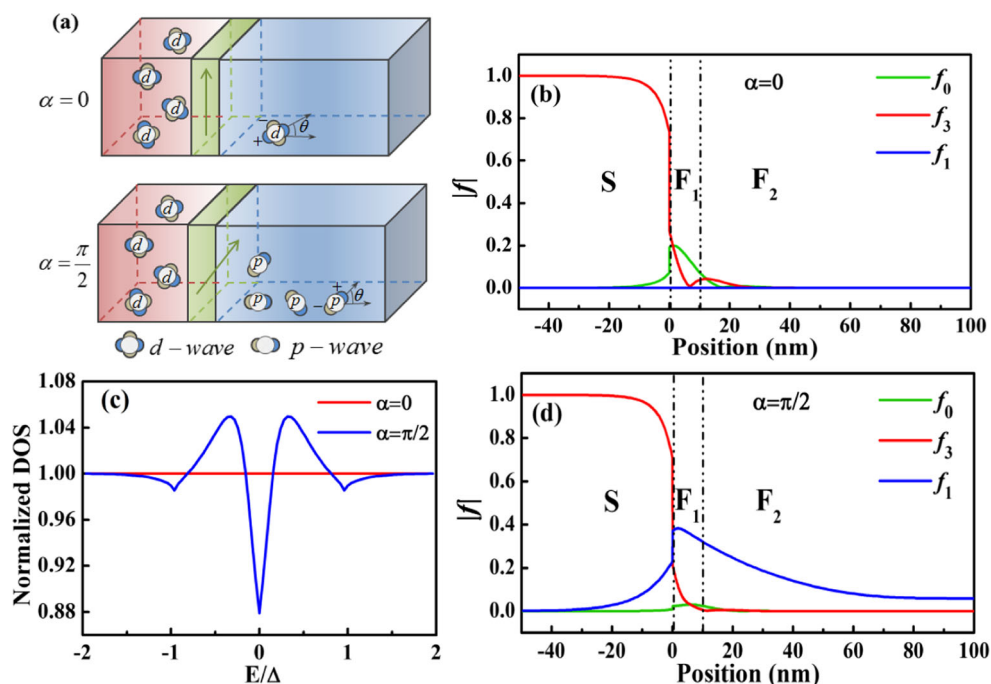


Fig. 3 **a** Schematic diagram of the proximity effect in two different S/F configurations. **b** Superconducting wave function amplitude ($|f|$) in the S/F₁/F₂ junction with F₁ and F₂ in parallel alignment. **c** The DOS for the two different situations of $\alpha = 0$ and $\alpha = \pi/2$ at $x = B_b$ position. **d** Superconducting wave function amplitude ($|f|$) in the S/F₁/F₂ junction with F₁ and F₂ in perpendicular alignment



the equal-spin triplet component (f_1) keeps always zero, since no equal-spin triplet pairs are induced in the simple S/F junction. In the superconductor layer near the S/F interface, the singlet component (f_3) decays gradually and the opposite-spin triplet component starts to emerge. Due to interfacial resistance and boundary condition, the wave function amplitude ($|f|$) is discontinuous at the interface. In the ferromagnetic layer, the singlet component (f_3) and the opposite-spin triplet component (f_0) are coupling via a homogeneous magnetization, $h(x)$. The opposite-spin triplet component is induced from conversion of singlet pairings through a *spin-mixing effect* [29] (opposite-spin electrons acquire different scattering phase shifts) at the S/F ferromagnetic interface. Both the two components hold a non-monotonic exponential decaying behavior with oscillations.

The calculated DOS for the F layer with two different thicknesses is shown in Fig. 2b. When the thickness of the F layer is 2 nm, the DOS manifests a zero-bias conductance valley, which is marked “0” state. On the contrary, in the case of the 10-nm F layer, the DOS presents a zero-bias conductance peak, which is marked “π” state. The DOS of the S/F junction converts from zero state to π state back and forth with the increase of F layer thickness. To better illustrate this oscillation of the DOS, we calculate the energy gap function for the whole junction with $\Delta(x) = \frac{\lambda}{\hbar} \int_0^{\hbar w_D} d\varepsilon (\frac{1}{2}) \text{Im}[f_3(\varepsilon, x)]$, where w_D is the Debye frequency [30], which is shown in Fig. 2c. It is explicit to find that the energy gap ($\Delta(x)$) oscillates with the thickness of the F layer. When a thin ferromagnet contacts with

a superconductor, the ferromagnet would acquire a “mini-gap” by leakage of Cooper pairs from superconductor. That is why the ferromagnet performances have similar superconductivity behavior. The oscillation of superconducting order parameter on the F side is attributed to Cooper pairs, which penetrate into ferromagnet and obtain a center of the mass momentum, $Q = 2\hbar / v_F$ [26].

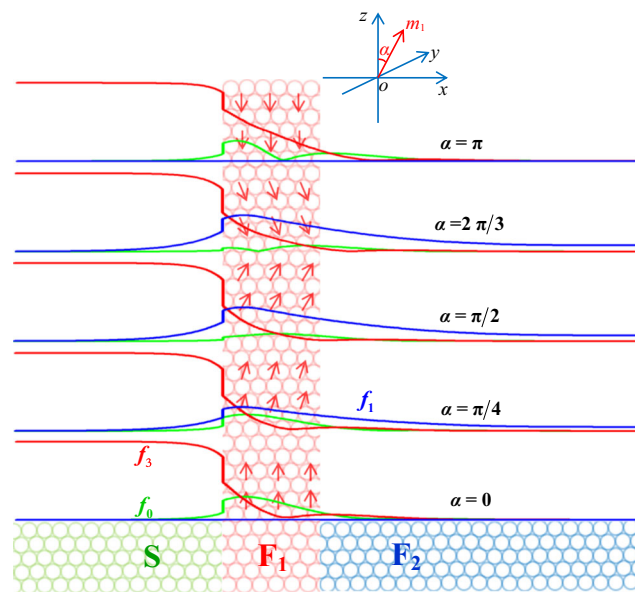


Fig. 4 Variation of superconducting wave function in the S/F₁/F₂ junction for a series of different angles of magnetization directions between F₁ and F₂

