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Transport of charge and spin in the weak link between misoriented $\text{PrOs}_4\text{Sb}_{12}$ superconductors

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Abstract

Recently, the ‘(p + h)-wave’ form of pairing symmetry has been proposed for the superconductivity in the $\text{PrOs}_4\text{Sb}_{12}$ compound (Parker *et al* 2004 *Preprint* cond-mat/0407254). In the present paper, a stationary Josephson junction as a weak-link between $\text{PrOs}_4\text{Sb}_{12}$ triplet superconductors is theoretically investigated. The quasiclassical Eilenberger equations are analytically solved. The spin and charge current-phase diagrams are plotted, and the effect of misorientation between crystals on the spin current and spontaneous and Josephson currents is studied. It is found that such experimental investigations of the current-phase diagrams can be used to test the pairing symmetry in the above-mentioned superconductors. It is shown that this apparatus can be applied as a polarizer for the spin current.

1. Introduction

The pairing symmetry of the recently discovered superconductor compound $\text{PrOs}_4\text{Sb}_{12}$ is an interesting topic of research in the field of superconductivity [1–3]. Superconductivity in this compound was reported in [4–6], and two different phases (A and B) have been considered for this kind of superconductor in [2, 7]. Although the authors of [2] at first considered the spin-singlet ‘(s + g)-wave’ pairing symmetry for this superconductor, later it was specified that the spin-triplet is the real pairing symmetry of the $\text{PrOs}_4\text{Sb}_{12}$ complex [1, 8]. Using the Knight shift in NMR measurements, the authors of paper [8] estimated the spin-triplet pairing symmetry for the superconductivity in $\text{PrOs}_4\text{Sb}_{12}$. Consequently, the ‘(p + h)-wave’ model of the order parameter was recently proposed for the pairing symmetry of the superconductivity in $\text{PrOs}_4\text{Sb}_{12}$ compound [1]. In [1], the self-consistent equation for the superconducting gap $\Delta(T)$ (BCS gap equation) has been solved for the finite temperature T numerically and for the temperatures T close to zero and the critical temperature T_c analytically. For this compound, using the ‘(p + h)-wave’ symmetry for the order parameter vector (gap function), the value of $\Delta(0)$ has been obtained for both A and B phases, in terms of

the critical temperature. In addition, the dependence of $\Delta(T)$ in the temperature limit of $T \rightarrow 0$ and $T \rightarrow T_c$ has been obtained. The authors of [1] have investigated the temperature dependence of the critical field, specific heat and heat conductivity. Also, the Josephson effect in the point contact between triplet superconductors with f-wave triplet pairing has been studied in [9]. In this paper the effect of misorientation on the charge transport has been studied and a spontaneous current tangential to the interface between the f-wave superconductors has been observed. Additionally, the spin-current in the weak-link between the f-wave superconductors has been investigated in our paper [10]. In [10], this kind of weak-link device has been proposed as the filter for polarization of the spin-current. These weak-link structures have been used to demonstrate the order parameter symmetry in [11].

In the present paper, the ballistic Josephson weak-link via an interface between two bulks of ‘(p + h)-wave’ superconductor with different orientations of the crystallographic axes is investigated. It is shown that the spin and charge current-phase diagrams are totally different from the current-phase diagrams of the point-contacts between conventional (s-wave) superconductors [12], high- T_c (d-wave) superconductors [13] and from the charge

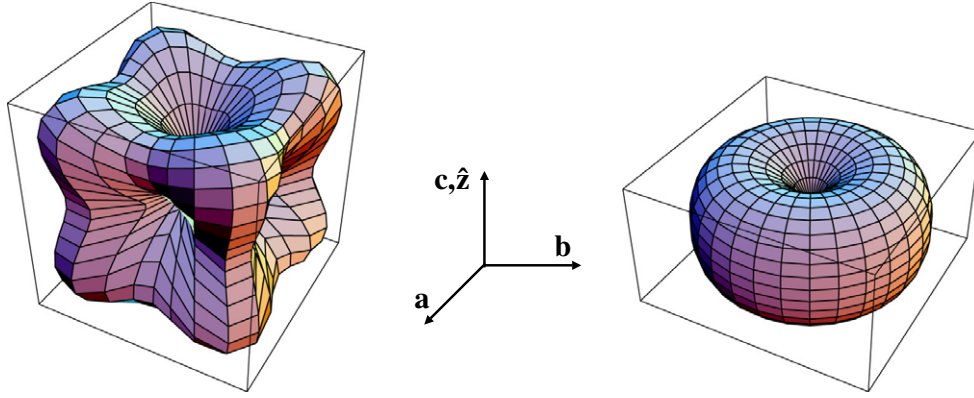


Figure 1. A-phase (left), B-phase (right) order parameters and direction of \mathbf{a} , \mathbf{b} , \mathbf{c} and $\hat{\mathbf{z}}$ unit vectors (middle) [1]. The A and B phases are high-field (high-temperature) and low-field (low-temperature) phases, respectively [14].

