Josephson current versus potential strength of the interface in ferromagnetic superconductors*

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(Received 9 September 2013; revised manuscript received 4 December 2013; published online 25 March 2014)

Based on the scattering theory, we calculate the Josephson current in a junction between two ferromagnetic superconductors as a function of the interface potential z. We consider the ferromagnetic superconductor (FS) in three different Cooper pairing states: spin singlet s-wave pairing (SWP) state, spin triplet opposite spin pairing (OSP) state, and spin triplet equal spin pairing (ESP) state. We find that the critical Josephson current as a function of z shows clear differences among the SWP, OSP, and ESP states. The obtained results can be used as a useful tool for determining the pair symmetry of the ferromagnetic superconductors.

Keywords: ferromagnetic superconductors, spin singlet s-wave pairing state, spin triplet opposite spin pairing state, spin triplet equal spin pairing state

PACS: 74.45.+c **DOI:** 10.1088/1674-1056/23/5/057402

1. Introduction

One of the interesting characteristic features in the junction between superconductors is the Josephson current, which was presented by Brian Josephson in 1961.[1,2] The Josephson current is important not only for applications but also for theoretical studies. It can be used as a probe for determining the pairing symmetry of superconductors. After the discovery of novel superconductors, one of the most asked questions is about the symmetry of Cooper pairing states in those superconductors.

Although ferromagnetism and superconductivity are known as two opposite phenomena, the coexistence of them was reported in 2000 and 2001.[3–5] Some research groups observed superconductivity in some ferromagnetic materials, such as $ZrZn_2$,[3] UGe_2,[4] and URhGe.[5] Those new materials were then called ferromagnetic superconductors (FSs). Theoretically, most challenges are about the kind of pairing symmetries in those superconductors. In the presence of ferromagnetism, it seems that FSs should fall into the spin triplet equal spin pairing state, while some evidences have been presented for other symmetries, such as the spin singlet s-wave pairing state.[6–10] For example, in a study about the nuclear relaxation rate in UGe_2, the possibility of the spin singlet s-wave pairing state was predicted.[6,7] Also, by using the theory of weak ferromagnetic Fermi liquid, the possibility of s-wave superconductivity was suggested.[8] The s-wave pairing state for UGe_2 was suggested to be mediated by local ferromagnetic spins.[9,10]

For the first time, based on the scattering theory, Furusaki and Tsukada presented a formula for calculating the Josephson current.[11] In the last years, different groups have modified their theories to the unconventional superconductors.[12,13] And the study of the Josephson current in the presence of ferromagnetism has shown that the Andreev reflection plays a key role in the spectra of the Josephson current.[14–18] Recently, the Josephson current for triplet pairing in the presence of ferromagnetism has been studied in various cases.[19–21] In Refs. [26]–[29], the Josephson currents for ferromagnetic superconductors with different pair symmetries have been studied. In all of them, the Josephson current versus the temperature and exchange field was studied, while in this paper, we study the Josephson current versus the potential strength of the junction. In fact, our goal is to show that the Josephson current versus the potential strength of the junction shows a clear difference for three different Cooper pairing states: spin singlet s-wave pairing (SWP) state, spin triplet opposite spin pairing (OSP) state, and spin triplet equal spin pairing (ESP) state. These pairing states are three candidates for the symmetry of ferromagnetic superconductors.[23–25]

In the current study, we calculate the critical Josephson current for an FS/I/FS junction, where FS and I indicate a ferromagnetic superconductor and an insulator, respectively. We consider the FS in the spin singlet s-wave pairing state, the spin triplet opposite spin pairing state, and the spin triplet equal spin pairing state respectively. These pairing symmetries for FSs have been presented in Refs. [19] and [20]. The critical Josephson current versus the potential strength of the insulator (z) shows clear distinctions among SWP, OSP, and ESP states. For the SWP, the Josephson current is a decreasing function of z; for the OSP, it is an increasing function of z, and with the increase of the FS exchange field (h), the Josephson current decreases. For the ESP state, the Josephson current is independent of h and increases with increasing z. The strength of the

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barrier potential for discriminating different pair potentials in ferromagnetic superconductors has been studied in Ref. [22]. In Ref. [24], it was found that in a strong barrier potential, the difference between s-wave pairing, OSP, and ESP states becomes clear. Therefore, with large h and z, the Josephson current versus z shows clear distinctions among SWP, OSP, and ESP states, which can be used as a useful tool for discriminating between them.

