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Anomalous dissipation in the mixed state of underdoped cuprates close to the superconductor-insulator boundary

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We present a comparative study of Nernst effect and resistivity in underdoped samples of $Bi_2Sr_2CuO_{6+\delta}$ and $La_{2-x}Sr_xCuO_4$. The Nernst effect presents a peak in a region of the H-T diagram where resistivity shows a nonmetallic temperature dependence. Our results illustrate that the mechanism of dissipation in the mixed state of underdoped cuprates is poorly understood. Large quantum superconducting fluctuations and vanishing vortex viscosity are among suggested explanations for an enhanced Nernst signal close to the superconductor-insulator boundary.

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Recently, the peculiar behavior of Nernst effect in copper oxide superconductors has become a subject of growing attention.[1–9] In conventional superconductors, Nernst effect, namely, the transverse component of the thermopower in a magnetic field, is known to be associated with vortex movement.[10] However, Xu *et al.*[1] reported that in underdoped $La_{2-x}Sr_xCuO_4$ a large residual signal persists in the normal state and well above T_c. This observation has been confirmed in other families of cuprate superconductors including $Bi_2Sr_2CuO_{6+\delta}$ and $YBa_2Cu_3O_{6+y}$.[2,3] The normal-state Nernst signal is present over a wide doping range, but attenuates as one moves towards the superconductor-insulator boundary or the overdoped regime in the phase diagram.[2] Remarkably, the temperature scale up to which such an anomalous Nernst signal extends is about 130 K, regardless of the particular system studied. Moreover, the Nernst signal is found to persist at magnetic fields as high as 30 T both in overdoped[3] and in underdoped[4] compounds.

The debate on the origin of this residual Nernst signal in the normal state of underdoped cuprates is still open and has stimulated a number of theoretical works during the past months. Fluctuations of the superconducting order parameter above T_c are considered to be the most plausible explanation for such a signal. Ussishkin, Sondhi, and Huse,[5] for example, used a time-dependent-Ginzburg-Landau approach. Within Gaussian approximation and subtracting magnetization currents, they found a sizable Nernst signal due to superconducting fluctuations. Weng and Muthukumar[7] have suggested that in a resonant-valence-bond picture, the coupling of spinon vortices to holons can give rise to an enhanced Nernst effect above T_c in the so-called spontaneous vortex phase. A different route has been taken by Kontani[6] who calculated Nernst coefficient beyond the relaxation-time approximation. By taking a self-consistent account of vertex corrections for currents, he found that the quasiparticle contribution to Nernst effect is no longer negligible in presence of antiferromagnetic and superconducting fluctuations. These studies point to the presence of strong superconducting fluctuations in the pseudogap regime and suggest that the superconducting transition is not a mean-field transition[11] but rather a vortex-antivortex unbinding type of transition.[12] It is puzzling, however, that these strong fluctuations are not detected in charge transport. Indeed, in the temperature window associated with the residual Nernst signal, the magnetoresistance does not present any strong feature. On the other hand, the quasiparticle contribution to the Nernst signal is expected to be small.[2] However, in absence of a satisfactory understanding of the electronic excitations in the normal state of the underdoped cuprates, one cannot exclude that the peculiar behavior of the Nernst effect is yet another anomalous transport property of the normal state.

In this paper, we focus on the behavior of the Nernst effect in the underdoped regime close to the supercoductor-insulator transition. In underdoped cuprates, the destruction of superconductivity in high magnetic fields is accompanied with the emergence of an ''insulating'' normal state presenting a weakly diverging nonmetallic resistivity.[13–15] Our study concentrates on very underdoped samples of $La_{2-x}Sr_xCuO_4$ and $Bi_2Sr_2CuO_{6+\delta}$ close enough to the superconductor-insulator boundary for a moderate magnetic field of 12 T to introduce a nonmetallic resistivity. By simultaneously measuring Nernst effect and resistivity in the mixed state, we found that these two transport properties, both supposedly associated with vortex motion, are no longer correlated in this regime. In sharp contrast with other superconductors, the maximum in the Nernst occurs in a temperature window associated with a nonmetallic resistivity. This result highlights the limits of our current understanding of the dissipation mechanism in a field-induced superconductor-insulator transition.

