Novel 0–π transitions in Josephson junctions between noncentrosymmetric superconductors*

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We study the Josephson effect between two noncentrosymmetric superconductors (NCSs) with opposite polarization vectors of Rashba spin–orbit coupling (RSOC). We find a 0–π transition driven by the triplet–singlet ratio of NCSs. Different from conventional 0–π transitions, the Andreev bound states change their energy range instead of phase shift in the 0–π transition found here. This novel property results in a feature that the critical current becomes almost zero at the transition point, not only a minimum. Furthermore, when the directions of RSOC polarization vectors are the same in two NCSs, the similar effect can also be found in the presence of a perpendicular exchange field or a Dresselhause spin–orbit coupling in the interlayer. We find novel oscillations of critical current without 0–π transition. These novel 0–π transitions or oscillations of critical current present new understanding of the Josephson effect and can also serve as a tool to determine the unknown triplet–singlet ratio of NCSs.

Keywords: noncentrosymmetric superconductors, Josephson effect, 0–π transition

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1. Introduction

Recently, the noncentrosymmetric superconductor (NCS) has attracted a great deal of attention for the coexistence of spin-singlet and spin-triplet superconductivity and the possibility of nontrivial topological phase developments.[1–8] In NCSs, the spin–orbit coupling (SOC) induced by the absence of inversion symmetry mixes the spin-singlet and spin-triplet components of superconducting pairing potentials.[9–11] If the spin-singlet and spin-triplet components have comparable magnitudes, the NCS has two effective superconducting gaps. The relative magnitude of the two components or triplet–singlet ratio determines the relative size of the two gaps and the main property of an NCS. The question of how to determine the triplet–singlet ratio has attracted a great deal of theoretical and experimental interest. There have been efforts which relate the two gaps to the steps in the current–voltage characteristics,[12] relate the triplet–singlet ratio to the low-temperature anomaly in the critical Josephson current,[13] or the transition from a 0 junction to a $\pi/2$ junction in the Josephson junction between an s-wave superconductor and an NCS.[14] Another work focused on the high-order harmonics in the charge and spin current–phase relations (CPRs) in a magnetic Josephson junction with NCSs.[15] Most recently, the triplet–singlet ratio was also related to the ground-state phase difference in an anomalous Josephson effect.[16] The convenient method to determine the triplet–singlet ratio is still desirable.

On the other hand, the 0–π transition in Josephson junctions has been intensively investigated.[17–23] Typically, the π junction state is realized in superconductor (S)/ferromagnet (F)/superconductor (S) junctions where the time reversal symmetry (TRS) is broken. However, TRS breaking is not necessary to realize a π junction. For example, the π junction without TRS breaking can be realized in a spin–orbit coupled junction between two triplet-superconductors.[24] No matter the difference in TRS, the common point in two types of π junctions is that the Andreev bound states (ABS) change mainly the phase shift compared with the conventional ABS in the transition, while the energy range of ABS (we refer to it as the amplitude of ABS from now on) keeps nearly unchanged. That is to say, the supercurrent carried by each set of spin-split ABS keeps nearly unchanged in the transition, but the phase difference between two sets of spin-split ABS determines the oscillation of critical current. In general, the 0–π transition is accompanied with an oscillation of the critical current except in the anomalous Josephson effect.[25–28] At the transition point, the critical current is a minimum because the first harmonic of CPR vanishes due to the π phase difference of two sets of ABS.[29] Due to the contributions from high-order harmonics, the critical current is usually nonzero.

In this paper, we introduce another kind of 0–π transitions which are novel in that ABS change the amplitude but not the phase shift in Josephson junctions between NCSs. The critical current is almost zero at the transition point. It is also found that the oscillation of critical current is not always accompanied with a 0–π transition in these junctions. We start with

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a normal junction between two NCSs with opposite polarization vectors of Rashba spin–orbit coupling (RSOC). This kind of junctions are experimentally possible due to the existence of twin domains and have been theoretically considered by a quasiclassical method.[30] Then the discussion is extended to a magnetic and a Dresselhaus spin–orbit coupled junction between two NCSs with the same Rashba polarization vector. In all these junctions, the Josephson current is sensitive to the triplet–singlet ratio of NCSs. In this sense, these junctions provide new methods to measure the triplet–singlet ratio. This ratio can even be determined directly by the critical current.