2. Theoretical framework

The junction under study is a two-dimensional system which is formed between two identical ferromagnetic superconductors, FS/I/FS, where I indicates an insulator whose potential is modeled by a delta function, FS indicates a ferromagnetic superconductor which can have one of the three different Cooper pairing states: spin singlet s-wave pairing state, spin triplet opposite spin pairing state, and spin triplet equal spin pairing state. The motion of the quasiparticles is described by the following Hamiltonian:[19,20]

$$\hat{\boldsymbol{H}} = \begin{pmatrix} f(\boldsymbol{k}) & \Delta(\boldsymbol{k}) \\ -\Delta^*(-\boldsymbol{k}) & -f^*(-\boldsymbol{k}) \end{pmatrix}, \tag{1}$$

where $f(\boldsymbol{k}) = \xi_{\boldsymbol{k}} + \boldsymbol{h}\cdot\boldsymbol{\sigma}$, $\xi_{\boldsymbol{k}}$, $\boldsymbol{h}$, and $\boldsymbol{\sigma}$ indicate the band energy measured from the Fermi energy, the intrinsic exchange field of the FS, and the Pauli matrix, respectively. For simplicity, we consider $\boldsymbol{h}$ in the z direction, $\boldsymbol{h} = h\hat{\boldsymbol{z}}$, where h is a constant. The $\Delta(\boldsymbol{k})$ denotes the FS pair potential. For the SWP state, it is described by the following equation:

$$\Delta(\boldsymbol{k}) = \mathrm{i}\Delta\sigma_y. \tag{2}$$

For OSP and ESP states, $\Delta(\boldsymbol{k}) = \mathrm{i}(\boldsymbol{d}(\boldsymbol{k})\cdot\boldsymbol{\sigma})\sigma_y$, where $\boldsymbol{d}(\boldsymbol{k})$ for OSP and ESP states are respectively defined as $\boldsymbol{d}(\boldsymbol{k}) = \hat{\boldsymbol{z}}(k_x + \mathrm{i}k_y)/|\boldsymbol{k}|$ and $\boldsymbol{d}(\boldsymbol{k}) = \hat{\boldsymbol{x}}(k_x + \mathrm{i}k_y)/|\boldsymbol{k}|$. Now, we are ready to consider SWP, OSP, and ESP states. For the OSP state, the eigenfunctions and the eigenvalues of electron-like quasiparticles are derived by solving the following equation:

$$\hat{\boldsymbol{H}}\begin{pmatrix} u_\pm \\ v_\pm \end{pmatrix} = E_\pm \begin{pmatrix} u_\pm \\ v_\pm \end{pmatrix}. \tag{3}$$

For hole-like quasiparticles, we have

$$\hat{\boldsymbol{H}}\begin{pmatrix} \sigma_y v_\pm \sigma_y \\ \sigma_y u_\pm \sigma_y \end{pmatrix} = -E_\pm \begin{pmatrix} \sigma_y v_\pm \sigma_y \\ \sigma_y u_\pm \sigma_y \end{pmatrix}. \tag{4}$$