Nernst coefficient, the ratio of the transverse electric field to the longitudinal thermal gradient, was measured in presence of a magnetic field parallel to the *c* axis with a one-heater-two-thermometer setup. The setup allowed to measure the resistance of the sample in the same conditions. The thermal gradient was obtained using two RuO_2 or Cernox thermometers connected via gold or silver wires to two electrodes along the sample. The same electrodes were used to measure the voltage drop induced by a charge current applied along the sample and therefore to monitor the resistance of the sample. Two other lateral electrodes were used to measure the dc transverse voltage produced by applying a heat current along the sample with a heater chip. The two thermometers and the heater were held in the vacuum by long thin highly resistive manganin wires which were also used to measure their resistance. In this way, the path of the heat current along the sample was controlled. No correction was made for the magnetoresistance of thermometers. We estimate that the error on the absolute magnitude of the temperature gradient at 12 T due to this approximation is less than 10%. Note that such a correction is only relevant for single crystals; for thin films, the thermal gradient is almost totally controlled by the substrate's thermal conductivity and is not expected to vary with the magnetic field. The heat current was kept low enough to keep $\nabla T/T$ below 5%. At each temperature, the Nernst signal was extracted by reversing the sign of the magnetic field and keeping only the antisymmetric part of the signal. In this way, the offset signal due to the misalignment of the contacts and an eventual contribution of the wires was subtracted.

The samples used in this study were two *c*-axis oriented thin films of $Bi_2Sr_2CuO_{6+\delta}$(Bi-2201) and a single crystal of $La_{1.94}Sr_{0.06}CuO_4$. The Bi-2201 thin films were epitaxially grown by rf magneton sputtering on a $SrTiO_3$ substrate.[16] The oxygen content of initially overdoped samples was reduced by annealing in controlled atmosphere as already detailed in a previous study of the evolution of resistivity with doping in $Bi_2Sr_{2-z}La_zCuO_{6+\delta}$.[17] Gold electrodes were sputtered on them and wires were connected with silver paint to these electrodes. The $La_{1.94}Sr_{0.06}CuO_4$ single crystal was made in an optical furnace using a traveling-solvent floating-zone technique and was already used and mentioned in our previous study.[4] It was subsequently oxygen annealed at 10 bar and 450 °C for ten days in order to enhance the homogeneity of oxygen distribution. Low-resistivity contacts on this crystal were made by baking Dupont 6838 silver paint electrodes with oxygen flow at 450 °C for ten min.

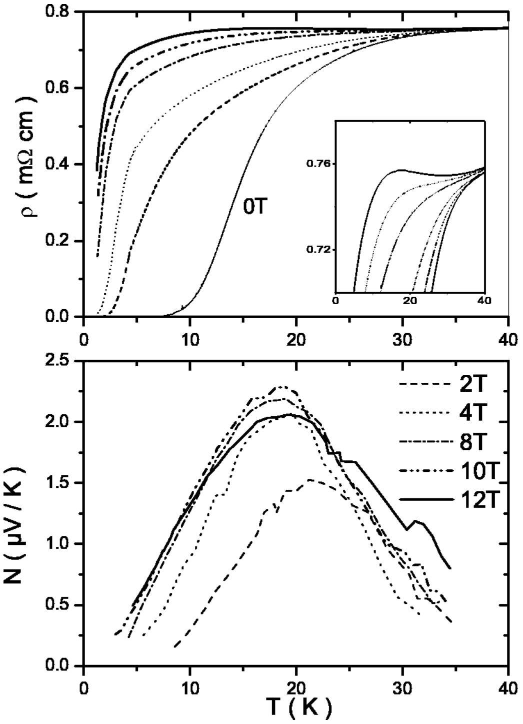

FIG. 1. Nernst effect (bottom) and resistivity (top) as a function of temperature up to 12 T in $Bi_2Sr_2CuO_{6+y}$ thin film with $T_c = 15$ K. The inset highlights the field-induced upturn in resistivity.

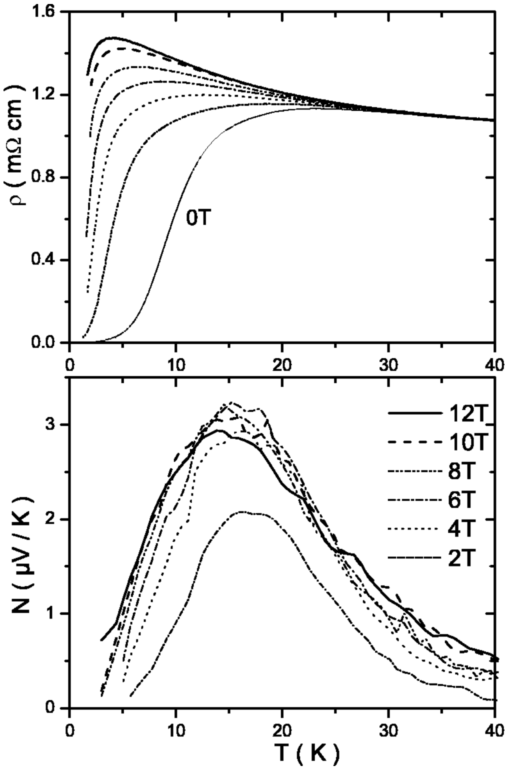

FIG. 2. Nernst effect (bottom) and resistivity (top) as a function of temperature up to 12 T in $Bi_2Sr_2CuO_{6+y}$ thin film with $T_c = 9$ K.

