# Anomalous Proximity Effect in Underdoped $YBa_2Cu_3O_{6+x}$ Josephson Junctions

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Josephson junctions were photogenerated in underdoped thin films of the $YBa_2Cu_3O_{6+x}$ family using a near-field scanning optical microscope. The observation of the Josephson effect for separations as large as 100 nm between two wires indicates the existence of an anomalously large proximity effect and shows that the underdoped insulating material in the gap of the junction is readily perturbed into the superconducting state. The critical current of the junctions was found to be consistent with the conventional Josephson relationship. This result appears to constrain the applicability of SO(5) theory to explain the phase diagram of high critical temperature superconductors.

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Despite being among the most intensely studied condensed-matter systems, high temperature superconductors (HTS) have resisted a microscopic understanding [1]. They are strongly anisotropic, highly correlated electronic systems, showing anomalous characteristics in both the superconducting and nonsuperconducting phases. In particular, the nature of the transition between the low carrier concentration insulating antiferromagnetic (AF) phase and the high carrier concentration metallic and superconducting (SC) phase is not known and is believed to be the key to uncovering the mechanism for superconductivity mechanism in these materials. The quest to gain a better understanding of these issues is reflected in extensive experimental and theoretical work [1–8]. A prevalent theme in these approaches is the existence of a quantum phase transition in the phase-diagram of HTS. One important model for describing the rich phase diagram of the HTS materials postulates superconducting pairing at a temperature $T^*$ well above the superconducting critical temperature $T_c$. The low stiffness of the superconducting order parameter [3] leads to fluctuations in the phase of the order parameter [4,5] between $T^*$ and $T_c$. It is not until phase coherence is achieved at $T_c$ that superconductivity is established in the material. The overall behavior of the superconductor between $T^*$ and $T_c$ resembles that of a Kosterlitz-Thouless transition in conventional two-dimensional superconductors. Recently, an elegant theory, based on SO(5) group symmetry [2], proposed an alternative framework to explain the HTS phase diagram. A five component superspin was introduced with two of its components associated with the order parameter in a $d$-wave SC state and the other three identified with the order parameter of the AF phase. In this theory, the quantum phase transition between the AF and SC phases corresponds to a change in the orientation of the superspin in this five-dimensional space.

The electronic properties of the underdoped cuprates near the superconducting state are significantly different from the normal state properties found in conventional superconductors. Consequently, the experimental manifestations of superconductivity may also be expected to differ. Within the framework of the SO(5) theory, Demler *et al.* [6] have predicted that the current-phase relationship in the coupling between two HTS separated by a thin AF layer (a *SAS* junction) is modified from the Josephson relation $I_J = I_0 \sin\varphi$, with $\varphi$ the superconducting phase difference across the junction [9]. The new current-phase relationship of a *SAS* junction leads to different behavior of Josephson junctions [7]. In particular, it was predicted that the magnetic field dependence of the critical current of the junctions $I_c(H)$ would show a cusp at $H = 0$ [7], instead of the quadratic low-field behavior found in conventional junctions.

Both the fluctuating-phase approach and the SO(5) theory share the possibility of a large proximity effect when the material separating the HTS is the insulating HTS precursor. These considerations suggest that Josephson junctions may be made by separating HTS with a relatively thick layer of the precursor material [3,6].

In this Letter we report experiments which probe the underdoped insulating material by the Josephson effect. Junctions are fabricated by exploiting the capability of locally photodoping insulating $RBa_2Cu_3O_{6+x}$ material (with $R$ a rare earth), to induce superconducting wires separated by a nonsuperconducting region [10]. The flexibility provided by our near-field scanning optical microscope (NSOM) allows us to vary the gap between the $w \sim 150$ nm wide superconducting wires.