(This figure is in colour only in the electronic version)

and spin-current phase diagrams in the weak-link between the f-wave superconductors [9, 10]. We have found that in the weak-link structure between the ‘(p + h)-wave’ superconductors, spontaneous current parallel to the interface, as the characteristic of unconventional superconductivity, can be present. The effect of misorientation on the spontaneous, Josephson and spin currents for the different models of the pairing symmetry (A and B phases in figure 1) are investigated. It is possible to find the value of the phase difference at which the Josephson current is zero, but a spontaneous current tangential to the interface is present. In some configurations and at zero phase difference, the Josephson current is not zero, but has a finite value. This finite value corresponds to a spontaneous phase difference, which is related to the misorientation between the gap vectors. Finally, it is observed that at certain values of the phase difference ϕ , at which the charge current is zero, spin current is present, and vice versa. In addition, in the configuration in which both gap vectors are directed along the $\hat{\mathbf{c}} \perp \hat{\mathbf{n}}$ axis ($\hat{\mathbf{n}}$ is the normal to the interface unit vector), only the normal to the interface spin current $\hat{\mathbf{s}}_{\hat{\mathbf{n}}}$ can be present and the other terms of the spin current are absent ($\hat{\mathbf{s}}$ is the spin vector of electrons). Consequently, this structure can be used as a filter for polarization of the spin transport. Furthermore, our analytical and numerical calculations have shown that the misorientation is the origin of the spin current.

The organization of the rest of this paper is as follows. In section 2 we describe our configuration which has been investigated. For a non-self-consistent model of the order parameter, the quasiclassical Eilenberger equations [15] are solved and suitable Green functions have been obtained analytically. In section 3 the obtained formulae for the Green functions have been used for calculation of the charge and spin current densities at the interface. An analysis of numerical results is done in section 4. The paper finishes with some conclusions in section 5.

2. Formalism and basic equations

We consider a model of a flat interface $y = 0$ between two misoriented ‘(p + h)-wave’ superconducting half-spaces (figure 2) as a ballistic Josephson junction. In the quasiclassical ballistic approach, in order to calculate the current, we use

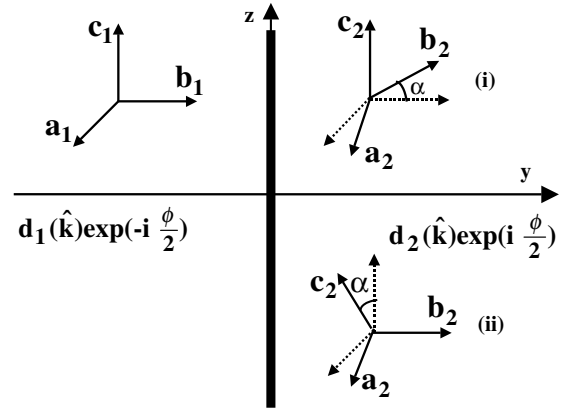


Figure 2. Scheme of a flat interface between two superconducting bulks, which are misoriented by angle α . In geometry (i), the ab -plane on the right side is rotated as much as α around the c -axis and in geometry (ii) the c -axis on the right side is rotated around the b -axis. The ab -planes and c -axis have been shown in figure 1.

‘transport-like’ equations [15] for the energy integrated Green matrix $\check{g}(\hat{\mathbf{v}}_F, \mathbf{r}, \varepsilon_m)$

$$\mathbf{v}_F \nabla \check{g} + \left[\varepsilon_m \check{\sigma}_3 + i \check{\Delta}, \check{g} \right] = 0, \quad (1)$$

and the normalization condition $\check{g} \check{g} = \check{1}$, where $\varepsilon_m = \pi T(2m + 1)$ are discrete Matsubara energies $m = 0, 1, 2, \dots$, T is the temperature, \mathbf{v}_F is the Fermi velocity and $\check{\sigma}_3 = \hat{\sigma}_3 \otimes \hat{1}$ in which $\hat{\sigma}_j$ ($j = 1, 2, 3$) are Pauli matrices. Also the matrix structure of the off-diagonal self-energy $\check{\Delta}$ in the Nambu space is

$$\check{\Delta} = \begin{pmatrix} 0 & \mathbf{d} \hat{\sigma} i \hat{\sigma}_2 \\ i \hat{\sigma}_2 \mathbf{d}^* \hat{\sigma} & 0 \end{pmatrix}, \quad (2)$$

where the gap vector \mathbf{d} , is the three-dimensional counterpart of the BCS energy-gap function Δ for the case of triplet superconductivity. The Green matrix \check{g} can be written in the form

$$\check{g} = \begin{pmatrix} g_1 + \mathbf{g}_1 \hat{\sigma} & (g_2 + \mathbf{g}_2 \hat{\sigma}) i \hat{\sigma}_2 \\ i \hat{\sigma}_2 (g_3 + \mathbf{g}_3 \hat{\sigma}) & i \hat{\sigma}_2 (g_1 - \mathbf{g}_1 \hat{\sigma}) i \hat{\sigma}_2 \end{pmatrix}. \quad (3)$$

Here, $g_1 + \mathbf{g}_1 \hat{\sigma}$ and $(g_2 + \mathbf{g}_2 \hat{\sigma}) i \hat{\sigma}_2$ [$i \hat{\sigma}_2 (g_3 + \mathbf{g}_3 \hat{\sigma})$] are the normal and anomalous Green function matrix, respectively.