Figures 1 and 2 show Nernst effect and resistivity as a function of temperature in two $Bi_2Sr_2CuO_{6+\delta}$ thin films, at several magnetic fields up to 12 T. At zero field, both samples present a broad resistive transition which shifts to lower temperatures with increasing magnetic field. The critical temperature, taken as the temperature associated with resistivity dropping to half of the full normal-state value, was found to be 15 K for the first and 9 K for the second sample. The resistivity of the 9-K sample presents a clear nonmetallic upturn that becomes more pronounced as the field is increased. In the case of 15-K sample, the nonmetallic behavior is absent at low fields but sets in at 12 T, indicative of a higher doping level. Using the critical temperature and the room-temperature resistivity of these samples, one can make a very rough estimate of doping level by comparing them with values obtained in systematic studies of doping dependence of resistivity[17,18] and thermopower.[19] This yields $\delta \sim 0.08$ for the 9-K sample and $\delta \sim 0.09$ for the 15-K sample.

In both samples, Nernst effect presents the broad peak commonly associated with the vortex movement in the mixed state of type-II superconductors. The amplitude of this peak increases initially with increasing magnetic field before starting to decrease at 10 T. But (save for the 2-T curve which displays a maximum at higher temperatures) the peak *does not* shift to lower temperatures as the field is increased. This is in sharp contrast with the behavior observed in optimally doped cuprates, where the Nernst peak follows the field-induced shift in resistive transition.[20] Note that in both samples at 12 T, the peak occurs at a temperature interval where resistivity is increasing with decreasing temperature. In the case of 15-K sample, while resistivity presents a continuous evolution from the low-field metallic to the high-field localization behavior, the temperature dependence of the Nernst effect remains unaffected. This, added to the fact that Nernst effect has a similar behavior in both samples, seems to suggest that Nernst effect is not disturbed by the onset of localization observed in resistivity. Comparing the two Bi-2201 thin films, one important feature is that the mismatch between the Nernst peak and the resistive transition becomes more pronounced as the magnetic field is increased or the doping is reduced at constant field. As these are the parameters that tune the superconductor-insulator transition, the anomalous dissipation that we report here might be related to this transition. Note, however, that the threshold field for nonmetallic resistivity does not correspond to the onset of this absence of correlation between Nernst effect and resistivity.

This contrasting behavior of Nernst effect and resistivity is even more pronounced in the $La_{1.94}Sr_{0.06}CuO_4$ as seen in Fig. 3. As a result of an extensive oxygen annealing, this sample presents a smooth zero-field resistive transition centered around 11.4 K in contrast with the broad double transition seen before annealing.[4] Nevertheless, the contrasting behavior of Nernst effect and resistivity was found to be robust to oxygen annealing and this rules out extrinsic inhomogeneity as a primary cause for it. As seen in the figure, for fields larger than 6 T, the resistivity does not show any sign of superconducting transition down to 1.2 K. However, a positive magnetoresistance is present up to 12 T. In the same temperature range, we observe a peak in Nernst effect which shifts to higher temperature with increasing magnetic field. After an initial increase, the amplitude of this peak begins to decrease with increasing magnetic field for fields exceeding 2 T. Moreover, as seen in the inset, the Nernst signal changes sign well above T_c, revealing a small quasiparticle contribution with opposite sign to the vortex Nernst signal, consistent with previous reports.[2]

Across a wide range of the cuprate phase diagram, the Nernst effect and resistivity do not give identical accounts of the way magnetic field destroys superconductivity. Recent high-field investigations of Nernst effect in overdoped $La_{1.8}Sr_{0.2}CuO_4$ indicate that the upper critical field extracted from the resistivity measurements is systematically lower than the H_{c2} obtained from the Nernst signal.[3] A similar discrepancy has also been reported in the case of electron-doped $Nd_{2-x}Ce_xCuO_4$ at different doping levels.[21] Our results indicate that the decoupling between the two probes of vortex state becomes particularly striking by approaching to the insulating side of the phase diagram and in the presence of field-induced nonmetallic resistivity.