The samples under study are $c$-axis oriented thin films. One is a 180 nm thick $GdBa_2Cu_3O_{6+x}$ film grown on (100) MgO substrates by dc-magnetron sputtering. The other sample is a 120 nm thick $YBa_2Cu_3O_{6+x}$ (YBCO) film deposited on a $SrTiO_3$ substrate by laser ablation. The as-grown films show good physical properties with linear temperature dependence of the dc resistivity. Their critical temperatures, determined by ac susceptibility, were

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$T_c = 89.4$ and 89.2 K, respectively. The oxygen content was adjusted to $x \sim 0.4$ [11], and the resistivity of the samples at 4 K was found to be $\rho \sim 3$–6 m$\Omega$ cm. This value of the resistivity places the samples in the insulating side of the of the metal-insulator (MI) transition, with $R_\square$ per CuO plane larger than a quantum of resistance. The results obtained in both samples are very similar, and we will concentrate on the data obtained in the YBCO film.

The film was mounted on the insert of a continuous-flow He cryostat and photodoped with an Al-coated aperture NSOM probe [10]. Light from either a 3 mW He-Ne or a 1 mW, $\lambda = 1.55$ $\mu$m, InGaAsP laser was coupled into the inputs of a 50/50 2 $\times$ 2 optical fiber coupler. One of the outputs of the coupler was connected to the NSOM probe, while the other was used to monitor the laser stability. Photogeneration was accomplished by illuminating with the 1.96 eV light from the He-Ne laser, which is close to the maximum of the photodoping efficiency [12]. The photoinduced changes in the sample were detected by imaging the reflectance variations at $\lambda = 1.55$ $\mu$m with the InGaAsP laser. The reflected light was collected in the far field with conventional optics [13]. The InGaAsP laser was chosen because $\lambda = 1.55$ $\mu$m radiation provides the maximum change in reflectivity when crossing the MI transition [14] and it does not induce any further photogeneration [10,12]. All of the measurements involving the NSOM were performed at room temperature. When necessary to prevent the superconducting wires from decaying by $e$-$h$ recombination [10,12,15], the NSOM head was removed, the cryostat closed and pumped to $10^{-6}$ Torr, and the sample cooled to 200 K in less than 15 min [16]. It is well documented [10,15] that below 250 K the photoinduced state is metastable.

Typical NSOM reflectance scans obtained using a 60 nm aperture NSOM probe are shown in Fig. 1. The wires were defined and the scans obtained as described in Ref. [10]. Figure 1 shows that the reflectance and $T_c$ of the wires increase with the duration of the photogeneration. These results are explained by the photoinduced local increase of free holes in the CuO planes of YBCO [10,12,15]. The critical current $I_c$ of the wire shown in Fig. 1a is 11.5 $\mu$A. A wire defined with a 100 nm aperture NSOM probe showing a nominally identical increase in reflectance is wider, $w \sim 250$ nm, but has a very similar $I_c \sim 12$ $\mu$A [17].

Josephson junctions were defined by photogenerating a wire and leaving an unilluminated gap along its length, as described in Ref. [10] and illustrated in Fig. 2a. We determine the gap $d$ between the superconducting wires from the reflectance data shown in Fig. 1. We define $d$ as the range where the reflectance is lower than that corresponding to the wire in Fig. 1b, which has a $T_c \sim 4$ K. The separation between these points is $\sim$90 nm. Because of the finite resolution of the NSOM *this procedure actually gives a lower limit of the length of the barrier between the wires*. After defining an identical junction and cooling the system to 4 K, $I$-$V$ characteristics were obtained, as shown in the inset of Fig. 2a. The zero dissipation region shows the existence of the Josephson effect between the wires [9]. The rounding of the $I$-$V$ curves is understood in terms of thermal fluctuations in the Josephson junction [9]. It is worth mentioning that no significant variation was observed when nominally identical junctions were defined in different positions of the sample.

