Normal state of extremely anisotropic superconducting cuprates as revealed by magnetotransport

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Normal state of extremely anisotropic superconducting cuprates as revealed by magnetotransport

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High magnetic-field studies of cuprate superconductors revealed a non-BCS temperature dependence of the upper critical field $H_{c2}(T)$ determined resistively by several groups. These determinations caused some doubts on the grounds of both the contrasting effect of the magnetic field on the in-plane and out-of-plane resistances reported for large Bi2212 samples and the large Nernst signal *well above* T_c. Here we present both $\rho_{ab}(B)$ and $\rho_c(B)$ of tiny Bi2212 crystals in magnetic fields up to 50 T. None of our measurements revealed a situation when on the field increase ρ_c reaches its maximum while ρ_{ab} remains very small if not zero. The resistive $H_{c2}(T)$ estimated from $\rho_{ab}(B)$ and $\rho_c(B)$ are approximately the same. Our results support any theory of cuprates that describes the state above the resistive phase transition as perfectly normal with a zero off-diagonal order parameter.

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A pseudogap is believed to be responsible for the non-Fermi-liquid normal state of cuprate superconductors. Various microscopic models of the pseudogap proposed are mostly based on strong electron correlations[1] and/or on strong electron-phonon interaction.[2] There is also a phenomenological scenario,[3] where the superconducting order parameter (the Bogoliubov-Gor'kov anomalous average $\mathcal{F}(\mathbf{r},\mathbf{r}')=\langle\psi_\downarrow(\mathbf{r})\psi_\uparrow(\mathbf{r}')\rangle$) does not disappear at T_c but at much higher (pseudogap) temperature. While the scenario[3] was found to be inconsistent with the "intrinsic tunneling" *I-V* characteristics, the discovery of the joule heating origin of the gaplike *I-V* nonlinearities made that objection irrelevant.[4] Some other measurements[5] also provide evidence in support of Ref. 3.

In line with the scenario, several authors[6–8] suggested a radical revision of the magnetic phase diagram of the cuprates with an upper critical field much higher than the resistive $H_{c2}(T)$. In particular, Ref. 6 questioned the resistive determination of $H_{c2}(T)$,[9,10] claiming that, while ρ_c measures the interplane tunneling, only the in-plane data represent a true normal state. The main argument in favor of this claim came from the radically different field dependencies of ρ_c and ρ_{ab} in Ref. 6 [shown below in our Fig. 2(b)]. According to this finding, a magnetic field sufficient to recover the normal state ρ_c, leaves in-plane superconductivity virtually unaffected. This discrepancy suggests that Bi2212 crystals do not lose their off-diagonal order in CuO_2 planes even well above $H_{c2}(T)$ determined from $\rho_c(B,T)$. However, this conclusion is based on one measurement and so certainly deserves experimental verification, which was not possible until recently because of the lack of reliable $\rho_{ab}(B,T)$ for Bi2212.

Quite similar conclusions followed from thermomagnetic studies of superconducting cuprates. Here the Nernst signal was found to be enormously large *well above* T_c and has been attributed to a motion of *superconducting vortices*.[7,8] Reference 8 claimed that the unusual Nernst signal provides "compelling evidence" that "the cuprate superconducting transition at T_c actually corresponds to the loss of long-range phase rigidity, as opposed to the vanishing of the Gor'kov pairing amplitude $\mathcal{F}(\mathbf{r},\mathbf{r}')$." As a result, the magnetic phase diagram of the cuprates has been revised radically. Most surprisingly, Ref. 7 estimated $H_{c2}(T)$ *at the zero-field transition temperature*, T_{c0}, of Bi2212 as high as 50−150 T.

On the other hand, any scenario with $\mathcal{F}(\mathbf{r},\mathbf{r}')\neq 0$ in the "normal" state is difficult to reconcile with the extremely sharp resistive and magnetic transitions at T_c in single crystals of cuprates. Above T_c, the uniform magnetic susceptibility is paramagnetic and the resistivity is perfectly "normal," showing only a few percent positive or negative magnetoresistance (MR). Both in-plane[11–13] and out-of-plane[9] resistive transitions remain sharp in the magnetic field in high-quality samples, providing a reliable determination of a genuine $H_{c2}(T)$. As concerns the anomalous thermomagnetic effects, a simple normal-state model with itinerant and localized carriers provides a quantitative single-parameter description of both the temperature and field dependencies of the Nernst signal measured experimentally above the resistive critical temperature $T_c(B)$ (see Ref. 14 for details). These and some other observations[15] do not support any superconducting order parameter above T_c.

