Role of pair-breaking and phase fluctuations in $c$-axis tunneling in underdoped $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

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Abstract

The Josephson Plasma Resonance is used to study the $c$-axis supercurrent in the superconducting state of underdoped $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ with varying degrees of controlled point-like disorder, introduced by high-energy electron irradiation. As disorder is increased, the Josephson Plasma frequency decreases proportionally to the critical temperature. The temperature dependence of the plasma frequency does not depend on the irradiation dose, and is in quantitative agreement with a model for quantum fluctuations of the superconducting phase in the $\text{CuO}_2$ layers.

Key words: Disorder, Interlayer coupling, Josephson Plasma Resonance, Quantum fluctuations

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1. Introduction

From the $d$-wave symmetry of the order parameter of cuprate superconductors, one expects an enhanced sensitivity of $c$-axis transport in the superconducting state to disorder, due to the enhancement of the quasiparticle density of states along the gap node directions, and due to impurity assisted hopping [1]. Both mechanisms lead to as yet unobserved $T^2$-dependences of the $c$-axis superfluid density $\rho_s^c$ at low $T$, with coefficients that strongly depend on the scattering rate $\Gamma$. On the other hand, underdoped cuprates are sufficiently disordered for (quantum) fluctuations of the order parameter phase to play a prominent role [2], leading to a $T$-linear behavior of $\rho_s^c$. Here, we report on the effect of controlled point disorder on interlayer tunneling of Cooper pairs in underdoped $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$.

2. Experimental details

Single-crystalline rods of underdoped $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ were grown using the traveling solvent floating zone technique under 25 mBar oxygen partial pressure [3]. The samples used for the study, with $T_c \approx 70$ K, were cleaved from the same crystalline piece. The crystals were then irradiated with 2.5 MeV electrons using the van der Graaf accelerator of the Laboratoire des Solides Irradiés. The irradiation produces homogeneously distributed Frenkel pairs, which have previously been identified as strong scattering centers [4].

The Josephson Plasma Resonance (JPR) frequency $f_{\text{JPR}}$ of the crystals was then measured using the cavity perturbation technique, exploiting $TM_{01n}$ harmonic modes to access different frequencies [6], and the bolometric technique using a waveg-
reveals a common and plotting these versus reduced temperature, reduces. This contradicts the prediction of Ref. [1] that the ratio of dominant role of quantum phase fluctuations. Then, Fig. 1(b). Normalising all results to dependence of in-plane quasiparticle conductivity [9]. The temperature dependence of the JPR frequency arises from the temperature of the in-plane phase stiffness \( \varepsilon_0 \). Figure 2 shows that Eq. (1) describes the results very satisfactorily.

Summarizing, the temperature- and disorder dependence of the c-axis Cooper pair tunnel current in underdoped \( \text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta} \) is well described assuming a strong effect of quantum phase fluctuations. A d-wave model without fluctuations cannot account for the \( T \)-dependence of c-axis coupling.

3. Results and Discussion

Sharp JPR resonant peaks were measured for all samples under study. Both \( T_c \) and \( f_{JPR}(T \to 0) \) decrease with irradiation dose. The sensitivity of \( f_{JPR} \) to even weak additional disorder contradicts the model of coherent interlayer Cooper pair tunneling [7]. Within the framework of a \( d \)-wave BCS model, the measured proportionality between \( f_{JPR}^2 \) and \( T_c \) can be understood as resulting either from (i) the dependence of the interlayer Josephson current \( j_c \propto \Delta \sigma_{qp} \) on the gap magnitude \( \Delta \) and the quasiparticle conductivity \( \sigma_{qp} \) [8], or (ii) from the decrease of the in-plane superfluid density due to strong phase fluctuations.

The origin of the temperature and disorder dependence of \( f_{JPR} \) can be pinpointed using Fig. 1(b). Normalising all results to \( f_{JPR}(T \to 0) \) and plotting these versus reduced temperature, reveals a common \( T \)-dependence independent of disorder. This contradicts the prediction of Ref. [1] that \( \rho_s \) should follow different powers of \( T \) depending on the ratio of \( T_c, \Delta, \) and \( \Gamma \). However, it agrees with a dominant role of quantum phase fluctuations. Then, 

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