

# Bi<sub>2</sub>Sr<sub>2</sub>CaCu<sub>2</sub>O<sub>8+δ</sub> Bicrystal *c*-Axis Twist Josephson Junctions: A New Phase-Sensitive Test of Order Parameter Symmetry

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## Abstract

Li *et al.* [Phys. Rev. Lett. **83**, 4160 (1999)] prepared atomically clean Bi<sub>2</sub>Sr<sub>2</sub>CaCu<sub>2</sub>O<sub>8+δ</sub> (BSCCO) Josephson junctions between identical single crystal cleaves stacked and twisted an angle  $\phi_0$  about the *c*-axis. For each bicrystal, the ratio  $J_c^J/J_c^S$  of the *c* axis twist junction critical current density to that across either single crystal part is unity, independent of  $\phi_0$  and the ratio  $A^J/A^S$  of junction areas. From extensive theoretical studies involving a variety of tunneling and superconducting order parameter (OP) forms, we conclude that the results provide strong evidence for incoherent *c*-axis tunneling and that the dominant OP is *s*-wave for  $T \leq T_c$ . Recently, Takano *et al.* [Phys. Rev. B **65**, 140513(R) (2002)] obtained results from BSCCO whisker twist junctions which also rule out a pure *d*-wave OP, but which are surprisingly suggestive of coherent *c*-axis tunneling from small Fermi surface hot spots.

*Key words:* Josephson junctions; order parameter symmetry; Bi<sub>2</sub>Sr<sub>2</sub>CaCu<sub>2</sub>O<sub>8+δ</sub>

## 1. Introduction

Phase-sensitive experiments to test the symmetry of the superconducting order parameter (OP) in the high transition temperature ( $T_c$ ) superconductors were mostly made on YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7-δ</sub> (YBCO) [1], for which the OP can have mixed ( $d_{x^2-y^2}+s$ ) symmetry. To reconcile the various results, Müller proposed that the surface might be mostly  $d_{x^2-y^2}$ -wave, and the bulk mostly *s*-wave [2]. Especially in Bi<sub>2</sub>Sr<sub>2</sub>CaCu<sub>2</sub>O<sub>8+δ</sub> (BSCCO), the *c*-axis transport above  $T_c$  is incoherent, [3], and scanning tunneling microscope studies revealed that it is electronically disordered on the scale of the superconducting coherence length,  $\approx 1.5$  nm [4], both unfavorable features for bulk *d*-wave superconductivity. Both *c*-axis Pb/BSCCO Josephson junctions [5] and a new phase-sensitive experiment on BSCCO are consistent with those observations [6].

## 2. The Bicrystal Twist Experiment

Li *et al.* cleaved a single crystal of BSCCO, twisted the two cleaves an angle  $\phi_0$  about the *c*-axis and fused them together, forming junctions of remarkably superior quality [6]. High resolution transmission electron spectroscopy and other studies revealed that the junction cross-sections were atomically clean over more

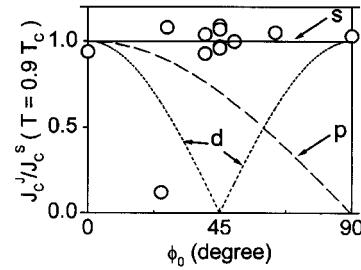


Fig. 1. Ratio at  $0.9T_c$  of the critical current densities  $J_c^J/J_c^S$  across *c*-axis twist junctions to that across single crystals of BSCCO, versus the twist angle  $\phi_0$  [6]. The curves are theoretical results for strongly incoherent *c*-axis tunneling [10].