Resolution of these issues, which affect fundamental conclusions about the nature of superconductivity in highly an-

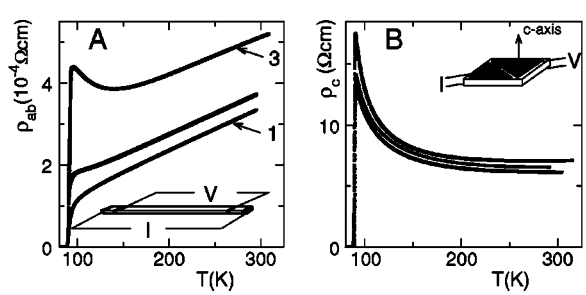

FIG. 1. Contact layout and examples of $\rho_c(T)$ and $\rho_{ab}(T)$ measured on small samples cleaved from the same Bi2212 crystal. ρ_c contamination of ρ_{ab} is indistinguishable for curve 1 and $\sim 10^{-5}$ for curve 3.

isotropic layered cuprates, requires further careful experiments and transparent interpretations. Here we present systematic measurements of both in-plane and out-of-plane MRs of small Bi2212 single crystals subjected to magnetic fields $B \leqslant 50$ T, $B \perp (ab)$. Our measurements reproduced neither the unusual field dependence of ρ_{ab} nor the contrasting effect of the field as in Ref. 6, which are most probably an experimental artefact. On the contrary, they show that $H_{c2}(T)$ estimated from ρ_{ab} and ρ_c are nearly identical. These results, along with a simple explanation of the unusual Nernst signal in cuprates as a normal-state phenomenon,[14] strongly support any microscopic theory of cuprates with a zero off-diagonal order parameter above resistive $T_c(B)$.

Reliable measurements of the resistivity tensor require defect-free samples. This is of prime importance for in-plane MR because, owing to the extreme anisotropy of Bi2212,[16] even unit-cell scale defects will result in a significant out-of-plane contribution. Not only are such minor defects impossible to detect by conventional techniques, but ρ_{ab} contamination with ρ_c might occur even in a perfect crystal with nonuniform current distribution. For these reasons, we paid special attention to sample preparation and selection.[16] Since the extremely high and temperature-dependent electric anisotropy of Bi2212 prevents reliable measurement of both the in-plane and out-of-plane resistances on the same sample, we measured ρ_c and ρ_{ab} on different pieces of the same high-quality, optimally, and slightly underdoped Bi2212 parent crystals with $T_{c0} \approx 87-92$ K. As the specific demands of pulsed field experiments make it essential to use tiny specimens, we measured ρ_c on samples with in-plane dimensions from $\simeq 30 \times 30$ to $\simeq 80 \times 80$ μm^2, while ρ_{ab} was studied on longer crystals, from $\simeq 300 \times 11$ to $\simeq 780 \times 22$ μm^2. The samples for this study were selected on the basis of comparative analysis of transport measurements of 7-12 pairs of such samples, cleaved from different places of the same parent crystal (typically of 1–3 μm thickness). To achieve a uniform *in-plane* current distribution, the current contacts were made by immersion of the crystals' ends into diluted conductive composite; ρ_c was measured with the contacts deposited on both *ab* faces, see Fig. 1. The uncertainty of the samples' dimensions is the most probable cause of the mismatch of ρ_c in different pieces, Fig. 1(b). Unlike $\rho_c(T)$ curves, $\rho_{ab}(T)$ of different pieces often reveal qualitatively different behavior, illustrated in Fig. 1(a). While the majority of the "ρ_{ab} samples" had the metallic type of zero-field $\rho_{ab}(T)$ represented by the curve 1, others demonstrated the sample-dependent $\rho_{ab}(T)$ upturn, which we attribute to ρ_c contamination. Only the samples with the lowest $\rho_{ab}(T)$ were selected for this study. The metallic type of zero-field $\rho_{ab}(T)$ and the *sign* of its normal-state MR (Ref. 16) indicate a vanishing ρ_c contribution. The absence of hysteresis in the $\rho(B)$ data obtained on the rising and falling sides of the pulse, and the consistency of $\rho(B)$ taken at the same temperature in pulses of different B_{max}, exclude any measurable heating effects. The Ohmic response is confirmed by the consistency of $\rho(B)$ measured at identical conditions with different currents, 10–1000 A/cm^2 for ρ_{ab} and 0.1–20 A/cm^2 for ρ_c.