The paper is organized as follows. In Section 2, we present the model Hamiltonian and introduce the analytical and numerical methods. In Section 3, we present results and relevant discussion. Finally, the conclusion will be given in Section 4.

2. Model and methods

We start with the Bogoliubov–de Gennes (BdG) Hamiltonian for an NCS in the momentum space

$$H = \begin{pmatrix} \varepsilon_{\boldsymbol{k}} + \lambda \boldsymbol{l}_{\boldsymbol{k}} \cdot \boldsymbol{\sigma} & \Delta(\boldsymbol{k}) \\ \Delta^{\dagger}(\boldsymbol{k}) & -\varepsilon_{\boldsymbol{k}} + \lambda \boldsymbol{l}_{\boldsymbol{k}} \cdot \boldsymbol{\sigma}^{*} \end{pmatrix}. \tag{1}$$

Here, $\varepsilon_{\boldsymbol{k}} = [\hbar^2(k_x^2 + k_y^2)]/2m - \mu = \hbar^2 k^2/2m - \mu$ is the spin-independent part of the band dispersion with μ the chemical potential, and $\boldsymbol{\sigma}$ is the vector of Pauli matrices. $\lambda \boldsymbol{l}_{\boldsymbol{k}} \cdot \boldsymbol{\sigma}$ is the antisymmetric RSOC with Rashba polarization vector $\boldsymbol{l}_{\boldsymbol{k}} = k_y \widehat{\boldsymbol{x}} - k_x \widehat{\boldsymbol{y}}$ and Rashba strength λ. The superconducting gap function is $\Delta(\boldsymbol{k}) = f(\boldsymbol{k})(\Delta_{\rm s} + \Delta_{\rm t} \boldsymbol{d}_{\boldsymbol{k}} \cdot \boldsymbol{\sigma}) {\rm i}\sigma_y$, where $\Delta_{\rm s} = \Delta_0 q$ and $\Delta_{\rm t} = \Delta_0(1-q)$ are spin-singlet and spin-triplet superconducting gaps respectively with $\Delta_0 = \Delta_{\rm s} + \Delta_{\rm t}$ and q turns between purely spin-triplet ($q = 0$) and purely spin-singlet ($q = 1$) pairings. We assume $\Delta_{\rm s}$, $\Delta_{\rm t}$, and Δ_0 are positive constants, and the orbital–angular-momentum pairing state is described by the structure factor $f(\boldsymbol{k})$. In this work, we consider only the case of s+p wave where $f(\boldsymbol{k}) = 1$, because the situation for two other types of pairing ($d + p$ and $d + f$) is similar. The spin-triplet pairing vector is aligned with Rashba polarization vector $\boldsymbol{d}_{\boldsymbol{k}} = \boldsymbol{l}_{\boldsymbol{k}}/k_{\rm F}$ where $k_{\rm F}$ is the Fermi wave vector and taken as the unit of the wave vector. When Rashba splitting is much less than the chemical potential, we can use the Andreev approximation $k_{\rm F}^{\pm} \approx k_{\rm F} = 1$ with $k_{\rm F}^{\pm}$ the spin-split Fermi wave vectors.

Under a spin rotation transformation, the Hamiltonian can be effectively written in the helicity basis as[16]

$$H = \begin{pmatrix} \varepsilon_{\boldsymbol{k}} - \lambda k & 0 & 0 & \Delta_- \\ 0 & \varepsilon_{\boldsymbol{k}} + \lambda k & \Delta_+ & 0 \\ 0 & \Delta_+ & -\varepsilon_{\boldsymbol{k}} - \lambda k & 0 \\ \Delta_- & 0 & 0 & -\varepsilon_{\boldsymbol{k}} + \lambda k \end{pmatrix}, \tag{2}$$

where $\Delta_{\pm} = \Delta_{\rm t} \pm \Delta_{\rm s}$, $k = \sqrt{k_x^2 + k_y^2}$, and $f(\boldsymbol{k}) = 1$ have been used. It is clear that the Hamiltonian shows a two-band nature that there are two bands with different superconducting gaps $|\Delta_{\pm}|$ uncoupled in the helicity basis. One band is for the Cooper pair made of spin-up electron and spin-down hole with gap $|\Delta_-|$, the other band is for the pair of spin-down electron and spin-up hole with gap Δ_+ with respect to the helicity basis.

