Magnetic-Field-Induced Localization of Quasiparticles in Underdoped La$_{2-x}$Sr$_x$CuO$_4$

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Competing order is an important emerging concept in high-$T_c$ superconducting cuprates. Recently, Hoffman et al. [2] reported scanning tunneling microscopy (STM) studies of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi2212) single crystals in magnetic fields, which revealed a “checkerboard-like” order of quasiparticle (QP) states with four-unit-cell periodicity surrounding vortex cores. This result documented a magnetic-field-induced charge density wave (CDW), which is in good correspondence with the magnetic-field-induced spin density wave (SDW) found by neutron scattering in La$_{2-y}$Sr$_y$CuO$_4$ (LSCO) [3, 4] and La$_2$CuO$_{4+\delta}$ [5], and these phenomena are likely to be results of competing antiferromagnetic and superconducting orders in those materials. In fact, several theoretical models [3, 4, 5, 6, 7, 8] have been proposed to describe the coexistence of $d$-wave superconductivity and spin/charge order in the vortex state as a consequence of competing orders. However, it is hardly known how such competition and magnetic-field-induced order affect the QP dynamics, the details of which would allow us to understand the nature of the novel magnetic-field-induced states.

In this Letter, we report that the magnetic-field dependence of thermal conductivity, $\kappa(H)$, of LSCO at low temperature demonstrates that the magnetic-field-induced order leads to unusual localization of QPs; moreover, we found that there is a distinct change in the behavior of $\kappa(H)$ near optimum doping and the QP localization occurs only in the underdoped samples. This magnetic-field-induced localization of QPs in the underdoped regime is clearly in correspondence with the well-known metal-to-insulator crossover, found in the low-temperature normal state under 60-T magnetic field, that occurs at optimum doping [11]. Moreover, this result suggests that the unusual “insulating normal state” of the cuprates under 60 T, that is characterized by a log(1/T) divergence in resistivity [12], is caused by the magnetic-field-induced order.

In high-$T_c$ cuprates, it is established that the superconducting gap $\Delta$ has essentially the $d_{x^2-y^2}$ symmetry, which has four nodes (where the gap magnitude vanishes) along the diagonals of the square Brillouin zone. Because of these nodes, QPs are easily created both by thermal fluctuations and by the impurity scattering, and the thermal conductivity $\kappa$ is a useful bulk probe of the QP excitations and their transport behavior [13, 14]. In the mixed state, where the magnetic field enters the superconductor in the form of quantized vortices, it is known that the magnetic field induces extended zero-energy QP states near the gap nodes and their population increases as $H^{1/2}$ [13, 14, 15]; this so-called “Volovik effect” is due to the Doppler shift of the QP energy spectrum in the presence of a supercurrent flowing around each vortex [16]. As a result, the QP heat transport is enhanced in magnetic fields at low temperatures (usually in the sub-Kelvin region) [17, 18, 19, 20], while at higher temperatures the QP heat transport is suppressed in magnetic fields because of the dominance of vortex scattering of QPs [21, 22, 23]. Interestingly, at intermediate temperatures a “plateau” shows up in the $\kappa(H)$ profile of Bi2212 [21], which, after a long debate (see Ref. [22] and references therein), can be understood to be a result of the competition between the increase in the QP population and the decrease in their mean free path with $H$ [13]. Till now, the magnetic-field-induced enhancement of QP transport was studied in optimally-doped YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) [17] and Bi2212 [18, 19] and in overdoped Tl$_2$Ba$_2$CuO$_{6+\delta}$ [20], but its doping dependence has been scarcely known.

