Two-Dimensional Superconducting Fluctuations in Stripe-Ordered La$_{1.875}$Ba$_{0.125}$CuO$_4$

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Recent spectroscopic observations of a $d$-wave-like gap in stripe-ordered La$_{2-x}$Ba$_x$CuO$_4$ with $x = 0.125$ have led us to critically analyze the anisotropic transport and magnetization properties of this material. The data suggest that concomitant with the spin ordering is an electronic decoupling of the CuO$_2$ planes. We observe a transition (or crossover) to a state of two-dimensional (2D) fluctuating superconductivity, which eventually reaches a 2D superconducting state below a Berezinskii-Kosterlitz-Thouless transition. Thus, it appears that the stripe order in La$_{2-x}$Ba$_x$CuO$_4$ frustrates three-dimensional superconducting phase order, but is fully compatible with 2D superconductivity and an enhanced $T_c$.

Charge and spin stripe order have been observed experimentally in a few special cuprate compounds, specifically La$_{1.875}$Ba$_{0.125}$CuO$_4$[1] and La$_{1.6-x}$Nd$_{0.4}$Sr$_x$CuO$_4$[2]. Some theoretical studies have proposed that stripe correlations should be good for pairing and high superconducting transition temperatures, $T_c$[2]; however, such notions have been highly controversial, given that the highest stripe ordering temperatures occur at $x = 0.125$, where $T_c$ is strongly depressed. A recent study of La$_{1.875}$Ba$_{0.125}$CuO$_4$ with angle-resolved photoemission and scanning tunneling spectroscopies (STS) [4] has found evidence for a $d$-wave-like gap at low temperature, well within the stripe-ordered phase but above the bulk $T_c$. An earlier infrared reflectivity study [3] demonstrated that an anisotropic gap, together with a narrowed Drude component, becomes apparent as soon as one cools below the charge-ordering temperature, $T_{co} = 54$ K. Is the observed gap due to exotic electron-hole pairing that reduces the density of states available for the formation of Cooper pairs? Alternatively, could the gap be associated with particle-particle pairing, but with stripe order interfering with superconducting phase order? In an attempt to resolve this issue, we have carefully studied the anisotropic transport and magnetization properties of La$_{1.875}$Ba$_{0.125}$CuO$_4$.

In this Letter, we present compelling evidence that the dominant impact of the stripe ordering is to electronically decouple the CuO$_2$ planes. The charge-ordering transition, at $T_{co}$, is correlated with a rapid increase in the anisotropy between the resistivity along the $c$-axis, $\rho_c$, and that parallel to the CuO$_2$ planes, $\rho_{ab}$. At the spin-ordering temperature, $T_{so}$, there is a sharp drop in $\rho_{ab}$ by an order of magnitude; we label the latter the magnetic-field-dependent transition as $T_{c2D}$(see Fig. 1). Below $T_{c2D}$, $\rho_{ab}(T)$ follows the temperature dependence predicted [2] for a 2D superconductor above its Berezinskii-Kosterlitz-Thouless transition temperature, $T_{BKT}$[3][4]. This state also exhibits weak, anisotropic diamagnetism and a thermopower very close to zero. Below the nominal $T_{BKT}(\sim 16$ K), we observe nonlinear voltage-current ($V-I$) behavior consistent with expectations for a 2D superconductor [10]. We conclude that charge inhomogeneity and 1D correlations are good for pairing in the CuO$_2$ planes, as has been argued theoretically [3][11]; however, the interlayer Josephson coupling is effectively zero in the stripe-ordered state of La$_{1.875}$Ba$_{0.125}$CuO$_4$.

The crystals studied here were grown in an infrared image furnace by the floating-zone technique. They are pieces from the same crystals used previously to characterize the optical conductivity [5], photoemission and STS [4], magnetization [6], and magnetic excitations [12]. In particular, the charge-stripe order has been characterized by soft x-ray resonant diffraction [13] and by diffraction with 100-keV X-rays [14]. The latter results show that $T_{co}$ occurs at precisely the same temperature as the structural phase transition, from orthorhombic ($Bmab$) to tetragonal ($P4_2/nmc$) symmetry. (Note that the structural transition is first order, with a two-phase coexistence region extending over a couple of degrees.) The spin ordering of the stripes, as determined by neutron diffraction [1], muon spin rotation spectroscopy [15], and high-field susceptibility [6], occurs at $\sim 40$ K [16].

Transport measurements were carried out by the four-probe method on two single crystals cut side-by-side from the same slab. The parent slab exhibited a bulk diamag-
nematic transition at 4 K, with 100% magnetic shielding at lower temperatures. To measure \( \rho_{ab} \), current contacts were made at the ends of the long crystal (7.5 \times 2 \text{ mm}^2 \times 0.3 \text{ mm} along the \( c \)-axis) to ensure uniform current flow; voltage pads were also in direct contact with the \( ab \)-plane edges. Voltage-current characteristics were measured over 5 orders of magnitude with pulsed current (\( \leq 1 \text{ ms} \)) to avoid sample heating. The thermoelectric power was measured by the four-probe dc steady state method with a temperature gradient along the \( ab \)-plane at 1% of \( T \) across the crystal. For \( \rho_c \), current contacts covered the major part (85%) of the broad surfaces of the crystal (7.5 \times 3.4 \text{ mm}^2 \times 1.15 \text{ mm} along \( c \)) to ensure uniform current flow, with voltage contacts on the same surfaces, occupying 5% of the area. By annealing the contact pads (Ag paint) at 200–450°C for 0.5 h under flowing \( \text{O}_2 \), low contact resistance (\( < 0.2 \Omega \)) was always obtained. Annealing the crystals under flowing \( \text{O}_2 \) at 450°C for 100 h did not alter the transport results. All resistivity data reported here were taken with a dc current of 5 mA. The magnetic susceptibility was measured on a third crystal, having a mass of 0.6 g using a SQUID (superconducting quantum interference device) magnetometer.

