Spontaneous Josephson spin current in triplet superconductor/ferromagnet/triplet superconductor junctions

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This paper theoretically studies Josephson spin current through triplet superconductor/ferromagnet/triplet superconductor junctions. At the ferromagnet/superconductor interfaces, the ferromagnetic scattering potential gives rise to coupling between the Andreev bound states and lifts their spin degeneracy. These spin-split Andreev states carry the Josephson spin current through the junctions. The generated spin supercurrent can be controlled by the magnetization of a ferromagnetic thin layer and bias voltage across the junctions.

Keywords: triplet superconductor, Andreev states, Josephson spin current

PACC: 7300, 7450

1. Introduction

Since the prediction of the Josephson effect in 1962, it has attracted intense interests as a surprisingly large supercurrent can flow between two superconducting electrodes separated by a thin insulating layer at zero bias voltage.[1] The dissipationless charge current through such a weak link is driven by the phase difference ϕ across the junction. The current–phase relation is given by $I_{\rm S}(\phi) = I_{\rm C}\sin(\phi)$.[2] If the weak link is normal metal, Cooper pairs can be transferred between two superconducting electrodes by a scattering process known as Andreev reflection[3] at low energy transport. An electron is transmitted into a hole at a normal metal-superconductor (NS) interface, generating a Cooper pair in one electrode. This hole is reflected by Andreev reflection as an electron at the other NS interface, carrying away a Cooper pair from the other electrode. One cycle of two reflections transfers a pair of correlated electrons between two electrodes, creating a supercurrent flow across the junction. The resulting electron–hole resonances are called Andreev resonant states. Andreev states at the NS interface are spin-degenerate. If the weak link consists of a thin ferromagnetic layer, the ferromagnetic barrier couples the Andreev states and lifts their spin degeneracy. Such spin-split states are believed to be responsible for the π phase state in superconductor–ferromagnet heterojunctions.[2]

As Cooper pairs in almost all conventional and unconventional superconductors have spin singlet and moment structure of $(\boldsymbol{k},\uparrow;-\boldsymbol{k},\downarrow)$, they cannot carry spin current. Recently, much attention has been devoted to generating and controlling Josephson charge and spin current in a variety of Josephson junctions involving a triplet superconductor.[4−12]

In this paper, we study the generation and control of Josephson spin current through triplet superconductor/ferromagnet/triplet superconductor (TSFTS) junctions. The Andreev bound states (ABSs) formed at the ferromagnet/superconductor interfaces carry the Josephson current. When the ferromagnetic scattering potential couples these ABSs and lifts their spin degeneracy, spin supercurrent is yielded and flows through the junction. The control of the spin supercurrent can be realized by adjusting the strength and direction of the magnetization of a ferromagnetic thin layer. We can also control the Josephson spin current by the bias voltage across the junctions.

2. Bogoliubov-de Gennes (BdG) equation

The TSFTS junction aligned along the z direction is displayed as a schematic picture in Fig. 1.

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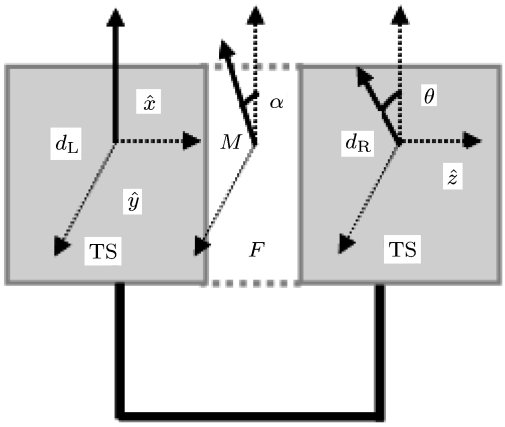


Fig. 1. A schematic picture of TSFTS junction.

