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Spin–orbit coupling and finite quasi-particle lifetime effects in normal metal/triplet superconductor junctions

Xiaowei Li *

School of Physics and Electronic Electrical Engineering, Huaiyin Normal University, Huaian 223300, China
State Key Laboratory of Functional Materials for Informatics, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai 200050, China

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ABSTRACT

The Bogoliubov–de Gennes equation and extended Blonder–Tinkham–Klapwijk model are applied to studying tunneling conductance in normal metal/triplet superconductor (N/TS) junctions. Three kinds of pairing for TS are chosen: p_x, p_y, and $p_x + ip_y$ wave. It is found that the tunneling conductance strongly depends on kinds of pairings, then is affected by the spin–orbit coupling (SOC) of the Rashba type and the finite quasi-particle lifetime. The obtained results may help to explore the properties of superconducting state in Sr_2RuO_4.

1. Introduction

Physics of superconducting junctions has been one of the exciting fields of solid state physics. Possible realization of spin-triplet superconductivity in Sr_2RuO_4 is currently widely discussed. A number of experimental results is consistent with the spin-triplet p-wave symmetry state in this material [1–7]. It is well-known that the zero-energy Andreev bound states (ABSs) are induced near interfaces in unconventional superconducting junctions where pair potential changes its sign across the Fermi surface [8–14]. The ABS manifests itself in quasiparticle tunneling experiments as zero bias conductance peak (ZBCP). Tunneling data in Sr_2RuO_4 junctions show ZBCP in accordance with theoretical predictions [15]. Actually, the ZBCP has been observed in junctions of Sr_2RuO_4 [7,16]. On the other hand, Laube et al. has observed a typical double-minimum structure and a single-minimum structure centered at $V = 0$ in junctions of Sr_2RuO_4 [17]. Recently, it was shown that the spin–orbit coupling (SOC) of the Rashba type that is present near the interfaces in s wave superconductor/insulator/p wave superconductor junction and normal metal/d wave or chiral p wave superconductor junction [18,19]. It is important to study the effects of interface SOC on differential conductance of normal metal/p_x, p_y, and $p_x + ip_y$ wave superconductor junctions in much more detail because this symmetry is most probably realized in the superconducting state in Sr_2RuO_4 [1,20–23].

In order to consider the shortening of finite quasiparticle lifetime due to the inelastic scattering in the superconductor near the interface, Plecenik et al. [24,25] introduced a Γ-factor into the Bogoliubov equations (Γ is the broadening parameter characterizing the finite lifetime of the quasi-particles) and found the Γ-dependent Bogoliubov coherence factors u and v. The theoretical dependencies fit their experimental curves very well [24].

In this paper, we study the tunneling conductance in normal metal/triplet superconductor (N/TS) junctions using the Blonder–Tinkham–Klapwijk (BTK) theory [26]. We choose p_x, p_y, and $p_x + ip_y$ wave symmetries for the pairing symmetries of spin-triplet superconductor. Due to the fact that two sides of the N/TS junctions have different crystal and electronic structure, the interface potential barrier is asymmetric, resulting in the SOC of the type originally proposed by Rashba for semiconductor heterostructures [18,19]. We also take into account the shortening of quasiparticle lifetime due to the inelastic scattering. The effects of both the interface SOC and the finite quasi-particle lifetime on the tunneling conductance are presented and discussed. The obtained results may help to explore the properties of superconducting state in Sr_2RuO_4.

The organization of this paper is as follows. In Section 2, the formula of the tunneling conductance in N/TS junction is given. The numerical results of the tunneling conductance spectrum are discussed in Section 3. Finally, we briefly summarize our results in Section 4.