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than 5  $\mu\text{m}$  [7], far superior to those used in tricrystal experiments [1]. They measured the  $c$ -axis critical current  $I_c^S$  and  $I_c^J$  across a single crystal and the twist junction near to  $T_c$ , respectively, and the respective areas  $A^S$  and  $A^J$ . They found that the ratio of the critical current densities  $J_c^J = I_c^J/A^J$  to  $J_c^S = I_c^S/A^S$  at  $0.9T_c$  was independent of  $\phi_0$ , as shown in Fig. 1 [6]. Here we argue that these data demonstrate that the bulk OP in BSCCO is  $s$ -wave for  $T \leq T_c$ , and the  $c$ -axis quasiparticle tunneling is strongly incoherent.

### 3. Group Theory and the Fermi Surface

Both YBCO and BSCCO are orthorhombic, but in different ways. For YBCO with point group  $C_{2v}^1$ , the mirror planes  $\sigma_x, \sigma_y$  (the  $ac, bc$  planes) contain the crystal axes  $a$  and  $b$  along the Cu-O bond direction in the  $\text{CuO}_2$  layers. In BSCCO with approximate point group  $C_{2v}^{13}$ , the mirror plane  $\sigma_b$  (the  $bc$ -plane) contains the  $b$  crystal axis (along a diagonal between the Cu-O bond directions) and the periodic lattice distortion [7,8]. The irreducible representations for the OPs in YBCO and BSCCO are given in Table I. Although  $s$ - and  $d_{x^2-y^2}$ -wave OP components are compatible in the bulk of YBCO, they are *incompatible* in BSCCO, requiring a second phase transition for bulk coexistence.

We assume the quasiparticle dispersion has either the tight-binding  $\xi(\mathbf{k}) = -t[\cos(k_x a) + \cos(k_y a)] + t' \cos(k_x a) \cos(k_y a) - \mu$  with  $t = 306$  meV,  $t'/t = 0.90$ , and  $\mu/t = -0.675$ , or hot spot  $[\cos(k_x a) - \cos(k_y a)]^2 - \nu^2$  forms, and a respective tetragonal Fermi surface (FS) with  $\xi(\mathbf{k}_F) = 0$ , shown in Fig. 2 [9,10].

### 4. The Twist Theorem and its Consequences

For weak tunneling across the twist junction,

$$J_c^J(\phi_0) = |4eT \sum_{\omega} \langle f_{\mathbf{k}, \mathbf{k}'}^J F_{\omega, \mathbf{k}} [R_{\mathbf{k}'}(\phi_0) F_{\omega, \mathbf{k}'}] \rangle|, \quad (1)$$

where  $F_{\omega, \mathbf{k}} = \Delta(\mathbf{k})/[\omega^2 + \xi^2(\mathbf{k}) + |\Delta(\mathbf{k})|^2]$ ,  $\Delta(\mathbf{k})$  is the OP,  $\omega$  represents the Matsubara frequencies,  $f_{\mathbf{k}, \mathbf{k}'}^J$  is the tunneling matrix element squared,  $\langle \dots \rangle$  is an average over each first Brillouin zone (BZ), and  $R_{\mathbf{k}'}(\phi_0)$  rotates the wave vectors  $\mathbf{k}'$  by  $\phi_0$  about the  $c$ -axis. For a single  $d$ -wave OP component,  $R_{\mathbf{k}}(\pi/2)\Delta(\mathbf{k}) = -\Delta(\mathbf{k})$ .

Table 1  
Irreducible representations (IR) of the OPs for orthorhombic point groups  $C_{2v}^1$  for YBCO (left) and  $C_{2v}^{13}$  for BSCCO (right).

IR YBCO OP	$\sigma_x, \sigma_y$	IR BSCCO OP	$\sigma_b$
$A_1  s + d_{x^2-y^2}\rangle$	+1	$A'_1  s + d_{xy}\rangle$	+1
$A_2  d_{xy} + g_{xy(x^2-y^2)}\rangle$ -1		$A'_2  d_{x^2-y^2} + g_{xy(x^2-y^2)}\rangle$ -1	