Now, we discuss a Josephson junction between two NCSs. The macroscopic phase difference between two NCSs is set to be φ. The superconducting gap is nonzero only in two NCSs and the self-consistent calculation of the gap is ignored. We first consider a normal junction between two NCSs with opposite RSOC polarization vector $\boldsymbol{l}_{\boldsymbol{k}}$ which is shown in Fig. 1(a). The triplet–singlet ratio is taken to be the same for two NCSs. The opposite Rashba polarization vector $-\boldsymbol{l}_{\boldsymbol{k}}$ in the right NCS is equivalent to the replacement of $\Delta_{\rm t}$ by $-\Delta_{\rm t}$. This replacement introduces an additional π phase shift and induces a π junction for the case of pure triplet pairing, while making no difference to the case of pure singlet pairing. This implies a 0–π transition driven by the triplet–singlet ratio. For general q, the change from $\Delta_{\rm t}$ to $-\Delta_{\rm t}$ also has another effect that the gap is different in two NCSs for each band. For the band with the gap Δ_- (Δ_+) in the left NCS, the corresponding gap in the right NCS becomes $-\Delta_+$ ($-\Delta_-$). It means that the critical supercurrent will be affected by q. Especially at $q = 0.5$ where the minor gap closes, the critical current should be zero, which means a critical point in the 0–π transition.

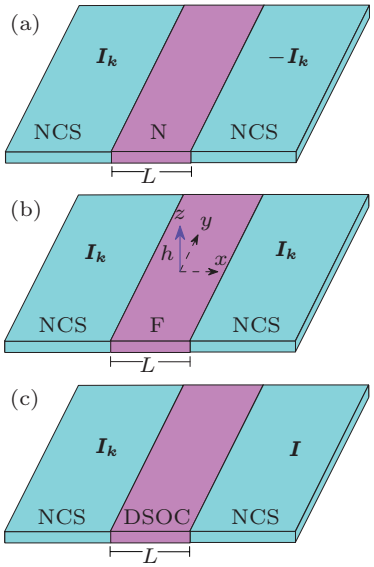


Fig. 1. (color online) Schematic diagrams of three types of junctions between two NCSs under consideration. (a) Normal junction between two NCSs with opposite Rashba polarization vectors. (b) Magnetic and (c) Dresselhause spin–orbit coupled junctions between two NCSs with the same Rashba polarization vector.

Besides rotating the Rashba polarizatin vector $\boldsymbol{l}_{\boldsymbol{k}}$ of the right NCS by π, we can also equivalently rotate the spin of electron and hole by π in the middle layer by introducing a magnetic or spin–orbit coupled interlayer (shown in Figs. 1(b) and 1(c)). The spin precession by π will switch the electron or hole from one band to the other when it travels from one

NCS to the other. For the magnetic junction, we choose the direction of magnetization to be along the z direction. The Hamiltonian for an electron in the magnetic interlayer reads $H_{\rm F} = \varepsilon_{\boldsymbol{k}} + h\sigma_z$ with h the strength of exchange field. For the spin–orbit coupled interlayer, we choose Dresselhause SOC (DSOC) because its spin quantum axis is perpendicular to a Rashba polarization vector of two NCSs. The Hamiltonian for an electron in a DSOC layer is $H_{\rm D} = \varepsilon_{\boldsymbol{k}} - \beta(k_x\sigma_x - k_y\sigma_y)$ where β is the DSOC strength.

