c-Axis Twist Bi2Sr2CaCu2O8+8 Josephson Junctions: A New Phase
-Sensitive test of Order Parameter Symmetry

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c-Axis Twist Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$
Josephson Junctions:
A New Phase-Sensitive Test of Order Parameter Symmetry$^1$

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Abstract. Li et al. found that the critical current density $J^f_c$ across atomically clean c-axis twist junctions of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ is the same as that of the constituent single crystal, $J^f_s$, independent of the twist angle $\phi_0$, even at $T_c$. We investigated theoretically if a $d_{x^2-y^2}$-wave order parameter might twist by mixing in $d_{xy}$ components, but find that such twisting cannot possibly explain the data near to $T_c$. Hence, the order parameter contains an $s$-wave component, but not any $d_{x^2-y^2}$-wave component. In addition, the c-axis Josephson tunneling is completely incoherent. We also propose a c-axis junction tricrystal experiment which does not rely upon expensive substrates.

**EXPERIMENTAL INTRODUCTION**

It has recently become possible to prepare extraordinarily perfect bicrystal Josephson junctions with Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi2212). [1,2] These junctions are prepared by cleaving a very high quality single crystal of Bi2212 in the $ab$-plane, quickly examining the cleaved parts under a microscope, rotating one part an arbitrary angle $\phi_0$ about the $c$-axis with respect to the other, placing them back together, and fusing them by heating just below the melting point for 30 h. [1,2] A schematic view of the resulting c-axis bicrystal is shown in Fig. 1. By examining these bicrystals with high resolution transmission electron microscopy (HRTEM), electron energy-loss spectroscopy, and energy dispersive x-ray spectroscopy, they were found to be atomically clean over the entire areas studied ($\approx 10^3\mu m^2$). HRTEM pictures

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showed that the periodic lattice distortion was atomically intact on each side of the twist junction. [1]

To each of the 12 bicrystals measured, six electrical leads were attached using Ag epoxy, two on opposite sides of each of the two constituent single crystals, and two across the bicrystal. By applying the current $I$ across the central leads straddling the bicrystal, and a voltage $V$ across two of the other leads, it was possible to measure the $I/V$ characteristics of the $c$-axis transport across each constituent single crystal, and across the twisted bicrystal junction in the same run. The critical current $I_c$ was easily identified, as $V$ dropped by 5-8 orders of magnitude at a well-defined $I$ value, provided that the temperature $T$ was less than the transition temperature $T_c$. [1,2] For each bicrystal junction, they measured the critical current $I_c^J(T)$ and the junction area $A^J$. Similarly, for each constituent single crystal, they measured the critical current $I_c^S(T)$ and the area $A^S$. Usually, $I_c$ was too large to measure at low $T$, so comparisons were made at $0.9T_c$, where all 12 samples were measured. [2]

Of the 12 bicrystal junctions, 7 were prepared with $40^\circ \leq \phi_0 \leq 50^\circ$, and one each at $0^\circ$ and $90^\circ$. Although $I_c^S$ and $I_c^J$ at $T = 0.9T_c$ varied from sample to sample, and the critical current densities $J_c^S = I_c^S/A^S$ and $J_c^J/A^J$ also varied from sample to sample, with only one exception (probably due to a sample that had weakly attached leads), the ratio $J_c^J/J_c^S$ of critical current densities was the same ($1.00 \pm 0.06$) for each sample! In a sample with $\phi_0 = 50^\circ$, $J_c^J(T)/J_c^S(T) = 1.0$ over the entire range $10K < T < T_c$, and $I_c(T)/I_c(0)$ fit the Ambegaokar-Baratoff curve. [2,3] As discussed in the following, these results comprise very strong evidence for an $s$-wave component of the superconducting order parameter (OP) at and below $T_c$, and cannot be explained within a dominant $d_{x^2-y^2}$-wave scenario.

GROUP THEORY

Although the crystal structure of Bi2212 is orthorhombic, the orthorhombic distortion is different from that of YBa$_2$Cu$_3$O$_{7-\delta}$, with different unit cell lengths $a$

![Figure 1](image.png)

**FIGURE 1.** Illustration of a $c$-axis twist junction with twist angle $\phi_0$. 
TABLE 1. Singlet superconducting OP eigenfunctions in the angular momentum ($\ell$) and lattice ($n, m$) representations, their group theoretic (GT) notations, and character table for the orthorhombic point group $C_{2v}$ in the form appropriate for Bi2212. $\sigma_b$ represents the strict $bc$-mirror plane reflection.

