Quantum Phase Transitions in the Cuprate Superconductor $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$

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To elucidate a quantum phase transition (QPT) in $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$, we measure charge and heat transport properties at very low temperatures and examine the following characteristics for a wide range of doping: normal-state resistivity anisotropy under 58 T, temperature dependence of the in-plane thermal conductivity κ_{ab}, and the magnetic-field dependence of κ_{ab}. It turns out that all of them show signatures of a QPT at the 1/8 hole doping. Together with the recent normal-state Hall measurements under 58 T that signified the existence of a QPT at optimum doping, the present results indicate that there are two QPTs in the superconducting doping regime of this material.

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One of the emerging paradigms in the condensed matter physics is the ubiquitous *competitions* in strongly correlated systems. For example, strong correlations in transition-metal oxides such as manganites and nickelates often result in nanoscale structures consisting of competing phases [1,2]. The competitions between different ground states sometimes give rise to a quantum phase transition (QPT) [3], which takes place at zero temperature when quantum fluctuations cause a cooperative ordering of the system to disappear or change; in fact, the strong correlations in heavy-fermion systems [4] and in ruthenates [5] are known to be responsible for a QPT between competing ground states. In high-T_c cuprates, competitions between the kinetic energy, the local exchange interaction, and the long-range Coulomb interaction produce nanoscale self-organized structure called stripes [6–8], and it is of significant current interest that various competing ground states may alternate at QPTs depending on material parameters and/or external parameters, causing the electronic properties to be largely governed by the competitions [9].

An important issue associated with the competing ground states is the quantum criticality, which helps one to sort out the physics in terms of universal scaling [10]. However, the quantum criticality becomes important only when the competition results in a second-order QPT, while some microscopic phase separations and associated colossal effects can happen [11] when the QPT is first order. Therefore, finding a QPT in a strongly correlated system is one thing, and determining whether there is an associated quantum criticality is quite another. In the case of cuprates, our understanding of the QPTs and the underlying orders is still far from satisfactory; in particular, most of the previous experimental works of cuprates regarding the QPT [10,12,13] just focused on the universal scaling behavior, but identifying the exact position and the nature of the putative QPT is probably even more important. To accomplish the latter, one needs to find a qualitative change in the electronic properties at very low temperatures as a function of a control parameter (such as doping), which is normally a formidable task, and experiments along this line are just emerging [14–16].

Very recently, a pulsed magnetic-field experiment [16] found strong evidence at low temperatures that there is, indeed, a QPT at optimum doping in a cuprate superconductor $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ (BSLCO). In that work, the doping dependence of the normal-state Hall coefficient measured under 58 T magnetic field was found to show a sharp break at optimum doping, indicative of a phase transition resulting in a dramatic change in the Fermi-surface states. Notably, the break in the doping dependence became sharper and sharper with lowering temperature, suggesting that the observed feature is truly a result of a zero-temperature transition; incidentally, it was argued that a QPT associated with the *d*-density-wave order [17] can produce such a sharp signature in the Hall coefficient [18].

However, there remains a puzzle in the BSLCO case: In the in-plane resistivity measurements of BSLCO under 60 T [19] that preceded the Hall measurements, it was found that the insulator-to-metal crossover, which may also signify a QPT, occurs near the 1/8 (= 0.125) doping, and this does not fit well with the QPT at optimum doping (0.16 holes per Cu). Therefore, the evidence for the QPT in BSLCO is rather controversial and a comprehensive picture for the zero-temperature phase transition(s) in BSLCO needs to be established as a step towards drawing a general phase diagram of the cuprates. In this work, to elucidate the zero-temperature phase diagram of BSLCO, we measure various transport properties at low temperature and carefully search for experimental signatures of a sharp change in the electronic properties as a function of doping. It is worthwhile to note that the transport properties are inherently suited to study the zero-temperature properties of a system, because they