The triplet superconductor gap function is taken as

$$\Delta_{\alpha\beta}(z,z') = \left[\Delta^j(z,z')(d_j\cdot\hat{\sigma})\,\mathrm{i}\,\hat{\sigma}_2\right]_{\alpha\beta}$$

with $\hat{\sigma}_i$ $(i=1,2,3)$ the Pauli matrices,

$$\Delta^j(z,z') = \mathrm{i}\,\Delta_0^j\left[\delta(z-z'-1)-\delta(z-z'+1)\right]/2$$

(lattice constant $a_0=1$) for describing an orbital p_z-wave symmetry, and vector $d_j=(\cos\theta_j,\sin\theta_j,0)$ for describing the spin structure. The $j=\mathrm{L(R)}$ refers to the left (right) superconductor of the junction. We take $\theta_{\rm L}\equiv 0$ ($d_{\rm L}\parallel\hat{x}$) and $\theta_{\rm R}=\theta$ with $d_{\rm R}$ lying in the spin x–y plane. The ferromagnetic moment $M(z,z')=M_0(\cos\alpha,\sin\alpha,0)\delta(z)\delta(z')$ at $z=0$ represents a magnetic scattering potential created by the thin ferromagnetic layer with the uniform magnetization.

We write the BdG equation as

$$\hat{H}\psi_j(z) = E_j\psi_j(z)\,,$$

where E is the energy of the Andreev states,[6,13]

$$\hat{H}=\begin{pmatrix} -\dfrac{\partial_z^2}{2m}-\mu & \mathrm{i}\,\mathrm{e}^{-\mathrm{i}\,\theta}\Delta_0^j\partial_z & \mathrm{e}^{-\mathrm{i}\,\alpha}M_0\delta(z) & 0 \\ \mathrm{i}\,\mathrm{e}^{\mathrm{i}\,\theta}\Delta_0^{j*}\partial_z & \dfrac{\partial_z^2}{2m}+\mu & 0 & \mathrm{e}^{\mathrm{i}\,\alpha}M_0\delta(z) \\ \mathrm{e}^{\mathrm{i}\,\alpha}M_0\delta(z) & 0 & -\dfrac{\partial_z^2}{2m}-\mu & \mathrm{i}\,\mathrm{e}^{\mathrm{i}\,\theta}\Delta_0^j\partial_z \\ 0 & \mathrm{e}^{-\mathrm{i}\,\alpha}M_0\delta(z) & \mathrm{i}\,\mathrm{e}^{-\mathrm{i}\,\theta}\Delta_0^{j*}\partial_z & \dfrac{\partial_z^2}{2m}+\mu \end{pmatrix} \tag{1}$$

and $\Delta_0^{\rm L}\equiv\Delta_0=\Delta_0^R\mathrm{e}^{-\mathrm{i}\,\phi}$ with Δ_0 chosen real and ϕ the phase difference. The boundary conditions are given by

$$\psi_{\rm L}(0)=\psi_{\rm R}(0), \tag{2}$$

$$\partial_z\psi_{\rm R}(0)-\partial_z\psi_{\rm L}(0) = -2mM_0\begin{pmatrix} 0 & \hat{P} \\ \hat{P}^+ & 0 \end{pmatrix}\psi_{\rm R}(0), \tag{3}$$

where $\hat{P}=\hat{\sigma}_3\cos\alpha-\mathrm{i}\,\hat{\sigma}_0\sin\alpha$. Solving the BdG equation yields two Andreev states with energies

$$\frac{E_{\rm a,b}}{k_{\rm F}\Delta_0} = \sqrt{D}\left[(A-C)^{1/2}\pm(B-C)^{1/2}\right], \tag{4}$$

where

$$A=\cos^2(\phi/2)\left[1-D\sin^2(\theta/2)\right],$$
$$B=\sin^2(\theta/2)\left[1-D\cos^2(\phi/2)\right],$$
$$C=(1-D)\left[\cos^2(\phi/2)-\cos^2(\theta/2)\right]\cos^2(\alpha-\theta/2),$$
$$D=(1+g^2)^{-1},\quad\text{and}\quad g=mM_0/k_{\rm F}.$$

3. Josephson spin current in TSFTS junctions

The Josephson charge current flowing through the ABSs is defined[2,6] as

$$I_{\rm C}=-\frac{e}{\hbar}\sum_{i=\mathrm{a,b}}\tanh(E_i/2k_{\rm B}T)\frac{\mathrm{d}E_i}{\mathrm{d}\phi}, \tag{5}$$

where ϕ is the phase difference of gap between the two superconductors on the left and right sides of the junction. Recently, besides the predication of unusual Josephson effects in TSFTS junctions,[6] the authors proposed several types of Josephson current switches which exhibit rich dependence of $I_{\rm C}$ on the relative orientation between the ferromagnetic moment and the d vector of the superconductors.