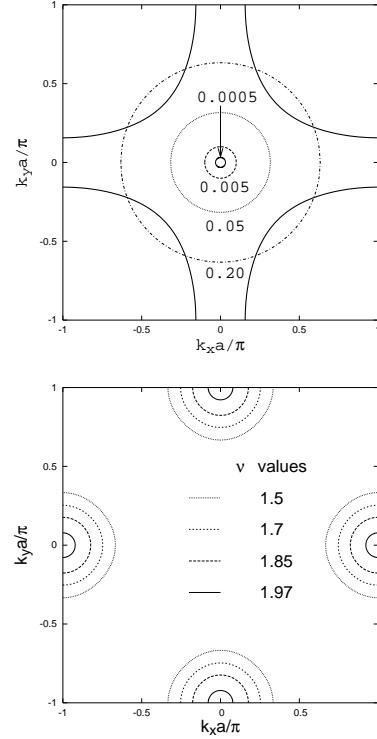


Fig. 2. Upper: tight-binding FS (solid) plus  $f^J$  half-width regions for indicated  $\tilde{\sigma}^2$  values [10]. Lower: hot spot FSs with  $\nu = 1.5, 1.7, 1.85, 1.97$ .

**Twist Theorem 1** For any weak tunneling matrix element squared satisfying  $f_{\mathbf{k}, \mathbf{k}'}^J = f_{\mathbf{k}', \mathbf{k}}^J$ , an arbitrary OP of general  $d_{x^2-y^2}$ - or  $d_{xy}$ -wave symmetry in a tetragonal crystal gives rise to a vanishing  $c$ -axis critical current across an internal  $45^\circ$  twist junction for  $T \leq T_c$ .

### PROOF.

$$\begin{aligned} Z_{\omega} &= \langle f_{\mathbf{k}, \mathbf{k}'}^J [R_{\mathbf{k}'}(\pi/4) F_{\omega, \mathbf{k}'}] F_{\omega, \mathbf{k}} \rangle \\ &= \langle f_{\mathbf{k}, \mathbf{k}'}^J F_{\omega, \mathbf{k}'} [R_{\mathbf{k}}(-\pi/4) F_{\omega, \mathbf{k}}] \rangle \\ &= \langle f_{\mathbf{k}, \mathbf{k}'}^J F_{\omega, \mathbf{k}'} [-R_{\mathbf{k}}(\pi/4) F_{\omega, \mathbf{k}}] \rangle \\ &= \langle f_{\mathbf{k}', \mathbf{k}}^J F_{\omega, \mathbf{k}} [-R_{\mathbf{k}'}(\pi/4) F_{\omega, \mathbf{k}'}] \rangle = -Z_{\omega} = 0. \end{aligned}$$

We studied a variety of OP and weak  $f_{\mathbf{k}, \mathbf{k}'}^J$  forms [10]. In Fig. 3, we show our results for the ordinary- $d$ - and ordinary- $s$ - OP forms proportional to  $\cos(k_x a) - \cos(k_y a)$  and 1, respectively. For a Gaussian form of  $f^J$ ,  $f_{\mathbf{k}, \mathbf{k}'}^J = f_0^J \exp[-(\mathbf{k} - \mathbf{k}')^2/\tilde{\sigma}^2]$ . We also studied exponential, Lorentzian, rotationally-invariant Lorentzian, and stretched Lorentzian forms [10]. Regardless of the form of  $f^J$ , the twist theorem requires  $J_c^J(\pi/4) = 0$  for a  $d$ -wave OP. From these and similar unpictured curves, it is evident that only an OP of general  $s$ -wave symmetry can fit the data. Moreover, the  $c$ -axis quasiparticle tunneling must be very incoherent.