<table>
<thead>
<tr>
<th>GT OP Eigenfunction</th>
<th>$E$</th>
<th>$\sigma_a$</th>
<th>$\sigma_b$</th>
<th>$C_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>$s + d_{xy}$</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
</tr>
<tr>
<td>$\tilde{a}<em>0 + \sqrt{2} \sum</em>{n=1}^{\infty} \tilde{a}_n \cos[2n(\phi_k - \pi/4)]$</td>
<td>$n,m$</td>
<td>$\sum_{n,m=0}^{\infty} { \cos(nk_xa) \cos(mk_ya)[\tilde{a}<em>{nm} + \tilde{a}</em>{-mn}]$</td>
<td>$\sin(nk_xa) \sin(mk_ya)[\tilde{c}<em>{nm} + \tilde{c}</em>{-mn}]$</td>
<td>+1</td>
</tr>
<tr>
<td>A2</td>
<td>$d_{x^2-y^2} + g_{xy}(s^2-y^2)$</td>
<td>$\tilde{b}<em>0 + \sqrt{2} \sum</em>{n=1}^{\infty} \tilde{b}_n \sin[2n(\phi_k - \pi/4)]$</td>
<td>$n,m$</td>
<td>$\sum_{n,m=0}^{\infty} { \cos(nk_xa) \cos(mk_ya)[\tilde{a}<em>{nm} - \tilde{a}</em>{-mn}]$</td>
</tr>
</tbody>
</table>

and $b$ along the diagonals between the Cu-O bond directions in the CuO$_2$ planes. In addition, there is an incommensurate lattice distortion $Q = (0, 0.212, 1)$ along one of these diagonals, the $b$-axis, which is clearly seen in the HRTEM pictures of the twist junctions. [1] Since $Q$ contains a $c$-axis component, only the $bc$-plane is a strict crystallographic mirror plane. [1] Group theory and Bloch’s theorem dictate that the superconducting OP must reflect the crystal symmetry. In Table 1, we have presented the allowable forms of the OP eigenfunctions for Bi2212. [4] We presented both the angular momentum (fixed $k_F$, variable $\phi_k$, with quantum numbers $\ell$) and the nearly tetragonal lattice (variable $k_x, k_y$, with quantum numbers $n, m$) representations of the OP eigenfunction forms. As indicated, the two OP eigenfunction forms are respectively even and odd with respect to rejections about the $bc$-plane (the $\sigma_b$ operation). [5] Thus, in Bi2212, $s$-wave and $d_{x^2-y^2}$-wave OP components are completely incompatible, and do not mix except possibly below a second (as yet unobserved) thermodynamic phase transition. [4]

LAWRENCE-DONIACH MODEL

Previously, we investigated whether it might be possible to explain the lack of any $\phi_0$-dependence of the $c$-axis critical current from a purely $d$-wave scenario. [6] We assumed that in the $n$th layer, the dominant OP component was $d_{x^2-y^2}$, the amplitude $A_n$ of which became non-vanishing below $T_c = T_{ca}$. By choosing the sub-dominant OP component to be $d_{xy}$ with amplitude $B_n$ and bare transition temperature $T_{cb} < T_{ca}$, we considered whether the overall OP could “twist” by mixing $d_{x^2-y^2}$- and $d_{xy}$-wave components, to accommodate for the physical twist in the Josephson junction between the adjacent layers $n = 1$ and $n = -1$. 
There are basically two distinct, relevant energy scales in this problem. One is the relative amount of the two d-wave components. This is determined mainly by the different in the bare $T_c$ values, $T_{cA}$ and $T_{cB}$. Now, if one assumes that there is only one observable zero-field superconducting phase transition (at $T_i = T_{cA}$), then $T_{cB} << T_{cA}$, and $|B_n| << |A_n|$ for $n \rightarrow \pm \infty$. This difference in $T_c$ values translates into a strong locking of the OP onto the lattice, with the anti-nodes of the $d_{x^2-y^2}$-wave OP component lining up with the Cu-O bond direction on each side of the twist junction. Fluctuations near to $T_c$ manifest in the diverging coherence length along the c-axis direction, allow some OP mixing, but that suppresses $I_c(\phi_0)$ for $\phi_0 \neq 0$, as shown in Figs. 2 and 3.

