Spin and charge currents in SNS Josephson junction with f-wave pairing symmetry

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Abstract

We study transport properties and local density of states in a clean superconductor–normal metal–superconductor Josephson junction with triplet f-wave superconductors, based on the Eilenberger equation. Effects of the thickness of normal metal and a misorientation between the gap vector of the superconductors on the spin and charge currents are investigated. A spin current, which arises from the misalignment of the d-vectors, in the absence of charge current for some values of phase difference between the superconductors is found. We also find unconventional behavior of the spin current associated with the 0–π transition. The misalignment of the d-vectors also gives rise to a zero energy peak in the density of states in the normal metal.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Superconductivity with spin-triplet pairing symmetry, which has been observed in a series of experiments in Sr$_2$RuO$_4$ [1–6], UPt$_3$ and some other heavy-fermion complexes [7–15], has attracted much interest in the field of condensed matter physics. Spin-triplet f-wave pairing symmetry has been considered as the cause of unconventional superconductivity in the heavy-fermion complex UPt$_3$ [16–19]. Superconductivity has been observed in the UPt$_3$ compound in two important states, the A-phase and B-phase. Although the different phases correspond to different symmetries of the superconducting gap on the Fermi surface, all of them belong to spin triplets. The f-wave order parameter has a more complex dependence on azimuthal angles in comparison with the well-known p-wave order parameter for the superfluid phases of $^3$He. The Fermi surface of UPt$_3$ is highly complex, with five or six complicated shape sheets. While the pairing mechanism of UPt$_3$ is unknown, a great number of experimental and theoretical works have considered its thermodynamic and transport properties. The Josephson junction between triplet superconductors is an accurate method to study physics in triplet superconductors.

In particular, using the Josephson junctions between single crystals of UPt$_3$, the authors of [20, 21] investigated the symmetries of the superconducting order parameter and observed experimental evidence of the $E_{2u}$ representation in UPt$_3$. Also, in [22, 23], the vortex lattice state in UPt$_3$ in the presence of an external magnetic field was studied, providing additional support for the identification of the gap symmetry in UPt$_3$.

It is well known that in a superconductor–normal metal–superconductor (SNS) junction a Josephson current flows as a result of the proximity effect [24]. Recently, the proximity effect in unconventional superconductor and normal metal junctions has attracted much attention [25–31]. The proximity effect in junctions between triplet superconductors and normal metals in the diffusive regime has been investigated theoretically [27–29]. It is found that the proximity effect is enhanced by the mid-gap Andreev bound state formed at the interface between the triplet superconductor and the normal metal due to the sign change of the pair potential [27]. As a result, the density of states in the normal metal has a zero energy peak rather than a gap. To investigate the proximity effect, the quasiclassical Green’s function method is quite...
useful. The SNS Josephson junction between spin-triplet p-wave superconductors in the ballistic regime has been studied recently [25]. The authors found a spin-polarized current dependent on the misorientation and thickness of normal metal sandwiched between the superconductors. In this paper, we apply the quasiclassical Eilenberger equation [32] to calculate the charge and spin currents and density of states in a f-wave triplet SNS junction.

The SNS Josephson effect is of great interest because of its industrial applications, such as superconducting quantum interference devices (SQUID) [33, 34]. The DC Josephson junction has a persistent current from the gradient of the macroscopic phase of superconductivity [35]. While the current charge is the better known property in Josephson junctions, the spin current is more interesting because of its applications in spintronics. The effect of a phase difference on the spin current in the spin-triplet SIS Josephson junction has been studied [36–38]. In [37], the authors obtained a polarized dissipation-less supercurrent of spins. It has been shown that the current–phase dependences are quite different from those of the junction between conventional s-wave superconductors [39, 40] and high temperature d-wave superconductors [41].

In this paper, we investigate spin and charge Josephson currents and the density of states in a junction between misorientated crystals of triplet f-wave superconductors sandwiching the mesoscopic normal metal layer.

The organization of the rest of this paper is as follows. In section 2, the quasiclassical equations for Green’s functions are presented. Green’s functions are obtained in section 3. The obtained formulas for the Green’s functions are used to calculate the charge and spin current densities and also the density of states in the normal region. In section 4, the numerical results for the charge and spin currents in the normal metal layer thickness between the superconductors are analyzed. The effects of the normal layer thickness between the superconductors and a misorientation between the d-vectors of the superconductors on the charge and spin currents and the density of states are investigated. Our conclusions are presented in section 5.