Figure 2 shows the typical $\rho_c(B)$ and $\rho_{ab}(B)$ taken below T_{c0} of a Bi2212 single crystal. The low-field portions of the curves correspond to the resistance driven by vortex dynamics. Here, a nonlinear $\rho(B)$ dependence is followed by a regime in which linear dependence fits the experimental observations rather well (Fig. 2). It is natural to attribute the high-field portions of the curves in Fig. 2 (assumed to be above H_{c2}) to a normal state.[10] Here, the *c*-axis high-field MR appears to be negative and quasilinear in B in a wide temperature range both above and below T_{c0}. Contrary to $\rho_c(B)$, the normal-state in-plane MR is *positive* (see Ref. 16 and references therein for an explanation). The resistive upper critical field, $H_{c2}(T)$, is estimated from $\rho_c(B)$ and $\rho_{ab}(B)$ either as the intersection of two linear approximations in Fig. 2, or from the flux-flow resistance as $H_{c2} = \rho_N(0,T)(\partial\rho_{FF}/\partial B)^{-1}$; both estimates are found to be almost identical. This procedure allows us to separate contributions originating from the normal and superconducting states and, in particular, to avoid ambiguity resulting from fluctuations in the crossover region. The downward deviations from the linear field dependence at fields around H_{c2} in Fig. 2 are most likely caused by the conventional [three-dimensional (3D)-*XY*][17] critical behavior rather than any stationary off-diagonal order parameter in the "normal" phase.[18] The reasonable concordance of $H_{c2}(T)$ estimates from $\rho_c(B)$ and $\rho_{ab}(B)$ [Fig. 2(a)] favors our association of the resistive H_{c2} with the upper critical field, especially given the apparently different mechanisms responsible for ρ_{ab} and ρ_c. The latter statement is strongly supported by the huge electric anisotropy of Bi2212, the vastly different types of the normal state $\rho_c(T)$ and $\rho_{ab}(T)$ (e.g., Fig. 1), and the opposite signs of the corresponding normal-state magnetoresistances (see Ref. 16 for more details).

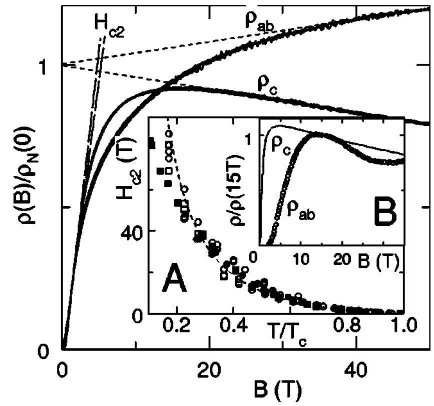

FIG. 2. $\rho_c(B)$ and $\rho_{ab}(B)$ of Bi2212 at $\sim$68 K, normalized by corresponding $\rho_N(0,T)$ obtained with the linear extrapolation from the normal-state region (short dashes). The linear fits, shown by long dashed lines, refer to the flux-flow region. Inset A: H_{c2} estimated from $\rho_{ab}(B)$ and $\rho_c(B)$ is shown by the open and solid symbols, respectively, together with the fit, $H_{c2}(T) \sim (t^{-1} - t^{1/2})^{3/2}$, with $t = T/T_c$ (Ref. 22, broken line). Inset B shows ρ_c and ρ_{ab} from Ref. 6.

Our conclusion is based on the results obtained during several hundred measurements performed on three pairs of crystals. None of those revealed a situation in which on field increase ρ_c reaches its maximum while ρ_{ab} remains very small if not zero as in Ref. 6 [see Fig. 2(b)]. Since the authors of Ref. 6 measured $'\rho_{ab}(B)'$ by means of contacts situ-

