Effects of spin-orbit scattering on Josephson current between s-wave superconductor and Sr_2RuO_4

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Abstract

The Josephson effect in *s*-wave superconductor / insulator/ Sr_2RuO_4 (S/I/SRO) junctions is studied. We focus on influences of spin-orbit scattering at the junction interface on the phase-current relation ship in the Josephson current. In the presence of the spin-orbit scattering, we find that the Josephson current has a term which is proportional to $\cos\varphi$, where φ is the phase-difference between S and SRO.

Key words: p-wave; Josephson current; Spin-orbit scattering

1. Introduction

The anisotropic superconductivity has been an important topics in condensed matter physics since unconventional superconductivity was discovered in heavy-fermion materials [1]. Anisotropic superconductivity was found in the layered perovskite Sr_2RuO_4 (SRO) in a recent study [2]. Stimulated by the suggested triplet pairing symmetry, several studies on transport properties have been performed [3–7]. The Josephson effect between different superconductors of opposite parity, i.e. Josephson current between *s*-wave superconductors and SRO, have been studied both theoretically and experimentally [8–14]. In general, there is no first order Josephson coupling between spin-singlet and spin-triplet superconductors when the spin-flip transmission is absent [1,15–17]. In the experiment [8], however, Josephson current was observed when the *c* axis of SRO is parallel to the junction interface. This is because the potential step near the insulators become a source of the spin-orbit coupling [15]. The Josephson current between two SRO's was also theoretically studied [18,19].

In general the Josephson current can be decomposed into a series of

$$J = \sum_{n=1}^{\infty}(a_n \cos n\varphi + b_n \sin n\varphi), \tag{1}$$

where φ is the phase-difference between two superconductors. In a presence of the time-reversal symmetry, in general, the Josephson current becomes an odd function of φ, i.e., $a_n = 0$. In general SIS junctions, $J \propto \sin\varphi$ because $b_n,\ n \geq 2$ are much smaller than b_1. However, in S/I/SRO junctions, it is known that b_1 vanishes because the wavefunction of the Cooper pairs in two superconductors are orthogonal to each other. Thus the Josephson current is proportional to $\sin 2\varphi$ in the absence of the spin-orbit scattering. In the presence of the spin-orbit scattering, a coefficient a_1 or b_1 may remain finite [1,15–17]. In this paper, we show that a_1 becomes finite in S/I/SRO junctions.

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2. Effect of spin-orbit scattering

We consider S/I/SRO junctions in two-dimensional space which corresponds to the ab-plane in SRO. The pair potential in SRO is given by $\hat{\Delta}_p = i\boldsymbol{d} \cdot \boldsymbol{\sigma}\sigma_2$ with $\boldsymbol{d} = \Delta_p e^{i\gamma}\boldsymbol{z}$, where σ_j are the Pauli matrices, $\boldsymbol{z}$ is a unit vector in the c axis of SRO and $e^{i\gamma} = \bar{k}_x + i\bar{k}_y$. The wavenumber in x and y direction on the Fermi surface are $\bar{k}_x = k_x/k_F$ and $\bar{k}_y = k_y/k_F$. The current flows in the x direction and the junction is at $x = 0$, where we consider the potential barrier $V_0\delta(x)$. The spin-orbit scattering is expressed by the Hamiltonian,

$$H_{so} = \frac{-i\hbar^2}{(2mc)^2}\boldsymbol{\sigma} \cdot (\boldsymbol{\nabla} V(\boldsymbol{r}) \times \boldsymbol{\nabla}). \tag{2}$$

In this study, we express spin-orbit scattering at the junction by the interface term $-iV_s/k_F\delta(x)\partial_y\sigma_3$ since the space-derivative of the barrier-potential only has a x component in the two-dimensional system. The Josephson current is calculated from [17]

$$J = \frac{e}{2}T\sum_{\omega_n}\boldsymbol{I}, \tag{3}$$

$$\boldsymbol{I} = \frac{N_c}{2}\int_{-\pi/2}^{\pi/2} d\gamma \mathrm{Tr}\left[\hat{\Delta}_0\hat{a}_1 - \hat{\Delta}_0^\dagger\hat{a}_2\right], \tag{4}$$

where $\hat{\Delta}_0 = \Delta_0 i\sigma 2$ is the pair potential in a s-wave superconductor, $\hat{a}_1$ and $\hat{a}_2$ are the Andreev reflection coefficients from the electron (hole) branch to the hole (electron) branch, $N_c = Wk_F/\pi$ is the number of propagating channels on the Fermi surface, and W is the width of the junction. In the limit of high potential barrier ($z_0 = mV_0/k_F >> 1$), we obtain