When the ABSs are spin-degenerate ($M\perp d_{\rm L,\,R}$, $\alpha=\pi/2$) and possess well-defined spin quantum number, $\sigma_a=\uparrow,\sigma_b=\downarrow$, they do not yield spin-polarised current. We believe that spin-polarised Josephson current occurs in TSFTS junction, when the ferromagnetic scattering barrier couples the ABSs ($\alpha\neq\pi/2$)

and lifts their spin degeneracy. At a primitive step, we study the generation and control of Josephson spin current in TSFTS junctions on the condition that the coupling induced by the magnetic scattering potential is extremely weak ($\alpha \approx \pi/2$) and the ABSs has approximately well-defined spin quantum number. Thus, the Josephson spin current accompanying the charge current is given by inserting $-\sigma_i\hbar/2e$ into the summation[5] as

$$I_{\rm S} = \sum_{i={\rm a,\ b}} (\sigma_i/2)\tanh(E_i/2k_{\rm B}T)\frac{{\rm d}E_i}{{\rm d}\phi} \tag{6}$$

with $\sigma_{\rm a} = 1$, $\sigma_{\rm b} = -1$. Josephson spin current at $d_{\rm L} \parallel d_{\rm R}$ ($\theta = 0$) is derived as

$$\begin{aligned} I_{\rm S} = & \left(\frac{\left[1-(1-D)\cos^2\alpha\right]\sin\phi}{8\sqrt{\cos^2(\phi/2)+(1-D)\sin^2(\phi/2)\cos^2\alpha}} + \frac{1}{4}[\mathrm{sgn}\,(\sin(\phi/2))]\sqrt{(1-D)}\cos\alpha\,\cos(\phi/2) \right) \\ & \times k_{\rm F}\Delta_0\sqrt{D}\tanh(E_{\rm a}/2k_{\rm B}T) \\ & - \left(\frac{\left[1-(1-D)\cos^2\alpha\right]\sin\phi}{8\sqrt{\cos^2(\phi/2)+(1-D)\sin^2(\phi/2)\cos^2\alpha}} - \frac{1}{4}[\mathrm{sgn}\,(\sin(\phi/2))]\sqrt{(1-D)}\cos\alpha\,\cos(\phi/2) \right) \\ & \times k_{\rm F}\Delta_0\sqrt{D}\tanh(E_{\rm b}/2k_{\rm B}T), \end{aligned} \tag{7}$$

where $\mathrm{sgn}(\sin(\phi/2))$ indicates the sign of $\sin(\phi/2)$

$$E_{\rm a} = k_{\rm F}\Delta_0\sqrt{D}\left[\sqrt{\cos^2(\phi/2)+(1-D)\sin^2(\phi/2)\cos^2\alpha}+\sqrt{(1-D)\sin^2(\phi/2)\cos^2\alpha,}\right], \tag{8}$$

$$E_{\rm b} = k_{\rm F}\Delta_0\sqrt{D}\left[\sqrt{\cos^2(\phi/2)+(1-D)\sin^2(\phi/2)\cos^2\alpha}-\sqrt{(1-D)\sin^2(\phi/2)\cos^2\alpha}\right]. \tag{9}$$

Josephson spin current exists in TSFTS junctions even when there is no phase difference between the superconductor gaps ($\phi = 0$). This indicates that the ferromagnetic scattering potential acts as a driving force leading to the generation of spin supercurrent.

We calculate the Josephson spin currents at varied strength and direction of the ferromagnetic moment M at $\phi = 0$, $\theta = 0$. Figure 2 shows the Josephson spin currents as a function of the angle α between the ferromagnetic moment and the d vector at $\phi = 0$, $\theta = 0$ (BCS temperature dependence of the superconductor gaps is assumed). There is no Josephson spin current in the junctions at $\alpha = \pi/2$ ($M \perp d_{\rm L,\,R}$), when the ABSs are not coupled through the ferromagnetic scattering potential. At $\alpha \neq \pi/2$, spin supercurrent flows through the spin-split ABSs caused by the ferromagnetic potential coupling in the junctions. Such a spin current is produced by the spin-filtering effect. The magnetic moment M in the spin quantization plane of each superconductor ($M \perp d_{\rm L}$, $d_{\rm R}$) defines a preferred direction and gives rise to a spin-dependent potential barrier, which is different for the scattering and transmission of each spin species of Cooper pairs. Thereby, one spin sector is selectively filtered out, leading to the finite Josephson spin current. The spin current increases as the angle α deviates from $\alpha = \pi/2$. If we substitute $\alpha' = \pi/2 + \Delta\alpha$ for α, the Josephson spin current becomes $I_{\rm S} \propto \sin(\Delta\alpha)$. And it becomes $I_{\rm S} \propto \Delta\alpha$ as $\Delta\alpha \to 0$ (see Fig. 2). Hence, we can adjust the spin supercurrent by controlling the magnetization direction of the ferromagnetic thin layer.