By solving the above equations, we obtain the energy spectra and the wave functions of quasiparticles for SWP and OSP states

$$\begin{aligned} &E_\eta = \sqrt{\xi_{\boldsymbol{k}}^2 + |\Delta|^2} + \eta h, \quad \eta = \pm, \\ &u_\eta = \sqrt{\frac{1}{2}\left(1 + \frac{\sqrt{(E_\eta - \eta h)^2 - |\Delta|^2}}{E_\eta - \eta h}\right)}(1 \pm \hat{\boldsymbol{z}}\boldsymbol{\sigma})/2, \\ &\quad \eta = \pm, \\ &v_\eta = \sqrt{\frac{1}{2}\left(1 - \frac{\sqrt{(E_\eta - \eta h)^2 - |\Delta|^2}}{E_\eta - \eta h}\right)}(1 \pm \hat{\boldsymbol{z}}\boldsymbol{\sigma})\frac{\Delta^*}{2|\Delta|}, \\ &\quad \eta = \pm. \end{aligned} \tag{5}$$

The energy spectrum for the ESP state is $E_\pm = \sqrt{(\xi_{\boldsymbol{k}} \pm h)^2 + |\Delta|^2}$, and the eigenfunctions are

$$\begin{aligned} &\begin{pmatrix} u_- \\ -v_-\,\mathrm{e}^{-\mathrm{i}\theta} \end{pmatrix}, \quad \begin{pmatrix} v_- \\ -u_-\,\mathrm{e}^{-\mathrm{i}\theta} \end{pmatrix}, \\ &\begin{pmatrix} u_+ \\ v_+\,\mathrm{e}^{-\mathrm{i}\theta} \end{pmatrix}, \quad \begin{pmatrix} v_+ \\ u_+\,\mathrm{e}^{-\mathrm{i}\theta} \end{pmatrix}, \end{aligned} \tag{6}$$

with

$$\begin{aligned} u_\pm &= \sqrt{\frac{1}{2}\left(1 + \frac{\sqrt{(E_\pm{}^2 - |\Delta|^2}}{E_\pm}\right)}, \\ v_\pm &= \sqrt{\frac{1}{2}\left(1 - \frac{\sqrt{(E_\pm{}^2 - |\Delta|^2}}{E_\pm}\right)}. \end{aligned} \tag{7}$$

Now, with the above information, we can write the wave functions of quasiparticles in both sides of the junction. The interface is located at $x = 0$. An incoming electron which moves to the interface from the left side has the following wave function:

$$\begin{aligned} \Psi_{\mathrm{L}}(x) = {} & \mathrm{e}^{\mathrm{i}k_{\mathrm{FS}}^{(\mathrm{L})}x\cos\theta_{\mathrm{L}}}\begin{pmatrix} u \\ v_{\mathrm{L}_+} \end{pmatrix} + a\,\mathrm{e}^{\mathrm{i}k_{\mathrm{FS}}^{(\mathrm{L})}x\cos\theta_{\mathrm{L}}^{\mathrm{a}}}\begin{pmatrix} \alpha \\ \beta_{\mathrm{L}} \end{pmatrix} \\ & + b\,\mathrm{e}^{-\mathrm{i}k_{\mathrm{FS}}^{(\mathrm{L})}x\cos\theta_{\mathrm{L}}}\begin{pmatrix} u \\ v_{\mathrm{L}_-} \end{pmatrix}, \end{aligned} \tag{8}$$

and the wave function in the right side of the interface is

$$\begin{aligned} \Psi_{\mathrm{R}}(x) = {} & c\,\mathrm{e}^{\mathrm{i}k_{\mathrm{FS}}^{(\mathrm{R})}x\cos\theta_{\mathrm{R}}}\begin{pmatrix} u \\ v_{\mathrm{R}_+} \end{pmatrix} \\ & + d\,\mathrm{e}^{-\mathrm{i}k_{\mathrm{FS}}^{(\mathrm{R})}x\cos\theta_{\mathrm{R}}}\begin{pmatrix} \alpha \\ \beta_{\mathrm{R}_-} \end{pmatrix}, \end{aligned} \tag{9}$$