The terms of g_i and \mathbf{g}_{ij} are coefficients of Green function matrix expansion in terms of the unit matrix and Pauli 2×2 matrices in the Nambu space. Also, the terms g_1 and \mathbf{g}_1 determine the charge and spin current densities through equations (8) and (9), respectively, and \mathbf{g}_2 and \mathbf{g}_3 are used to determine the gap vector, \mathbf{d} , using the self-consistent relations (equation (5) and its conjugate). It is worth noting that, in this paper, the unitary states, for which $\mathbf{d} \times \mathbf{d}^* = 0$, are investigated. Also, the unitary state vectors $\mathbf{d}_{1,2}$ can be written as

$$\mathbf{d}_n = \Delta_n \exp i\psi_n, \quad (4)$$

where $\Delta_{1,2}$ are the real vectors in the left and right sides of the junction. The gap (order parameter) vector \mathbf{d} has to be determined from the self-consistency equation:

$$\mathbf{d}(\hat{\mathbf{v}}_F, \mathbf{r}) = 2\pi T N(0) \sum_m \langle V(\hat{\mathbf{v}}_F, \hat{\mathbf{v}}'_F) \mathbf{g}_2(\hat{\mathbf{v}}'_F, \mathbf{r}, \varepsilon_m) \rangle, \quad (5)$$

where $V(\hat{\mathbf{v}}_F, \hat{\mathbf{v}}'_F)$, is a potential of pairing interaction, $\langle \dots \rangle$ stands for averaging over the directions of an electron momentum on the Fermi surface $\hat{\mathbf{v}}'_F$ and $N(0)$ is the electron density of states at the Fermi level of energy. Solutions to equations (1) and (5) must satisfy the conditions for Green functions and vector \mathbf{d} in the bulks of the superconductors far from the interface as follows:

$$\check{g}(\pm\infty) = \frac{\varepsilon_m \check{\sigma}_3 + i\check{\Delta}_{2,1}}{\sqrt{\varepsilon_m^2 + |\Delta_{2,1}|^2}}; \quad (6)$$

$$\mathbf{d}(\pm\infty) = \Delta_{2,1}(\hat{\mathbf{v}}_F) \exp\left(\mp \frac{i\phi}{2} + i\psi_{2,1}\right), \quad (7)$$

where ϕ is the external phase difference between the order parameters of the bulks. Equations (1) and (5) have to be supplemented by the continuity conditions at the interface between superconductors. For all quasiparticle trajectories, the Green functions satisfy the boundary conditions both in the right and left bulks as well as at the interface.

The system of equations (1) and (5) can be solved only numerically. For unconventional superconductors such solution requires information on the function $V(\hat{\mathbf{v}}_F, \hat{\mathbf{v}}'_F)$. This information, as that of the nature of unconventional superconductivity in novel compounds, in most cases is unknown. Usually, the spatial variation of the gap vector and its dependence on the momentum direction can be separated in the form of $\Delta(\hat{\mathbf{v}}_F, y) = \Delta(\hat{\mathbf{v}}_F)\Psi(y)$. It has been shown that the absolute value of a self-consistent order parameter and $\Psi(y)$ are suppressed near the interface and at distances of the order of the coherence length, while its dependence on the direction in the momentum space ($\Delta(\hat{\mathbf{v}}_F)$) remains unaltered [16]. Consequently, this suppression does not influence the Josephson effect drastically. This suppression of the order parameter keeps the current-phase dependence unchanged, but it changes the amplitude value of the current. For example, it has been verified in [13] for the junction between an unconventional d-wave, in [16] for the case of 'f-wave' superconductors and in [17] for pinholes in ^3He that there is a good qualitative agreement between self-consistent and non-self-consistent results. Also, it has been observed that the results of the non-self-consistent investigation of the $D-N-D$ structure in [18] are coincident with the experimental results

of [19] and the results of the non-self-consistent model in [20] are similar to the experiment [21]. Consequently, despite the fact that self-consistent numerical results cannot be applied directly for a quantitative analysis of a real experiment, only a qualitative comparison of calculated and experimental current-phase relations is possible. In our calculations, a simple model of the constant order parameter up to the interface is considered and the pair breaking and the scattering on the interface are ignored. We believe that under these particular assumptions our results describe the real situation qualitatively. In the framework of such a model, the analytical expressions for the current can be obtained for an arbitrary form of the order parameter.