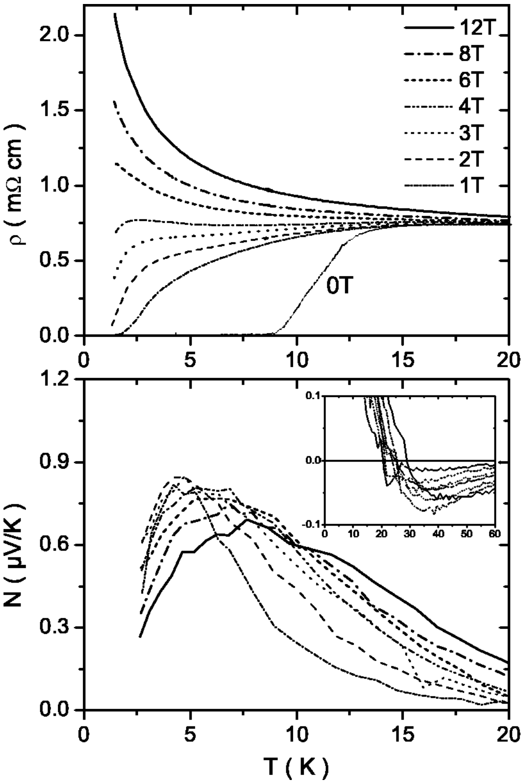

FIG. 3. Nernst effect (bottom) and resistivity (top) as a function of temperature up to 12 T in $La_{1.94}Sr_{0.06}CuO_4$ single crystal with $T_c = 11.4$ K. The inset shows the sign change of the Nernst signal at higher temperatures.

Recently, in order to explain the absence of correlation between Nernst effect and resistivity, Ikeda proposed a model based on quantum superconducting fluctuations described by a two-dimensional Ginzburg-Landau action.[8] Noticing that in underdoped cuprates, the normal-state resistance per CuO_2 plane becomes comparable to the quantum of resistance $\mathbf{R}_q = h/4e^2 = 6.45\ \mathrm{k}\Omega$, he argued that in the underdoped regime, as a result of a reduced superfluid density, superconducting fluctuations are not only enhanced, but become quantum in nature in contrast to the optimally doped regime dominated by thermal fluctuations. The same formalism has already been used to describe quantum fluctuations in the context of the field-tuned superconductor-insulator transition in dirty two-dimensional superconducting films,[22] accounting for nonuniversal values of resistance and the absence of a well-defined critical field at the transition by including effects of Coulomb repulsion.[23]

In Ikeda's scenario,[8] the apparent contradiction between a vortexlike behavior in Nernst effect and a normal-state-like resistivity is due to a vanishingly small vortex contribution to the total resistivity which is thus dominated by the insulating background, whereas the Nernst effect is enhanced in the quantum fluctuation regime. Decomposing the pair wave function on Landau levels and taking into account the $\omega \neq 0$ terms, the theory provides expressions for transport entropy and conductivity in presence of quantum fluctuations as a function of the propagator of the first two Landau-level fluctuation fields. This model can mimic the observed behavior of both transport energy and resistivity reported here in the high-temperature window above the Nernst peak.[9]

The doping dependence of vortex viscosity may constitute an alternative explanation for the observed discrepancy between resistivity and Nernst data. The vortex equation of movement contains a dissipative term proportional to vortex viscosity η.[10] Since the Nernst signal is inversely proportional to this viscosity ($N \sim S_\Phi/\eta$, with S_Φ the vortex entropy), a vanishing viscosity would lead to an enhanced Nernst signal as well as a rapid saturation of resistivity to its normal-state value. A scenario along these lines was suggested to account for the anomalous behavior of the resistive transition in overdoped $Tl_2Ba_2CuO_{6+\delta}$.[24] In the latter compound, the apparent H_{c2} extracted from resistivity lies below the thermodynamic one deduced from specific-heat data.[25] Experimental evidence for a reduced vortex viscosity in overdoped Bi-2201 has been recently provided by microwave surface impedance measurements at low fields.[26] On the other hand, studying the properties of a *d*-wave superconductor in a slave boson-U(1) gauge theory, Ioffe and Millis proposed that viscosity should vanish in the vicinity of the Mott insulator.[27] Therefore, in such a picture, the coexistence between an enhanced Nernst signal and a saturated flux-flow resistivity is expected to enhance with underdoping. Further investigations of the doping dependence of vortex viscosity are necessary to shed more light on this issue.

Finally, we note that recent scanning tunnelling microscopy studies indicate that vortex cores in cuprates present an unusual electronic excitation spectrum.[28] Moreover, in the underdoped regime, inelastic neutron-scattering[29] and nuclear-magnetic-resonance[30,31] experiments have revealed enhanced antiferromagnetic correlations associated with vortex cores. The possible contribution of these excitations to the Nernst signal is yet to be explored.

In conclusion, we found that the decoupling between Nernst effect and resistivity becomes more pronounced as one sweeps the cuprate phase diagram from optimal doping to the very underdoped limit. In particular, the Nernst effect presents a peak where the corresponding resistivity is nonmetallic. Such an anomalous dissipation regime may prove to be relevant for the studies of superconductor-insulator transition in dirty conventional superconducting thin films.

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