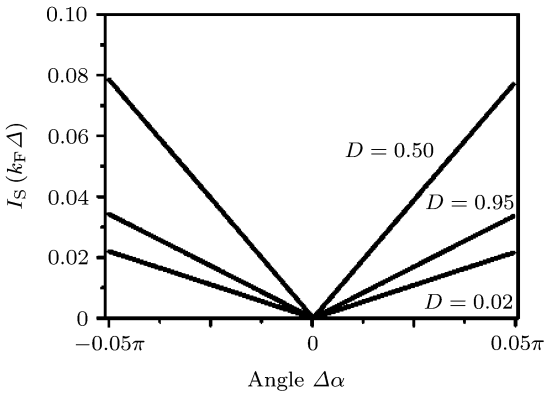


Fig. 2. Josephson spin currents $I_{\rm S} = I_{\rm S}(k_{\rm F}\Delta)/2$ as a function of the angle $\Delta\alpha$ for different ferromagnetic scattering potentials: (a) $D = 0.02$, (b) $D = 0.50$, (c) $D = 0.95$ with the reduced temperature $T/T_{\rm C} = 0.02$.

When we change the strength of ferromagnetic barrier, the scattering D varies. This leads to the enhanced or decreased Josephson spin current. Figure 3 shows the change of the spin supercurrent as

a function of the scattering D. There is no Josephson spin current in the junctions at $D = 0$ (infinite ferromagnetic scattering potential) and $D = 1$ (zero potential). A maximal Josephson spin current occurs at $D = 0.50$. We can choose the optimized ferromagnetic material to make the scattering D around 0.50 and obtain enhanced spin supercurrent.

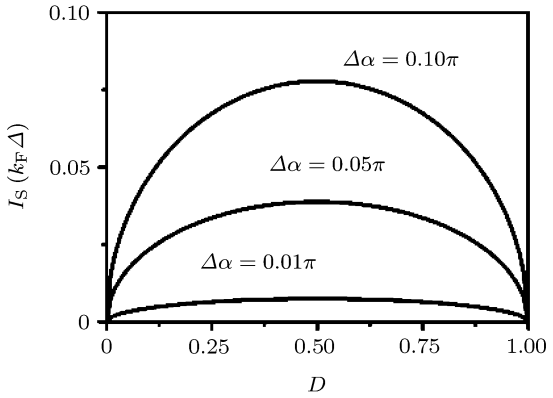


Fig. 3. Josephson spin currents $I_S = I_S(k_F\Delta)/2$ as a function of the strength of the ferromagnetic scattering potentials with the reduced temperature $T/T_C = 0.02$ at the different angles: (a) $\Delta\alpha = 0.01\pi$; (b) $\Delta\alpha = 0.05\pi$; (c) $\Delta\alpha = 0.10\pi$.

The spin flow direction can be tuned by a perturbation voltage pulse with proper bias. The equation (7) indicates that spin current I_S depends on $\mathrm{sgn}(\sin(\phi/2))$. Perturbation voltage pulse with different bias can induce a small phase difference $\phi = 2eV\tau$ with minus $(-)$ or plus $(+)$ sign between the two superconductor gaps. Therefore, the $\mathrm{sgn}(\sin(\phi/2))$ changes as the bias of the perturbation voltage pulse changes, giving rise to the reversion of spin current direction in the junctions. This may lead to the realization of a voltage-controlled Josephson spin current switch.

One attractive observation is the existing Josephson spin current and the vanishing Josephson charge current at $\phi = 0$, $\theta = 0$ and $\alpha \neq \pi/2$. This implies that the pure spin supercurrent flowing through the TSFTS junctions is driven by the ferromagnetic scattering potential. We can obtain pure spin supercurrent as well by adjusting the phase difference ϕ and the d_R-vector angle θ to make the charge supercurrent disappear. The interplay of ferromagnetic scattering potential, the phase difference ϕ and the d_R vector angle θ determines the Josephson charge and spin current across the junctions.