The second energy scale is the strength of the Josephson coupling $\eta$ (and $\eta'$ across the twist junction) of the OP components between adjacent layers. When this coupling is strong, as expected for a rather isotropic layered superconductor, then it is possible to obtain a finite $I_c(45^\circ)$ at $T \approx 0.7T_c$, as pictured in Figs. 2 and 3. However, Bi2212 is extremely anisotropic, and we thus expect $\eta \approx \eta' << 1$. In Fig. 3, we recalculated $I_c(\phi_0, T)$ for this case. Clearly, for $\eta = \eta' = 0.001$, $I_c(45^\circ) \approx 0$. Thus, we conclude that it is impossible to explain the data of Li et al. by assuming a dominant $d_{x^2-y^2}$-wave OP component. [2,4,6]

**CONCLUSIONS**

We thus conclude that the superconducting OP in Bi2212 is the the group $A_1$, which contains the s-wave component, but does not contain any purported $d_{x^2-y^2}$-wave OP component. 

![Figure 2](image-url)

**FIGURE 2.** Plot of $I_c(\phi_0)/I_c(0)$ for the case of a dominant $d_{x^2-y^2}$-wave and subdominant $d_{x^y}$-wave OP, the relative amounts varying with layer index away from the twist junction. [6] The parameters for these curves are $T_{cB}/T_{cA} = 0.2$, $T_{cB}/T_{cA} = 0.1304$, $\epsilon/\delta \alpha = 0.5$, $\delta/\delta \alpha = 0.1$, and the curves for $\eta = \eta' = 1$ are indicated. At $t = 0.7$, curves for $\eta = 1$ and various $\eta'$ values are indicated.
wave component near to $T_c$. There are then two possible additional interpretations of these experiments. If there were a substantial amount of coherent interlayer tunneling, then one might be tempted to claim that the OP were entirely isotropic $s$-wave in form. For free-particle Fermi surfaces, such a scenario is quite possible, as rotated Fermi surfaces on opposite sides of the twist are degenerate. However, Bi2212 is generally thought to have a tight-binding Fermi surface. In this case, inter-twist coherent tunneling is only possible for $\phi_0 \approx 0^\circ, 90^\circ$, for which a finite fraction of the rotated Fermi surfaces are degenerate. Thus coherent tunneling would result in a larger $I_c(\phi_0)$ for $\phi_0 = 0^\circ, 90^\circ$ than for any other $\phi_0$ value, contrary to experiment. [2] Hence, we conclude that the interlayer tunneling is entirely incoherent, without any discernible interlayer forward scattering, even between adjacent layers on the same side of the twist junction. [6]

Thus, we can only say that the OP is in the group $A_1$, which contains the $s$-wave component. The overall OP eigenfunction could exhibit nodes, but it is even about reflections in the $bc$-mirror plane, and thus does not contain any amount of the odd $d_{x^2-y^2}$-wave OP component. This conclusion is further supported by new $c$-axis Josephson junction experiments between Bi2212 and Pb, which showed strong evidence for an $s$-wave component at low $T$. [7]

NEW TRICRYSTAL EXPERIMENT PROPOSAL

Since the $c$-axis junctions are qualitatively superior to the $ab$-plane thin film junctions, we propose a new tricrystal (or tetracystal) experiment using $c$-axis junctions, as pictured in Fig. 4. This experiment does not require any expensive

![Graph]

**FIGURE 3.** Plot of $I_c(\phi_0)/I_c(0)$ for the case considered in [6] of a dominant $d_{x^2-y^2}$-wave and subdominant $d_{xy}$-wave OP, the relative amounts varying with layer index away from the twist junction. Curves for $\eta = \eta' = 0.1$ and $\eta = \eta' = 0.001$ with $t = T/T_{cA} = 0.99, 0.9, 0.5$ are presented. The other parameters are the same as in Fig. 2.
substrates, and the grain boundaries are intrinsically far superior to those of the planar junctions. [1,8] In addition, since $I_c$ for the c-axis junctions is ordinarily much larger than for the $ab$-plane due to larger junction areas, it is much easier to satisfy the experimental requirement $I_c L / \Phi_0 >> 1$, where $L$ is the induction of the ring and $\Phi_0$ is the flux quantum. [4]

REFERENCES