3. Analytical results

The solution of equations (1) and (5) allows us to calculate the charge and spin current densities. The expression for the charge current is

$$\mathbf{j}_e(\mathbf{r}) = 2i\pi e T N(0) \sum_m \langle \mathbf{v}_F g_1(\hat{\mathbf{v}}_F, \mathbf{r}, \varepsilon_m) \rangle, \quad (8)$$

and for the spin current we have

$$\mathbf{j}_{s_i}(\mathbf{r}) = 2i\pi \left(\frac{\hbar}{2}\right) T N(0) \sum_m \langle \mathbf{v}_F (\hat{\mathbf{e}}_i \mathbf{g}_1(\hat{\mathbf{v}}_F, \mathbf{r}, \varepsilon_m)) \rangle, \quad (9)$$

where $\hat{\mathbf{e}}_i = (\hat{\mathbf{x}}, \hat{\mathbf{y}}, \hat{\mathbf{z}})$. We assume that the order parameter does not depend on the coordinates and in each half-space it equals its value (7) far from the interface in the left or right bulks. For such a model, the current-phase dependence of a Josephson junction can be calculated analytically. It enables us to analyse the main features of current-phase dependence for different models of the order parameter of '(p+h)-wave' superconductivity. The Eilenberger equations (1) for Green functions \check{g} , which are supplemented by the condition of continuity of solutions across the interface, $y = 0$, and the boundary conditions at the bulks, are solved for a non-self-consistent model of the order parameter analytically. Two diagonal terms of the Green matrix which determine the current densities at the interface, $y = 0$, are shown below. For the term relating to the charge current we obtain

$$g_1(0) = \frac{\varepsilon_m(\Omega_1 + \Omega_2) \cos \beta + i\eta(\Omega_1\Omega_2 + \varepsilon_m^2) \sin \beta}{i\eta\varepsilon_m(\Omega_1 + \Omega_2) \sin \beta + (\Omega_1\Omega_2 + \varepsilon_m^2) \cos \beta + \Delta_1\Delta_2}, \quad (10)$$

and for the case of spin current we have

$$\mathbf{g}_1(0) = \Delta_1 \times \Delta_2 [(B-1)^2(\eta\Omega_1 + \varepsilon_m)(\eta\Omega_2 + \varepsilon_m) \exp(i\beta) - (B+1)^2(\eta\Omega_2 - \varepsilon_m)(\eta\Omega_1 - \varepsilon_m) \exp(-i\beta)] \times [2\eta(A+B)|\Delta_1|^2|\Delta_2|^2]^{-1}, \quad (11)$$

where $\eta = \text{sgn}(v_y)$, $\Omega_n = \sqrt{\varepsilon_m^2 + |\Delta_n|^2}$, $\beta = \psi_1 - \psi_2 + \phi$,

$$B = \frac{\eta\varepsilon_m(\Omega_1 + \Omega_2) \cos \beta + i(\Omega_1\Omega_2 + \varepsilon_m^2) \sin \beta}{i\eta\varepsilon_m(\Omega_1 + \Omega_2) \sin \beta + (\Omega_1\Omega_2 + \varepsilon_m^2) \cos \beta + \Delta_1\Delta_2} \quad (12)$$

and

$$A = \frac{\Delta_1\Delta_2}{2} \times \left[\frac{(B-1) \exp(i\beta)}{(\eta\Omega_1 - \varepsilon_m)(\eta\Omega_2 - \varepsilon_m)} + \frac{(B+1) \exp(-i\beta)}{(\eta\Omega_1 + \varepsilon_m)(\eta\Omega_2 + \varepsilon_m)} \right]. \quad (13)$$

