Evidence for nonuniversal behavior of paraconductivity caused by predominant short-wavelength Gaussian fluctuations in $YBa_2Cu_3O_{6.9}$

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We report on in-plane paraconductivity measurements in thin $YBa_2Cu_3O_{6.9}$ films. Our analysis of the data shows that the temperature dependence of paraconductivity is affected by lattice disorder and deviates at all temperatures from the universal power laws predicted by both scaling and mean-field theories. This gives evidence for the absence of critical fluctuations and for the failure of the Aslamazov-Larkin universal relation between critical exponent and dimensionality of the spectrum of Gaussian fluctuations. We account quantitatively for the data within the experimental error by introducing a short-wavelength cutoff into this spectrum. This implies that three-dimensional short-wavelength Gaussian fluctuations dominate in $YBa_2Cu_3O_{6.9}$ and suggests a rapid attenuation of these fluctuations with decreasing wavelength in short-coherence-length systems as compared to the case of the conventional Ginzburg-Landau theory.

I. INTRODUCTION. FLUCTUATIONS IN CUPRATE SUPERCONDUCTORS: CONTROVERSIAL RESULTS

Thermal fluctuations of the order parameter near the critical temperature T_c are large in cuprate superconductors due to the high T_c and the short coherence length ξ. Fluctuation measurements in cuprates show good reproducibility but the published interpretations remain controversial. For the sake of simplicity we restrict ourselves to the discussion of published results on $YBa_2Cu_3O_{6.9}$ (YBCO). The objective of most studies was the determination of the dimensionality D of the fluctuation spectrum,[1–13] since the layered structure of the cuprates raised the fundamental question of the relationship (if any) between the quasi two dimensionality of the electronic structure and high T_c. In all the above studies, D was extracted from the measurement of critical exponents according to the *universal* predictions of Levanyuk[14] and Aslamazov-Larkin[15] within the framework of the mean-field theory of Ginzburg and Landau. With the exception of two studies,[1,13] the validity of the above predictions was never discussed for the cuprates, despite the fact that these predictions were originally derived for long-coherence-length superconductors in the limit $\xi \gg \tilde{\lambda}$, where $\tilde{\lambda}$ is the short-wavelength cutoff of the fluctuation spectrum. Estimates of the zero-temperature in-plane and out-of-plane coherence lengths are in the range of $\xi_{\parallel,0}=1.2-2.0$ nm and $\xi_{\perp,0}=0.1-0.3$ nm, respectively.[16–18] It follows that the limit $\xi \gg \tilde{\lambda}$ is possibly violated in the whole fluctuation region accessible to experiment, since $\tilde{\lambda}$ can be much larger than the interatomic distance.[14] The disagreement in the literature concerns not only the dimensionality, but also the number of components of the order parameter[19–20] and the possible relevance of critical fluctuations.[20–23,9,12]

Here we attempt to clarify the above controversy by carefully analyzing a large number of in-plane paraconductivity data on epitaxial, *c*-oriented YBCO films. First, we show that one source of disagreement is the variety of nonequivalent methods of data analysis. In particular, the critical exponent of paraconductivity α, where $\delta\sigma \sim t^{-\alpha}$ and $\delta\sigma$ is the paraconductivity, is usually determined on the basis of logarithmic plots, since $\alpha = -\log\delta\sigma/\log t$. The disadvantage of this method is that it requires the determination of T_c, while *different* methods of determining T_c are reported in the literature. In the analysis of our data we verify the universal predictions of mean-field and scaling theories by analyzing the raw data and by avoiding the use of logarithmic plots and fitting procedures.

Our analysis indicates that a second source of controversy is the arbitrary assumption that universal predictions are valid for YBCO in some temperature range. We show that the experiments contradict this assumption, independent of the method of data analysis. We explain our data quantitatively within the experimental error by using a generalized Aslamazov-Larkin result[24] which does not require the approximation $\xi \gg \tilde{\lambda}$. We show that the deviations of the experimental data from the universal predictions of mean-field and scaling theories give evidence for predominant short-wavelength Gaussian fluctuations in the whole fluctuation region accessible to experiment. This confirms the three-dimensional localized character of the superconducting state of YBCO and implies that a modification of the conventional fluctuation spectrum of the Ginzburg-Landau theory is necessary for short-coherence-length systems.

