Spin Currents in a Triplet Superconductor Junction

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Abstract. The Josephson effect must be generalized in junctions involving triplet superconductors to account for the possibility of spin transport. We use a quasiclassical method to study the appearance of a Josephson junction in a model triplet superconductor junction with a magnetically active tunneling barrier. We identify three distinct mechanisms for producing a Josephson spin current, characterize their symmetry properties, and provide physical explanations for each.

1. Introduction

There has recently been much interest in the properties of Josephson junctions involving triplet superconductors [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. Although the triplet pairs carry a finite spin, relatively little attention has been directed at understanding the spin transport properties of these devices [7, 9, 10, 11, 12]. In this paper we present the results of a systematic examination of the conditions under which a Josephson spin supercurrent appears in a model triplet-superconductor–ferromagnet–triplet-superconductor (TFT) junction. We identify three general mechanisms for the appearance of such a current: spin-filtering, misalignment of the $d$ vectors of the two triplet superconductors, and spin-flipping off a transverse barrier moment. For each mechanism, we analyze the symmetry properties of the resulting spin current in detail, and give physical explanations for the origin of the spin transport. We demonstrate that when the barrier moment does not conserve the Cooper pair spin, the spin currents on either side of the barrier need not be identical.

2. Model and Method

A schematic diagram of the TFT junction studied in this work is shown in Fig. (1). The junction is described by the Hamiltonian $H = \int \mathcal{H}(z, z') dz dz'$ with Hamiltonian density

$$\mathcal{H}(z, z') = \sum_{\sigma, \sigma'} \psi^\dagger_{\sigma'}(z') \delta(z' - z) \left[ -\frac{\hbar^2}{2m} \frac{\partial^2}{\partial z^2} - \mu + U_P \delta(z) \right] \delta_{\sigma\sigma'} - \delta(z) \mathbf{M} \cdot \hat{\sigma}_{\sigma\sigma'} \right] \psi^\dagger_{\sigma}(z')$$

$$+ \left\{ \frac{1}{2} \Delta(z, z') \left[ e^{-i\theta_\nu} \psi^\dagger_{\uparrow}(z') \psi^\dagger_{\downarrow}(z) - e^{i\theta_\nu} \psi^\dagger_{\downarrow}(z') \psi^\dagger_{\uparrow}(z) \right] + \text{H.c.} \right\}$$

(1)

where $\psi^\dagger_{\sigma}(z)$ ($\psi_{\sigma}(z)$) is the fermionic creation (annihilation) operator for a spin-$\sigma$ particle with co-ordinate $z$. The quasiparticles have effective mass $m$ and chemical potential $\mu$ in the superconductors. The superconducting gap is antisymmetric with respect to particle interchange, i.e. $\Delta(z, z') = -\Delta(z', z)$. We take $p_z$ pairing orbitals in both superconductors.
and assume equal gap magnitudes displaying BCS temperature-dependence [6, 10]. A phase difference $\phi$ is assumed between the two condensates. In the interests of simplicity, we neglect the spatial variation of the gaps within the superconducting regions. The $d$-vector on the left hand side of the junction defines the $x$-axis, whereas the $d$-vector on the right lies within the $x-y$ plane, inclined at an angle $\theta$ to the $x$-axis. As the two $d$-vectors have no $z$-component, this is the mutual spin orientation for pairing in the two superconductors. At the barrier we allow potential scattering by $U_p$ and magnetic scattering by the moment $M = (M_L \cos \alpha, M_L \sin \alpha, M_\parallel)$; $\sigma_{\alpha'\alpha}$ denotes the vector of Pauli matrices. In what follows, we set $\hbar = 1$ and quote values of $M_L, M_\parallel$ and $U_p$ in units of $m/k_F$ where $k_F$ is the Fermi momentum.

We obtain the Josephson currents flowing across the barrier via integration of the continuity equation for the charge and spin density, generalizing the approach of Ref. [13]. The resulting expressions for the spin and charge currents can be re-written in terms of the Green’s function $\mathcal{G}(z, z', \Omega; i\omega_n)$, which is a $4 \times 4$ matrix in Nambu-spin space. We hence define the Josephson charge $(I^c_\nu)$ and $\mu$-component of the spin $(I^\nu_{s,\mu})$ currents on the $\nu$-side of the junction

$$I^c_\nu = -i \frac{e}{4m} \sum_{\nu} \lim_{z-\rightarrow 0, z'+\rightarrow 0} \left( \frac{1}{2} \frac{\partial}{\partial z} - \frac{1}{2} \frac{\partial}{\partial z'} \right) \text{Tr} \left\{ \mathcal{G}_{\nu}(z, z', \Omega; i\omega_n) \right\}$$

(2)

$$I^\nu_{s,\mu} = i \frac{1}{8m} \sum_{\nu} \lim_{z-\rightarrow 0, z'+\rightarrow 0} \left( \frac{1}{2} \frac{\partial}{\partial z} - \frac{1}{2} \frac{\partial}{\partial z'} \right) \text{Tr} \left\{ \mathcal{G}_{\nu}(z, z', \Omega; i\omega_n) \right\} \sigma_{\nu \mu} \hat{0} \sigma^*_{\mu}$$

(3)

where $\int_i$ indicates an integration over half the spherical Fermi surface, $\Omega$ is the solid angle and $\mathcal{G}_{\nu}(z, z', \Omega; i\omega_n)$ is the Green’s function for $z, z' > (\leq 0)$ when $\nu = R(L)$. In the absence of chiral symmetry-breaking, the currents only flow along the $z$-axis. The spin structure of the Josephson currents are best appreciated by isolating the contributions to the total currents from each spin sector: choosing the $z$-axis for our spin basis, we define the spin-$\sigma$ charge current on the $\nu$-side of the barrier as $I^c_{\nu,\sigma} = (I^c_\nu - 2eI^\nu_{s,\nu})/2$, and the spin-$\sigma$ spin current $I^\nu_{s,\nu,\sigma} = -\sigma I^c_{\nu,\sigma}/2e$.

