Josephson Tunneling and Pairing Symmetry of High Tc Superconductor

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Abstract

The temperature dependent Josephson critical current $J_c(T)/J_c(0)$ between high T_c superconductors along the *a*-axis is theoretically studied. The interface influence on the wave functions of quasi-particles is included in the theory within the framework of the two-dimensional t-J model. It is found that the experimental results can be satisfactorily explained by the present model with *d* wave pairing symmetry.

Keyword : High T_c Superconductors, d wave, Josephson tunneling

I. Introduction

Since the discovery of superconductivity in the layered copper oxide materials [1], a number of microscopic models have been proposed [2-5]. For a proper understanding of high T_c superconductivity, it is imperative to determine the correct symmetry of the superconducting order parameter. There have been conflicting experimental evidences whether the superconducting condensate state has s-, d-, s-d, or s*-d mixed symmetries, where s* is the extended s-wave [6-8]. Tunneling data along the c-axis of quasi-tetragonal copper oxides clearly show an s-wave character [9]. On the other hand, tunneling along the a- or b-axis of YBCO has indicated a d-wave character with some exceptions [10-13]. In order to explain these conflicting experiments, various theories including $s+id$ and s^*+id symmetries were proposed [7,8,14,15]. In this paper, we include the interface effect in theory and compare theories with various symmetries to the experiments.

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II. Theory

We develop a general theory which can accomodate various symmetries mentioned above. We employ the two-dimensional t-J model in order to describe tunneling for YBCO [16, 17]. The t-J Hamiltonian is given by

$$H=-t\sum_{\langle ij\rangle\sigma}(c_{i\sigma}^{+}c_{j\sigma}+h.c.)-\mu\sum_{i\sigma}c_{i\sigma}^{+}c_{i\sigma}-J\sum_{\langle ij\rangle}b_{ij}^{+}b_{ij,} \qquad (1)$$

Where $<ij>$ means the nearest neighbor pairs $b_{ij}^{+}=c_{i\uparrow}^{+}c_{j\downarrow}^{+}-c_{i\downarrow}^{+}c_{j\uparrow}^{+}$ and μ is chemical potential. Using the mean-field result of the 2-D t-J model with the order parameter $\Delta_{ij}=2<c_{j\downarrow}c_{i\uparrow}>$ and we obtain

$$x_{ij} = \sum_\sigma < C^+_{i\sigma} C_{j\sigma} > = 2 < C^+_{i\uparrow} C_{j\downarrow} >,$$

$$\Delta_k = J \sum_{k'} V_{kk'} \frac{\Delta_{k'}}{E_{k'}} \tanh \frac{\beta E_{k'}}{2}, \quad (2)$$

$$\delta = \frac{1}{N} \sum_k \frac{\varepsilon_k}{E_k} \tanh \frac{\beta E_k}{2} \quad (3)$$

and

$$x = \frac{1}{2N} \sum_k \gamma_k [1 - \frac{\varepsilon_k}{E_k} \tanh \frac{\beta E_k}{2}]. \quad (4)$$

where

$$\varepsilon_k = -(2t + xJ)\gamma_x - \mu,$$

$V_{k,k'} = 2[\cos(k_x - k_{x'}) + \cos(k_y - k_{y'})]$,
$\gamma_k = (\cos k_x + \cos k_y)$, $\beta = 1/k_B T$ and energy spectrum is $E_k = \sqrt{\varepsilon_k^2 + J^2|\Delta_k|^2}$ [17]. δ represents the average hole doping concentration. In order to develop a general theory, we follow Xu et al.'s approach and assume an order parameter $\Delta_k = \Delta_s + i\Delta_d(\cos k_x - \cos k_y)$

Here, we note that the simplest even parity expression for s*+id has a form of $\Delta_k = c_0\Delta_s + ic_2\Delta_d$, where $c_0 = \cos k_x + \cos k_y$ and $c_2 = \cos k_x - \cos k_y$. Other symmetries follow immediately by choosing c_0 and c_2 accordingly.

We substitute the above expressions into Eq.(2) and solve for Δ_k . In the calculation the k-summation is confined to the first Brillouin zone [17,18]. For numerical values, we use J ∋ 0.124 eV obtained from the NMR data [19]. The hopping parameter, t, is estimated to be t …0.19 eV in optimal doping [20]. At $T = 0K$, we obtain 4(0)=18~19 meV and 4(0)/$k_B T_c$= 2.32~2.52 when the ratio of s* component to d-wave component is varied from 0 to 1.

In analyzing the Josephson tunneling phenomena, the pairing symmetry plays a crucial role. The space is no longer homogeneous near the junction. We here ignore inhomogenity on the superconducting order parameter. However, the existence of the interface is expected to become a quasiparticles. The uasiparticle states are determined by the Bogoliubov-de Gennes(BdG) equations [21] which are obtained from the mean-field result of the 2-D t-J model.

$$\sum_j [-(\tilde{t} + \mu)u_k(j) - \Delta v_k(j)] = E_k u_k(i)$$
$$\sum_j [(\tilde{t} + \mu)v_k^*(j) - \Delta u_k^*(j) = E_k v_k^*(i) \quad (5)$$

where $\tilde{t}$ =t +xJ, 4_{ij} =4 and j is a nearest neighbor of i along x(or y) direction. Solutions to the above equations are

$$u_k(j) = \zeta_+ \sin k_x j_x e^{ikj_y}$$
$$u_k(j) = -\zeta_-(k) \operatorname{sgn}(\Delta_k) \sin k_x j_x e^{ikj_y} \quad (6)$$

with $\zeta_\pm = \frac{1}{\sqrt{N}}(1 \pm \frac{e_k}{E_k})^{1/2}$. From Eq.(6), we note that the quasiparticles are described by the standing wave functions along the normal direction of the interface.