II. EXPERIMENTAL MEASUREMENTS OF PARACONDUCTIVITY

To verify the variability of the paraconductivity term, we have measured a dozen YBCO films prepared under nearly the same conditions with zero-resistance critical temperatures, T_{c0}'s, ranging from 88 to 91 K. Details on film preparation are reported elsewhere.[26] Resistance data were recorded with standard ac technique at 77.7

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Hz. The resistivity was obtained from the resistance using the van der Pauw method.[27] The error bars of the resistivity data are typically $\pm 10\%$, being determined by the error bars in the values of film thickness. The temperature was controlled to within an accuracy of ± 0.02 K and with a precision of 0.1 K by carrying out the measurement in the dynamical regime. Each measurement was carried out twice by cooling down and heating up the sample. Cooling and heating rates were ≈ 10 and ≈ 1 mK/s above and below the fluctuation region, respectively. These rates turned out to be sufficiently low to avoid any thermal hysteresis.

The excess $\delta\sigma$ of conductivity (paraconductivity) due to the thermal fluctuations $\delta\eta$ of the superconducting order parameter η produces a characteristic rounding of the transition (see Fig. 1). Due to the marked linearity of the temperature dependence of the resistivity at high temperatures, this rounding is clearly distinguishable. Under these conditions, it is justified to determine $\delta\sigma$, as is commonly done, to be $\delta\sigma = 1/\rho - 1/\rho_L$, where ρ is the experimental resistivity and ρ_L is the linear extrapolation of ρ above the fluctuation region. This procedure is reliable because $\delta\sigma$ turns out to be stable over small variations of ρ_L. We have verified this stability by extrapolating ρ in different temperature intervals ranging from 120–180 to 200–300 K. We have used not only linear, but also quadratic and cubic polynomials. $\delta\sigma$ remains unchanged within 10% in the interval $T_{c0}-100$ K. This is the only range of interest of our analysis, since it corresponds to the relevant mean-field and critical regions.[28] We have not measured films with $T_{c0} < 88$ K because these films show a marked downturn in the resistivity at all temperatures and there is no clear distinction between this feature and the rounding of the transition due to the fluctuations.

III. RESULTS

In Fig. 2 the temperature dependence of the paraconductivity of several samples is shown. As is commonly done, the data are plotted as $\delta\sigma^{-1}$ since $\delta\sigma$ diverges at T_c. The main difference between samples is observed in the slope. Larger slopes and larger magnitudes of $\delta\sigma^{-1}$ are found in films with more linear resistivity curves. This is because the rounding of the transition is less pronounced for these curves. We have reported elsewhere[29] that more linear curves are found in films with less lattice disorder. This correlation was already observed in amorphous superconductors[30] and is consistent with the fact that disorder enhances the fluctuations.

In addition to the difference in the slopes, the $\delta\sigma^{-1}$ curves of all samples exhibit the same qualitative temperature dependence: above ≈ 100 K the curves exhibit an upturn; below ≈ 100 K this feature disappears and the temperature dependence becomes linear. Near the transition, at ≈ 2 K above T_{c0}, an abrupt downturn is observed. As in the case of the slope, the variations of the curvature are also sample dependent. In particular, more linear $\delta\sigma^{-1}$ curves are found in films with less linear resistivity curves. In the films with more linear resistivity curves, the upturn of $\delta\sigma^{-1}$ persists at lower temperatures and the downturn near the transition is less pronounced.

The characteristic temperature dependence of $\delta\sigma^{-1}$ reported above appears as a characteristic *s*-shaped curve in $\log\delta\sigma$-$\log t$ plots (see Fig. 3). We emphasize that this shape is independent of the choice of T_c for the determination of t. The same characteristic shape has been reported for YBCO,[3,5,7–9,31,11,13] $Bi_2Sr_2CaCu_2O_{8+\delta}$,[32] $La_{2-x}Sr_xCuO_4$,[9] and several amorphous alloys.[30,33]

In addition for the high-temperature region above ≈ 100 K, the region of the tail of the transition is not considered here either. Such analysis would require the treatment of nonlinear effects, such as the dependence of the paraconductivity on the magnitude of the electric field. These effects have been investigated elsewhere.[34–37]