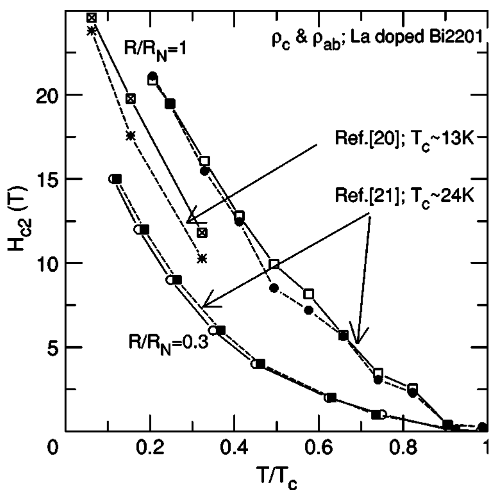

FIG. 3. $H_{c2}(T)$ obtained from independent resistance measurements in Bi2201 (Refs. 20 and 21); broken lines correspond to the data taken from ρ_c, solid lines from ρ_{ab}.

ated on the same face of the crystal while the current was injected into the opposite face, their curve could *not* represent the true ρ_{ab}. We cannot exclude the possibility that this observation might be caused by current redistribution in the medium with field- and temperature-dependent anisotropy. This opinion is supported by the independent study of current redistribution in homogeneous Bi2212.[19] However, the threefold ρ_c enhancement warrants inhomogeneity of the huge crystal in Ref. 6 so that the results of Ref. 19 may not be directly applicable to this case. Neither the current redistribution nor imperfections of the crystal were accounted for in Ref. 6.

Our findings and conclusions are additionally supported by independent studies of a single-layer cuprate Bi(La)2201 with similar anisotropy. If we apply the routine procedure for the $H_{c2}(T)$ evaluation,[9] very similar values of $H_{c2}(T)$ are obtained from ρ_{ab} *and* ρ_c measured on *the same* crystals[20] and films[21] (see broken and solid lines in Fig. 3).

The functional similarity of $H_{c2}(T)$ dependences estimated for the same conditions from resistivities of physically different origin is evident from Figs. 2(a) and 3. Remarkably, these $H_{c2}(T)$ are compatible with the Bose-Einstein condensation field of preformed charged bosons[22] [Fig. 2(a)], and also with some other models.[23] The described experiments were performed in optimally doped or only slightly underdoped samples. It would be desirable to extend these studies to more underdoped samples, where the conditions for bosonic superconductivity[2] are definitely satisfied.

To conclude, we have shown that reliable experimental data do not require radical revision of the magnetic phase diagram of cuprates.[24] In particular, the reasonable concordance of resistive upper critical fields estimated from $\rho_{ab}(B)$ and $\rho_c(B)$ favors our assignment of resistive H_{c2} to the genuine upper critical field, especially given the apparently different mechanisms responsible for the in-plane and out-of-plane resistivity in the normal state of Bi2212 and Bi(La)2201, as evidenced by the huge and temperature-dependent anisotropy, $\rho_c/\rho_{ab} \geqslant 10^4 - 10^5$. Our experimental $\rho_{ab}(T,B)$ and $\rho_c(T,B)$ in the same Bi2212 crystals and the model of the Nernst signal[14] support virtually any microscopic theory that describes the state above the resistive and magnetic phase transition in superconducting cuprates as perfectly "normal" with $\mathcal{F}(\mathbf{r},\mathbf{r}')=0$. The carries could be normal-state fermions, as in any BCS-like theory of cuprates, normal-state charged bosons, as in the bipolaron theory,[2] or a mixture of both.