For numerical calculation, we consider a two-dimensional Josephson junction between two NCSs which have opposite or the same $\boldsymbol{l}_{\boldsymbol{k}}$. The middle layer can be a normal metal (N), an F layer, or a DSOC layer. The junction lies in the x–y plane and the interlayer has a finite width L. The junction is along the x direction and the momentum in the y direction is conserved. We use the lattice Green's function technique as the numerical method to solve the supercurrent. The ABS can also be identified by the peaks of particle density. The Hamiltonian in the lattice model and the process of method are described in detail in Ref. [16].

3. Numerical results and discussion

3.1. NCS/N/NCS junction with opposite $\boldsymbol{l}_{\boldsymbol{k}}$

We first see the NCS/N/NCS junction with opposite $\boldsymbol{l}_{\boldsymbol{k}}$ which is shown in Fig. 1(a). The particle density in the N layer at normal incidence $k_y = 0$ is shown in Fig. 2, which demonstrates the evolution of ABS with the singlet percentage q increasing. It is shown that the junction is a π junction for $q < 0.5$, while a 0 junction for $q > 0.5$. At the critical point of transition $q = 0.5$, the ABS vanish completely because the minor gap Δ_- is closed. As the vector $\boldsymbol{l}_{\boldsymbol{k}}$ is opposite in the right NCS, the band with a gap Δ_- (Δ_+) in the left NCS will see a gap $-\Delta_+$ ($-\Delta_-$) in the right NCS. Therefore, the ABS can only exist in the energy range $[-|\Delta_-|, |\Delta_-|]$. Furthermore, for each band, the sign for two gap functions of left and right NCSs Δ_- (Δ_+) and $-\Delta_+$ ($-\Delta_-$) is the same when $\Delta_- < 0$, namely, $q > 0.5$. But when $q < 0.5$, the signs for two gap functions are opposite, which mean an additional π phase shift and lead to a π junction. In this 0–π transition driven by q, the ABS change the amplitude but not the phase shift compared with the conventional ABS, which is very different from conventional 0–π transitions where the ABS change mainly the phase shift.

The CPRs of the total Josephson current are plotted in Figs. 3(a)–3(d). The higher the temperature is, the more sinusoidal the CPR becomes. Just as the ABS at $k_y = 0$ imply, the junction is a π junction for $q < 0.5$, while a 0 junction for $q > 0.5$. At the critical point of transition $q = 0.5$, the Josephson current is fully suppressed. The great consistency between the total supercurrent and the ABS at normal incidence indicates that the contribution from normal incidence is dominant. In Fig. 3(e), we plot the critical current $I_{\rm c}$ and the current $I(\pi/2)$ at $\varphi = \pi/2$ as functions of singlet percentage q at $T = 0.9T_{\rm c}$. Because the CPR for $T = 0.9T_{\rm c}$ is nearly sinusoidal, we can approximately have $I_{\rm c} = I(\pi/2)$ for $I(\pi/2) > 0$, while $I_{\rm c} = -I(\pi/2)$ for $I(\pi/2) < 0$. It is noticeable that $I(\pi/2)$ increases linearly with the increase of q. It means that we can easily determine the triplet–singlet ratio of NCS only by the amplitude and sign of critical current in such junctions.