The observation of the Josephson effect for a separation between superconducting wires much greater than the coherence length in the superconducting state ($\xi_0 \sim$ 9 nm [18]) is one of the main results of this paper. This "colossal" proximity effect is inexplicable in terms of the conventional proximity effect. Since the gap material is insulating, the dirty limit for the coherence length in the normal material has to be used, $\zeta_n \simeq \sqrt{\hbar D/2\pi k_B T}$, where $D$ is the diffusion coefficient [19]. By using the results from Ref. [19], we obtain $\zeta_n \sim 15$ nm. From these considerations we conclude that the insulating material in the junctions exhibits an anomalously large proximity effect. Further evidence that a superconducting state is induced in the gap material is provided by the value of the critical current of the junction. For the $d = 45$ nm junction, $I_c = 2.6$ $\mu$A, comparable to the measured value of $I_c = 11.5$ $\mu$A for the wire of Fig. 1a.

As can be seen in the inset of Fig. 2b, $I_c R_N$ ($R_N = dV/dI|_{I=7\,\mu\mathrm{A}}$ is the shunt resistance of the junction) is nearly independent of $d$ for $d < 110$ nm. This fact has implications for both SO(5) theory and the fluctuating-phase models. When the existence of free vortices is used to explain the lack of phase coherence in the gap material, $I_c R_N \propto \exp(-d/2\zeta_g)$ is expected when $d \ll \zeta_g$, where $\zeta_g \simeq \xi_0 \exp(T_\Theta/T)$ is the correlation length for phase fluctuations, and $T_\Theta$ is the phase stiffness expressed in temperature units [4]. From the observed weak $d$ dependence of $I_c R_N$ when $\lesssim$100 nm, it follows that $\zeta_g > 90$ nm. As the separation between wires increases, however, a collapse in the phase coherence is observed and no Josephson effect is obtained. In the SO(5) theory $I_c \propto \exp(-d/\xi_A)$ is expected, where $\xi_A$ represents a new superconducting correlation length in the AF [6]. This strong decay in $I_c(d)$ is not observed, implying that the correlation length satisfies $\xi_A \gg d$ [6]. It is possible to have strong $d$ dependence in both $I_c$ and $R_N$ that cancel each other, as in the case of a tunnel Josephson junction in conventional superconductors. This possibility is ruled out, however, by the measured temperature dependence of the resistance of the nonsuperconducting material. $R_N$ is temperature independent *if the Josephson effect is observed*. Once the separation between the wires is large enough that the Josephson effect is absent, an insulatinglike response is observed for the unphotodoped material. The difference found in the temperature dependence of the nonsuperconducting material for different junctions is attributable to their difference in length, as shown in Fig. 3. The minor deviations between the data sets might be associated with the specific geometric details of the path followed by the transport current in each case, together with the definition of $d$.

