$BI_2SR_2CACU_2O_{8+\delta}$ C-AXIS BICRYSTAL TWIST AND CROSS-WHISKER EXPERIMENTS

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Abstract The combined bicrystal, artificial cross-whisker, and natural cross-whisker c-axis twist experiments on $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) provide strong evidence that the superconducting order parameter is predominantly s-wave for $T \leq T_c$, and that the c-axis tunneling is strongly incoherent.

Keywords: Order parameter; incoherent tunneling; Josephson junctions

Introduction

There has long been a raging debate over the orbital symmetry of the superconducting order parameter (OP) in the high transition temperature (T_c) superconductors.[1] Many experiments were interpreted as providing evidence for a predominantly $d_{x^2-y^2}$-wave OP, but others were interpreted as providing evidence for a predominantly s-wave OP. Müller argued that the OP is d-wave on the surface and s-wave in the bulk.[1]

$Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) forms a disordered array of superconducting and non-superconducting pseudogap nanodomains, as revealed by scanning tunneling microscopy studies.[2] Hence, only phase-sensitive experiments can distinguish s-wave from d-wave OP's in Bi2212.

1. Bicrystal Twist Josephson Junctions

Li *et al.* made extraordinarily perfect artificial c-axis twist bicrystal junctions.[3] These junctions were extensively characterized using high resolution transmission electron microscopy (HRTEM), electron energy loss spectroscopy, and low energy electron diffraction, etc., and the results were compared with computer simulations.[4] More recently, off-axis electron holography provided compelling evidence of the remarkable atomic perfection and reproducibility of the twist junctions.[5]

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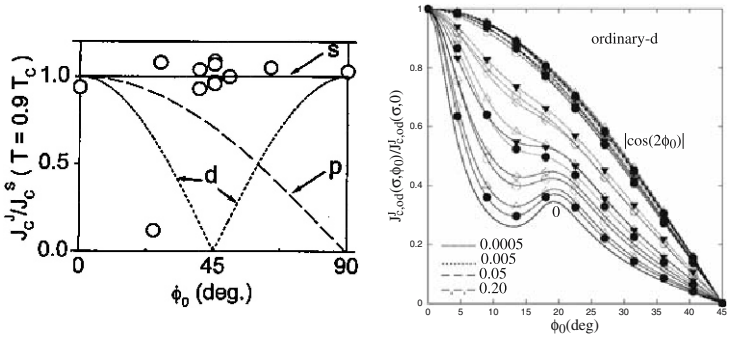

Figure 1. Left: Plot of the bicrystal $J_c^J(\phi_0)/J_c^S$ at $0.9T_c$.[3] The curves refer to the incoherent limits for single OP components. Right: Weak tunneling $J_c(\phi_0)^J/J_c^J(0)$ at 0.9 T_c assuming the tight-binding Fermi surface appropriate for Bi2212 and a $d_{x^2-y^2}$-wave OP.[6] The σ^2 values are given in the legend. Curves marked 0 and $|\cos(2\phi_0)|$ are the coherent and incoherent limits, respectively. The Gaussian (•), exponential (○), rotationally invariant Lorentzian (△), stretched Lorentzian (solid inverted triangles), and Lorentzian (◇) tunneling model results are shown. [6]

Li *et al.* measured the critical current densities J_c^J and J_c^S across the twist junction and constituent single crystals for 12 samples with different ϕ_0 values. They found $J_c^J(\phi_0)/J_c^S = 1$ near to T_c, as shown in the left panel of Fig. 1.[3]

Since $d_{x^2-y^2}$-wave and d_{xy} OP's are orthogonal, $J_c(45°) = 0$ for a single d-wave OP component in a tetragonal crystal with weak interlayer tunneling.[6] Although Bi2212 is slightly orthorhombic, $J_c(\phi_0^*) = 0$ for a d-wave OP, where $\phi_0^* \approx 45°$, inconsistent with the Li *et al.* data. [3, 7] The mixing of OP components to compensate for the physical twist junction might allow a predominant $d_{x^2-y^2}$-wave OP to result in a substantially ϕ_0-independent J_c^J for $T \ll T_c$, but not for $T \approx T_c$, where the measurement was performed.[3, 7] An additional d-wave scenario leading to a non-vanishing (albeit very small) $J_c(45°)$ could arise if the c-axis tunneling were strong and coherent.[8] Those authors also showed that the overlap of two tight-binding Fermi surfaces rotated ϕ_0 with respect to each other decreases greatly with increasing ϕ_0, leading to a substantial reduction in the coherent tunneling matrix element.[8]

Bille *et al.* studied the weak tunneling case of a tetragonal crystal with a variety of single-component OP and tunneling matrix element forms. In each tunneling model, the single parameter σ^2 characterizes the change $\Delta \boldsymbol{k}$ in the intralayer wave vector relative to π/a, where a is the lattice constant, with $\sigma^2 \to 0, \infty$ in the coherent and incoher-