2. Formalism and basic equations

In this section, we consider a clean normal metal such as copper between two misorientated f-wave superconductors. A normal metal layer with a thickness $l$ is sandwiched between two triplet superconductors. The interfaces between the normal metal and the superconductors have been considered as totally transparent. For the case $l \gg \lambda_F$, we can use the ballistic quasiclassical Eilenberger equation [32]

$$\hbar \nu_F \cdot \nabla \tilde{g} + [\varepsilon_m \tilde{\sigma}_3 + i \tilde{\Delta}, \tilde{g}] = 0,$$

and the normalization condition $\tilde{g}^\dagger \tilde{g} = \tilde{1}$, where $\varepsilon_m = \pi k_B T (2m + 1)$ are discrete Matsubara energies with $m = 0, 1, 2, \ldots$, $T$ is the temperature, $\nu_F$ is the Fermi velocity and $\tilde{\sigma}_3 = \tilde{\tau}_3 \otimes \tilde{1}$, in which $\tilde{\tau}_3$ is the Pauli matrix in particle–hole space. $\tilde{\sigma}_j$ ($j = 1, 2, 3$) denote Pauli matrices in spin space in what follows.

The Matsubara propagator $\tilde{g}$ can be written in the standard form:

$$\tilde{g} = \begin{pmatrix} g_1 \sigma_1 + g_1 & g_2 \sigma_2 i \sigma_3 \\ i \sigma_2 g_2 \sigma_1 & g_1 i \sigma_3 \end{pmatrix},$$

where the matrix structure of the off-diagonal self-energy $\tilde{\Delta}$ in the Nambu space is

$$\tilde{\Delta} = \begin{pmatrix} 0 & d \sigma i \sigma_3 \\ i \sigma_3 d^* \sigma & 0 \end{pmatrix}.$$  

In this paper, we focus on the unitary states, $(d \times d^*) = 0$. Also, we use the Eilenberger equation for $d = 0$ in the normal metal region ($0 \leq z \leq l$). From the Eilenberger equation it is clear that the Green’s functions in the normal metal, $g_{IN}$ and $g_{NI}$, are constant for $0 \leq z \leq l$. Solutions of equation (1) have to satisfy the conditions for Green’s functions in the bulk superconductors $\tilde{g}(\pm \infty) = \frac{\epsilon_m \tilde{\sigma}_3 + i \tilde{\Delta}_s}{\sqrt{\epsilon^2_m + d^2_1 \lambda^2_1}}$.

In addition, solutions of equations (1) must satisfy the continuity conditions at the interfaces between the metal and the superconductors ($z = 0, l$) for all quasiparticle trajectories. Here, as in [42], a simple step-like non-self-consistent model of the constant order parameter up to the interfaces is considered:

$$d(z, \tilde{\nu}_F) = \begin{cases} d_1(\tilde{\nu}_F)e^{i\phi/2} & z < 0 \\
0 & 0 < z < l \\
d_2(\tilde{\nu}_F)e^{-i\phi/2} & z > l,
\end{cases}$$

where $\phi$ is the external phase difference between the gap functions of superconducting bulks. We assume that the order parameter does not depend on the coordinates and in each superconductors is equal to its value far from the interface in the left or right bulks [24, 39, 41]. In particular, in [24] it was pointed out that the model with the magnitude of delta independent on space coordinates is valid if the Fermi velocity in the superconductors exceeds the Fermi velocity of the electrons in the normal metal. For such a model, the current–phase dependence of a Josephson junction can be calculated for a specific model of f-wave pairing symmetry. We believe that under this assumption our results describe the real situation qualitatively [41, 43]. In the framework of such a model, the analytical expressions for the charge and spin currents and the density of states can be obtained for an arbitrary form of the gap vector.