IV. ANALYSIS OF THE DATA: FAILURE OF UNIVERSAL PREDICTIONS

Following previous reports, we first analyze our paraconductivity data within the conventional frame-

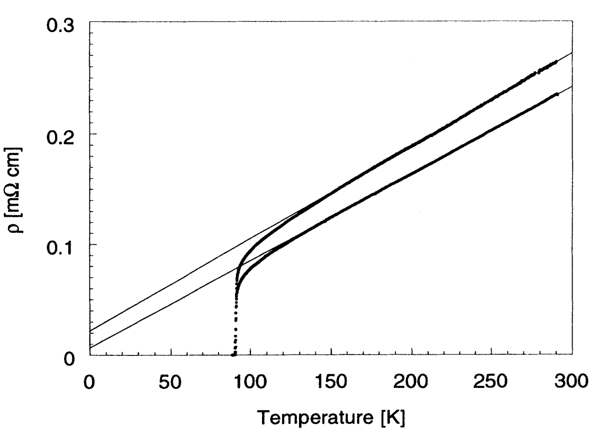

FIG. 1. Examples of the procedure of linear extrapolation used to determine the excess of conductivity (paraconductivity) due to thermal fluctuations. The paraconductivity is visible as a rounding of the transition and is determined by subtracting the experimental curve from the extrapolated one.

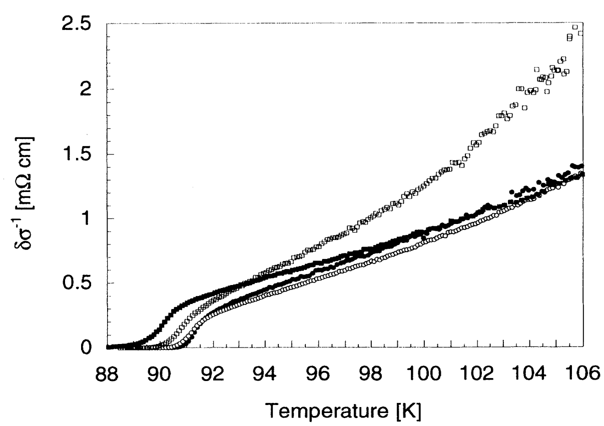

FIG. 2. Experimental behavior of the paraconductivity $\delta\sigma$ in some of our YBCO films. The curves marked with open and full circles correspond to the upper and lower curves of Fig. 1, respectively. The differences in slope arises from differences in the degree of linearity of the temperature dependence of the resistivity, as discussed in the text.

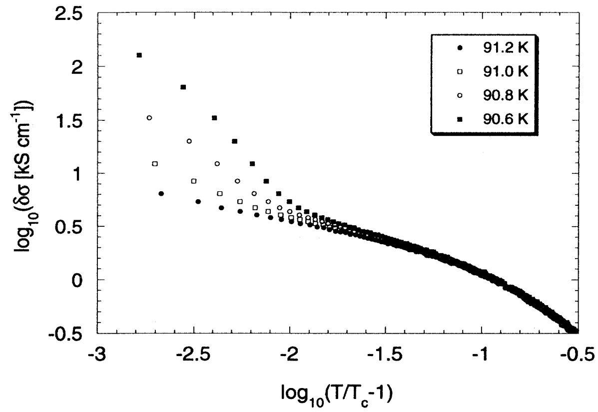

FIG. 3. Temperature dependence of $\delta\sigma$ in our YBCO films on a logarithmic scale for different choices of critical temperature T_c. We note that the slope of the curves, i.e., the critical exponent α is sensitive to slight changes of T_c. However, for any choice of T_c, the temperature dependence of α exhibits the same characteristic s-shaped behavior.

