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 $La_{2-x}Ba_xCuO_4$ with $x = \frac{1}{8}$ 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 $La_{2-x}Ba_xCuO_4$ frustrates three-dimensional superconducting phase order, but is fully compatible with 2D superconductivity and an enhanced T_c.

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Charge and spin stripe order have been observed experimentally in a few special cuprate compounds, specifically $La_{2-x}Ba_xCuO_4$ [1] and $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ [2]. Some theoretical studies have proposed that stripe correlations should be good for pairing and high superconducting transition temperatures, T_c [3]; however, such notions have been highly controversial, given that the highest stripe ordering temperatures occur at $x = \frac{1}{8}$, 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 [5] 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, ρ_c, and that parallel to the CuO_2 planes, ρ_{ab}. At the spin-ordering temperature, T_{so}, there is a sharp drop in ρ_{ab} by an order of magnitude; we label the latter magnetic-field-dependent transition as T_c^{2D} (see Fig. 1). Below T_c^{2D}, $\rho_{ab}(T)$ follows the temperature dependence predicted [6] for a 2D superconductor above its Berezinskii-Kosterlitz-Thouless transition temperature, T_{BKT} [7,8]. 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 [9]. We conclude that charge inhomogeneity and 1D correlations are good for pairing in the CuO_2 planes, as has been argued theoretically [3,10]; 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 [11], 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 ($P4_2/ncm$) 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 [11], occurs at ~40 K [16].

Transport measurements were carried out by the four-probe method on two single crystals cut side-by-side from

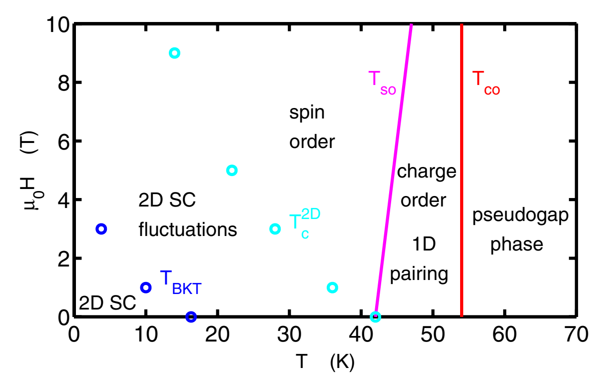

FIG. 1 (color online). Experimental phase diagram for $La_{1.875}Ba_{0.125}CuO_4$. The transition lines for charge order and spin order are from [11]. The boundaries labeled T_c^{2D} and T_{BKT} are described in the text.

the same slab. The parent slab exhibited a bulk diamagnetic transition at 4 K, with 100% magnetic shielding at lower temperatures. To measure ρ_{ab}, current contacts were made at the ends of the long crystal ($7.5 \times 2\ \mathrm{mm}^2 \times 0.3$ 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 (≤ 1 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 ρ_c, current contacts covered the major part (85%) of the broad surfaces of the crystal ($7.5 \times 3.4\ \mathrm{mm}^2 \times 1.15$ 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 O_2, low contact resistance ($< 0.2\Omega$) was always obtained. Annealing the crystals under flowing 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 ρ_{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 $La_{2-x-y}Nd_ySr_xCuO_4$ and $La_{2-x}Ba_xCuO_4$ [17–19]. In contrast, ρ_{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 $\sim 2\ \mathrm{k}\Omega$, well within the metallic regime. Consider also the results for ρ_c/ρ_{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 ρ_{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} [5]. Since the gap does not seem to impact the 2D conductivity, it appears that it must be associated with 1D correlations within the stripes [3,10,20]. 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.

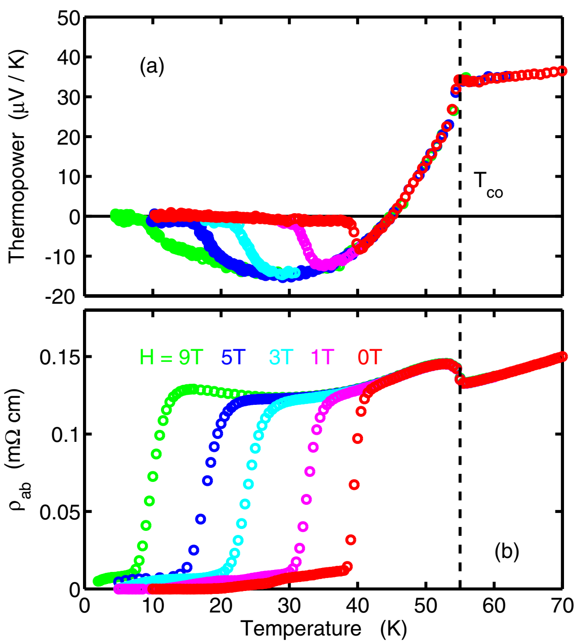

FIG. 2 (color online). (a) Thermoelectric power vs temperature for several different magnetic fields [as labeled in (b)], applied along the c-axis. (b) In-plane resistivity vs temperature for the same magnetic fields as in (a). The vertical dashed line indicates T_{co}.