3. Analytical results of Green’s functions

The solution of Eilenberger equations allows us to calculate the charge and spin current densities in the normal metal. The expression for the charge current is:

$$j_e(\mathbf{r}) = 2i\pi e T N(0) \sum_m \langle \nu_F g_1(\tilde{\nu}_F, \mathbf{r}, \varepsilon_m) \rangle,$$

that for the spin current is:

$$j_s(\mathbf{r}) = i\pi h T N(0) \sum_m \langle \nu_F (\tilde{e}_j g_1(\tilde{\nu}_F, \mathbf{r}, \varepsilon_m)) \rangle$$
For both the geometries (i) and (ii), we consider a rotation only in the half-space is selected parallel to the partition between the side has been rotated around the $a$-axis by $\alpha$. The two different geometries correspond to the different orientations of the crystals in the right and left sides of the interface. In geometry (i) the $bc$-plane in the right side has been rotated around the $a$-axis by $\alpha$. In geometry (ii), the $ab$-plane in the right side has been rotated around the $c$-axis by $\alpha$. For both the geometries (i) and (ii), we consider a rotation only in the right superconductor, and the crystallographic $a$-axis in the left half-space is selected parallel to the partition between the superconductors ($x$-axis).

and that for local density of states at the energy $E$ is:

$$N(E, r) = N(0) \langle \text{Reg}_1(\hat{v}_F, r, \varepsilon_m \rightarrow iE + \delta) \rangle$$

where $\langle \cdot \cdot \cdot \rangle$ stands for averaging over the directions of electron momentum on the Fermi surface $\hat{v}_F$. $N(0)$ is the electron density of states at the Fermi surface and $\hat{e}_z = (\hat{x}, \hat{y}, \hat{z})$.

The calculated Green’s functions in the normal metal are the following:

$$\mathcal{G}^{IN} = \frac{\eta(A - B)}{A + B + 2|d_1 \cdot d_2|^2}$$  

$$\mathcal{G}^{IN} = \frac{2\eta d_1^* \cdot d_2 (d_1 \times d_2^*)}{A + B + 2|d_1 \cdot d_2|^2}$$

where $\eta = \text{sgn}(v_z)$, $\Omega_m = \sqrt{\varepsilon_m^2 + |d_1|^2}$,

$$A = d_1^* \cdot d_2 (\varepsilon_m + \eta \Omega_1)(\varepsilon_m + \eta \Omega_2) \exp\left(\frac{+2\varepsilon_m l}{|v_z|}\right)$$

and

$$B = d_1 \cdot d_2^* (\varepsilon_m - \eta \Omega_1)(\varepsilon_m - \eta \Omega_2) \exp\left(\frac{-2\varepsilon_m l}{|v_z|}\right).$$

Using these Green’s function, we obtain the charge and spin current through the SNS Josephson junction and also the density of states of system in the normal region $0 \leq z \leq l$.

4. Numerical results of currents and density of states

In this section we calculate charge and spin currents in SNS junctions bearing in mind that UPt$_3$ is a $f$-wave superconductor. Two famous models for the order parameter of UPt$_3$ are considered. The first is the axial state [44, 37, 36]:

$$d(T, \psi_F) = \Delta(T) k_x (k_x + ik_y)^2,$$  

and the other is the planar state [17]:

$$d(T, \psi_F) = \Delta(T) k_z [k_x^2 - k_y^2] + \frac{2k_x k_y].$$

The coordinate axes $\hat{x}, \hat{y}, \hat{z}$ are chosen along the crystallographic axes $\hat{a}, \hat{b}, \hat{c}$ in the left side of figure 1. The function $\Delta(T)$ in equations (12) and (13) describes the dependence of the order parameter $d$ on the temperature $T$. Using Green’s function in equations (8) and (9), we have numerically calculated the charge and spin currents and the density of states in a $f$-wave Josephson junction with pairing symmetry of equations (12) and (13).

The two superconducting bulks may have a misorientation created by either geometries (i) and (ii) in figure 1. For the two geometries and specific models of $f$-wave pairing symmetry we have plotted the currents in terms of the phase difference in figures 2–6. The obtained currents are periodic functions of the phase difference between the superconductors.
Figure 3. The normal component (z component) of the charge current versus the phase difference $\phi$ for the planar state (13), $T = 0.05T_C$, different thicknesses of normal metal and different misorientations between superconductors. Panel (a) is for geometry (i) and panel (b) for geometry (ii).

Figure 4. The normal component of the spin current ($j_{sx}$) versus the phase difference $\phi$ for the axial state (12), geometry (i), $T = 0.05T_C$, different thicknesses of normal metal and different misorientations between superconductors. Spin currents ($j_{sx}$), ($j_{sy}$), ($j_{sz}$) for geometry (i) and ($j_{sx}$), ($j_{sy}$), ($j_{sz}$) for geometry (ii) are absent because of equation (9). Currents are calculated in units of $j_0 = \pi N(0)\nu_F/\Delta(0)$.