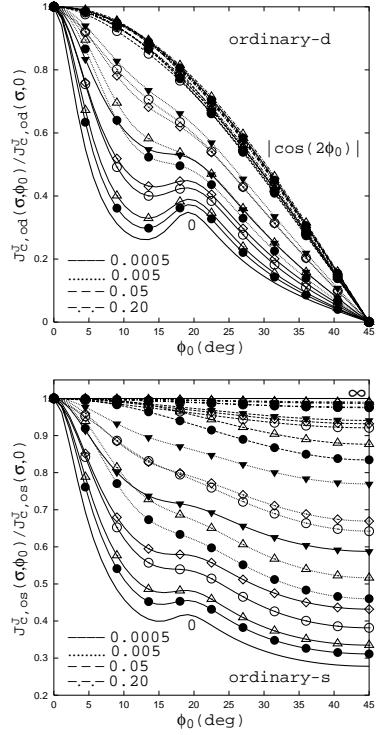


Fig. 3. Plots of  $J_c^J(\phi_0)/J_c^J(0)$  near  $T_c$  with the tight-binding FS in Fig. 2 for the ordinary  $d_{x^2-y^2}$  (top) and  $s$  (bottom) OPs. The thick solid lines labelled 0 are for coherent tunneling, and those labelled  $|\cos(2\phi_0)|$  and  $\infty$  are for purely incoherent tunneling. Other curve types labelled with the values of  $\sigma^2$  measure the fraction of the first BZ involved in the tunneling, as shown in Fig. 2. Results for the Gaussian ( $\bullet$ ), exponential ( $\circ$ ), Lorentzian ( $\diamond$ ) rotationally-invariant Lorentzian ( $\triangle$ ), and stretched Lorentzian (solid inverted triangles)  $f^J$  forms are shown [10].

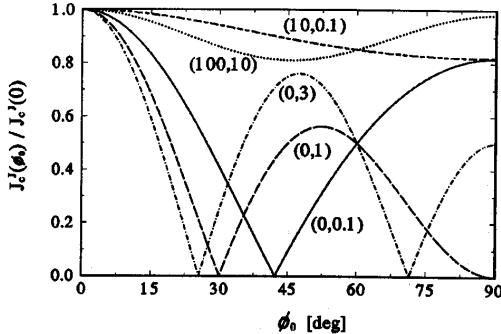


Fig. 4. Plots of  $|A + \cos(2\phi_0) + B \cos(4\phi_0)|/|1 + A + B|$ , with the  $A, B$  values, for  $J_c^J(\phi_0)/J_c^J(0)$  from the  $A'_1, A'_2$  OP IRs. [8].

#### 4.1. Orthorhombicity

When orthorhombicity is included, the theorem is not rigorous. However, including a small  $g_{xy(x^2-y^2)}$  OP component in a dominant- $d_{x^2-y^2} A'_2$  OP will only shift

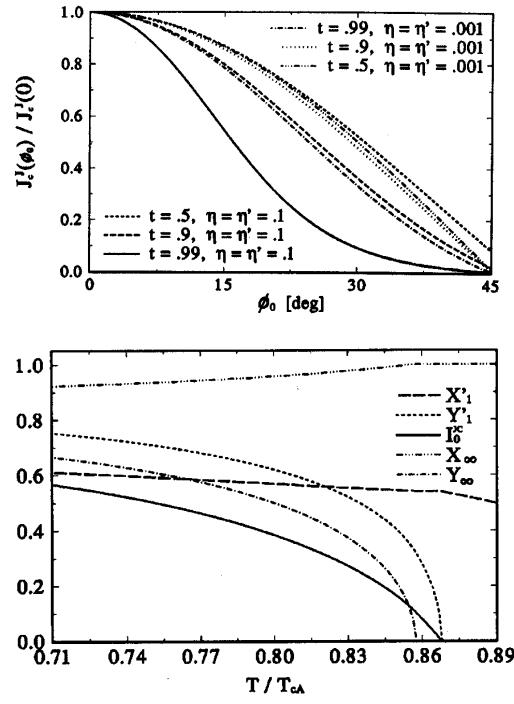


Fig. 5. Upper: Plots of  $J_c^J(\phi_0)/J_c^J(0)$  at different  $t = T/T_c$  values for a  $d_{x^2-y^2} + id_{xy}$  symmetry in the bulk, with  $T_{cB}^0 = 0.1T_c$ .  $\eta$  and  $\eta'$  are the Josephson couplings across bulk and the twist junctions, respectively. Lower (solid):  $T/T_{cA} = t$  dependence of  $J_c^J(45^\circ)$  for a twist junction with  $d_{x^2-y^2} + is$  symmetry in the bulk, and  $T_{cB}^0 = 0.9T_c$  [8].