work of mean-field and scaling theories. We shall apply the results of Aslamazov-Larkin,[15] Maki-Thompson,[38] and Lawrence-Doniach[39] in the first case and of Glover[40] and Lobb[21] in the second case. With the exception of the Maki-Thompson result, all the above results predict a simple universal behavior of α (see Table I). We already mentioned that α is usually determined as $\alpha \equiv -\log\delta\sigma/\log t$. We shall not adopt this method since it requires the determination of the critical temperature T_c. This is a delicate point because we are treating the quantity $\delta\sigma$ which diverges at the transition and the character of this divergence (in particular the critical exponent) is affected by slight changes of T_c (see Refs. 30, 9, 13, and Fig. 3), and every group has its own method for determining T_c: (i) $T_c \equiv T_{c0}$;[10] (ii) $T_c \equiv$ midpoint of the transition;[1,3] (iii) $T_c \equiv$ interaction of the tangent to the transition curve with the temperature axis;[11,13] (iv) $T_c \equiv$ intersection of the linear extrapolation of $\delta\sigma^{-2}$ with the temperature axis, by assuming valid in some temperature range the Aslamazov-Larkin prediction in three dimensions [see Eq. (1b)] $\alpha = 1/2$.[2,41]

Such a variety of different procedures partly explains the aforementioned controversy in the literature on the value of α and on the dimensionality D of the fluctuations. We note that none of the above procedures (i)–(iv) is reliable. In particular, the T_c obtained with methods (i)–(iii) depends on the features of the resistivity curve in the tail or in the middle of the transition. We emphasize that these sections of the curve are, in general, sample dependent. Method (iv) *a priori* assumes that, in some temperature range, the experimental value of α follows the predictions of Aslamazov-Larkin in three dimensions, whereas this assumption is not justified in the general case.

TABLE I. Critical exponent of paraconductivity predicted by mean-field (m) and scaling theories (s). Except for the Maki-Thompson result, all the results predict universal values for the critical exponent.

Theory	Critical exponent α
Aslamazov-Larkin (m) (Ref. 15)	$2-D/2$
Maki-Thompson (m) (Ref. 38)	Not defined
Lawrence-Doniach (m) (Ref. 39)	$1\rightarrow 1/2$
Glover (s) (Ref. 40)	$2/3$
Glover-Lobb (s) (Ref. 21)	$2/3\rightarrow 1/3$

The determination of α by using logarithmic plots has generated a great deal of controversy not only because of the uncertainty in determining T_c, but also because for any choice of T_c, the characteristic s-shaped behavior of $\log\delta\sigma$-$\log t$ plots is rather complex (see Fig. 3). Hence α depends on temperature and its determination is arbitrary, as pointed out by Ausloos, Klippe, and Laurent.[42]

We conclude that the verification of the predictions of Table I based on logarithmic plots is not reliable. This is the reason why, in the following sections, we carry out this verification without determining T_c. For each prediction of the type $\delta\sigma \sim t^{-\alpha}$, we plot $\delta\sigma^{-1/\alpha}$ as a function of temperature and verify whether the temperature dependence is linear. This enables the direct verification of each single prediction, thus avoiding unnecessary intermediate steps in the analysis of the data.

A. Verification of the predictions of scaling theory

According to Table I, we plot the experimental data as $\delta\sigma^{-3/2}$ and as $\delta\sigma^{-3}$ [see Figs. 4(a) and 4(b)]. In both cases a nonlinear behavior is observed. In all curves of Fig. 4(a) and in some of Fig. 4(b) the sudden downturn observed in $\delta\sigma^{-1}$ plots is still visible and an upward curvature appears at higher temperatures. In the other curves of Fig. 4(b) a significant upturn is visible at any temperature. Hence the predictions of scaling theory do not account for our experimental data. We recall that the characteristic s-shaped temperature dependence of $\delta\sigma$ leading to this conclusion has been also observed in amorphous superconductors and no evidence for critical fluctuations has been ever reported in those superconductors. This supports our conclusion that critical fluctuations are not observed in YBCO in the range of temperatures accessible to our experiment $T \gtrsim T_{c0}+0.5$ K or $t \gtrsim 5\times 10^{-3}$. We conclude that mean-field fluctuations dominate in this range of temperatures. At lower temperatures the tail of the transition appears. Hence, we can not extend our analysis to these temperatures and $t \approx 5\times 10^{-3}$ is our estimated upper limit for the Ginzburg temperature t_G, which is the lower limit of applicability of the Ginzburg-Landau theory.[43] Our estimate is in agreement with independent estimates based on measurements of the jump of the specific heat ΔC and of ξ. Earlier measurements were affected by large uncertainties. This has generated controversial estimations of t_G. Recent and more reliable results obtained in single crystals and in epitaxial films have reduced the uncertainty as follows: $\Delta C = 5$–6 J K^{-1} mole^{-1},[44] $\xi_{\parallel,0} = 1.2$–2.0 nm, $\xi_{\perp,0} = 0.1$–0.3 nm.[16–18] This corresponds to $t_G = 3.6\times 10^{-3}$–3.25×10^{-2}, in agreement with Inderhees *et al.*,[19] Fiory *et al.*,[45] and Loram *et al.*[12]