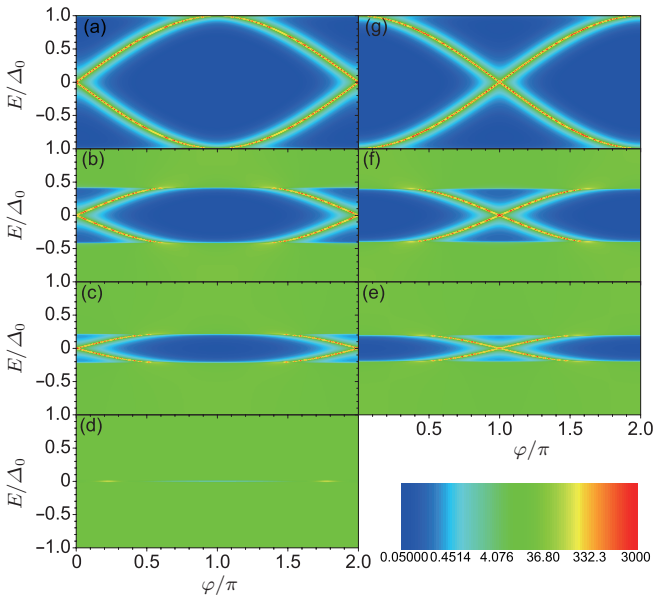


Fig. 2. (color online) Particle densities in the N layer at normal incidence $k_y = 0$ for an NCS/N/NCS junction with opposite $\boldsymbol{l}_{\boldsymbol{k}}$. From panel (a) to panel (g), $q = 0$, 0.3, 0.4, 0.5, 0.6, 0.7, 1. Here, φ is the phase difference between two NCSs. Other parameters are: $\Delta_0 = 0.01\mu$, $\lambda = 0.1\mu$.

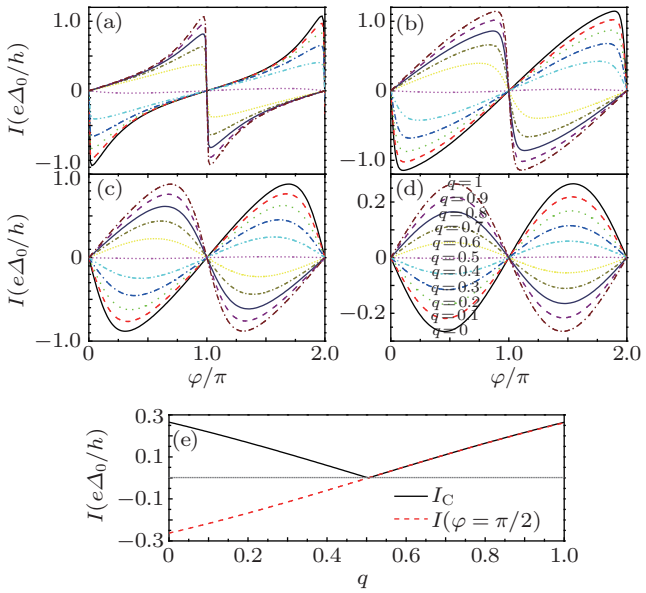


Fig. 3. (color online) (a)–(d) The current–phase relations of total Josephson current for the NCS/N/NCS junction with opposite $\boldsymbol{l}_{\boldsymbol{k}}$ at different temperatures: $T = 0.01T_{\rm c}$ (a), $0.1T_{\rm c}$ (b), $0.5T_{\rm c}$ (c), $0.9T_{\rm c}$ (d) with $T_{\rm c}$ the critical temperature. In each panel, various values of q are considered. (e) The critical current and the current at $\varphi = \pi/2$ as functions of q at $T = 0.9T_{\rm c}$. Other parameters are the same as those in Fig. 2.

3.2. NCS/F/NCS junction with the same $\boldsymbol{l_k}$

As discussed in Section 2, the NCS has two effective gaps, each corresponds to a spin subband. In the NCS/N/NCS junction with opposite $\boldsymbol{l_k}$ discussed above, the gap with the same amplitude is related to the opposite spin subband in two NCSs. Alternatively, we can precess the spin of electron and hole in the middle layer to let the particle see different gaps in the left and right NCSs, so it is expected that the 0–π transition driven by q can also occur in the NCS/F/NCS junction with the same $\boldsymbol{l_k}$.

Figure 4 shows the total Josephson current for the NCS/F/NCS junction with the same $\boldsymbol{l_k}$. The dependence of the current at $\varphi = \pi/2$ on the spin precession angle is shown in Fig. 4(a). Because the junction should be either a 0 junction or a π junction and the CPR is nearly sinusoidal at $T = 0.9T_c$, the current at $\varphi = \pi/2$ is the characteristic feature of a CPR. The spin precession angle in the F layer is approximately hL where h is the strength of exchange field and L is the length of F layer. With precession angle increasing, the Josephson current keeps nearly unchanged for $q = 0$, while it oscillates heavily and can go negative for $q = 1$. For negative values of the current at $\varphi = \pi/2$, it means a π junction. This can be easily understood if we see the problem in the spin quantum axis of the exchange field, namely, the z axis. In the z axis, the triplet ($q = 0$) means an equal-spin pairing while the singlet ($q = 1$) means an opposite-spin pairing. The exchange field in the F layer will bring a phase shift hL for the opposite-spin pairing, but not at all for the equal-spin pairing.