3. Results

Proceeding to calculate the Josephson currents from Eq. (2) and Eq. (3), we identify three distinct mechanisms for the appearance of a spin current: spin-filtering, misalignment of the $d$-vectors, and spin-flipping by a spin non-conserving moment.

3.1. Spin-Filtering

Using a spin-filter is the most straight-forward way to produce a spin current in our junction. The spin-filter requires both a finite $U_p$ and a magnetic moment $M \perp d_L, d_R$. The moment defines a preferred direction in the quantization plane of the two superconductors; working within this
quantization basis, we find spin-dependent effective barriers in the two spin channels, $U_P - \sigma |M|$. This implies that the transparency of the tunneling barrier is different in the two spin sectors, thus preferentially allowing the transmission of one spin species of Cooper pair over the other. As such, the current through each spin sector is different, resulting in a finite transport of spin across the barrier. The spin current produced by the spin-filter is antisymmetric in both $\phi$ and $M$. In Fig. (2)(a) and (b) we respectively show the charge and spin current produced by a spin filter with $M = M_{||} \hat{z}$. As the barrier moment conserves the spin of the tunneling Cooper pairs, the currents through each spin sector are the same on either side of the barrier.

3.2. $\mathbf{d}$-Vector Misalignment

It has recently been shown by Asano that misaligning the $\mathbf{d}$-vectors on either side of a non-magnetic barrier produces a spin current with spin component along $\mathbf{d}_L \times \mathbf{d}_R$ [11, 12]. In a perfect solid state analogy to the situation in superfluid $^3$He, the gradient of the order parameter in spin space drives the spin current [14]. Letting the intersection of the quantization planes of the two superconductors define our spin basis, we find spin-dependent effective phase differences $\phi_{\sigma} = \phi - \sigma \theta$ in the two spin channels [5, 10, 14]. The charge currents through each spin sector for a typical scenario with misaligned $\mathbf{d}$-vectors are presented in Fig. (2)(c): they are $2\theta$ out of phase with respect to one another but otherwise identical. As such, the spin currents carried through each spin sector do not cancel and we obtain the finite spin current shown in Fig. (2)(d). Note that unlike the case of the spin filter, a finite spin current here flows even when the total charge current is vanishing. The spin current produced by the $\mathbf{d}$-vector misalignment is symmetric in $\phi$ and antisymmetric in $\theta$. Like the spin-filter, this is a spin-conserving mechanism.
3.3. Spin-Flipping

The third fundamental mechanism for the generation of a spin current requires that we have a spin non-conserving moment at the tunneling barrier, i.e. $\mathbf{M} \cdot \mathbf{d}_{L,R} \neq 0$. We therefore consider the case with aligned $d$-vectors, and only a transverse moment at the junction (i.e. $M_\parallel \neq 0$, $M_\parallel = U_P = \theta = 0$). We then find that the $z$-component of the spin current is non-vanishing for $0 < \alpha < \pi/2$. The magnitude of the $\nu = L$ and $\nu = R$ spin currents are the same, but their sign is reversed, i.e. $I_{S,z}^L = -I_{S,z}^R$. The spin current on each side of the barrier is also $2\pi$ periodic and antisymmetric in $\alpha$, while symmetric in $\phi$. The charge current and its decomposition into spin-$\uparrow$ and spin-$\downarrow$ components on each side of the barrier is shown in Fig. (2)(e), while the spin currents on the LHS are shown in Fig. (2)(f). The plot of the charge currents reveals the physical origin of this behaviour: the current through the spin-$\uparrow$ ($\downarrow$) sector on the LHS of the junction is equal to the current through the spin-$\downarrow$ ($\uparrow$) sector on the RHS. That is, the spin of some of the tunneling Cooper pairs is flipped by the transverse moment. When a spin-$\sigma$ electron-like (hole-like) quasiparticle tunneling between two normal regions undergoes a spin-flip at the tunneling barrier, the transmitted and reflected quasiparticles acquire a phase shift of $+(-)\sigma \alpha$. This spin-dependent phase shift is ultimately the origin of the spin current.

4. Conclusions

As a result of a systematic study, we have identified three fundamental mechanisms for generating a spin current in a model TFT junction: spin-filtering, $d$-vector misalignment, and spin-flipping. We have discussed the physical origin of the spin transport for each mechanism, and analyzed the symmetry properties of the resulting spin current-phase relationships. Because of the very different symmetries of each mechanism, it is possible to exercise considerable control over the spin currents flowing through the junction by combining the three basic mechanisms [15].

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