We consider the Josephson tunneling in the a-axis direction through a junction of a normal metal between two YBCO superconductors with perfectly flat interfaces. To describe the electron transport process in the junction, we use the Ambegaokar-Baratoff theory [22]. The tunneling Hamiltonian given by

$$H_T = \sum_{ij} T_{ij} c_i^+ d_j + h.c. \quad (7)$$

where T_{ij} is the matrix element transferring electrons through the junction from right-hand side to left-hand side. c_i^+ and d_j are the creation and annihilation operator in the left and right superconductor, respectively. It is expected that the largest tunneling is between the nearest neighbors. Since the coordinate system can be independently defined for the left and right superconductors, we make the choice that the nearest neighbors on the yz-planes adjacent to the junction take the same value of coordinate. Thus the ij-summation in above Hamiltonian is carried out with the conditions; $i_x = j_x = 1$, $i_y = j_y$ and $i_z = j_z$. Using the standard perturbation treatment, we obtains for the Josephson critical current [22]

$$J_c(T) = 4eN|T_0|^2 \frac{1}{\beta} \sum_{i,j} \sum_n F_{ji}^+(iw_n) F_{ij}(iw_n) \quad (8)$$

where T_0 is the matrix element of nearest neighbors tunneling and N_{yz} is the total number of sites on one of the interfaces. $F_{ij}(i\omega_n)$ with $\omega_n = \pi(2\nu+1)/\downarrow$ is the Fourier transformation of the Gorkov's pair

Gorkov's pair correlation function,

$$F_{ij}(\tau) = -< T_c c_{i\uparrow}(T) c_{j\downarrow}(0) > \qquad (9)$$

Note that the Gorkov's pair correlation function is defined in the semi-infinite space : i_x•*1*, *-1*• i_y•*1* and j_x•*1*, *-1*• j_y•*1*. We evaluate the Gorkov's pair correlation function using the mean-field approximation,

$$F_{ij}(iw_n) = \sum_k \left[\frac{u_k(i_x) v_k^*(j_x)}{iw_n - E_k} - \frac{u_k(j_x) v_k^*(i_x)}{iw_n + E_k} \right] \qquad (10)$$

$$= -\frac{1}{N} \sum_k \frac{\Delta_k}{w_n^2 + E_k^2} \sin(k_x i_x) \sin(k_x j_x) e^{ik_j(i_y - j_y)}$$

III. Results and discussions

Combining Eq.(6), Eq.(8), and Eq.(10) and taking a frequency summation, we obtain a formula for $J_c(T)$ as

$$J_c(T) = \frac{4e|T_0|^2 N_{yz}}{N^2} \sum_{k,k'} \frac{\Delta_k \Delta_{k'}}{E_k E_{k'}} x(k,k') \sin^2 k_x \sin^2 k'_x \Big|_{k'_y = k_y} \qquad (11)$$

with

$$x(k,k') = \frac{\tanh(\beta E_k / 2) + \tanh(\beta E_{k'} / 2)}{E_k + E_{k'}} - \frac{\tanh(\beta E_k / 2) - \tanh(\beta E_{k'} / 2)}{E_k - E_{k'}} \qquad (12)$$

In Fig.1, we exhibit the calculated result for $J_c(T)$ as a function of T for various symmetries and com

pared to experimental results[7,8,15]. Clearly, the d wave tunneling model with the interface effect describes the experimental results satisfactorily comparing to other symmetry waves. Our result demonstrates that s*+*id* is not necessary to fit the experimental data contrary to the Xu et al's claim [14]. It should be noted that the main disagreement between previous d-symmetry theories and the present model arises mainly from neglect of the interface effect.

IV. Conclusions

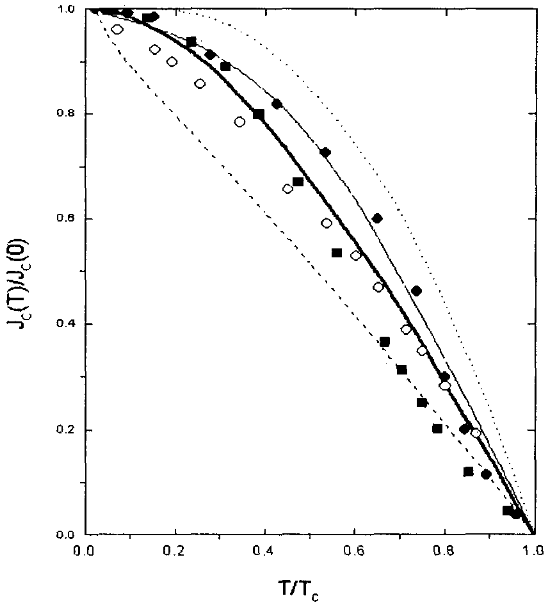

Fig. 1. Josephson critical current J(T)/J(0) as a function o temperature T. The solid bold line is the present result o pure d-wave symmetry. The experimental results(0: ref[7] ●: ref[8], ■:ref[15]) are also shown as well a s-wave(dotted line), d-wave without interface ef fect(dashed-line) and s*+*id* with φ4$_{s*}$ φ= 0.2φ4$_d$ (soli thin line) for the comparison.

In summary, using the 2-D *t-J* model, we have investigated Josephson tunneling between YBCO superconductors. It is shown that the d-wave symmetry with the interface explains the experiment satisfactorily. We also have shown that the interface effect is critical in explaining the experimental results.

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