Let us first consider the changes near \( T_{co} \). Figure 2 shows the thermopower and \( \rho_{ab} \) as a function of temperature. The thermopower shows a drastic drop below the transition, going slightly negative below 45 K. This behavior is consistent with previous studies of the thermopower and Hall effect in \( \text{La}_{2-x-y}\text{Nd}_x\text{Sr}_y\text{CuO}_4 \) and \( \text{La}_{2-x}\text{Ba}_x\text{CuO}_4 \) [17, 18, 19]. In contrast, \( \rho_{ab} \) shows a modest jump and then continues downward with a slope similar to that above the transition; the sheet resistance at 45 K is \( \sim 2 \text{ k}\Omega \), well within the metallic regime. Consider also the results for \( \rho_c/\rho_{ab} \), shown in Fig. 3(a). This ratio grows on cooling, especially below \( T_{co} \); such behavior is inconsistent with expectations for a Fermi-liquid.

The drop in thermopower suggests that the densities of filled and empty states close to the Fermi level become more symmetric when charge-stripe order is present. At the same time, the small change in \( \rho_{ab} \) indicates that the dc conductivity in the planes remains essentially 2D. We also know that the gap feature in the optical conductivity shows up below \( T_{co} \) [3, 11, 20]. A possible model for this state is the “sliding” Luttinger-liquid phase [21], especially in the form worked out for neighboring layers of orthogonal stripes [22], since we know that the orientation of the charge stripes rotates by \( \pi/2 \) from one layer to the next, following the glide symmetry of the crystal structure [23]. The latter model
predicts both 2D metallic resistivity in the planes and $\rho_c/\rho_{ab} \sim T^{-\alpha}$ with $\alpha > 1$, qualitatively consistent with our observations.

Next we consider $T_{c}^{2D}$. One can see in Fig. 2 that $\rho_{ab}$ rapidly drops by about an order of magnitude at $\sim 40\, K$, while the magnitude of the thermopower simultaneously drops to nearly zero. It is apparent that $T_{c}^{2D}$ is quite sensitive to a magnetic field applied along the c-axis. Figure 1(a) indicates that the transition is also sensitive to the current used to measure the in-plane resistivity. In Fig. 3(a), one can see that $\rho_{c}/\rho_{ab}$ grows by an order of magnitude; this indicates that the drop in $\rho_{ab}$ involves purely 2D behavior, with no communication between the planes.

The sensitivity of $T_{c}^{2D}$ to magnetic fields and current suggests a connection with superconductivity. In fact, we had previously attributed the transition to filamentary superconductivity associated with local variations in hole content [5]. There is a serious problem with this explanation, however: the transition temperature is higher than the highest bulk $T_c$ (33 K) in the La$_{2-x}$Ba$_x$CuO$_4$ phase diagram [24].

Things get even more interesting when we examine the finite-resistivity state below $T_{c}^{2D}$. The solid lines in Fig. 3(b) are fits to the formula

$$\rho_{ab}(T) = \rho_n \exp \left(-b/\sqrt{T}\right),$$  \hspace{1cm} (1)
The decoupling between the planes in our sample is not perfect, and defects are likely to become increasingly relevant as the temperature decreases. At twin boundaries, the crystal structure is modified, and a local coupling might be possible. The statistical distribution of dopant ions could also lead to local variations. In zero field, \( \rho_c \) starts to decrease below \( \sim 35 \text{ K} \) [inset of Fig. 3(b)], although the ratio \( \rho_c / \rho_{ab} \) remains \( > 10^4 \). Magnetic susceptibility measured (after zero-field cooling) in a field of 2 Oe applied parallel to the planes shows the onset of weak diamagnetism at 28 K, reaching \( \sim 1\% \) of the full shielding response at 10 K.

We see that we have a number of experimental signatures compatible with 2D superconducting fluctuations below \( T_c^{2D} \). The necessary decoupling of the planes is consistent with the highly anisotropic state below \( T_{co} \). It appears that \( T_{co} \) provides an upper limit to the onset of 2D superconducting fluctuations. Furthermore, there are indications of true 2D superconductivity for \( T < T_{BKT} \approx 16 \text{ K} \). Theoretically, such behavior requires that the net interlayer Josephson coupling equal zero; Berg et al. [20] have proposed a plausible model for frustration of the coupling.

To summarize, we have found that the main impact of stripe ordering is to electronically decouple the CuO$_2$ planes. Fluctuating 2D superconductivity appears below \( T_c^{2D} \), with a finite resistivity due to phase fluctuations. \( \rho_{ab} \) goes to zero at a BKT transition. The evidence of 2D superconducting correlations indicates that static stripes are fully compatible with pairing, and we note that the high value of \( T_c^{2D} \) correlates with the maximum of the antinodal gap at \( x = \frac{1}{4} \). The downside is that stripe order, at least as realized in La$_2$-xBaxCuO$_4$, competes with superconducting phase order.

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