the angle  $\phi_0^*$  at which  $J_c^J(\phi_0^*) = 0$  by a small amount from  $45^\circ$ , as pictured in Fig. 4. Hence, orthorhombicity cannot explain the data of Li *et al.* [6].

#### 4.2. Order Parameter Twisting

At low  $T$ , it is possible to obtain  $J_c^J(\pi/4) \neq 0$  with a predominant- $d_{x^2-y^2} A'_2$  OP symmetry, provided that a subdominant  $A'_1$  OP component can exist. Near to the twist junction, the dominant  $A'_2$  OP would be suppressed, and the subdominant  $A'_1$  OP increases in amplitude, so that the overall OP effectively rotates near the twist junction [8]. However, the amount of twisting is strongly limited by the second bare transition temperature  $T_{cB}^0$  and by the bulk and twist junction Josephson coupling strengths  $\eta, \eta'$ . In Fig. 5, we show the results obtained with subdominant OPs of the  $d_{xy}$ - and  $s$ -wave forms, respectively. Neither case can fit the data of Li *et al.* [6]. Figure 5 shows that an experiment just below  $T_c$  can rule out OP twisting effects, unless  $T_{cB}^0 = T_c$ , for which the overall bulk OP would be nearly isotropic at low  $T$ .

### 4.3. Strong Coupling and Other Models

We also considered both weak and strong coherent  $c$ -axis tunneling with a variety of FS forms [9]. In Fig. 6, we show the tight-binding FS  $J_c^J(\phi_0)$  for second order coherent tunneling. In Fig. 7, the  $J_c^J(\phi_0)$  for weak coherent tunneling with two hot spot FSs in Fig. 2 are shown. None of these curves fit the data of Li *et al.* [6].

## 5. BSCCO Whisker $c$ -Axis Twist Experiments

Recently, Takano *et al.* performed low- $T$   $c$ -axis twist mesa experiments using overdoped BSCCO whiskers with  $45^\circ \leq \alpha \equiv \phi_0 \leq 90^\circ$  [11]. Their data, pictured in Fig. 7, are distinctly different from those of Li *et al.* [6], with a strong  $J_c^J(\phi_0)$  dependence. Especially since  $J_c^J(\phi_0)$  for  $\phi > 80^\circ$  was anomalously large, Takano *et al.* suspected an extrinsic  $\phi_0$  dependence to  $f_{\mathbf{k},\mathbf{k}'}^J$  [11]. Nevertheless, in Fig. 7 we fit the data using Eq. (1) by assuming the quasiparticles have a hot spot dispersion and intrinsically coherent  $c$ -axis tunneling. Subsequently, they found  $J_c^J(\phi_0) \approx C \neq 0$  from many junctions with  $\phi_0 \approx 45^\circ$ , and provided preliminary Fraunhofer and Shapiro evidence that the non-vanishing  $J_c^J(45^\circ)$  arises from first-order Josephson tunneling [12]. Hence, the whisker experiments rule out a pure  $A'_2$  (e. g.,  $d_{x^2-y^2}$ ) OP, but are presently consistent with an OP either of pure  $A'_1$  (e. g.,  $s$ ) symmetry, or of mixed  $A'_1$  and  $A'_2$  (e. g.,  $d_{x^2-y^2} + is$ ) symmetry. From our theoretical studies, whisker experiments just below  $T_c$  might determine if their bulk OP is also pure  $A'_1$  [6], and measurements above  $T_c$  could investigate if the  $c$ -axis transport is indeed coherent, strikingly inconsistent with single crystal BSCCO [3].