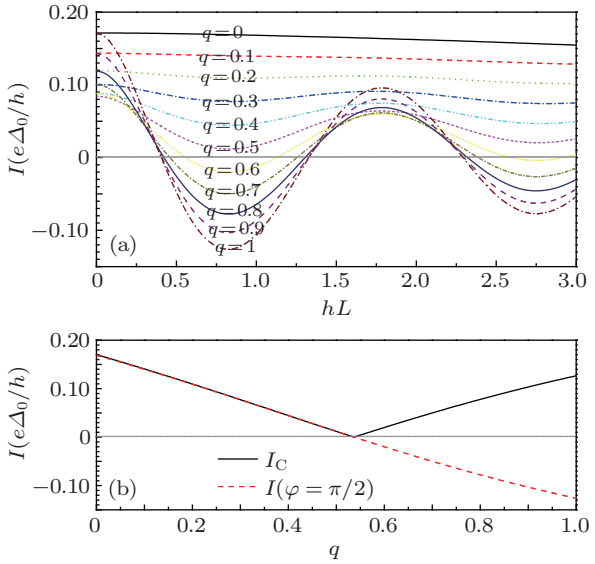


Fig. 4. (color online) The total Josephson current for the NCS/F/NCS junction with the same $\boldsymbol{l_k}$. (a) The current at $\varphi = \pi/2$ as functions of exchange field-induced spin precession angle hL for various q. (b) The critical current and the current at $\varphi = \pi/2$ as functions of q when $hL = 0.82\pi$. The temperature is $T = 0.9T_c$, and other parameters are the same as those in Fig. 2.

When the phase shift $hL = \pi$, we can expect a π junction for $q = 1$, but still a 0 junction for $q = 0$. The oscillations in the current for $q = 1$ imply the conventional 0–π transitions driven by the exchange field or the length of F layer. It is noticeable that the first minimum in the oscillation locates at nearly 0.82π instead of π because of the contribution from inclined incidence, namely, the components with $k_y \neq 0$. The phase shift in the inclined incidence is larger than that in the normal incidence. With increasing q from 0 to 1, the amplitude of oscillation increases. Roughly speaking, the junction stays in a 0 junction for $q < 0.5$ with increasing hL, while it changes into a π junction at some values of hL for $q > 0.5$. For triplet-dominant cases ($q < 0.5$), we find novel oscillations of the critical current which are not associated with the 0–π transition. At $hL = 0.82\pi$, figure 4(b) shows that the accurate transition point in the 0–π transition driven by q is nearly at $q = 0.54$, weakly larger than 0.5, still due to the contribution from inclined incidence.

In order to better understand the in–between cases where both singlet and triplet components exist, figure 5 shows the evolution of ABS with increasing hL at normal incidence ($k_y = 0$) for $q = 0.4$. With increasing hL from 0 to π, the ABS in the energy region $|\Delta_-| < |E| < |\Delta_+|$ blur gradually and disappear finally, due to the spin precession in the F layer. When the precession angle $hL = \pi$, the electron or hole is entirely switched from one spin subband to the other when travelling through the F layer. Therefore, the two sets of ABS pertain to two spin subbands becoming degenerate. The ABS in the energy region $|\Delta_-| < |E| < |\Delta_+|$ disappear totally, which leads to the oscillation of Josephson current.