2. Formulation

For the model of the calculation, we consider a two dimensional N/TS junction in the clean limit as shown in Fig. 1. We assume a flat interface at $x = 0$. The interface potential may be modeled [18,19]

$$U(x) = [U_0 + U_1 n \cdot (\hat{\sigma} \times \hat{k})]\delta(x) \quad (1)$$

* Address: School of Physics and Electronic Electrical Engineering, Huaiyin Normal University, Huaian 223300, China. Tel.: +86 517 83526160.
E-mail address: lxw62@hotmail.com

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where $n = \hat{x}$ is the unit vector along the interface normal, U_0 and U_1 are the strengths of the spin-independent and the Rashba SOC contributions, respectively, $\hat{\sigma}$ are the Pauli matrix and $\hat{k} = -i\nabla$. We assume that the pair potential is a constant independent of x,

$$\hat{\Delta}(\theta, x) = \hat{\Delta}(\theta)\Theta(x) \tag{2}$$

where $\Theta(x)$ is the Heaviside step function. The pair potentials $\hat{\Delta}(\theta)$ are given by

$$\hat{\Delta}(\theta) = \begin{pmatrix} \Delta_{\uparrow\uparrow}(\theta) & \Delta_{\uparrow\downarrow}(\theta) \\ \Delta_{\downarrow\uparrow}(\theta) & \Delta_{\downarrow\downarrow}(\theta) \end{pmatrix} \tag{3}$$

In spin-triplet superconductors, the pair potentials have the form [27]

$$\Delta_{\uparrow\downarrow}(\theta) = \Delta_{\downarrow\uparrow}(\theta) = \Delta_0 f(\theta) \tag{4}$$

$$\Delta_{\uparrow\uparrow}(\theta) = \Delta_{\downarrow\downarrow}(\theta) = 0 \tag{5}$$

where the direction of the d vector is parallel to the c axis and

$$f(\theta) = \begin{cases} \cos\theta & \text{for } p_x \text{ symmetry} \\ \sin\theta & \text{for } p_y \text{ symmetry} \\ e^{i\theta} & \text{for } p_x + ip_y \text{ symmetry} \end{cases} \tag{6}$$

We adopt the Bogoliubov–de Gennes (BdG) approach to study the N/TS junction. The four-component BdG equation is decoupled into two sets of two-component matrix equations. One is for the spin-up electronlike and spin-down holelike quasiparticle wave-function $(u_\uparrow, v_\downarrow)$, the other for $(u_\downarrow, v_\uparrow)$. The BdG equation for $(u_\uparrow, v_\downarrow)$ has the form [28]

$$\begin{pmatrix} H_0 & \Delta_{\uparrow\downarrow} \\ \Delta^*_{\uparrow\downarrow} & -H^*_0 \end{pmatrix} \begin{pmatrix} u_\uparrow \\ v_\downarrow \end{pmatrix} = E \begin{pmatrix} u_\uparrow \\ v_\downarrow \end{pmatrix} \tag{7}$$

where $H_0 = -\frac{\nabla^2}{2m} - i\Gamma - E_F + U_\sigma$ with $U_\sigma = (U_0 + i\sigma U_1 \nabla_y)\delta(x)$, $\sigma = \pm 1$ for different spin orientation. $\Gamma = \hbar/\tau$, τ is the finite quasiparticle lifetime and E is the quasiparticle energy measured from the Fermi energy. We assume that the Fermi energy E_F and the effective mass m in the normal metal are equal to those in the superconductor.

Consider a beam of electrons incident on the interface at $x = 0$ from the normal metal at an angle θ to the interface normal. With general solutions of the Eq. (7), the wave functions in two regions are described by

$$\Psi_1 = \begin{pmatrix} 1 \\ 0 \end{pmatrix} e^{ik_F x\cos\theta} + a_{\bar{\sigma}} \begin{pmatrix} 0 \\ 1 \end{pmatrix} e^{ik_F x\cos\theta} + b_\sigma \begin{pmatrix} 1 \\ 0 \end{pmatrix} e^{-ik_F x\cos\theta}, \quad x < 0 \tag{8}$$

$$\Psi_2 = c_\sigma \begin{pmatrix} u_+ e^{i\phi_+} \\ v_+ \end{pmatrix} e^{ik_F x\cos\theta} + d_{\bar{\sigma}} \begin{pmatrix} v_- e^{i\phi_-} \\ u_- \end{pmatrix} e^{-ik_F x\cos\theta}, \quad x \geqslant 0 \tag{9}$$

where a_σ, b_σ, c_σ and d_σ correspond, respectively, to coefficients, for the Andreev reflection (AR) [29], normal reflection, transmission to the right triplet superconductor as electronlike quasiparticles and transmission as holelike quasiparticles. The electron and hole components of the wave functions in the TS region are given by [24]