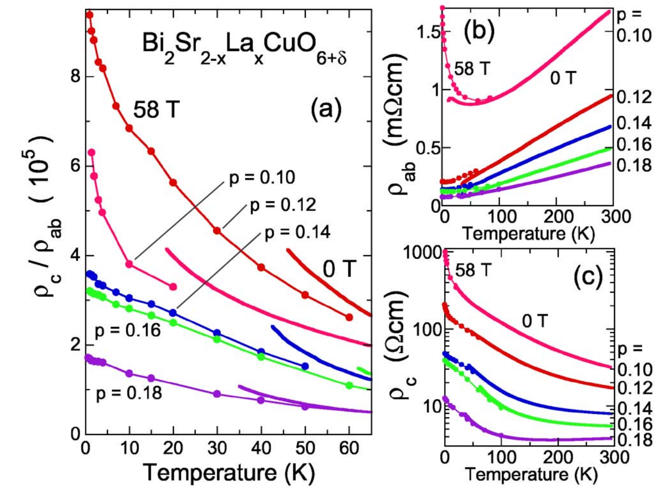

FIG. 1 (color online). Resistivity behavior of BSLCO single crystals. (a) Temperature dependences of the resistivity anisotropy ratio ρ_c/ρ_{ab}, measured in zero field (thick solid lines) and in 58 T field (solid circles). Note that ρ_c/ρ_{ab} remains finite in the zero-temperature limit for $p \geq 0.14$, while it shows a divergence for $p \leq 0.12$. The data of ρ_{ab} and ρ_c used for calculating ρ_c/ρ_{ab} are shown in (b) and (c).

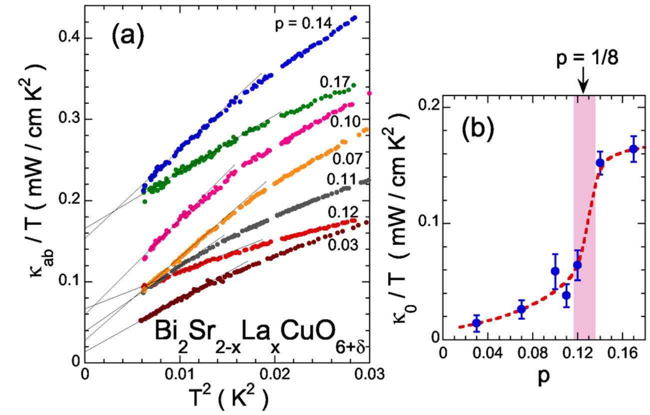

FIG. 2 (color online). Thermal conductivity in 0 T measured in the mK region. (a) Plots of κ_{ab}/T vs T^2 give the residual quasiparticle term κ_0/T as the zero intercept of the linear fit (thin solid lines) to the lowest temperature data. (b) Doping dependence of κ_0/T (solid circles); the dashed curve is a guide to the eyes. The sudden increase in κ_0/T (marked by a shaded band) across $p \simeq 1/8$ signals a QPT in the superconducting ground state.

are governed by very low energy excitations at low temperature.

As has been noted before [16,19], BSLCO is an ideal cuprate system for a systematic study of the low-temperature normal state: High-quality single crystals can be produced over a wide doping range [20] and a magnetic field of 60 T is enough to suppress superconductivity. The hole doping per Cu, p, can be controlled between 0.03 and 0.18 by changing the La content x, and the correspondence between x and p has been sorted out [21]. In this work, we essentially employ two experimental techniques we have specialized in: resistivity measurements under pulsed magnetic fields up to 58 T [19] and thermal conductivity measurements at very low temperatures [22,23]. Details of each technique are described in the cited papers. For this work, different sets of samples [24] are prepared for the measurements of the in-plane resistivity ρ_{ab} [Fig. 1(b)], out-of-plane resistivity ρ_c [Fig. 1(c)], in-plane thermal conductivity κ_{ab} below 300 mK (Fig. 2), and the magnetic-field dependence of κ_{ab} (Fig. 3); here, the data for a total of 21 samples are presented, all of which are similar in size [$\sim(1\text{–}2) \times 1 \times 0.05$ mm^3]. We concentrate on identifying the QPT(s) in the superconducting doping regime by looking at a qualitative change in the electronic properties at very low temperatures, and it is not the interest of the present study to determine whether the QPT we find is accompanied by the quantum criticality.

The first property we look at is the charge confinement characteristics [25] in the zero-temperature limit: We measure ρ_{ab} and ρ_c in the normal state by suppressing superconductivity with 58 T pulsed magnetic fields, and calculate the normal-state anisotropy ratio ρ_c/ρ_{ab}. Figure 1(a) shows the temperature dependences of ρ_c/ρ_{ab} for $p = 0.10$–0.18, and Figs. 1(b) and 1(c) show the raw data for ρ_{ab} and ρ_c, respectively. One can easily see in Fig. 1(a) that there is a qualitative change in the temperature dependence across $p \simeq 0.13$; namely, for $p \geq 0.14$, ρ_c/ρ_{ab} hits a finite value in the zero-temperature limit, while for $p \leq 0.12$, ρ_c/ρ_{ab} diverges with lowering temperature. This result indicates that the characteristics of the charge confinement, which is one of the most peculiar electronic properties of the cuprates [25], changes across $p \simeq 1/8$ ($= 0.125$). It appears that for $p < 1/8$ the charge confinement becomes increasingly more effective with decreasing temperature, suggesting that the ground state is strictly two dimensional; on the other hand, since ρ_c/ρ_{ab} stays finite for $p > 1/8$, the ground state can be viewed as an anisotropic three-dimensional state on this side, though the anisotropy is extremely large. Such a change in the effective dimensionality naturally points to a transformation in the fundamental nature of the ground state in the zero-temperature limit, and thus is indicative of a QPT at $p \simeq 1/8$ in the normal state under high magnetic fields.

