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The Phase-sensitive c-Axis Twist Experiments on $Bi_2Sr_2CaCu_2O_{8+\delta}$ and Their Implications

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There are presently three sets of c-axis twist experiments on $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212)[1]: the bicrystal experiments of Li *et al.*[2], the artificial cross-whisker experiments of Takano *et al.*[3], and the natural cross-whisker experiments of Latyshev *et al.*[4] We summarize these experiments and the extensive theoretical analyses of their possible implications, so that reliable conclusions can be inferred. The theoretical discussion includes the allowable order parameter symmetries, the twist theorem for the c-axis critical current of d-wave superconductors across a 45° twist junction, treatments of weak, first-order c-axis tunneling with coherent and incoherent components, and effects of the Fermi surface, strong coherent tunneling, orthorhombicity, nanoscale disorder, and OP twisting near the physical twist junction. As a minimum, all three experiments can only be understood in terms of a substantial s-wave superconducting order parameter component in Bi2212 for $T \leq T_c$. An anisotropic s-wave order parameter can fit all three experiments quantitatively. The bicrystal and natural cross-whisker experiments are also consistent with the preponderance of other data that the c- axis tunneling in Bi2212 is strongly incoherent, so that all of the c-axis critical current arises from the s-wave order parameter component. These three sets of experiments appear to rule out a purely repulsive pairing interaction.

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