Figure 4 shows that the Josephson spin current varies as a function of θ and D. At finite angle of θ, the misalignment of the d-vector of superconductors results in a gradient of the order parameter in the spin space and provides a driving force for spin current.[5] Thus, we may yield and control the spin supercurrent by rotating the d-vector angle θ.

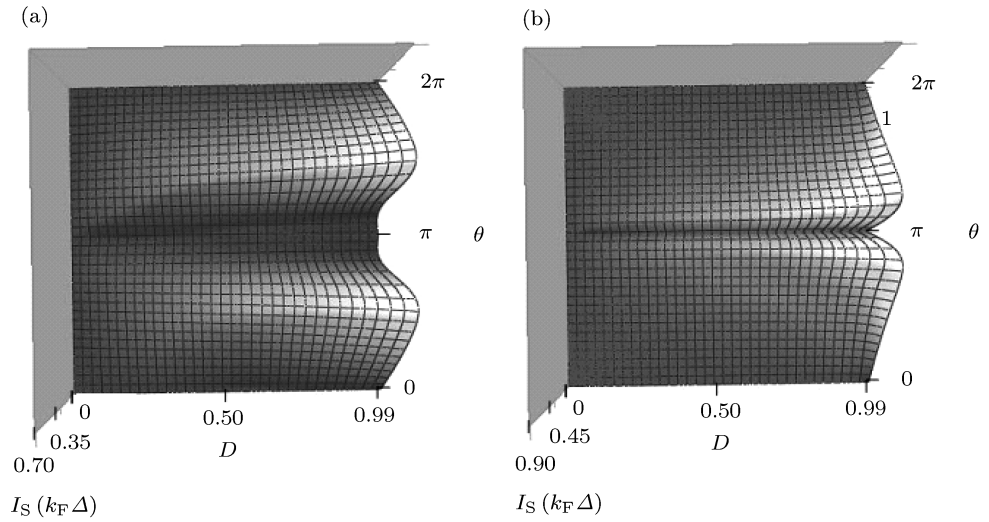


Fig. 4. Josephson spin currents $I_S = I_S(k_F\Delta)/2$ as a function of d_R-vector angle θ and scattering parameter D with the reduced temperature $T/T_C = 0.2$ and $\Delta\alpha = 0.005\pi$ at the phase differences: (a) $\phi = \pi/4$ and (b) $\phi = \pi/20$.

The generated Josephson spin current with no dissipation in TSFTS junctions has potential spin-based device applications. A spin current switch may be realized by adjusting the magnetization direction from $\alpha = \pi/2$ (0 state) to $\alpha \neq \pi/2$ (1 state). Experimentally, we propose to use the surfaces parallel to the c axis (d-vector direction) of the triplet superconductor Sr_2RuO_4 as the substrates for sequent epitaxial growth of thin ferromagnetic layer and thin Sr_2RuO_4 film.[14] The realization of TSFTS junctions depends on the delicate choice of ferromagnetic materials and control of the epitaxial growth process. Presently, a considerable challenge is measuring the Josephson spin current. Many methods have been proposed and experimentally confirmed to detect spin current.[15] Kerr rotation microscopy was used to observe the spin accumulation at the sample edges and by this the spin current is deduced.[16] A promising idea is to use a spin-mechanical device to detect and generate spin current by nanomechanical torque.[17,18] A spin-orbit device may also be applied to detect the spin current in TSFTS junctions.[19]

Other possible methods to generate spin supercurrent were proposed to use the curved structures of triplet superconductor[20] or Josephson junctions made by superconductors with spiral magnetic order.[21,22] The Zeeman magnetic field was found to have a significant influence on the coherent transport of Josephson current.[23−26] It is desirable to investigate the Zeeman effect on the Josephson spin current in TSFTS junctions. In normal metal/d-wave superconductor junctions, a remarkable zero bias conductance peak was found and attributed to the internal phase of the pair potential of the d-wave superconductor.[27−32] Such an internal phase is a desirable factor for generating and controlling the Josephson spin current in the triplet superconductor and d-wave superconductor heterojunctions.

4. Summary

In summary, we theoretically studied the generation and control of Josephson spin current in TSFTS junctions. The ferromagnetic scattering potential leads to the occurrence of spin-split ABSs in the junctions, which carry the spin supercurrent. The dissipationless spin supercurrent can be controlled by the magnetization of the ferromagnetic layer and bias voltage across the junction. In the future, we will consider the effect of spatial variation of the ferromagnetic potential on the generation of Josephson spin current.

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