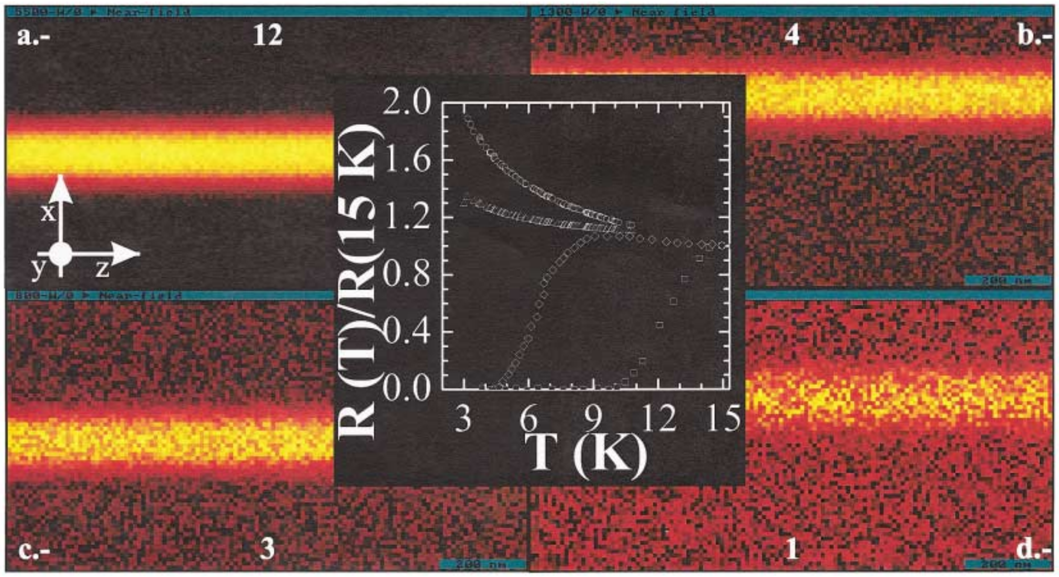


FIG. 1 (color). Reflectance of photodoped wires. The wires were photodoped for (a) 5000, (b) 1300, (c) 800, and (d) 600 s. The number in each $1.24 \times 0.64\ \mu\text{m}^2$ image indicates the percentile increase in reflectance of the wire (at $\lambda = 1.55\ \mu\text{m}$) with respect to the unphotodoped material. The coordinate system used throughout the paper is shown in (a). The inset shows the temperature dependence of the resistance for each wire (□, ◇, △, and ○ for the wires a–d, respectively), normalized by the value of the resistance at 15 K.

The observed behavior of these Josephson junctions may be expected if the gap material *is thermodynamically very close to the superconducting state*, and the presence of the superconducting leads quenches the superconducting phase fluctuations in the gap material. The induction of superconductivity in the nonsuperconducting material is a feature of both the SO(5) theory [2,6] and the fluctuating phase models [3]. More generally, as discussed in Ref. [6], the only ingredient necessary to obtain such a large correlation length is the close proximity to a second order quantum phase transition.

Our geometry is reminiscent of the situation described in Ref. [6], *if the material between the superconducting wires is in the AF phase*. Within this theory, the observed behavior of $I_c R_N$ suggests $\xi_A \gg d$. In this scenario the usual Josephson relation is modified leading to $I_J \propto \varphi$,

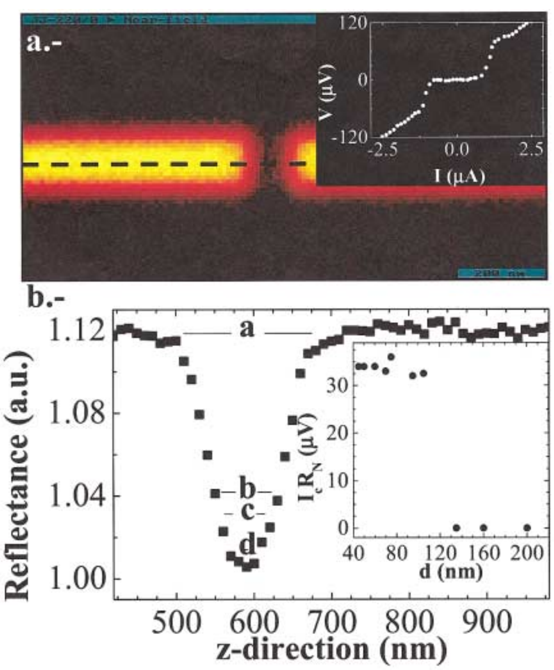


FIG. 2 (color). Josephson effect in photogenerated junctions. (a) $1.24 \times 0.64\ \mu\text{m}^2$ reflectance data of a photogenerated junction, normalized to the reflectance of the unphotodoped material. The inset shows the $I$-$V$ characteristic curve. (b) Line cut along the dotted line in (a). The letters represent the different intensities observed in Fig. 1. The inset shows the value of $I_c R_N$ for junctions fabricated with different $d$.