In our fluctuation data, the condition $\delta\sigma \sim \sigma$ (normal-state conductivity) is fulfilled in the whole fluctuation region. We emphasize that, contrary to what is commonly stated, this condition is compatible with the absence of

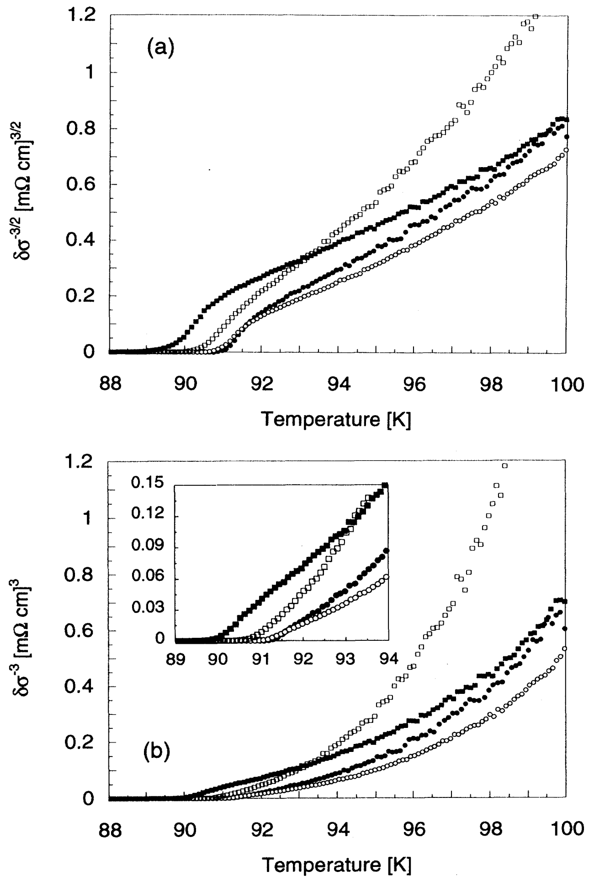

FIG. 4. The same data of Fig. 2 are plotted as $\delta\sigma^{-3/2}$ (a) and as $\delta\sigma^{-3}$ (b) to examine the validity of the predictions of scaling theory (see Table I).

critical fluctuations. This is because the mean-field approximation $\sqrt{\langle|\delta\eta|^2\rangle} \ll \sqrt{\langle|\eta|^2\rangle}$ does *not* require that the fluctuation correction of a given physical quantity is small in comparison with its unperturbed value and the latter has in general no relation with $\langle|\eta|^2\rangle$, as is indeed the case of the normal-state conductivity σ. Thus the condition $\delta\sigma \sim \sigma$ is *not* related to the crossover to the critical regime. The only reliable criterion to estimate the crossover temperature is the Ginzburg criterion $t = t_G$.[43]

B. Predictions of mean-field theory: Aslamazov-Larkin term

We first verify the mean-field predictions of Aslamazov and Larkin:[15]

$$\delta\sigma \sim t^{D/2-2} . \tag{1a}$$

The proportionality factor is

$$\begin{cases} \dfrac{\pi e^2}{16 h \xi_0}, & D=3 \\ \dfrac{\pi e^2}{8hd}, & D=2 \\ \dfrac{\pi^2 e^2 \xi_0}{8hS}, & D=1 , \end{cases} \tag{1b}$$

where $d \ll \xi$ and $S \ll \xi^2$ are the thickness of the film and the cross-sectional area of the whisker in the two- and three-dimensional cases, respectively.