Here we choose to study the low-temperature heat transport of LSCO, in which the hole doping can be well controlled over a wide range. High-quality La$_{2-x}$Sr$_x$CuO$_4$ single crystals ($x = 0.08, 0.10, 0.14, 0.17$, and 0.22) are grown by the traveling-solvent floating-zone technique [24]. The crystals are cut into rectangular platelets with typical size of $1.5 \times 0.5 \times 0.1$ mm$^3$, where the $c$ axis is perpendicular to the platelets within an accuracy of 1°, determined by the X-ray Laue analysis. The samples at $x = 0.08-0.17$ are annealed at 800–880 °C in air for 60 hours, followed by rapid quenching to room
temperature, to remove oxygen defects, while the sample at $x = 0.22$ is annealed in oxygen and quenched to 77 K. Magnetic susceptibility measurements show that the superconducting transition temperature $T_c$ is 22, 28.5, 35.5, 36.5 and 28 K for $x = 0.08, 0.10, 0.14, 0.17$ and 0.22, respectively. The zero-field heat transport in these samples at milli-Kelvin temperatures has already been reported in a previous paper [25]. In this work, both the temperature and the magnetic-field dependences of $\kappa$ are measured from 0.3 to 7 K in a $^3$He refrigerator by using the conventional steady-state “one heater, two thermometer” technique [10]. The magnetic field up to 16 T is applied along the c axis of the crystals while the heat current flows in the ab plane. To avoid complications that are associated with the vortex-pinning-related hysteresis [15], the $\kappa(H)$ data are taken in the field-cooled procedure [14, 23].

Figure 1 shows the zero-field $\kappa(T)$ of LSCO crystals in a wide temperature range, where the additional data from 5 to 150 K are taken using a Chromel-Constantan thermocouple in a $^3$He cryostat, and the very low temperature $\kappa(T)$ data [23] are also shown in the inset. The measured thermal conductivity is a sum of the electron (or QP) term $\kappa_e$, and the phonon term $\kappa_{ph}$, whose temperature dependences are proportional to $T$ and $T^3$ in the low-$T$ limit, respectively. Thus, in the $\kappa(T)$ vs $T^2$ plot (Fig. 1 inset), it is clear that the $\kappa_e$ component increases with $x$. In the main panel of Fig. 1, the superconducting transition can barely be recognized by a weak hump in $\kappa$, which is easiest to see in the optimally-doped sample ($x = 0.17$).

Figure 2 shows the magnetic-field dependences of the thermal conductivity $\kappa$ for the optimum (a) and overdoped (b) LSCO crystals ($x = 0.17$ and 0.22, respectively). Solid lines in each panel show fits of the low-$T$ data to the $H^{1/2}$ dependence, which is expected when the magnetic-field enhancement in $\kappa$ is mainly due to the increase in the QP population by the Volovik effect.
in optimum and overdoped LSCO is qualitatively similar to that in the optimally-doped Bi2212 and YBCO.

The most surprising result of the present work is the behavior of $\kappa(H)$ in underdoped LSCO ($x = 0.08, 0.10$ and 0.14). As shown in Fig. 3, $\kappa$ always decreases quickly with $H$ at all temperatures down to 0.36 K in all the underdoped crystals studied, which is vastly different from the $\kappa(H)$ behavior of optimum and overdoped crystals. To understand the implication of this result, it should first be recognized that the impurity scattering cannot be the source of such a strong magnetic-field suppression of QP heat transport, because it has been demonstrated that impurities just strongly diminishes the $H$ dependence of $\kappa$. Therefore, the effect of magnetic field on the QP heat transport must have been changed fundamentally in underdoped samples. When the data in Fig. 3 are compared to those in Fig. 2, it is obvious that both the magnetic-field enhancement of $\kappa$ at low $T$ and the “plateau” feature at high $T$ are absent in underdoped samples, which points to an increased role of vortex scattering and a diminished role of magnetic-field-induced QPs. Given that the specific heat measurements have already demonstrated that the QP density-of-states are always enhanced with $H$ (i.e., QPs are certainly created by magnetic fields) in underdoped LSCO, it is most reasonable to conclude the following: (i) the magnetic-field-induced QPs are localized and contribute little to the heat transport in underdoped LSCO, and (ii) vortices strongly scatter QPs in underdoped samples even at low $T$, while they do not effectively scatter QPs in optimum and overdoped samples at low $T$.

These results are most naturally understood in the light of the recently-found magnetic-field-induced CDW/SDW in the cuprates [2, 3, 4, 5]. For LSCO, neutron scattering experiments have shown [4, 5] that the magnetic-field-induced SDW is dynamical at optimum doping, while it becomes a static, zero-energy object in underdoped samples. Thus, the magnetic-field-induced order is expected to be relevant to the low-temperature properties only in underdoped LSCO. Moreover, the STM study of Bi-2212 found checkerboard-like CDW around vortices [2], which is naturally expected to cause enhanced QP scattering. Therefore, it is likely that in underdoped LSCO the magnetic-field-induced order is responsible for both the QP localization and the enhanced QP scattering off the vortices. It is thus reasonable to conclude that the peculiar $\kappa(H)$ behavior of underdoped LSCO points to novel magnetic-field-induced localization of QPs that is caused by the magnetic-field-induced order around vortices.