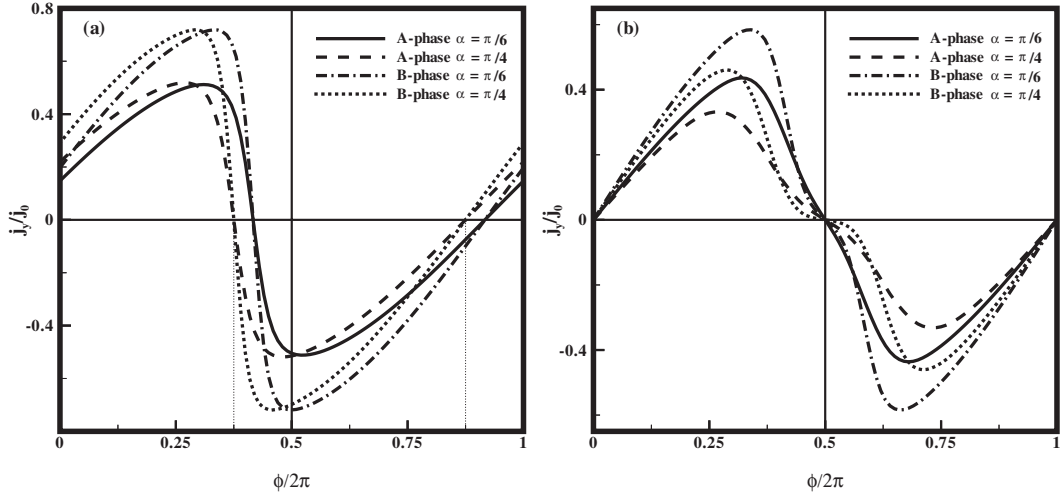


Figure 3. Component of charge current normal to the interface (Josephson current) versus the phase difference ϕ for A and B phases, $T/T_c = 0.08$ and different misorientations. Part (a) is plotted for geometry (i) and part (b) for geometry (ii). The charge currents are given in units of $j_0 = \frac{\pi}{2} e N(0) v_F \Delta_0(0)$.

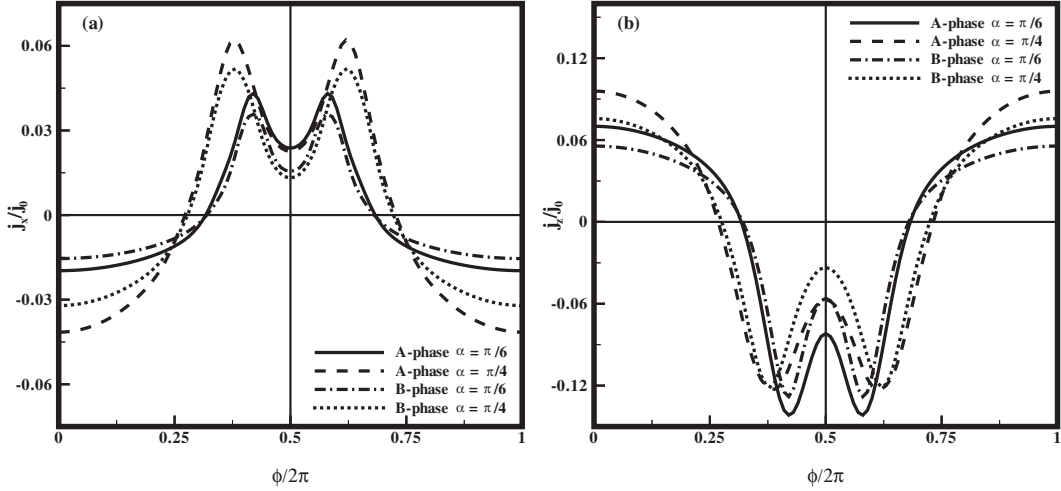


Figure 4. Components of charge current tangential to the interface versus the phase difference ϕ for the A and B phases, geometry (ii), $T/T_c = 0.08$ and the different misorientations. Part (a) is plotted for the x -component and part (b) for the z -component.

Also, $n = 1, 2$, label the left and right half-spaces, respectively. We consider a rotation \tilde{R} only in the right superconductor (see figure 2), i.e., $\mathbf{d}_2(\hat{\mathbf{k}}) = \tilde{R} \mathbf{d}_1(\tilde{R}^{-1} \hat{\mathbf{k}})$; $\hat{\mathbf{k}}$ is the unit vector in the momentum space. The crystallographic c -axis in the left half-space is selected parallel to the partition between the superconductors (along the z -axis in figures 1, 2). To illustrate the results obtained by computing formula (10), we plot the current-phase diagrams for different models of the ‘(p + h)-wave’ pairing symmetry (14), (15) and for two different geometries. These geometries correspond to the different orientations of the crystals on the right and left sides of the interface (figure 2):

- (i) The basal ab -plane on the right side has been rotated around the c -axis by α ; $\hat{\mathbf{c}}_1 \parallel \hat{\mathbf{c}}_2$.
- (ii) The c -axis on the right side has been rotated around the b -axis by α (y -axis in figure 2); $\hat{\mathbf{b}}_1 \parallel \hat{\mathbf{b}}_2$.

Further calculations require a certain model of gap vector (order parameter vector) \mathbf{d} .

4. Analysis of numerical results

In the present paper, two forms of ‘(p + h)-wave’ unitary gap vector \mathbf{d} in PrOs₄Sb₁₂ are considered. The first model to explain the properties of the A phase of PrOs₄Sb₁₂ is (left side of figure 1)

$$\mathbf{d} = \Delta_0(T) (k_x + ik_y) \frac{3}{2} (1 - \hat{k}_x^4 - \hat{k}_y^4 - \hat{k}_z^4) \hat{\mathbf{z}}. \quad (14)$$

