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Anomalous in-plane paraconductivity in single-crystal $YBa_2Cu_3O_7$

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We have studied the in-plane paraconductivity in single crystals of $YBa_2Cu_3O_7$ with exceptionally sharp transitions. For temperatures greater than ~1 K above the transition temperature T_c, we find good qualitative and some quantitative agreement with the two-dimensional Aslamazov-Larkin theory. The jump to zero resistance occurs in a narrow interval of less than 0.5 K. Our data are inconsistent with the Lawrence-Doniach expression for crossover from two to three dimensions.

Studies on single crystals of the high-T_c oxide $YBa_2Cu_3O_7$ have shown that the electronic properties both in the normal and superconducting states are highly anisotropic.[1,2] Worthington *et al.*[3] measured the H_{c2} (upper-critical field) anisotropy and found values between 6 and 13, depending on the temperature. Tozer *et al.*[4] reported a room-temperature value of 30 for the ratio of the out-of-plane to in-plane resistivity (ρ_c/ρ_{ab}). Hagen *et al.*[5] and Iye *et al.*[6] have reported much larger resistivity anisotropies (up to 200 to 300 at T_c). In the new oxide[7] $Bi_2Ca_1Sr_2Cu_2O_x$, the resistivity anisotropies (varying from 300 to 10^5) and $H_{c2}(\sim 55)$ are reportedly even larger.[8] The large electronic anisotropy raises many interesting questions. To what degree are the charge carrying excitations confined to the CuO_2 planes in the normal state? The large anisotropy implies that fluctuations into the superconducting state which can be detected by resistivity measurements should be predominantly two-dimensional (2D). As the temperature T decreases towards T_c, the Ginzburg-Landau (GL) coherence length normal to the planes ξ_c should increase, leading to coupling of the planes. A good understanding of the crossover to 3D behavior derived from paraconductivity studies may shed light on the nature of the superconducting mechanism itself.

In conventional superconductivity, the Aslamazov-Larkin (AL) theory[9] considers the enhancement of the conductivity due to the nucleation and decay of superconducting droplets for $T > T_c$. It predicts for 2D films the paraconductivity

$$\sigma'_{2D} = e^2/(16\hbar d)1/\varepsilon \quad \text{(AL)}, \tag{1}$$

where d is the film thickness and $\varepsilon = (T - T_c)/T_c$. In clean films such as Al, the 2D Maki-Thompson term, which is much more significant at large ε, is also observed.[10] For strongly anisotropic 2D crystals, Lawrence and Doniach[11] (LD) used an anisotropic-mass formulation of the AL theory to derive

$$\sigma'_{LD} = e^2/(16\hbar d)1/\{\varepsilon[1+\nu(\varepsilon)]^{1/2}\}, \tag{2}$$

where $\nu(\varepsilon) = [2\xi_c(\varepsilon)/d]^2$. Equation (2) predicts that a crossover from $\sigma'_{LD} \sim 1/\varepsilon$ to $\sim 1/\sqrt{\varepsilon}$ (2D to 3D behavior) occurs as $T \to T_c$.

Previous studies[12] on paraconductivity in polycrystalline bulk $YBa_2Cu_3O_7$ have fitted σ' for values of ε below 0.1 and found general agreement with an averaged coherence length ξ between 13 and 22 Å. For ε exceeding 0.1 the paraconductivity σ' reported in these studies falls steeply to zero much faster than any power law. However, studies of highly c-axis-oriented thin films by Oh *et al.*[13] have shown 2D paraconductivity behavior at high T, with a crossover to 3D behavior at $\varepsilon \cong 0.06$. The data of Oh *et al.* are fitted over a large range in ε to Eq. (2). Recently several groups[14-16] have suggested that σ' appears to be better fitted to the function related to $\sigma' = -A\ln\varepsilon + B$ (over the range $10^{-3} < \varepsilon < 10^{-1}$) rather than a power law.

We have investigated the in-plane paraconductivity contribution in single crystals which have exceptionally sharp resistive transitions, and found that the temperature dependence of σ' is highly unusual. Whereas 2D AL behavior at high T is confirmed in our crystals, the LD crossover is *not* observed. Instead, the jump to zero resistance is much more abrupt than indicated in Eq. (2). The crystals are grown from a BaO-CuO flux. As previously reported,[5,15] Montgomery's technique was used to obtain both ρ_{ab} and ρ_c. The temperature regulation near T_c has been improved so that data can be obtained every 0.1 K. In most samples, both ρ_{ab} and ρ_c are obtained simultaneously after T is stabilized. A measure of the transition width ΔT is provided by the width of the peak of the derivative $d\rho_{ab}/dT$ at half height, which is shown in Fig. 1 for four of the samples. Samples with ΔT exceeding 1 K often show multiple peaks which suggest inhomogeneity. Most of our analyses are confined to samples with ΔT under 0.2 K (A , D , E), although many of our conclusions are applicable to all samples studied. The discussion of σ' falls naturally into two parts: $\varepsilon > 0.1$ and $\varepsilon < 0.1$. We describe the large-ε data first.