3.2 $\alpha \neq 0$ Situation

Next, we consider the special configuration of F_1 and F_2 layers, for which the magnetization directions are perpendicular with each other. Because of magnetic misalignment, *breaking spin-rotation symmetry mechanism* [29] will lead to a spin-flip process and make $m_z = 0$ opposite-spin triplet into $m_z = \pm 1$ equal-spin triplet correlations. Just as what we have seen in Fig. 3d, $m_z = \pm 1$ equal-spin triplet component (blue line) is induced greatly and penetrates into the F layer surviving for a long distance. We also calculate the DOS in the two different situations as shown in Fig. 3c. The DOS for $\alpha = 0$ situation manifests a horizontal line like

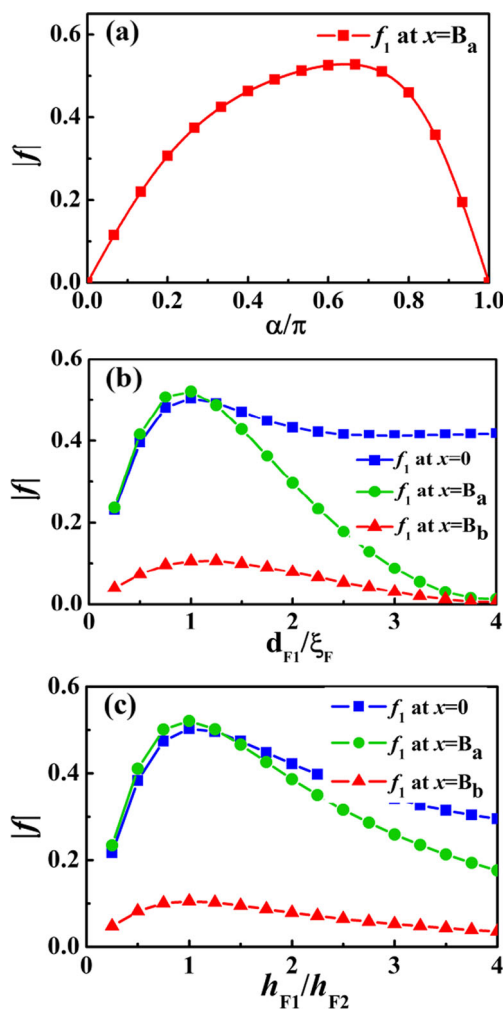


Fig. 5 **a** Equal-spin triplet component function amplitude (f_1) varies with angle α . **b** Equal-spin triplet component function at boundary positions (the blue line indicates a position at $x = 0$, and the green and red lines indicate a position at $x = B_a$ and $x = B_b$, respectively) as a function of the thickness of the F_1 layer. **c** Equal-spin triplet component function amplitude at boundary positions as a function of exchange field ratio (h_{F1}/h_{F2})

the DOS of a normal metal. We mark it “high impedance state,” for which only normal electrons can flow through this junction. The DOS for $\alpha = \pi/2$ situation exhibits a split zero-bias conductance peak with a superconducting energy gap structure. And we mark it “low resistance state,” for which the equal-spin triplet Cooper pairs play an important role in the conduction process.

We further study the effect of various parameters (α is the angle of magnetization directions of F_1/F_2 layers, d_{F1} is the thickness of the F_1 layer, and h_{F1}/h_{F2} is the ratio of ferromagnetic exchange fields in F_1/F_2 layers) on the induced long-range equal-spin triplet pairing.

In Fig. 4, one can clearly find that the $m_z = \pm 1$ equal-spin triplet component is induced when $\alpha \neq 0, \pi$. To quantify the relation between α and induced $m_z = \pm 1$ triplet component, we plot the calculated results in Fig. 5a. Interestingly, the equal-spin triplet component can be induced maximally at $\alpha = 2/3\pi$. Figure 5b, c shows that the equal-spin triplet component can also be induced maximally when the thickness of the F_1 layer is approximate to the coherence length (ξ_F) and the ratio of exchange fields is close to 1.

4 Conclusion

In this paper, we have extended the Eilenberger equations to suit for the d wave superconductor/ferromagnet/ferromagnet ($S/F_1/F_2$) hybrid system. By calculating the superconducting wave functions (f_3 , f_0 , and f_1) and the DOS, we find that when F_1 and F_2 layers are in parallel magnetization, only normal electrons can flow through this junction. When the magnetization directions of F_1 and F_2 layers are non-collinear, equal-spin triplet pairings (f_1) are induced and dominate the conductance of the $S/F_1/F_2$ junction. We also study some parameters (α , d_{F1} , h_{F1}/h_{F2}) that influence on inducing equal-spin triplet pairings. Especially, we find that p wave equal-spin triplet pairings (f_1) can be maximally induced as the angle between F_1 and F_2 of approximates $2/3\pi$. Such a tunable $S/F_1/F_2$ trilayer junction could be attained by experimentally choosing the proper materials to fabricate, e.g., $YBa_2Cu_3O_{7-\delta}/La_{0.7}Sr_{0.3}MnO_3/CoFe_2O_4$. By magnetic field whether controlling the induction of triplet component or not, this “field-effect transistor” $S/F_1/F_2$ based on the long-range spin-triplet superconductivity could be used as a superconducting switch device.

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