The coordinate axes $\hat{\mathbf{x}}, \hat{\mathbf{y}}, \hat{\mathbf{z}}$ are chosen along the crystallographic axes $\hat{\mathbf{a}}, \hat{\mathbf{b}}, \hat{\mathbf{c}}$ on the left side of figure 2; $\hat{\mathbf{k}}$ is the unit vector along \mathbf{v}_F . The scalar function $\Delta_0 = \Delta_0(T)$ describes the dependence of the gap vector \mathbf{d} on the temperature T . The second model to describe the gap vector of the B phase of PrOs₄Sb₁₂ is (right side of figure 1)

$$\mathbf{d} = \Delta_0(T) (k_x + ik_y) (1 - \hat{k}_z^4) \hat{\mathbf{z}}. \quad (15)$$

Our numerical calculations are done at low temperature, $T/T_c = 0.08$, and we have used the formulæ

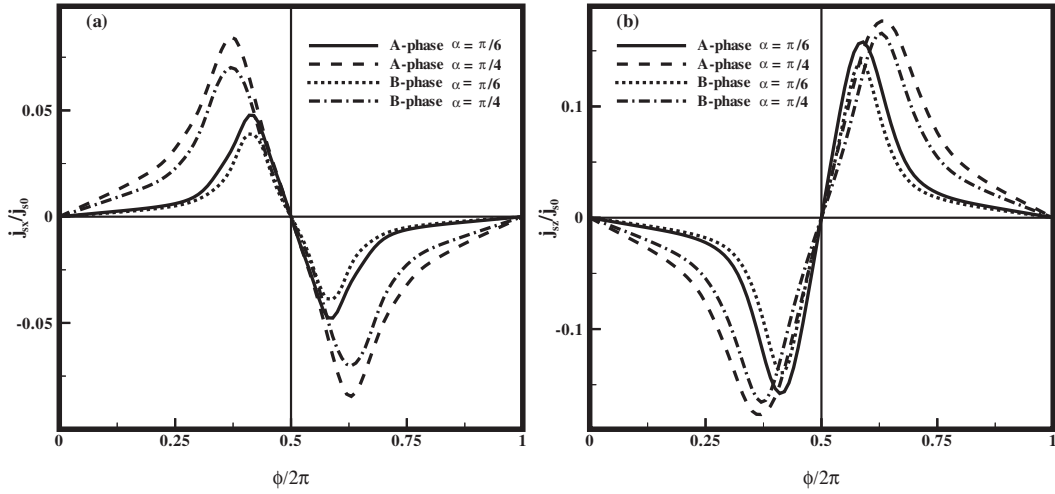


Figure 5. Components of spin current (s_y) tangential to the interface versus the phase difference ϕ for geometry (ii), $\frac{T}{T_c} = 0.08$ and different misorientations between the A and B phases of the ‘(p + h)-wave.’ Part (a) is plotted for the x-component and part (b) for the z-component. The spin currents are given in units of $j_{s0} = \frac{\pi}{4} \hbar N(0) v_F \Delta_0(0)$.

$\ln(\Delta(T)/\Delta(0)) = -\frac{7\pi\zeta(3)}{8} \left(\frac{T}{\Delta(0)}\right)^3$ for the A phase and $\ln(\Delta(T)/\Delta(0)) = -\frac{135\pi\zeta(3)}{512} \left(\frac{T}{\Delta(0)}\right)^3$ for the B phase, from [3], for the temperature dependence of the gap functions $\Delta_0(T)$ at the low temperatures ($T \ll T_c$). Also, in [3] the value of $\Delta_0(T)$ has been calculated in terms of the critical temperature for both A and B phases. They are $\Delta(0)/T_c = 2.34$ and $\Delta(0)/T_c = 1.93$ for the A and B phases, respectively. Using these two models of order parameters (14), (15) and the solution to the Eilenberger equations (10), (11), we have calculated the current density at the interface numerically. These numerical results are listed below.