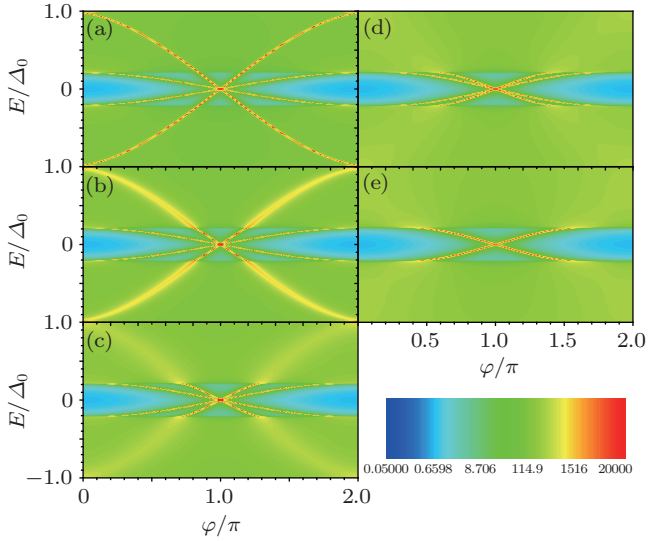


Fig. 5. (color online) Particle densities in the F layer at normal incidence $k_y = 0$ for the NCS/F/NCS junction with the same $\boldsymbol{l_k}$. From panel (a) to panel (e), $hL = 0$, 0.25π, 0.5π, 0.75π, π, $q = 0.4$. Other parameters are the same as those in Fig. 2.

3.3. NCS/DSOC/NCS junction with the same $\boldsymbol{l_k}$

Besides the magnetic junction, we also consider the spin–orbit coupled junction between two NCSs with the same $\boldsymbol{l_k}$. Here, we consider the Dresselhaus type of SOI to precess the

spin of electron or hole because the spin quantum axis is perpendicular to the Rashba polarization vector of NCSs. Figure 6 shows the oscillation of the total Josephson current with the increase of the precession angle for the NCS/DSOC/NCS junction with the same $\boldsymbol{l_k}$. As opposed to the case of a magnetic junction, with precession angle increasing, the Josephson current keeps nearly unchanged for $q = 1$ and oscillates more and more heavily for q decreasing. That is because that the DSOC term in the interlayer only brings a phase shift βL to the CPR for the equal-spin pairing, but not for the opposite-spin pairing in the case of normal incidence. When $k_y = 0$ and $\beta = \pi$, the junction is a π junction for $q = 0$ while a 0 junction for $q = 1$. Another big difference from the magnetic junction case is that the contribution from inclined incidence is comparable with that from normal incidence. Therefore, the total Josephson current just exhibits heavy oscillations, but without the accompanying 0–π transition.

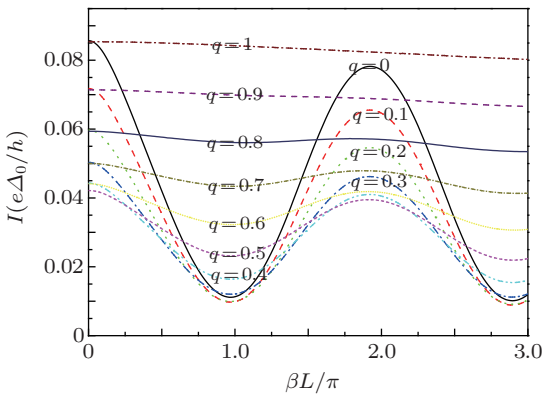


Fig. 6. (color online) The total Josephson current at $\varphi = \pi/2$ with the increase of the precession angle βL due to DSOC in the NCS/DSOC/NCS junction with the same $\boldsymbol{l_k}$. The temperature is $T = 0.9T_c$, and other parameters are the same as those in Fig. 2.

4. Conclusion

In summary, we explore the novel 0–π transition driven by the triplet–singlet ratio in the Josephson junction between two NCSs with opposite polarization vectors of RSOC. This 0–π transition is very different from the conventional 0–π transitions in magnetic Josephson junctions in that the Andreev bound states change their energy range instead of phase shift in the transition. That leads to an important signature that the critical current is almost zero at the transition point, not only a minimum. Similar effects are also discussed in junctions between two NCSs with the same polarization vectors of RSOC in the presence of exchange field or DSOC in the interlayer. Besides 0–π transitions, we also find novel oscillations of critical current without 0–π transition. Both 0–π transitions and oscillations of critical current are very sensitive to the triplet–singlet ratio of NCSs. These findings present a new understanding of the Josephson effect and as well serving as a tool to determine the unknown triplet–singlet ratio of NCS.

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