In some earlier studies, the excess conductivity was determined by first fitting the normal-state resistivity ρ_N at high temperatures (e.g., $2T_c < T < 300$ K) to the linear form $\rho_N = aT + b$ and then extrapolating the straight line down to temperatures near T_c. The paraconductivity was taken to be $\sigma' = \sigma(T) - \sigma_N$, where $\sigma(T)$ is the total observed in-plane conductivity and $\sigma_N = 1/\rho_N$. Using such an analysis on our data we find that the derived σ' falls very rapidly to zero for $\varepsilon > 0.1$ in agreement with Refs. 12. This rapid decrease actually reflects an overestimate

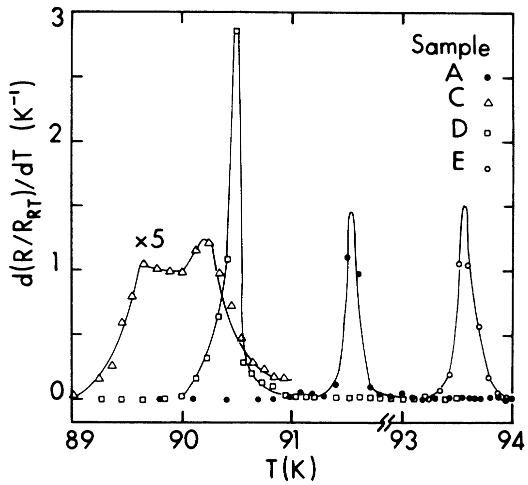

FIG. 1. Plot of $(d\rho/dT)/\rho(300\ K)$ vs T for samples A, C, D, and E. The widths (measured at half height) are less than 0.2 K for A, D, and E.

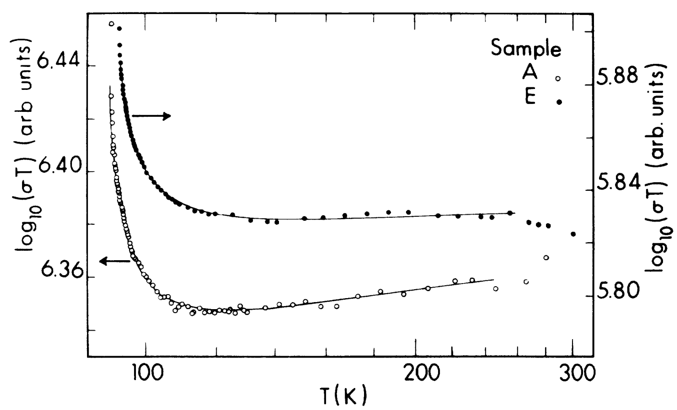

FIG. 2. Fit of the total conductance σ to Eq. (3) shown on log-log scale. (The product σT is plotted to emphasize the curvature near 100 K.) The solid line is the best fit to Eq. (3).

of the background conductivity σ_N using the rather arbitrary selection of temperature range to fit ρ_N. [Note that both σ' (if indeed 2D) and σ_N vary as $1/T$ at high T. Hence, such subtraction procedures always underestimate σ'.]

To avoid this ambiguity, we recalculated σ' by a different method. The total conductivity is first multiplied by T to remove the leading term in $1/T$, and then fitted to the four-parameter function

$$\sigma T = T/(aT+b) + CTT_0/(T-T_0) \qquad (3)$$

over the range $T_c + 1 < T < 260$ K. The second term is an assumed 2D AL form that diverges at the temperature T_0. [Both Eqs. (1) and (2) have the limiting form $1/\varepsilon$ at high T. However, because the behavior of σ' near T_c strongly disagrees with Eq. (2), we have not used the LD form to determine the large-ε behavior.] From the fit of the parameters a and b we calculate $\sigma'(T) = \sigma(T) - 1/(aT+b)$ at *all T*.

Equation (3) provides a very good fit to all five samples provided T_0 is allowed to assume a value lower than the observed T_c (Fig. 2.) The fits derived show that the 2D AL term is consistent with the data. As a consequence, we feel that subtraction procedures based on an arbitrary temperature interval (to determine σ_N) are not justified. The value of the parameter C compares well with the coefficient $e^2/16\hbar d$ in Eq. (1). Using for d the value 5.9 Å (the mean distance between CuO_2 planes in $YBa_2Cu_3O_7$), we obtain an "ideal" AL value $C = 262$ $(\Omega\ cm)^{-1}$. While the parameter C in two of the samples comes close to this value (Table I), in three C is 3–5 times smaller. It is not clear whether variation in sample quality is affecting the result for C; this number appears uncorrelated with T_c, ΔT (transition width), or the value of ρ_{ab} at room temperature.