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[1] For a review see T. Timusk and B. Statt, Rep. Prog. Phys. **62**, 61 (1999).
[2] A. S. Alexandrov, *Theory of Superconductivity* (IOP, Bristol, 2003).
[3] V. J. Emery and S. A. Kivelson, Nature (London) **374**, 434 (1995).
[4] V. N. Zavaritsky, Physica C **404**, 440 (2004).
[5] J. Corson, R. Mallozzi, J. Orenstein, J. N. Eckstein, and I. Bozovic, Nature (London) **398**, 221 (1999); C. Meingast, V. Pasler, P. Nagel, A. Rykov, S. Tajima, and P. Olsson, Phys. Rev. Lett. **86**, 1606 (2001).
[6] N. Morozov, L. Krusin-Elbaum, T. Shibauchi, L. N. Bulaevskii, M. P. Maley, Yu. I. Latyshev, and T. Yamashita, Physica C **341–348**, 1511 (2000); Phys. Rev. Lett. **84**, 1784 (2000).
[7] Z. A. Xu, N. P. Ong, Y. Wang, T. Kakeshita, and S. Uchida, Nature (London) **406**, 486 (2000); Y. Wang, S. Ono, Y. Onose, G. Gu, Y. Ando, Y. Tokura, S. Uchida, and N. P. Ong, Science **299**, 86 (2003).
[8] Y. Wang, N. P. Ong, Z. A. Xu, T. Kakeshita, S. Uchida, D. A. Bonn, R. Liang, and W. N. Hardy, Phys. Rev. Lett. **88**, 257003 (2002).
[9] A. S. Alexandrov, V. N. Zavaritsky, W. Y. Liang, and P. L. Nevsky, Phys. Rev. Lett. **76**, 983 (1996).
[10] V. N. Zavaritsky and M. Springford, JETP Lett. **68**, 448 (1998); V. N. Zavaritsky, *ibid.* **71**, 80 (2000).
[11] A. P. Mackenzie, S. R. Julian, G. G. Lonzarich, A. Carrington, S. D. Hughes, R. S. Liu, and D. C. Sinclair, Phys. Rev. Lett. **71**, 1238 (1993).
[12] M. S. Osofsky, R. J. Soulen, S. A. Wolf, J. M. Broto, H. Rakoto, J. C. Ousset, G. Coffe, S. Askenazy, P. Pari, I. Bozovic, J. N. Eckstein, and G. F. Virshup, Phys. Rev. Lett. **71**, 2315 (1993); *ibid.* **72**, 3292 (1994).
[13] D. D. Lawrie, J. P. Franck, J. R. Beamish, E. B. Molz, W. M. Chen, and M. J. Graft, J. Low Temp. Phys. **107**, 491 (1997).
[14] A. S. Alexandrov and V. N. Zavaritsky, Phys. Rev. Lett. **93**, 217002 (2004).
[15] J. W. Loram, K. A. Mirza, J. R. Cooper, W. Y. Liang, and J. M. Wade, J. Supercond. **7**, 243 (1994).
[16] V. N. Zavaritsky, J. Vanacen, V. V. Moshchalkov, and A. S. Alexandrov, Physica C **404**, 444 (2004).

[17] T. Schneider and J. M. Singer, *Phase Transition Approach to High Temperature Superconductivity* (Imperial College Press, London, 2000).

[18] As is clear from Fig. 2 the deviation in $\rho_{ab}(B)$ occurs at fields somewhat higher than in $\rho_c(B)$. This could be explained within a phenomenological model of preformed pairs (bosons) by critical enhancement of the relaxation time of bosons near their Bose-Einstein condensation temperature, $T_c(B)$, $\tau \propto [T - T_c(B)]^{-1/2}$, as in atomic Bose-gases, e.g., T. Lopez-Arias and A. Smerzi, Phys. Rev. A **58**, 526 (1998). As was shown earlier by C. J. Dent, A. S. Alexandrov, and V. V. Kabanov, [Physica C **341**, 153 (2000)], the Landau diamagnetism of normal state bosons could be responsible for a diamagnetic response of underdoped cuprates experimentally measured somewhat above $T_c(B)$ [e.g., R. Jin, A. Schilling, and H. R. Ott, Phys. Rev. B **49**, 9218 (1994)].

[19] R. Busch, G. Ries, H. Werthner, G. Kreiselmeyer, and G. Saemann-Ischenko, Phys. Rev. Lett. **69**, 522 (1992).

[20] Y. Ando, G. S. Boebinger, A. Passner, N. L. Wang, C. Geibel, and F. Steglich, Phys. Rev. Lett. **77**, 2065 (1996).

[21] Y. Z. Zhang, R. Deltour, J.-F. de Marneffe, Y. L. Qin, L. Li, Z. X. Zhao, A. G. M. Jansen, and P. Wyder, Phys. Rev. B **61**, 8675 (2000).

[22] A. S. Alexandrov, Phys. Rev. B **48**, 10 571 (1993).

[23] A. A. Abrikosov, Phys. Rev. B **56**, 446 (1997); D. S. Fisher, M. P. A. Fisher, and D. A. Huse, *ibid.* **43**, 130 (1991); Y. N. Ovchinnikov and V. Z. Kresin, *ibid.* **54**, 1251 (1996).

[24] V. N. Zavaritsky, V. V. Kabanov, and A. S. Alexandrov, Europhys. Lett. **60**, 127 (2002), and references therein.