Figure 5. The normal component of the spin current ($j_{sx}$) versus the phase difference $\phi$ for the planar state (13), geometry (i), $T = 0.05T_C$, different thicknesses of normal metal and different misorientations between superconductors. Note that spin currents ($j_{sx}$), ($j_{sy}$), ($j_{sz}$) vanish.

Figure 6. The normal component of the spin current ($j_{sx}$) versus the phase difference $\phi$ for the planar state (13), geometry (ii), $T = 0.05T_C$, different thicknesses of normal metal and different misorientations between superconductors. Note that spin currents ($j_{sx}$), ($j_{sy}$), ($j_{sz}$) vanish.

with a period of $2\pi$. It is clear that by increasing the thickness of the normal layer, the amplitude of the currents decreases, which is understandable because with increasing thickness of the normal metal, the quantum coherence of the macroscopic phases between the left and right superconductors decreases [25]. The current–phase relations are qualitatively different from the case of the s-wave [39] and d-wave Josephson junction [47, 41] while they are qualitatively similar to the current–phase relations of the p-wave SNS junction obtained in [25]. In particular, an interesting case is the zero of charge current at finite phase $\phi_0$ in figure 2(b), which occurs for most of the junctions exactly at $\phi = 0$ or $\pi$. On the other hand, for a finite misorientation between the left and right gap vectors, even at zero phase difference we obtain a finite charge current. This is because according to equation (12) in geometry (ii) the misorientation $\alpha$ plays the role of a phase difference—rotation by $\alpha$ gives the phase factor $\exp(2i\alpha)$. Also, in figures 4–6, it is found that the spin current
and also the planar state \((9)\) in geometry (i), and spin currents. Solid lines are for geometry (ii) and dotted lines are for geometry (i).

Here and in figure 8, we define \(j_{ec} = \text{Max}_{\phi} j_{e}(\phi) = j_{e}(\phi^*)\) and \(j_{cs} = j_{s}(\phi^*)\).

Figure 8. Critical charge and spin currents as a function of misorientation angle for the planar state \((13)\), \(l/\xi = 0.5, T = 0.05T_c\). Solid lines are for geometry (ii) and dotted lines are for geometry (i).

of the Josephson junction between two triplet superconductors is created by a misorientation between the gap vectors of the superconductors \([37]\). For the case of geometry (ii) and axial state \((12)\), the spin current is absent because both gap vectors are in the same direction. Also, by using equation (9), we find that spin currents \((j_{cs})_x\) and \((j_{cs})_z\) for the axial state \((12)\) and also the planar state \((9)\) in geometry (i), and spin currents \((j_{cs})_x\) and \((j_{cs})_z\) for the planar state \((9)\) in geometry (ii) are absent. In contrast to the charge current, the spin current has a large value at \(\phi = \pi\) (or at \(\phi = 0\) for a large misorientation angle). It is seen that the charge current is generally an odd function whereas the spin current is an even function of the phase difference because the charge current is odd in time reversal while the spin current is even. Since the spin current is an even function of phase, its derivative becomes odd in phase and hence should be zero at \(\phi = 0\) and \(\pi\). Thus, the spin current has a local maximum or minimum at \(\phi = 0\) and \(\pi\). We also see that as \(\phi = \pi\) for some phases the spin current exists but the charge current disappears. This is a purely spin transport in the absence of charge current. This effect cannot be observed in singlet superconducting junctions like conventional or high \(T_c\) superconductors. Only in the case of a superconductor–ferromagnet–superconductor junction with inhomogeneous magnetization is this spin current present \([45]\).

The critical currents as a function of the misorientation angle are shown in figures 7 and 8. Critical charge and spin currents, defined as \(j_{ec} = \text{Max}_{\phi} j_{e}(\phi) = j_{e}(\phi^*)\) and \(j_{cs} = j_{s}(\phi^*)\), respectively, are plotted as a function of misorientation angle \(\alpha\) for the specified temperature and normal layer thickness \((T = \frac{\pi}{10}, l = \frac{1}{2})\). In figures 2, 3, 7, and 8 it is shown that the sign of the Josephson current may be changed by a variation of misorientation which is called the 0–\(\pi\) transition. Also, at the 0–\(\pi\) transition point for both symmetries in geometry (i) we have a jump of spin current due to the jump of the phase, as found in \([45]\), but in geometry (ii) there is no 0–\(\pi\) transition and hence no jump of spin current. It should be emphasized that variation of the thickness of normal metal only changes the magnitude of currents and does not change the sign of current, thus the thickness of normal metal cannot produce a 0–\(\pi\) transition.