- (1) In part (a) of figure 3, the component of current normal to the interface of current, which is known as the Josephson current, is plotted for both the A and B phases, geometry (i), misorientations $\alpha = \pi/4$ and $\pi/6$. It is observed that the critical values of current for the B phase is larger than for the A phase. Also, unlike a Josephson junction between the conventional superconductors, here, at $\phi = 0$, the current is not zero. The current is zero at the phase difference value $\phi = \phi_0$, which depends on the misorientation between the gap vectors. In figure 3, the value of the spontaneous phase difference ϕ_0 is close to misorientation α .
- (2) In part (b) of figure 3, the Josephson current is plotted for both the A and B phases, geometry (ii) and different misorientations. Again, the maximum value of the current for the B phase is larger than for the A phase. On increasing the misorientation between the gap vectors, the maximum value of the current decreases. It is demonstrated that at the phase difference values $\phi = 0, \pi$ and 2π , the Josephson current is zero while both spontaneous and spin currents are not zero and have a finite value. Increasing the misorientation between the gap vectors decreases the derivative ($\frac{dj_y}{d\phi}$) of the current with respect to the phase difference close to $\phi = \pi$, which is known as the **SQUID** sensitivity and it is important from the application point of view.
- (3) In figure 4, the tangential components of the charge current (x- and z-components) in terms of the phase difference ϕ are plotted. It is seen that at $\phi = 0, \pi$ and 2π , at which the Josephson current is zero, the parallel spontaneous currents have finite values. However, the normal component of charge current (see part (b) of figure 3) is an odd function of the phase difference with respect to the line of $\phi = \pi$ while the parallel charge currents for this geometry (ii) are even functions of the phase difference with respect to $\phi = \pi$ (compare part (b) of figure 3 with 4).
- (4) In figure 5, the tangential components of the spin (s_y) current are plotted in terms of the phase difference, for geometry (ii) and different misorientations. By increasing the misorientation the maximum value of the spin current increases. In spite of the charge current for this state, the spin current at the phase differences $\phi = 0, \pi$ and 2π is zero exactly (compare figure 4 with 5).
- (5) In figure 6, the normal components of the charge and spin current (j_y and j_{s_y}) are plotted for different misorientations and A and B phases respectively. An interesting case in our observations is the finite value of normal spin current at $\phi = 0, \pi$ and 2π at which the normal charge current (j_y) is zero (see figure 6).
- (6) In part (a) of figure 7, the Josephson current is plotted in terms of the phase difference for the case of the p-wave, and the A and B phases of the ‘(p + h)-wave’. The p-wave pairing symmetry as the first candidate for the superconducting state in Sr_2RuO_4 is as follows [23]:
$$\mathbf{d} = \Delta_0(T)(k_x + ik_y)\hat{\mathbf{z}}. \quad (16)$$
It is observed that the maximum value of the Josephson current (j_y) of the junction between the p-wave superconductors is larger than for the B phase of the ‘(p + h)-wave’ and the Josephson current of B phase is larger than its value for the A-phase counterpart. Also, the place of the zero of the charge current for these three types of superconductor (geometry (i)) is the same. It is at the spontaneous phase difference which is close to the

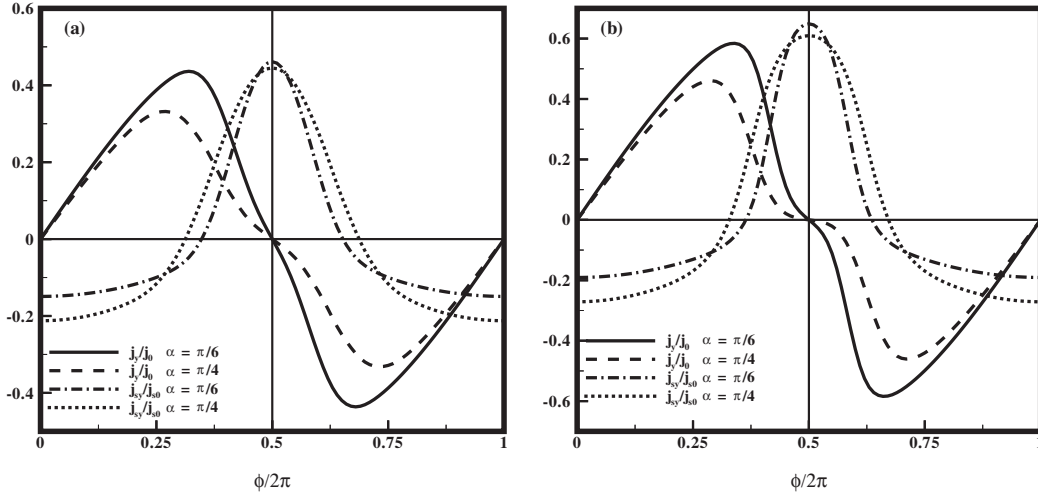


Figure 6. Component of charge and spin currents (j_y and j_{sy}) normal to the interface versus the phase difference ϕ for geometry (ii), $\frac{T}{T_c} = 0.08$, $\alpha = \frac{\pi}{6}$ and $\alpha = \frac{\pi}{4}$. Part (a) is plotted for the A phase and part (b) for the B phase.