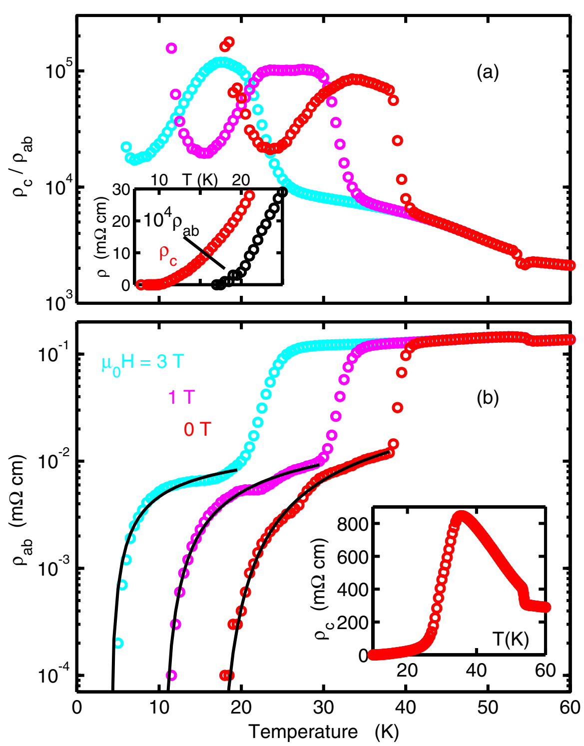

FIG. 3 (color online). (a) Ratio of ρ_c to ρ_{ab} vs temperature in fields of 0, 1 T, and 3 T, as labeled in (b). Inset shows zero-field resistivity vs temperature; note that ρ_{ab} reaches zero (within error) at 18 K, while ρ_c does not reach zero until 10 K. (b) In-plane resistivity vs temperature on a semilog scale, for three different c-axis magnetic fields, as labeled. The lines through the data points correspond to fits to Eq. (1). Inset shows ρ_c at zero field on a linear scale.

Next we consider T_c^{2D}. One can see in Fig. 2 that ρ_{ab} rapidly drops by about an order of magnitude at ~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 4(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 ρ_c/ρ_{ab} grows by an order of magnitude; this indicates that the drop in ρ_{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 $La_{2-x}Ba_xCuO_4$ 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

$$\rho_{ab}(T) = \rho_n \exp(-b/\sqrt{t}), \tag{1}$$

where $t = (T/T_{BKT}) - 1$. This is the predicted [6] form of the resistivity in a two-dimensional superconductor at temperatures above the BKT transition, T_{BKT}, where true superconductivity is destroyed by phase fluctuations due to the unbinding of thermally-excited vortex-antivortex pairs [7,8]. This formula is valid only for zero magnetic field; one expects an activated contribution to ρ_{ab} due to field-induced vortices. Instead, we obtain a reasonable fit with Eq. (1) by allowing the parameters to be field dependent (see Table I). Note that the nominal T_{BKT} at 1 T and above falls into the regime where $\rho_c \sim 0$ in zero field [see inset of Fig. 3(a)] and the resistivity might be dominated by imperfections of the sample.

In a 2D superconductor, one expects to have a critical current of zero and

$$V \sim I^p, \tag{2}$$

with $p = 3$ just below T_{BKT} and growing with decreasing temperature [9]. Figure 4(b) shows plots of V vs I at temperatures spanning $T_{BKT} = 16.3$ K. We see that on approaching the transition, p deviates from 1; it grows rapidly below 16 K. By interpolating, p reaches 3 at $T = 15.6$ K, close to the T_{BKT} determined by fitting $\rho_{ab}(T)$.

If we truly have 2D superconducting fluctuations present within the CuO_2 planes below T_c^{2D}, then we would expect to see a weak diamagnetic response in the magnetic susceptibility χ_c, as a field applied along the c-axis should generate an orbital response in the planes. In contrast, there should be no diamagnetic response in χ_{ab}, with the field parallel to the planes. Figure 5 shows measurements of χ_c and χ_{ab} vs temperature on cooling in field; χ is reversible for the data ranges shown. One can see that the susceptibility is dependent on the magnetic field used for the measurement. For $\mathbf{H} \parallel \mathbf{c}$, the high-field susceptibility is dominated by the response of the ordered Cu moments [11]. Relative to that, we see that there is a weak diamagnetism below ~40 K that decreases with increasing field, consistent with superconducting correlations. For $\mathbf{H} \perp \mathbf{c}$, there is no diamagnetism, as expected. Instead, χ_{ab} actually decreases with increasing field. This is due to a paramagnetic contribution that saturates at a field of ~1 T and remains to be understood. The weak, anisotropic diamagnetism looks similar to the results of Li *et al.* [25] in under-doped $La_{2-x}Sr_xCuO_4$.