We next turn to the interesting issue of the behavior of σ' very near the observed T_c, in particular, whether the LD model [Eq. (2)] provides a valid description of the crossover to 3D behavior. If we plot the T dependence of σ' obtained from Eq. (3) on a log-log scale (Fig. 3) we find that the slope (i.e., the exponent α in $\sigma' \sim \varepsilon^{-\alpha}$) decreases from 1 (at large ε) to a value (as $\varepsilon \rightarrow 10^{-3}$) significantly smaller than the value $\frac{1}{2}$ predicted by Eq. (2). [In Fig. 3, we also show as a broken line the spurious behavior of σ' if the incorrect subtraction procedure is used to derive σ' for sample A. We point out that the different fitting procedures used to remove the normal background affect only the high-temperature data. Thus the disagreement with Eq. (2) is not an artifact of the particular fitting procedure used to isolate σ'.]

In a log-log plot such as Fig. 3 the behavior at small ε is sensitive to the choice of T_c, so that the question arises if a different choice of T_c might affect the fit to Eq. (2). To address this question, we have plotted in Fig. 4 some of the data as $1/\sigma'$ vs T, and compared them with the LD

TABLE I. Parameters obtained from fit to Eq. (3) (see text) using data exceeding 1 K above T_c. The theoretical value of C is 262 $(\Omega\ cm)^{-1}$.

Sample	a ($\mu\Omega$ cm/K)	b ($\mu\Omega$ cm)	C [$(\Omega$ cm$)^{-1}$]	T_0	T_c
A	0.423	5.43	267	87.8	91.5
B	0.647	0.809	283	87.0	90.6
C	0.592	0.850	71	88.8	89.9
D	0.554	16.3	50	88.7	90.4
E	1.46	7.87	69	89.3	93.5

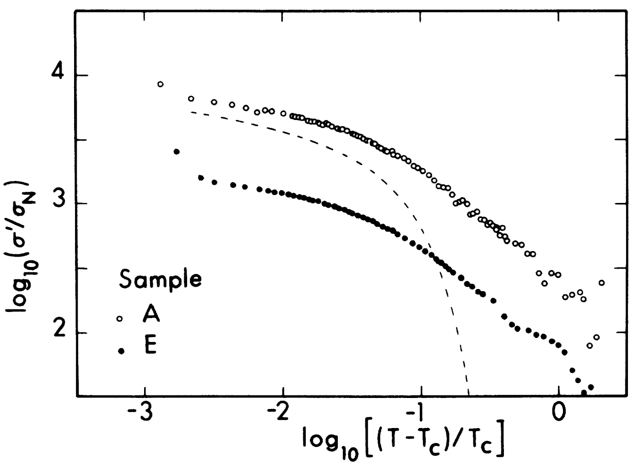

FIG. 3. Plot of the paraconductivity σ' vs reduced temperature ε on log-log scale for samples A and E. The data points are calculated from $\sigma(T) - \sigma_N$ where σ_N is derived from the fit to Eq. (3). An alternate procedure used to determine σ_N by fitting σ to $1/(aT+b)$ in the temperature range 200–300 K generates data for sample A which fall on the broken line.

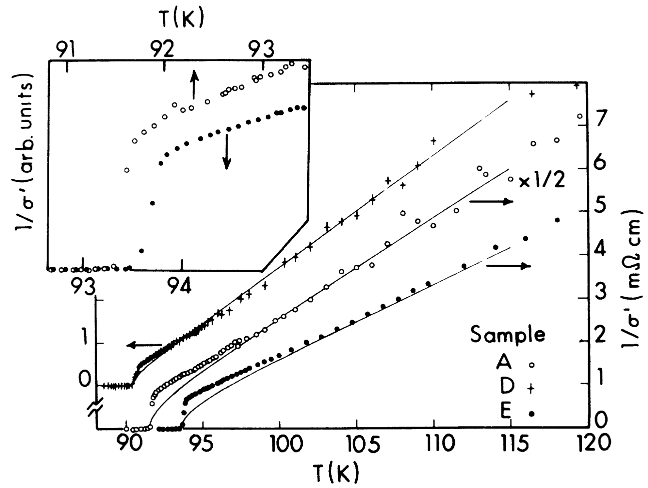

FIG. 4. (Main panel) The comparison of $1/\sigma$ vs T for samples A, D, and E with the best fit (solid lines) using the effective-mass model [Eq. (2)]. The disagreement is particularly serious near T_c for samples A and E. The behavior of $1/\sigma'$ near T_c for samples A and E (inset). Data points are spaced 0.1 K apart near T_c.