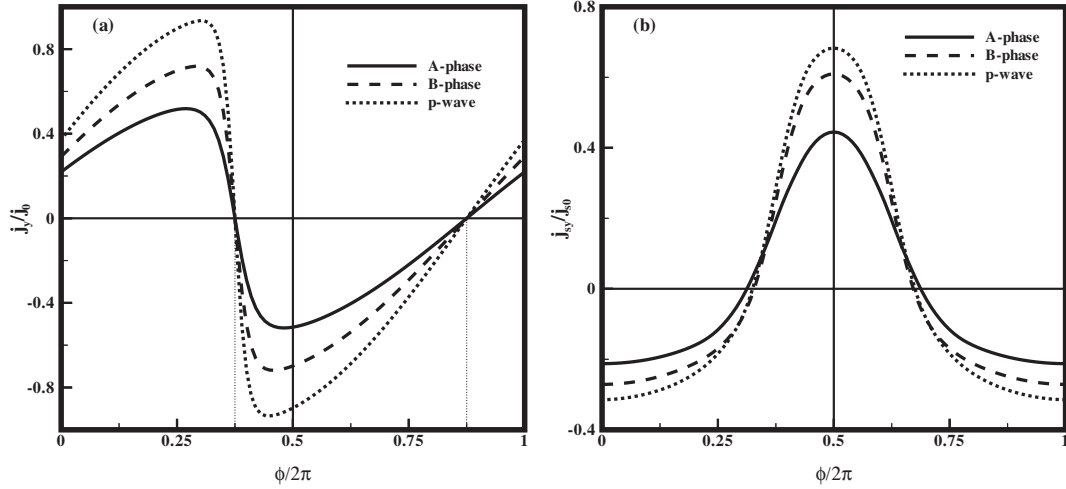


Figure 7. Component of charge and spin currents normal to the interface versus the phase difference ϕ , $\frac{T}{T_c} = 0.08$, $\alpha = \frac{\pi}{4}$, A phase, B phase and p-wave pairing symmetry. Part (a) is plotted for charge current and geometry (i) and part (b) is for the case of spin current and geometry (ii).

misorientation $\phi_0 = \alpha$ (see part (a) of figure 3 and part (a) of figure 7).

- (7) In part (b) of figure 7, the normal component of the spin current is plotted for the p-wave, and the A and B phases of the ‘(p + h)-wave’ pairing symmetries and for a specified value of misorientation $\alpha = \frac{\pi}{4}$. In both parts (a) and (b) of figure 7, the maximum value of the current of the junction between the p-wave superconductors is larger than for the B phase. For the B phase the current has the maximum value, which is larger than the value for the junction between the ‘(p + h)-wave’ superconductors in the A phase. This different characteristic of the current-phase diagrams enables us to distinguish between the three states. Also, it is observed that at phase differences $\phi = 0$, π and 2π , the spin current has a finite value which may be its maximum value. This is a counterpart of part (b) of figure 3, in which the charge currents are zero at the mentioned values of the phase difference, but the spin current has a finite value.

Furthermore, our analytical and numerical calculations have shown that the origin of the spin current is misorientation between the gap vectors [cross product in equation (11)]. Because the geometry (i) is a rotation by α around the \hat{z} -axis and both the left and right gap vectors are in the same direction, the cross product between the gap vectors, and consequently the spin current for geometry (i), is zero. It is shown that in this structure (the y-direction is normal to the interface, c-axis is selected in the z-direction and rotation is done around the y-direction) only the current of the s_y flows and other terms of the spin current are absent. So, this kind of weak-link experiment can be used as a filter for the polarization of spin transport. Since the spin is a vector, the spin current is a tensor and we have the current of spin s_y in the three \hat{x} , \hat{y} and \hat{z} directions.

5. Conclusions

We have theoretically studied spin and charge transport in the ballistic Josephson junction in the model of an ideal transparent interface between two misoriented PrOs₄Sb₁₂

crystals with '(p + h)-wave' pairing symmetry, which are subject to a phase difference ϕ . Our analysis has shown that the different misorientations and different models of the gap vectors influence the spin and charge currents. This has been shown for the charge current in the point contact between two bulks of 'f-wave' superconductors in [9] and for the spin current in the weak link between 'f-wave' superconductors in [10]. In this paper, it is shown that the misorientation of the superconductors leads to a spontaneous phase difference that corresponds to the zero Josephson current and to the minimum of the weak link energy. This phase difference depends on the misorientation angle. We have found a spontaneous charge current tangential to the interface which is not equal to zero in the absence of the Josephson current generally. It has been found that the spin current is the result of the misorientation between the gap vectors. Furthermore, it is observed that a certain model of the gap vectors and geometries can be applied to polarize the spin transport. Finally, as an interesting and new result, it is observed that at certain values of the phase difference ϕ , the charge-current vanishes while the spin-current flows, although the carriers of both spin and charge are the same (electrons). The spatial variation of the phase of the order parameter plays a role as the origin of the charge current and, similarly, due to the broken $G^{\text{spin-orbit}}$ symmetry, a spatial difference of the gap vectors in two half-spaces is the cause of the spin currents. This is because there is a position-dependent phase difference between 'spin-up' and 'spin-down' Cooper pairs and, although the total charge current vanishes, there can be a net transfer of the spin. Therefore, in our system, there is a discontinuous jump between the gap vectors, and consequently the spin currents should generally be present. For instance, if spin-up states and spin-down states have a velocity in the opposite direction, the charge currents cancel each other, whereas the spin current is being transported. Mathematically speaking, $\mathbf{j}_{\text{charge}} = \mathbf{j}_{\uparrow} + \mathbf{j}_{\downarrow}$, $\mathbf{j}_{\text{spin}} = \mathbf{j}_{\uparrow} - \mathbf{j}_{\downarrow}$, so it is possible to find the state in which one of these current terms is zero and the other term has a finite value [22]. In conclusion, spin current in the absence of charge current can be observed and vice versa.

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