Figure 4 shows the hole-doping dependence of $\kappa$ at 0.36 K in 0 and 16 T, which summarizes our main finding. In 0 T, $\kappa$ shows a relatively smooth change with $x$, but $\kappa$ in 16 T shows a pronounced jump at optimum doping. As one can see in Fig. 4, this jump is caused by the fact that $\kappa$ is suppressed with $H$ in the underdoped regime, while it is enhanced with $H$ in the optimum and overdoped regime; we discussed that the former is caused by the magnetic-field-induced localization of QPs that is likely associated with the competing order, while the latter reflects extended QPs created by magnetic fields. Therefore, Fig. 4 depicts the fact that the role of magnetic field changes drastically at optimum doping.

An intriguing implication of the present result is that the magnetic-field-induced QP localization may also be responsible for the “insulating” normal-state resistivity under 60 T [11, 12]. The fact that the “insulating normal state” under 60 T is observed only in underdoped samples [11] is strongly suggestive of the correspondence. In fact, it is easy to imagine that the charge-ordered region around vortices completely overlap in 60-T field and all the electrons are incorporated into the magnetic-field-induced ordered state. Thus, it is tempting to assert that the $\log(1/T)$ behavior of the resistivity under 60 T [12] is a property of the state where the magnetic-field-induced order proliferates. In this regard, it is worth noting that a recent Nernst effect measurement found a sizable Nernst signal in the “insulating normal state” in high magnetic fields [23]. In fact, the behavior of the Nernst signal below $T_c$ is not much different between underdoped and overdoped LSCO, which probably reflects the fact that the observed Nernst signal primarily comes from the vortex motion and is insensitive to the QP contribution [23, 24]. Incidentally, the Nernst effect has been utilized to measure the upper critical field $H_{c2}$ of cuprates, where $H_{c2}$ was found to show a rather smooth change across optimum doping [23, 24]; this fact rules out the possibility that the observed change in $\kappa(H)$ between $x = 0.14$ and 0.17 might be caused by a sudden change in $H_{c2}$, which would cause the reduced field $H/H_{c2}$ to vary drastically.

It is useful to note that our previous results in zero magnetic field have shown [23] that the residual electronic thermal conductivity divided by $T$, $\kappa_{res}/T$, is much larger than what the normal-state resistivity under 60 T would suggest in the underdoped LSCO, which may indicate a strong violation of the Wiedemann-Franz law. The present new data show that in underdoped LSCO the QP transport is strongly suppressed with $H$ even at low $T$, and thus it is expected that the $\kappa_{res}/T$ value in high magnetic field may smoothly match the value estimated from the normal-state resistivity under 60 T. This is an indication that the magnetic-field-induced order around vortices ultimately changes the global properties of underdoped LSCO in high magnetic field. Therefore, the thermal transport properties give evidence that the magnetic field can cause a drastic change in the low-energy physics of underdoped cuprates because of the magnetic-field-induced localization of QPs, which is likely related to the inherent competition between antiferromagnetic and superconducting orders.

In summary, we measure the magnetic-field dependences of the thermal conductivity of LSCO single crys-
We discuss that this phenomenon is associated with the magnetic-field-induced localization of QPs in the underdoped regime.

FIG. 3: Magnetic-field dependences of \( \kappa \) for the underdoped LSCO crystals \((x = 0.08, 0.10, \text{and } 0.14)\) at various temperatures down to 0.36 K. Note that the magnetic-field enhancement of \( \kappa \) is gone in those underdoped samples.

FIG. 4: Hole-doping dependence of the thermal conductivity \( \kappa \) at 0.36 K in 0 T (open circles) and in 16 T (solid circles). \( \kappa \) in 16 T shows a pronounced jump at optimum doping (marked by a gray band), which demonstrates that the role of magnetic field changes drastically at optimum doping. The suppression of \( \kappa \) with \( H \) in the underdoped regime is a result of the magnetic-field-induced localization of QPs.

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