where a and b are the Andreev reflection and the normal reflection coefficients, respectively, and $k_{\mathrm{FS}}^{(\mathrm{L})(\mathrm{R})}$, $\theta_{\mathrm{L}(\mathrm{R})}$, and $\theta_{\mathrm{L}}^{\mathrm{a}}$ are the wave vector FS in the left (right) side for both spin-up and spin-down quasiparticles, the angle of electron-like quasiparticle with respect to the normal interface in the left (right) side, and the angle of the reflected hole with respect to the normal interface in the left side, respectively. The α, $v_{\mathrm{L}_{+(-)}}$, v_{R_+}, β_{R_-}, and β_{L} are defined as

$$\begin{aligned} &\alpha = v, \\ &v_{\mathrm{L}_{+(-)}} = v\mathrm{e}^{-\mathrm{i}\Phi_{\mathrm{L}} - \mathrm{i}\gamma_{+(-)}}, \quad \beta_{\mathrm{L}} = u\mathrm{e}^{-\mathrm{i}\Phi_{\mathrm{L}} - \mathrm{i}\gamma_-}, \\ &v_{\mathrm{R}_+} = v\mathrm{e}^{-\mathrm{i}\Phi_{\mathrm{R}} - \mathrm{i}\gamma_+}, \quad \beta_{\mathrm{R}_-} = u\mathrm{e}^{-\mathrm{i}\Phi_{\mathrm{R}} - \mathrm{i}\gamma_-}, \end{aligned} \tag{10}$$

where u and v are defined in Eqs. (5) and (6), and $\Phi_{\mathrm{L}(\mathrm{R})}$ is the external phase of the FS in the left (right) side, and $\gamma_{+(-)}$ is the internal phase of the FS in a different Cooper pairing. Now we can apply the boundary conditions to the junction

$$\begin{aligned} &\Psi_{\mathrm{R}}(x=0) = \Psi_{\mathrm{L}}(x=0), \\ &\Psi'_{\mathrm{R}}(x=0) - \Psi'_{\mathrm{L}}(x=0) = \tfrac{2mV_0}{\hbar^2}\Psi(x=0). \end{aligned} \tag{11}$$

Under these boundary conditions, we find the Andreev reflection coefficient

$$a_\eta(E,\theta,\varphi) = \frac{(E+\eta h)(\cos\varphi-1)-\mathrm{i}\sin\varphi\sqrt{(E+\eta h)^2-|\Delta|^2}-z_\theta^2[(E+\eta h)(1-\cos(\gamma_1-\gamma_2))-\mathrm{i}\sin(\gamma_1-\gamma_2)\sqrt{(E+\eta h)^2-|\Delta|^2}]}{2(E+\eta h)^2-|\Delta|^2(1+\cos\varphi)+z_\theta^2[2(E+\eta h)^2-|\Delta|^2(1+\cos(\gamma_1-\gamma_2))]}\,|\Delta|, \quad (12)$$

where φ ($=\Phi_\mathrm{R}-\Phi_\mathrm{L}$) is the phase difference between ferromagnetic superconductors. The Andreev reflection coefficient for the SWP state is obtained from the above equation by replacing $\gamma_1=\gamma_2=0,\eta=\pm$, and $z_\theta=z/\cos\theta$, for the OSP state by replacing $\gamma_1=\theta,\gamma_2=\pi-\theta,\eta=\pm$, and $z_\theta=z/\cos\theta$, for the ESP state by replacing $\gamma_1=\theta,\gamma_2=\pi-\theta,\eta=0$, and $z_\theta=z/[\cos\theta\sqrt{1\mp h/(E_\mathrm{F}\cos^2\theta)}]$, where we have $z=mV_0/(\hbar^2k_\mathrm{F})$.