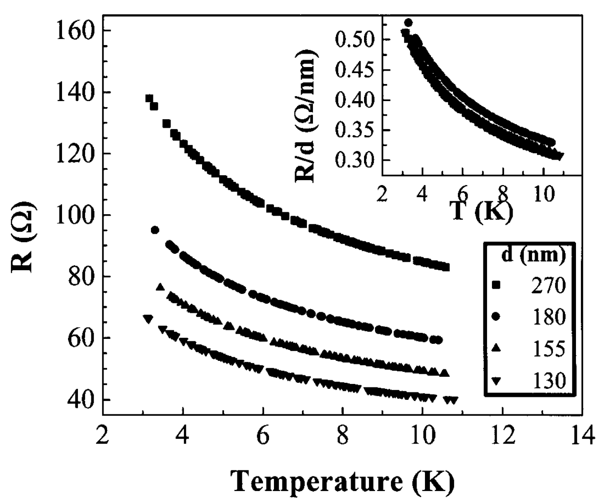


FIG. 3. Temperature dependence of the resistance of the junctions that do not show Josephson effect. The inset shows the data normalized by the separation between the superconducting wires.

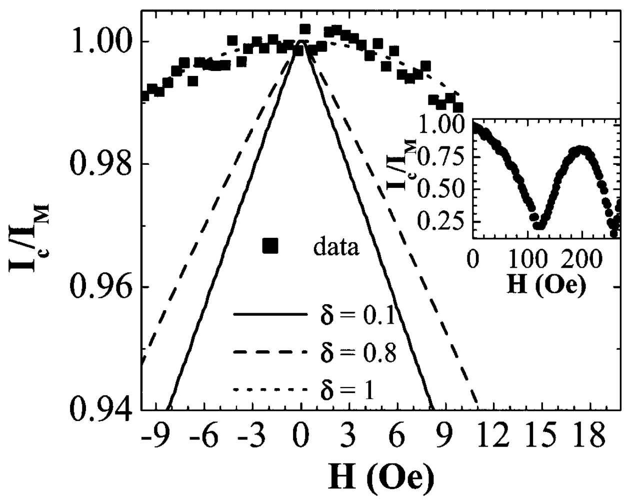


FIG. 4. Magnetic field dependence of the critical current close to $H = 0$ Oe. For comparison, $I_c(H)$ obtained from Ref. [7] for different values of $\delta = \frac{d}{d_c}$ is included. In all cases the curves have been normalized for $H = 0$ Oe. The inset shows $I_c(H)$ over an extended magnetic field range.

up to a critical phase difference $\varphi_c$. As previously mentioned, one consequence is that $I_c(H)$ should show a cusp for $H \to 0$ [7]. Since in our geometry $w > d$, we expect the critical feature that leads to the cusp behavior, i.e., the locking of the order parameter into the superconducting subspace when $\varphi \to 0$, to be preserved, even in the presence of the surrounding AF material. The results obtained for small magnetic fields are shown in Fig. 4. The figure shows that for $H \to 0$, $I_c(H) \not\propto |H|$, but is better described by a quadratic dependence. Also shown in the figure is the calculated $I_c(H)$, using the model from Ref. [7]. As shown in the figure, *the agreement between the experimental data and the calculation is reasonable only if $d \sim d_c$*, in clear contradiction with the $\xi_A \gg d$ conclusion obtained from Fig. 2b. The experimental value of $H = 135$ Oe for the first flux-quantum $\Phi_0$ trapped in the junction was used in the calculation. This value of $H$ is in reasonable agreement with $H \sim \frac{\Phi_0}{w(d+w)}$ [20] (the differences attributable to the details of the Josephson effect in the defined junctions).

In summary, the results described in this Letter show that the local combination of superconducting and insulating materials, obtained by photodoping insulating YBCO with a NSOM, provides an ideal opportunity to probe superconductivity in the poorly understood underdoped YBCO near the MI transition. The observation of the Josephson effect for separations $d \sim 100$ nm cannot be explained by the conventional proximity effect and are in qualitative agreement with fluctuating-phase models. We conclude that the material between the superconducting wires, although insulating, must be very close to a superconducting phase transition since superconductivity with a large phase coherence length can be induced in it. Our results also appear to restrict the margin of applicability of the SO(5) theory to explain the phase diagram of HTS.

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