form expressed as $C/\{\varepsilon[1+\nu(0)/\varepsilon]^{1/2}\}$. The T_c used for the LD fit is the temperature where $1/\sigma'$ extrapolates to zero in Fig. 4. [The uncertainty in fixing T_c (± 100 mK) makes a negligible difference to the comparison of Eq. (2) with the data.] The two parameters C and $\nu(0)$ are then fixed by fitting the LD curve to the data at large T. The values of $\nu(0)$ thus obtained[17] correspond to $\xi_c(0) = d\sqrt{\nu}(0)/2 \sim 1.0 - 1.7$ Å (comparable to that obtained in Ref. 13). However, the great discrepancy between the measured $1/\sigma'$ and the fit in the interval a few K above T_c invalidates any meaningful interpretation of the data using Eq. (2). We find that the discrepancy is especially pronounced in crystals with sharp transitions ($\Delta T < 0.2$ K). [In samples with broad transitions it is possible that a spread of transitions could lead to a smoother approach of $1/\sigma'$ to zero, in apparent agreement with Eq. (2).]

At high temperatures, the single-crystal data show that the in-plane paraconductivity is predominantly 2D and well described by Eq. (1), with a mean-field temperature T_0 that is 3 to 5 K below the actual observed T_c. As T approaches T_c the coherence length ξ_c increases. In the simplest mean-field theory[11] [Eq. (2)] describing the 2D to 3D crossover, σ' should change slowly from a $1/\varepsilon$ to $1\sqrt{\varepsilon}$ behavior a few K above T_c. What we find instead is that σ' remains close to the 2D behavior until ~ 0.5 K above T_c. Within a narrow interval (<0.5 K) the total resistance is driven to zero, and long-range superconducting order sets in. The jump to zero resistance (inset, Fig. 4) is much more abrupt than described by Eq. (2) (as shown in Fig. 4).

A plausible interpretation of the abrupt jump at T_c is that there might exist a percolative path which first becomes superconducting, thereby shorting out the current. However, we judge this to be highly improbable for the following reasons. If the shorting path is fragile, σ should be highly non-Ohmic near T_c. We failed to detect any non-Ohmicity in the T range ($10^{-3} < \varepsilon < 0.2$) up to current densities of 100 A/cm^2. If the shorting path is wide, then the superconducting fluctuations due to this path should dominate the paraconductivity of the lower T_c medium. This is not apparent in Fig. 4. Finally, the absence of mulitple peaks in the derivative $d\rho_{ab}/dT$ in samples A, D, and E also argues against the existence of large shorting paths.

A more likely interpretation of the striking failure of Eq. (2) is that mean-field (MF) theory is not valid in describing the coupling of fluctuations between adjacent planes very near T_c. The very short ξ_c (1.7 Å$\ll$ unit-cell dimension along **c**) derived from the attempted fits in Fig. 4 already indicates a serious flaw in applying the effective-mass approach: Along **c** the GL wave function Ψ varies much too rapidly on the scale of d to justify an effective-mass expansion. Hence, the large disagreement near T_c is perhaps to be expected. A closely related issue[18] is the width of the critical region defined as the range ε_c where the condensation energy per coherence volume is of the order of thermal energy, i.e., $[H_c^2(\varepsilon_c)/8\pi]$. $\xi_{ab}(\varepsilon_c)^2\xi_c(\varepsilon_c) \sim k_BT_c$. ($H_c$ is the thermodynamic field and ξ_{ab} is the in-plane coherence length.) An interesting possibility is that in the oxide superconductors the critical region is entered *before* the MF crossover to three dimensions occurs, i.e., the critical region is ~ 0.5 K in width or $\varepsilon_c \sim 5\times 10^{-3}$. Thus, in this respect, the oxide superconductors would be closer to superfluid ^{4}He than to conventional superconductors (where $\varepsilon_c \sim 10^{-10}$). A very short ξ_c would be consistent with this scenario. In this case σ' is clearly not expected to follow the MF predictions.

No evidence of the 3D $1/\sqrt{\varepsilon}$ behavior is obtained in the five crystals studied. Moreover, the 2D Maki-Thompson contribution, which would be ~ 20 times larger than the AL term [and vary as $(\ln\varepsilon)/\varepsilon$ at large ε], is insignificant. A recent study[19] on ceramic samples claims that the exponent a (in $\sigma' \sim \varepsilon^{-a}$) *increases* from $\frac{1}{2}$ to 1 (3D to 2D) as ε decreases from 0.1 to 10^{-3}, in sharp disagreement with the data in Fig. 3. We believe this highly unusual behavior is an artifact of the large width of the transition ($\Delta T \sim 1$ K) in the samples used in Ref. 19, and the extreme sensitivity of α to the choice of T_c for $\varepsilon < 0.01$. The arbitrary subtraction procedure used in Ref. 19 to isolate σ' from σ also leads to a sharp increase in α for $\varepsilon > 1.0$, as shown by the broken line in Fig. 3.

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