With the aid of the Andreev reflection coefficient, the DC Josephson current may be obtained from the Furusaki–Tsukada formula

$$I = \frac{ek_\mathrm{B}T|\Delta|}{2\hbar}\times\sum_{\omega_n}\int_{-\pi/2}^{\pi/2}\mathrm{d}\theta\cos\theta\left[\frac{a_+(\mathrm{i}\omega_n,\theta,\varphi)-a_+(\mathrm{i}\omega_n,\theta,-\varphi)}{\Omega_{+n}}+\frac{a_-(\mathrm{i}\omega_n,\theta,\varphi)-a_-(\mathrm{i}\omega_n,\theta,-\varphi)}{\Omega_{-n}}\right], \quad (13)$$

where $\Omega_{+n}=\Omega_{-n}=\sqrt{\omega_n^2+|\Delta|^2}$ for the ESP state, and $\Omega_{\pm n}=\sqrt{(\omega_n\pm\mathrm{i}h)^2+|\Delta|^2}$ for the OSP and SWP states, with the Matsubara frequency $\omega_n=\pi k_\mathrm{B}T(2n+1)$. From Eqs. (12) and (13), we finally obtain the Josephson current for $\varphi=\pi/2$ in the following form:[26]

$$R_\mathrm{N}I_\mathrm{OSP}^{[\mathrm{SWP}]} = \frac{\pi\overline{R}_\mathrm{N}k_\mathrm{B}T}{e}\sum_{\omega_n}\int_{-\pi/2}^{\pi/2}\mathrm{d}\theta\frac{\cos\theta}{1+z_\theta^2}\times\frac{\omega_n^2-h^2+\alpha(\theta)\Delta^2(T,h)}{(\omega_n^2-h^2+\alpha(\theta)\Delta^2(T,h))^2+4\omega_n^2h^2}|\Delta|^2, \quad (14)$$

with $\alpha(\theta)=[1+z_\theta^2(1-\cos2\theta)]/2(1+z_\theta^2)$ for the OSP state and $\alpha(\theta)=(1+2z_\theta^2)/2(1+z_\theta^2)$ for the SWP state, $\overline{R}_\mathrm{N}^{-1}=\int_{-\pi/2}^{\pi/2}[\mathrm{d}\theta\cos\theta/1+z_\theta^2]$, and $z_\theta=z/\cos\theta$. For the ESP state, we have

$$R_\mathrm{N}I_\mathrm{ESP} = \frac{\pi\overline{R}_\mathrm{N}k_\mathrm{B}T}{e}\sum_{\omega_n}\sum_{\eta=\pm}\int_{-\pi/2}^{\pi/2}\mathrm{d}\theta\frac{\cos\theta}{1+\lambda_\eta^2z_\theta^2}\times\frac{1}{(\omega_n^2+\alpha_\eta(\theta)\Delta^2(T,h))^2}|\Delta|^2, \quad (15)$$

with

$$\overline{R}_\mathrm{N}^{-1}=\int_{-\pi/2}^{\pi/2}\mathrm{d}\theta\frac{\cos\theta}{1+z_\theta^2},$$
$$\alpha_\eta(\theta)=\frac{1+\lambda_\eta^2z_\theta^2(1-\cos2\theta)}{2(1+\lambda_\eta^2z_\theta^2)},$$
$$\lambda_\eta=\sqrt{1-\eta h/(E_\mathrm{F}\cos^2\theta)},\quad z_\theta=z/\cos\theta.$$

In the above equations, R_N denotes the resistance of the normal–insulator–normal junction. Note that one should multiply the Heaviside step function $\Theta(\theta_\mathrm{c}-|\theta|)$ with $\theta_\mathrm{c}=\cos^{-1}\sqrt{h/E_\mathrm{F}}$ for minority spin ($\eta=+$) in the case of the ESP state (Eq. (15)) because of the mismatch of the Fermi surfaces of majority and minority spins.[24,25]