$$\boldsymbol{I} = \frac{-2N_c\Delta_p\cos\varphi}{z_0^4\Omega_0}\int_{-\pi/2}^{\pi/2} d\gamma\ \cos^2\gamma \times \frac{z_0 z_s\Omega_0\Omega_p\sin^2\gamma + \Delta_0\Delta_p\cos^2\gamma\sin\varphi}{\omega_n^2 + \Delta_p^2\sin^2\gamma}, \tag{5}$$

where $\Delta_0(\Delta_p)$ is the amplitude of the pair potential in S (SRO), $\Omega_{0(p)} = \sqrt{\omega_n^2 + \Delta_{0(p)}^2}$, and $z_s = mV_s/k_F$ represents a strength of the spin-orbit scattering. In the absence of the spin-orbit scattering, the Josephson current is not proportional to $\sin\varphi$ but proportional to $\sin 2\varphi$ as shown in the second term in Eq. (5). This is because the wavefunction of the Cooper pair in spin-singlet superconductors and that in spin-triplet superconductors are orthogonal to each other. In the presence of the spin-orbit scattering at the junction interface, a term proportional to $\cos\varphi$ appears in the Josephson current as shown in the first term of Eq. (5). This apparent shift of the Josephson phase φ by $\pi/2$ appears due to the fact that the Josephson coupling mediated by spin-orbit scattering involves the transverse p-wave pairing component (here k_y) only which has a phase of $\pi/2$ in our definition. Thus the stable junction is reached at $\varphi_0 = \pi/2$. When $\gamma = 0$, we note that the denominator of Eq. (5) goes to zero in the limit of the zero temperature. This is because that the zero-energy resonance states [20–23] are formed at the interface for quasiparticles with perpendicular injection to the interface. It is expected that the temperature dependence of the Josephson current is seriously influenced by this state [18,19,21–23]. In the forthcoming paper, we would like to clarify this in detail.

References

[1] M. Sigrist and K. Ueda: Rev. Mod. Phys. **63** (1991) 239.

[2] Y. Maeno, H. Hashimoto, K. Yoshida, S. Nishizaki, T. Fujita, J. G. Bednorz and F. Lichtenberg: Nature **372** (1994) 532.

[3] M. Yamashiro, Y. Tanaka and S. Kashiwaya: Phys. Rev. B **56** (1997) 7847.

[4] C. Honerkamp and M. Sigrist: J. Low. Temp. Phys. **111** (1998) 895.

[5] M. Yamashiro, Y. Tanaka and S. Kashiwaya: J. Phys. Soc. Jpn. **67** (1998) 3364.

[6] N. Yoshida, Y. Tanaka, J. Inoue and S. Kashiwaya, J. Phys. Soc. Jpn. **68** (1999) 1071.

[7] T. Hirai, N. Yoshida, Y. Tanaka, J. Inoue and S. Kashiwaya, J. Phys. Soc. Jpn. **70** (2001) 1885.

[8] R. Jin, Y. Liu, Z. Q. Mao and Y. Maeno: Europhys. Lett. **51** (2000) 341.

[9] A. Sumiyama, T. Endo, Y. Oda, Y. Yoshida, A. Mukai, A. Ono and Y.Onuki: Physica C **367** (2002) 129.

[10] M. Yamashiro, Y. Tanaka and S. Kashiwaya: J. Phys. Soc. Jpn. **67** (1998) 3364.

[11] Y. Hasegawa, K. Machida and M. Ozaki: J. Phys. Soc. Jpn. **69** (2000) 336.

[12] Y. Tanaka and S. Kashiwaya, J. Phys. Soc. Jpn. **68** (1999) 3485.

[13] Y. Tanaka and S. Kashiwaya, J. Phys. Soc. Jpn. **69** (2000) 1152.

[14] C. Honerkamp and M. Sigrist: Prog. Theor. Phys. **100** (1998) 53.

[15] V.B. Geshkenbein and A.I. Larkin, Pis'ma Zh. Eksp. Teor. Fiz. **43**, 306 (1986) [JETP Lett. **43**, 395 (1986)].

[16] A. Millis, D. Rainer, and J. A. Sauls, Phys. Rev. B **38**, 4504 (1988).

[17] Y. Asano: Phys. Rev. B **64** (2001) 224515.

[18] Y. S. Barash, H. Burkhardt and D. Rainer: Phys. Rev. Lett. **77** (1996) 4070.

[19] Y. Asano: J. Phys. Soc. Jpn. **71** (2002) to be published.

[20] Y. Tanaka and S. Kashiwaya: Phys. Rev. Lett. **74** (1995) 3451.

[21] Y. Tanaka and S. Kashiwaya: Phys. Rev. B **53** (1996) 11957.

[22] Y. Tanaka and S. Kashiwaya: Phys. Rev. B **56** (1997) 892.

[23] S. Kashiwaya and Y. Tanaka: Rep. Prog. Phys. **63** (2000) 1641.