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Theoretical study of proximity effect on normal metal/triplet p-wave superconductors

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Abstract

Superconducting proximity effect in normal metal (N)/triplet p-wave superconductor (P) junctions is studied on the basis of the quasi-classical Green's function theory. We assume the attractive interelectron potentials which can induce subdominant s-wave pair potentials in the N side, where spatial dependencies of the pair potentials are determined self-consistently. In the case of an N/p_x-wave junction, a zero-energy peak (ZEP) in tunneling spectra emerges due to the spin-commutated proximity effect through Andreev reflection in low barrier. Moreover, by varying the transparency of the junction, we obtain the broad line shaped tunneling spectra with the sharp ZEP similar to actual experiment of Ru/Sr_2RuO_4. In high barrier, our obtained results are consistent with previous works in isolated p-wave superconductors.

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1. Introduction

Tunneling spectroscopy via Andreev surface bound states (ABS's) can be used to determine pairing symmetry of spin-singlet d-wave superconductors if one can prepare well-oriented surfaces/interfaces in the superconducting planes. These ABS's arise at the surfaces/interfaces when the injected and reflected quasiparticles feel different sign change of pair potentials. Now, it is known that the tunneling spectroscopy via ABS's enables us to detect the sign change in the pair potential as well as its nodal structure [1,2]. The existence of ABS's, which manifests itself as a zero-bias conductance peak (ZBCP), has been observed for cuprates, and so on. In contrast, it is of great interest to investigate the pairing symmetry of spin-triplet triplet superconductors from the tunneling spectroscopy via ABS's.

As a possible candidate for spin-triplet p-wave pairings, ruthenate superconductor Sr_2RuO_4 has attracted much attention [3]. Actually, the ZBCP in tunneling experiments by Mao et al. [4] is observed in Sr_2RuO_4 with Ru-inclusions. The overall-line shaped spectra is broad shaped structure with a sharp ZBCP (like a bell), and the situation is different from the cases of cuprates or organic superconductors [5]. Moreover, it is known that the critical temperature of Ru/Sr_2RuO_4 junction enhances up to 3 K (the intrinsic T_c of Sr_2RuO_4 is 1.5 K) [6]. In such a case, it is pointed out by Sigrist and Monien [7] that the proximity effect plays an important role near the interface of Ru/Sr_2RuO_4 junctions. Since Ru is a metal with a conventional BCS superconductor, we can regard the Ru/Sr_2RuO_4 junctions as normal metal (N)/triplet p-wave (P) superconductor junctions.

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Motivated by these points, in order to study the proximity effect, we calculate the tunneling spectra in N/P junctions based on quasiclassical Green's function methods. In the N side, we assume attractive interelectron potentials which induce subdominant s-wave components. The spatial dependencies of the pair potentials both in the N and P sides are determined self-consistently. In the present study, we take into account three pairing symmetry (i) p_x-wave, (ii) p_y-wave, and (iii) $p_x + ip_y$-wave in the P side. The local density of states (LDOS) at the interface of the N/P junctions are studied in detail by changing the reflection probability R of the junction.

2. Model and results

We introduce the spin-triplet Andreev equation [8],

$$E_n \Psi_n(\hat{\boldsymbol{k}},\boldsymbol{r}) = -\left[\mathrm{i}\hbar v_{\mathrm{F}} \hat{\boldsymbol{k}}\cdot\nabla + \hat{\Delta}(\hat{\boldsymbol{k}},\boldsymbol{r})\right]\hat{\tau}_3 \Psi_n(\hat{\boldsymbol{k}},\boldsymbol{r}), \quad (1)$$

$$\hat{\Delta}(\hat{\boldsymbol{k}},\boldsymbol{r}) = \begin{pmatrix} 0 & \Delta(\hat{\boldsymbol{k}},\boldsymbol{r})\cdot\boldsymbol{\sigma}\mathrm{i}\sigma_y \\ \mathrm{i}\sigma_y \Delta^*(\hat{\boldsymbol{k}},\boldsymbol{r})\cdot\boldsymbol{\sigma} & 0 \end{pmatrix}, \quad (2)$$

where the quantities $\hat{\boldsymbol{k}}$ and $\boldsymbol{r}$ stand for the unit vector of the wave number of the Cooper pair which is fixed on the Fermi surface ($\hat{\boldsymbol{k}} = \boldsymbol{k}_{\mathrm{F}}/|\boldsymbol{k}_{\mathrm{F}}|$), and the position of the center of mass of Cooper pair, respectively. The wave function $\Psi_n(\hat{\boldsymbol{k}},\boldsymbol{r})$ is obtained by neglecting the rapidly oscillating plane-wave part following the quasiclassical approximation. The $\hat{\boldsymbol{k}}$ dependence of $\Delta(\hat{\boldsymbol{k}},\boldsymbol{r})$ represents the symmetry of the pair potential.

Next, we consider the N/P junction separated by an insulating interface at $x = 0$, where the normal metal is located at $x < 0$ and the p-wave superconductors extends elsewhere. For the simplicity, two dimensional system is assumed and the x-axis is taken perpendicular to the interface.