$$(u_\pm)^2 = 1 - (v_\pm)^2 = \left(\frac{1}{2} + \frac{1}{2}\sqrt{\frac{(E + i\Gamma)^2 - |\Delta_\pm|^2}{(E + i\Gamma)^2}} \right) \tag{10}$$

where $\Delta_+ = \Delta_0 f(\theta)$ for electronlike and $\Delta_- = \Delta_0 f(\pi - \theta)$ for holelike. All the wave vectors in Eqs. (9) and (10) are approximately equal to k_F. The $\phi_\pm$ stand for the phase of the superconductor, where $e^{i\phi_\pm} = \frac{\Delta_\pm}{|\Delta_\pm|}$.

The wave functions must satisfy the boundary conditions [26]

$$\Psi_1(x = 0^-) = \Psi_2(x = 0^+) \tag{11}$$

$$\left(\frac{d\Psi_2}{dx}\right)_{x=0^+} - \left(\frac{d\Psi_1}{dx}\right)_{x=0^-} = k_F z_\sigma \Psi_2(x = 0^+) \tag{12}$$

where $z_\sigma = z_0 - \sigma z_1 \sin\theta$ with $z_0 = 2mU_0/(\hbar^2 k_F)$ and $z_1 = 2mU_1/\hbar^2$. The dimensionless parameters z_0 and z_1 characterize the strengths of the potential and the SOC scattering, respectively.

The tunneling differential conductance across the N/TS superconductor junction has been given by the Blonder–Tinkham–Klapwijk (BTK) theory, with the contribution of AR being included. The differential conductance in the N/ TS junction is given by [26]

$$G_S = \sum_\sigma \int_{-\pi/2}^{\pi/2} d\theta \cos\theta [1 + A_{\bar{\sigma}} - B_\sigma] \tag{13}$$

for the temperature $T = 0$ K, $A_{\bar{\sigma}} = |a_{\bar{\sigma}}|^2, B_\sigma = |b_\sigma|^2$ represent, respectively, the probabilities of Andreev reflection, normal reflection. G_N is the conductance for a normal metal /normal metal junction with the interface potential given by

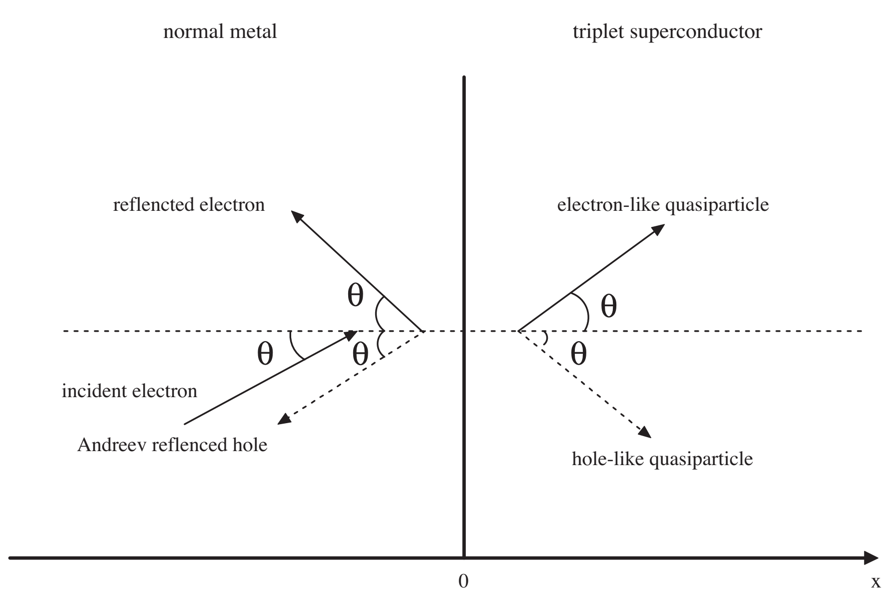

Fig. 1. Schematic illustration of the reflection and the transmission process of the quasiparticle reflection and transmission processes at the N/TS.