The second property we look at is the in-plane thermal conductivity κ_{ab} in the mK region, where we can separate the contributions of phonons and quasiparticles to the heat transport [22,26], and therefore the quasiparticle behavior at zero field (in the superconducting state) can be traced with this tool. Figure 2(a) shows the plots of κ_{ab}/T vs T^2 for 77–170 mK; in these plots, the zero-temperature intercept of the linear fit to the lowest-temperature data gives the residual quasiparticle term κ_0/T, which is a measure of the quasiparticle population at zero temperature [22,26]. Remember that in d-wave superconductors the "impurity band" in the quasiparticle spectrum gives rise to a finite κ_0/T, which does not depend on the impurity concentration but depends on the Fermi velocity and the steepness of the d-wave gap at the nodes in the clean limit [27]. The slopes of the linear fits are determined by the phonon contribution, which we have confirmed to be in the boundary scattering regime (the phonon mean free paths [22,26] estimated from the slopes are consistent with our crystal dimensions within a factor of 0.4–1.3). In Fig. 2(a), although the range of the data over which we can apply linear fitting is rather limited, we can determine κ_0/T with a certain error bar; for example, the κ_0/T values for $p = 0.03$, 0.07, and 0.14 are obtained within an error of ± 0.01 mW/cm K^2 [28]. As shown in Fig. 2(b), the p dependence of κ_0/T shows a jump across $p \simeq 1/8$, and this jump is much larger than our error bar. It is useful to note that the κ_0/T value for $p = 0.14$ and 0.17 is ~ 0.16 mW/cm K^2, which is essentially the same as the values obtained for other cuprates at optimum doping [29]; therefore, the superconducting state of BSLCO near optimum doping is considered to be canonical. What is unusual is the small values of κ_0/T for $p < 1/8$, which is not easily understood [22,29] within the standard theory for d-wave superconductors [27]. [Similar anomaly in the behavior of κ_0/T was also reported for $La_{2-x}Sr_xCuO_4$ (LSCO) [22,29].] Although the exact reason for the small κ_0/T value is not known, it is probably related to the "insulating" nature of the normal state under high magnetic field [19] and is possibly a result of some novel localization effects [30,31]. In any case, the jump of κ_0/T across $p \simeq 1/8$ signifies a change in the nature of the superconducting state at zero temperature and thus gives evidence for a QPT in the superconducting state.

We further look at the magnetic-field dependence of the low-temperature thermal conductivity, $\kappa_{ab}(H)$, which has recently been shown [23] to be useful for probing a QPT: In underdoped LSCO, it was found that the magnetic field induces a new phase where the superconductivity coexists with a static incommensurate antiferromagnetism, which can be viewed as a field-induced spin density wave [32]; this novel phase in underdoped LSCO leads to a field-induced localization of quasiparticles [23], which causes κ to *decrease* with H even at subkelvin temperatures [23,33], while κ is known to *increase* with H at $T \lesssim 2$ K in cuprates near optimum doping [23]. It is notable that the crossover between the two behaviors occurs abruptly across optimum doping at very low temperatures in LSCO [23], which is indicative of a QPT. Figure 3 shows the behavior of $\kappa_{ab}(H)$ of BSLCO, measured at low temperatures down to 0.36 K, for four doping levels. One can see that the $\kappa_{ab}(H)$ behavior shows a qualitative change across $p = 1/8$ at the lowest temperature and this change is essentially the same as that observed in LSCO across optimum doping. The increase in κ_{ab} with H indicates that extended quasiparticles (that contribute to the heat transport) are created with H as in ordinary d-wave superconductors [34–36], while the decrease in κ_{ab} with H for $p < 1/8$ at subkelvin temperatures is indicative of the field-induced localization of quasiparticles and suggests a coexistence of the spin density wave [23,35]. As in LSCO, the sharp change in the $\kappa_{ab}(H)$ behavior as a function of doping is indicative of a QPT at $p \simeq 1/8$ in the mixed state of BSLCO.