The pair potentials for $l(=\mathrm{N},\mathrm{P})$ sides are given by

$$\begin{aligned}\Delta^l(\phi,x) = \sum_{0\le m<\omega_c/2\pi T} \frac{1}{4\pi}\int_{-\pi/2}^{\pi/2} \mathrm{d}\phi' [V^l(\phi,\phi'_+) \\ \times \{[\hat{g}^l_{++}(\phi'_+,x)]_{12} - [\hat{g}^{l\dagger}_{++}(\phi'_+,x)]_{12}\} \\ - V^l(\phi,\phi'_-)\{[\hat{g}^l_{--}(\phi'_-,x)]_{12} \\ - [\hat{g}^{l\dagger}_{--}(\phi'_-,x)]_{12}\}],\end{aligned} \quad (3)$$

where ω_c is the cutoff energy. Here, the above $[\hat{g}^l_{\alpha\alpha}(\phi_\alpha,x)]_{12}$ means the 12 element of the quasiclassical Green's function $\hat{g}^l_{\alpha\alpha}(\phi_\alpha,x)$ given as

$$\hat{g}^l_{\alpha\alpha}(\phi_\alpha,x) = \frac{\mp\alpha\mathrm{i}}{1 - D^l_\alpha(x)F^l_\alpha(x)} \begin{pmatrix} 1 + D^l_\alpha(x)F^l_\alpha(x) & 2\mathrm{i}F^l_\alpha(x) \\ 2\mathrm{i}D^l_\alpha(x) & -1 - D^l_\alpha(x)F^l_\alpha(x) \end{pmatrix}. \quad (4)$$

Here, $D_\alpha(x) = -\mathrm{i}v_n^{(+)}(\phi_\alpha,x)/u_n^{(+)}(\phi_\alpha,x)$ and $F_\alpha(x) = \mathrm{i}u_n^{(-)}(\phi_\alpha,x)/v_n^{(-)}(\phi_\alpha,x)$, obey the following Riccati type equations:

$$\hbar|v_{\mathrm{F}x}|\frac{\partial}{\partial x}D^l_\alpha(x) = \alpha\left[2\omega_m D^l_\alpha(x) + \Delta^l(\phi_\alpha,x)D^l_\alpha(x)^2 - \Delta^l(\phi_\alpha,x)^*\right], \quad (5)$$

$$\hbar|v_{\mathrm{F}x}|\frac{\partial}{\partial x}F^l_\alpha(x) = -\alpha\left[2\omega_m F^l_\alpha(x) - \Delta^l(\phi_\alpha,x)^* F^l_\alpha(x)^2 + \Delta^l(\phi_\alpha,x)\right]. \quad (6)$$

Based on the self-consistently determined pair potentials, the LDOS in the N and P sides can be calculated as

$$\begin{aligned} N_N(E,x) &= \mathrm{Im}\frac{N_0}{4\pi}\int_{-\pi/2}^{\pi/2}\mathrm{d}\phi\ \mathrm{Tr}\left[\hat{g}^N_{--} - \hat{g}^N_{++})\hat{\tau}_3\right]_{\mathrm{i}\omega_m\to E+\mathrm{i}\delta}, \\ N_P(E,x) &= \mathrm{Im}\frac{N_0}{4\pi}\int_{-\pi/2}^{\pi/2}\mathrm{d}\phi\ \mathrm{Tr}\left[\hat{g}^P_{++} - \hat{g}^P_{--})\hat{\tau}_3\right]_{\mathrm{i}\omega_m\to E+\mathrm{i}\delta}, \end{aligned} \quad (7)$$

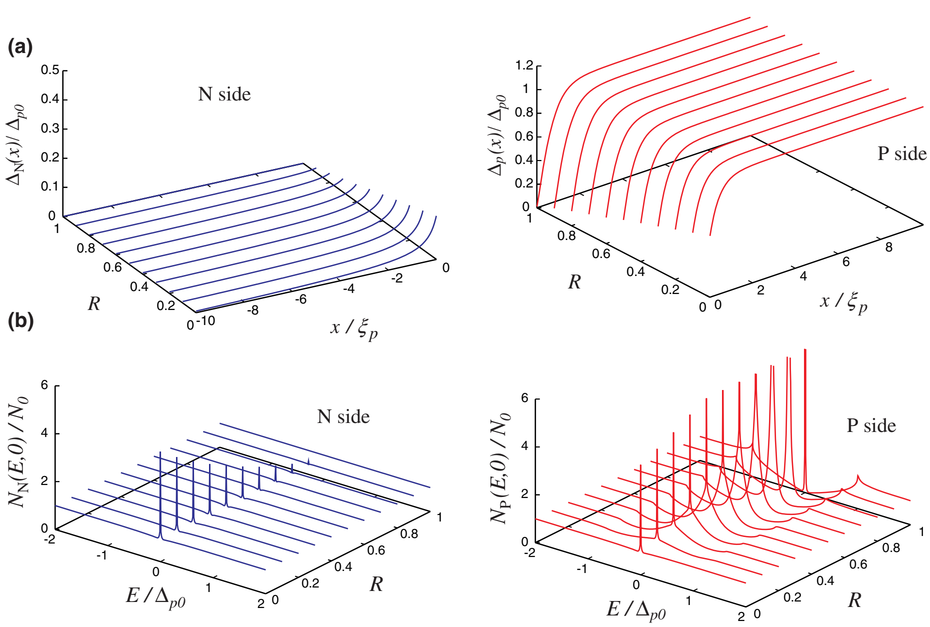

Fig. 1. (a) Spatial dependence of N/p_x-wave junctions and (b) the corresponding LDOS at the interface.