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, ρ_c starts

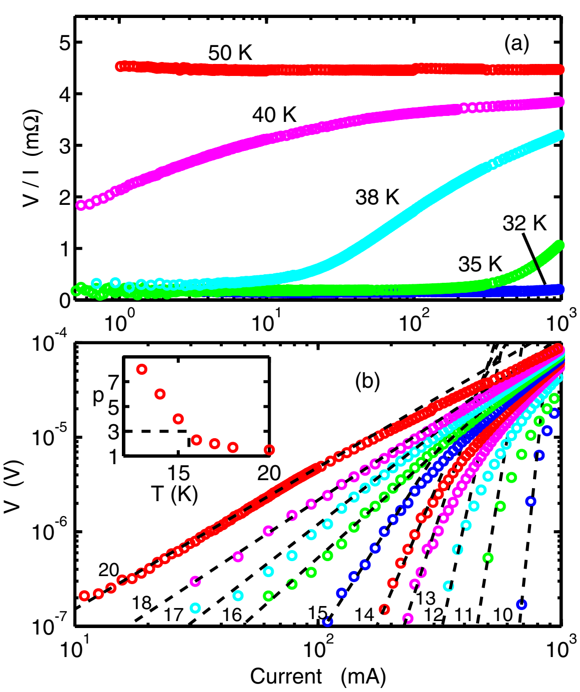

FIG. 4 (color online). (a) In-plane V/I vs I at five temperatures, as labeled. Note that I is on a log scale. (b) Log-log plot of in-plane V vs I at temperatures from 20 to 10 K. Each curve is labeled by T in K. Dashed lines are approximate fits to the slopes at low current; slope = p. Inset: plot of p vs T. Dashed line indicates that p crosses 3 at $T = 15.6$ K.

TABLE I. Values of parameters obtained in fitting Eq. (1) to the resistivity data in Fig. 3(b). Numbers in parentheses are uncertainties in the last digit.

$\mu_0 H$ (T)	T_{BKT} (K)	ρ_n (mΩ cm)	b
0	16.3(3)	0.13	2.7(1)
1	10.0(5)	0.041(6)	2.1(1)
3	3.8(3)	0.022(3)	2.0(1)

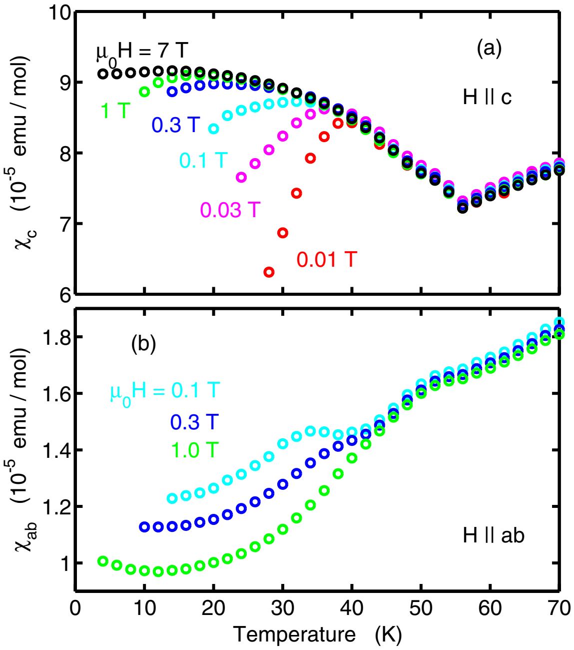

FIG. 5 (color online). (a) χ_c vs temperature for several different magnetic fields, as labeled. (b) χ_{ab} vs temperature for several magnetic fields as labeled. Note that, for each applied field, measurements at temperatures lower than the plotted data range are unreliable due to excessive noise in this regime, possibly associated with the unusual state of the sample.

to decrease below ~35 K [inset of Fig. 3(b)] although the ratio ρ_c/ρ_{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 ~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_{so} 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 K. Theoretically, such behavior requires that the net interlayer Josephson coupling equal zero; Berg *et al.* [26] 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. ρ_{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 $x = \frac{1}{8}$ [4]. The downside is that stripe order, at least as realized in $La_{2-x}Ba_xCuO_4$, competes with superconducting phase order.

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