## 6. Conclusions

The data of Li *et al.* demonstrate that the OP in the bulk of BSCCO has  $A'_1$  ( $s$ ) symmetry for  $T \leq T_c$ , and that the  $c$ -axis tunneling is strongly incoherent. The data of Takano *et al.* presently rule out a pure  $A'_2$  ( $d_{x^2-y^2}$ ) OP, but surprisingly suggest that the weak  $c$ -axis tunneling in BSCCO whiskers might be coherent with a FS consisting of small hot spots.

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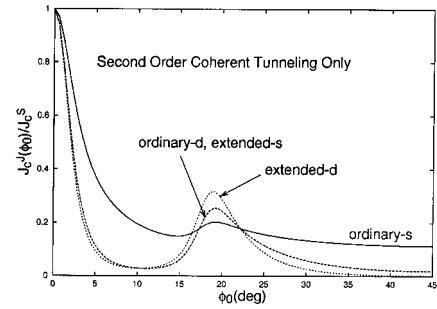


Fig. 6.  $J_c^J(\phi_0)/J_c^J(0)$  near to  $T_c$  for the  $s$ ,  $d_{x^2-y^2}$ , extended- $s$  [ $|\cos(k_x a) - \cos(k_y a)|$ ] and extended- $d$  OPs, [10] obtained for coherent second order twist junction tunneling only.

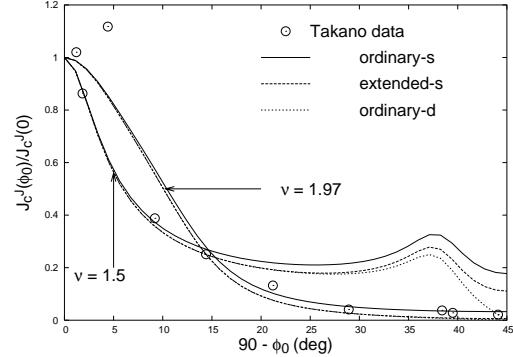


Fig. 7.  $J_c^J(\phi_0)/J_c^J(0)$  near  $T_c$  for weak coherent tunneling with the hot spot FSs in Fig. 2 with  $\nu = 1.5, 1.97$ , for the ordinary- $s$ , extended- $s$ , and ordinary- $d_{x^2-y^2}$  OPs. The whisker data ( $\circ$ ) of Takano *et al.* are also shown [11].

## References

- [1] C. C. Tsuei and J. R. Kirtley, Rev. Mod. Phys. **72**, 969 (2000).
- [2] K. A. Müller, Phil. Mag. Lett. **82**, 279 (2002).
- [3] J. J. McGuire *et al.*, Phys. Rev. B **64**, 094503 (2001), and references within.
- [4] K. M. Lang *et al.*, Nature (London) **415**, 412 (2002).
- [5] M. Mölle and R. Kleiner, Phys. Rev. B **59**, 4486 (1999).
- [6] Qiang Li, Y. N. Tsay, M. Suenaga, R. A. Klemm, G. D. Gu, and N. Koshizuka, Phys. Rev. Lett. **83**, 4160 (1999).
- [7] Y. Zhu *et al.*, Phys. Rev. B **57**, 8601 (1998); Y. Zhu *et al.*, Mircosc. Microanal. **3**, 423 (1997).
- [8] R. A. Klemm, C. T. Rieck, and K. Scharnberg, Phys. Rev. B **58**, 1051 (1998); *ibid.* **61**, 5913 (2000).
- [9] G. B. Arnold and R. A. Klemm, Phys. Rev. B **62**, 661 (2000).
- [10] A. Bille, R. A. Klemm, and K. Scharnberg, Phys. Rev. B **64**, 174507 (2001).
- [11] Y. Takano *et al.*, Phys. Rev. B **65**, 140513(R) (2002).
- [12] M. Tachiki, private communication.