3. Results and conclusion

Now we are ready to present the numerical results of the Josephson current in Eqs. (14) and (15) for three different Cooper pairings. Figures 1 and 2 show the dependence of the Josephson current on z at temperature $k_\mathrm{B}T/\Delta_0=0.05$ for SWP, OSP, and ESP states at $h/\Delta_0=0$–0.2 and $h/\Delta_0=0.3$–0.6 respectively, where k_B is the Boltzman constant. The vertical axes in Figs. 1 and 2 are defined as J/J_0, where J equals to $I_\mathrm{OSP}^{[\mathrm{SWP}]}$ for OSP and SWP states and equals I_ESP for the ESP state (see Eqs. (14) and (15)), and J_0 equals $\pi\Delta_0/eR_\mathrm{N}$. The order parameter at finite temperature and the exchange field $\Delta(T,h)$ are derived from the BCS-like equations (for more details see the appendix of Ref. [25]).

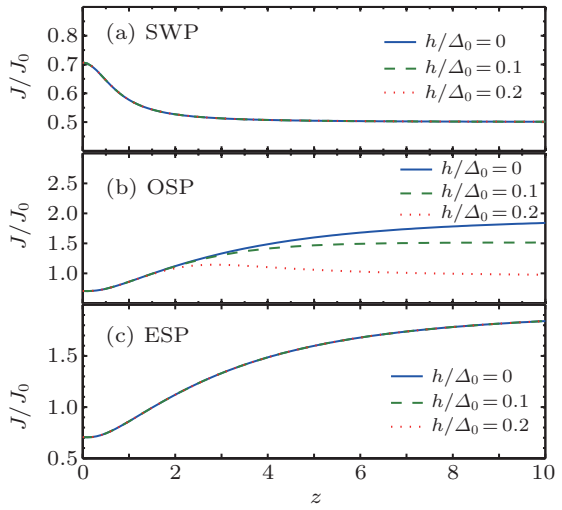


Fig. 1. (color online) Josephson current J/J_0 versus the potential strength of junction (z) for: (a) SWP, (b) OSP, and (c) ESP states at $k_\mathrm{B}T/\Delta_0=0.05$ and $h/\Delta_0=0$–0.2

Figure 1(a) shows that the Josephson current decreases very quickly as a function of z, and at $z\approx3$, it reaches a finite value. Analytically, with a little attempt from Eq. (14), we find that in the limit of large z, the Josephson current tends to a finite value, and in the high transparent limit $z\to0$, it has a maximum value. Figures 1(a) and 2(a) also show that the Josephson current versus z does not change qualitatively for different exchange fields.

Figures 1(b) and 2(b) show the z dependence of the Josephson current in the OSP state. From Figs. 1(b) and 2(b),

we find three different behaviors for the OSP state: increasing behavior for a small exchange field, splitting behavior with respect to different exchange fields, and fast decreasing behavior for a large exchange field. From Fig. 1(b), we find that the Josephson current increases in small exchange fields (see the curve for $h = 0$ in Fig. 1(b)). The reason for this behavior goes back to the sign change of the pair potential in the case of the OSP state. In fact, due to the sign change of the pair potential, zero-energy states form at the interface. One should note that at $h = 0$, the OSP and the ESP states are identical. The splitting behavior of the Josephson current comes from the fact that the wave functions of the OSP state depend on the exchange field (see Eq. (5)). We also find a fast decrease in the Josephson current in Fig. 2(b) for large exchange fields. This is because the absolute value of the order parameter $|\Delta(T,h)|$ decreases as a function of h, and it tends to zero at $h/\Delta_0 \approx 0.7$.[25] On the other hand, as Eq. (14) shows, the Josephson current is proportional to $|\Delta(T,h)|^2$, so it rapidly decreases at large h.