We believe that our numerical results can be used to make a qualitative distinction between the axial and planar states equations \((12)\) and \((13)\) of the order parameter in UPt3. In panel (b) of figures 2 and 3, at \(\phi = \pi\), we observe a finite current for the axial state, whereas for the planar state the current is absent. For a finite misorientation such as \(\alpha = \frac{\pi}{10}\), we see an opposite sign of spin current for the axial and planar states in figures 4 and 5. Also, in geometry (ii) a finite spin current is obtained for the planar state, as is shown in figure 6, but the spin current for the axial state in geometry (ii) is zero. In addition, there is a qualitative difference between the two models in the dependence of the critical charge current on the misorientation angle \((\text{figures 7 and 8)}\). In the solid lines (geometry (ii)) of the upper panels of figures 7 and 8, on increasing the misorientation angle \(\alpha\) the critical value of charge current for the axial state remains constant whereas for the planar state the critical charge current decreases. These above mentioned properties can be applied to make an experimental distinction between the axial and planar states in UPt3.
Figure 10. Local density of states in the normal metal for both geometries with $\alpha = \frac{\pi}{10}$, $\phi = \frac{\pi}{2}$, $T = 0.05T_c$, and different thicknesses of normal metal $l$. Panels (a) and (b) are for axial state (12) and panels (c) and (d) are for planar state (13). Left plots are for geometry (i) and right plots are for geometry (ii).

Figure 11. Local density of state in the normal metal for $l/\xi = 0.5$, $T = 0.05T_c$, $\phi = \frac{\pi}{2}$, and two different misorientations. Panels (a) and (b) are for axial state (12) and panels (c) and (d) for planar state (13). Left plots are for geometry (i) and right plots are for geometry (ii). In panel (b), plots of $\alpha = \frac{\pi}{3}$ and $\alpha = \frac{\pi}{6}$ (which are coincident) are shown as a solid line.

Finally, in figures 9–11 we have plotted the density of states in the normal region. Note that the normal Green’s functions are independent of the position in the normal region and hence the density of states does not depend on $x$. It is known that the proximity effect in the SNS junction strongly changes the density of states in the normal metal. In our calculations, we obtained Andreev bound states in the junctions, as shown in figures 9–11. This is understandable,
as an interference effect of electrons and holes in the normal metal. An electron will be reflected by Andreev reflection as a hole. This process is also repeated on the other SN interface. Thus, interference of holes and electrons increases the effective Andreev reflection probability and proximity effect at low energies.

In figure 9, we obtain a mini-gap like s-wave and d-wave superconductors [46]. Also, it should be noted that the densities of states are the same at zero misorientation for the two axial and planar models. Exactly at $\phi = \pi$ we obtain a peak at the Fermi energy. Here, like a Josephson junction between other types of unconventional superconductors [46], we obtain a finite density of states for energies inside the gap ($-\Delta < E < \Delta$). The results for a finite misorientation and different $\ell$ are shown in figure 10. The density of states gets smeared by increasing $\ell$. In figure 11 we plotted the density of states for both geometries and both symmetries. It is observed that on increasing the misorientation, the two peaks gradually merge into one and there will be a peak at zero energy at $\ell = \frac{\pi}{2}$. The increase in the density of states at low energy corresponds to that of the spin current. We find that the effect of the thickness of the normal layer is only quantitative, but that misorientation changes the currents and the density of states qualitatively. Our theoretical predictions in the present paper can be verified by phase sensitive experiments such as the experiments in [20, 21].

5. Conclusions

In this paper, we have investigated the transport properties and the local density of states in a triplet SNS Josephson junction with two f-wave superconductors. The spin-polarized current normal to the interface is investigated theoretically. It is observed that the normal layer decreases both charge and spin currents. It is also found that a misorientation of the d-vector between the left and right superconducting bulks produces a spin-polarized current which can flow even in the absence of charge current. We also discovered a jump of the spin current associated with the $0-\pi$ transition. In addition, the density of states has been calculated for varied phase difference, normal metal thickness and misorientation. The normal metal thickness has only a quantitative effect on the mid-gap states. Misorientation of the d-vectors drastically changes the junction properties. A generalization of the calculations of this paper to superconductor–ferromagnet–superconductor junctions would be an interesting subject. We will carry out this generalization in our next work.

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