The above results show that the low-temperature transport properties give evidence for a QPT taking place at $p \simeq 1/8$ in all three possible states of a type-II superconductor: superconducting Meissner state, mixed state under intermediate magnetic fields, and the normal state under high magnetic fields. Therefore, the present set of

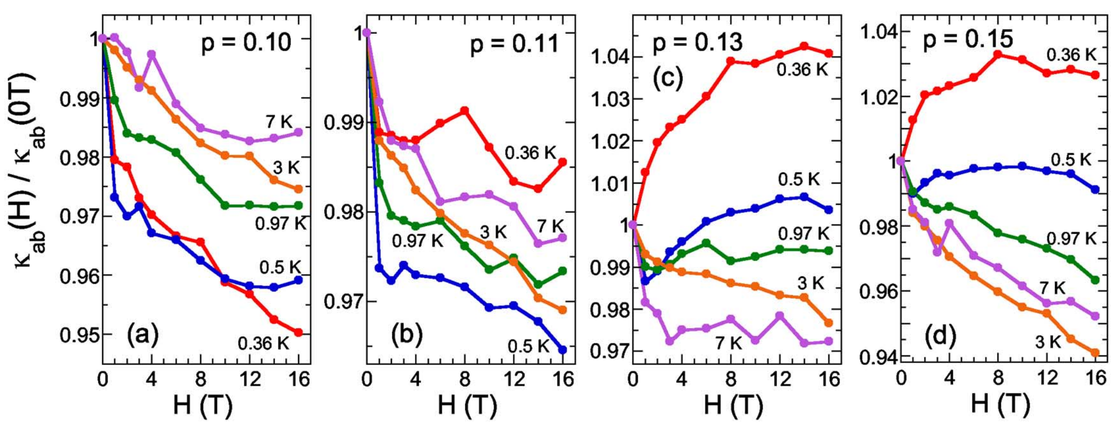

FIG. 3 (color online). Magnetic-field dependences of κ_{ab} at various doping levels, (a) $p = 0.10$, (b) $p = 0.11$, (c) $p = 0.13$, and (d) $p = 0.15$. The increase in κ_{ab} with H seen in (c) and (d) at 0.36 K is a standard behavior of ordinary d-wave superconductors where extended quasiparticles are created by magnetic fields; on the other hand, the decrease in κ_{ab} with H seen in (a) and (b) even at 0.36 K signifies the field-induced localization of quasiparticles. This qualitative change in the behavior of $\kappa_{ab}(H)$ gives evidence for a QPT at $p \simeq 1/8$ in the mixed state.

data adds another QPT to the phase diagram suggested by the normal-state Hall measurements [16], which gave evidence for a QPT at optimum doping. Furthermore, the present results confirm that the insulator-to-metal crossover observed in the previous ρ_{ab} measurements [19] was, indeed, due to a QPT. Based on these results, the phase diagram concluded for BSLCO can be summarized as follows: The QPT at $p \simeq 1/8$ (QPT1) separates two regimes, regime 1 ($p < 1/8$) and regime 2 ($1/8 < p < 0.16$). The resistivity anisotropy suggests that in regime 1 under high magnetic fields the charge confinement is strong, which seems to be consistent with the idea that some texturing of the electrons, such as charge density wave or spin density wave [32], is fundamentally responsible in regime 1; such texturing of the electrons can naturally account for the magnetic-field-induced localization of quasiparticles signified by the H dependence of κ_{ab}. The heat transport behavior cannot be understood by the standard transport theories for d-wave superconductors [27,34] in regime 1, while the canonical heat transport behavior is observed in regime 2. The other QPT at optimum doping (QPT2) separates regime 3 ($p > 0.16$) from regime 2; throughout regimes 1 and 2 the effective carrier density in the zero-temperature limit measured by the Hall coefficient shows a linear increase with T_c [16], which is reminiscent of the Uemura relation for the superfluid density [37], and there appears to be an abrupt change in the Fermi-surface states at QPT2 [16]. Intriguingly, the heat transport properties in the superconducting state do not give any hint of QPT2.

The existence of two QPTs in BSLCO probably tells us that the physics of the cuprates in the superconducting doping regime is governed by competitions between at least three different ground states. Whatever the nature of the ground states, it is clear that a number of phases are competing in the cuprates, and therefore a promising model of high-T_c superconductivity must have multiple competing phases as possible ground states. It is yet to be seen how or whether the competition is related to the occurrence of superconductivity, but it is intriguing to see that the cuprates are no exception of the strongly correlated systems where ubiquitous competitions govern the essential physics.

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