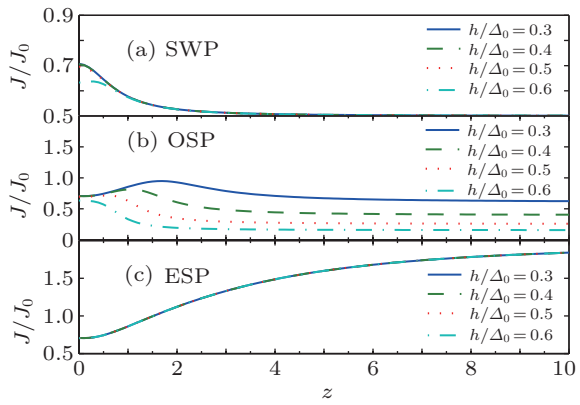


Fig. 2. (color online) Josephson current J/J_0 versus the potential strength of junction (z) for: (a) SWP, (b) OSP, and (c) ESP states at $k_B T/\Delta_0 = 0.05$ and $h/\Delta_0 = 0.3$–0.6.

Figure 1(b) shows an increasing behavior with z, and at large z for different exchange fields, it splits. This is because the wave functions of the OSP state (see Eq. (55)) depend on h and they split. Figure 2(b) shows that the magnitude of the Josephson current decreases for large h. The Josephson current goes to zero for large h.

Figures 1(a) and 1(b) show a main difference in the Josephson current behavior for SWP and OSP states. The origin of this behavior comes from the difference in the order parameter of FSs in the SWP and the OSP states. On the other hand, because of the sign change of the order parameter on the Fermi surface, zero-energy states (ZESs) are formed at the interface, while there are no ZESs in the case of the SWP state.

Considering Figs. 1(c) and 2(c), we find two important behaviors in the Josephson spectra for the ESP state: independent behavior with respect to the exchange field and increasing behavior with increasing z. As can be seen in Figs. 1(c) and 2(c), the Josephson current does not depend on the exchange field. This is because the wave function of the FS in the case of the ESP state does not show any sensitivity to the exchange field (see Eq. (7)). Therefore, the Josephson spectrum does not change with varying FS exchange field. The increasing behavior in the Josephson current as a function of z comes from the formation of ZESs at the interface. The ZESs are responsible for this peculiar behavior of the Josephson spectrum versus z. Figures 1(c) and 2(c) show that the effect of ZESs is weak in low z, while strong in large z. One should note that in Figs. 1 and 2, we have plotted $J(z)/J_0$ as the Josephson current. Since, for large z, J_0 ($= \pi\Delta_0/eR_N$) is proportional to $1/z^2$, one finds that the absolute value of $J(z)$ always decreases with increasing z. The difference between singlet and triplet is that, the decrease of $J(z)$ for the singlet case is very fast in comparison to the triplet case. Now, we compare our results with those in some previous works. In Refs. [27] and [28], it was found that under certain conditions, there is an enhancement in the Josephson current with an anti-parallel configuration. In the current study, as Figs. 1 and 2 show, the exchange field decreases the Josephson current in the cases of SWP and OSP states. This is because our system is different from those studied in Refs. [27] and [28]. In fact, our system is a junction in which the two sides are identical, i.e., both of them are in the opposite spin triplet state. The anti-parallel system in Refs. [27] and [28] consisted of a junction in which the exchange field of the right side was in the up (down) direction and the left side was in the down (up) direction with s-wave pairing. So, the results are different from each other, and we have not seen any enhancement in the Josephson current.

Thus we have found a clear distinction in the critical Josephson current versus the strength potential of the junction for three different Cooper pairing states (SWP, OSP, and ESP states). In the SWP state, the critical Josephson current is a decreasing function of z. In the OSP state, the critical Josephson current versus z splits for different FS exchange fields. While in the ESP state, the critical Josephson current shows an increasing behavior with increasing z.

In summary, we have calculated the critical DC Josephson current as a function of the potential strength of the junction which is placed between two ferromagnetic superconductors. we have found a clear difference in the z dependence of the Josephson spectra for SWP, OSP, and ESP states, and our results can be used as a useful tool for determining the pair symmetry of ferromagnetic superconductors.

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