The validity of the above predictions for $D=2$, 3, and 1 would be shown by a linear temperature dependence of $\delta\sigma^{-1}$, $\delta\sigma^{-2}$, and $\delta\sigma^{-2/3}$, respectively [see Figs. 2, 5(a), and 5(b)].

(i) $D=2$. As noted before, in the section of the $\delta\sigma^{-1}$ curves preceding the downturn near the transition, a rather linear behavior is observed below ≈ 100 K (see Fig. 2). This behavior does not correspond to the conventional temperature dependence of the fluctuations in two dimensions predicted by Aslamazov-Larkin. If this was the case, the extrapolated value of T_c obtained from Eqs. 1(a) and 1(b) would be several degrees lower than T_{c0}, which has no physical sense. A second linear section of the $\delta\sigma^{-1}$ curves could be the region between the downturn of the curves and T_{c0}. If this was the case, the presence of the downturn and of the linear part at higher temperatures mentioned before would imply the existence of an intermediate high-dimensional regime between two-dimensional regimes. Such a double dimensional crossover is indeed predicted by Varlamov and Yu[46] for the cuprates. The argument is as follows. In the cuprates, the Lawrence-Doniach crossover from three to

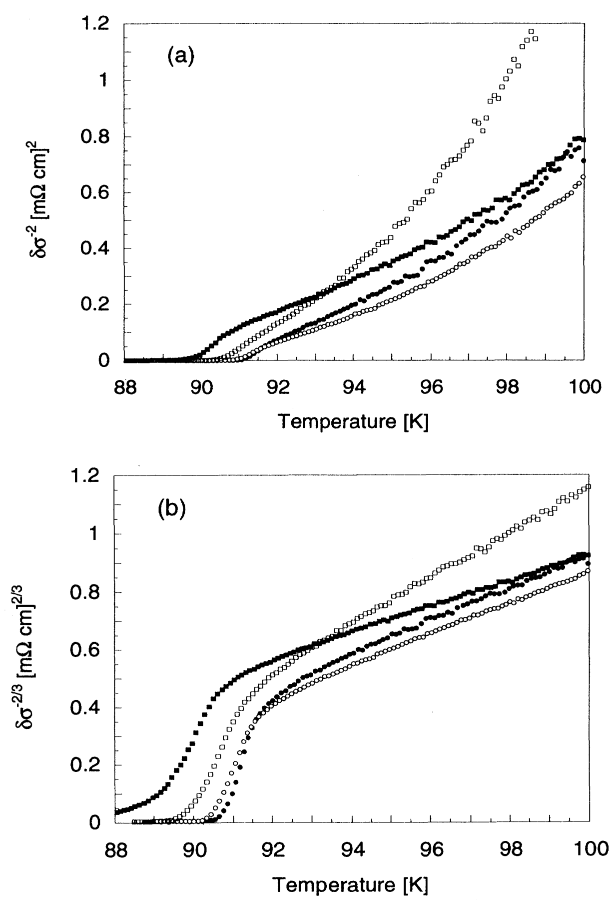

FIG. 5. The same as in Fig. 4 for the predictions of Aslamazov-Larkin in three (a) and one (b) dimensions.

two dimensions [see Ref. 39, Eq. (3) and Table I] should be followed by a second and opposite crossover because the out-of-plane lattice coherence is reduced by stacking faults and other defects which are intrinsic to the layered structure. Thus, sufficiently close to the transition, the out-of-plane coherence length exceeds the thickness of lattice coherence and the system behaves as if it was two dimensional. However, the prediction of Varlamov and Yu does not account quantitatively for the experimental behavior of our films. As already mentioned, the curvature of the $\delta\sigma^{-1}$ curves is sample dependent and does not correspond to the predicted crossover $1\rightarrow 1/2\rightarrow 1$ of α. Even by assuming the existence of this crossover, the estimated value of the thickness of lattice coherence would be only $d=3-7$ nm. On the basis of transmission electron micrographs, we have no evidence for such a short lattice coherence length in our films. Moreover, there is no reason to explain why the same reduced temperature $\log_{10}t\approx -2\pm 0.1$ for the hypothetical $1/2\rightarrow 1$ crossover (see Refs. 3, 5, 7–9, 31, 11, 13, and Fig. 3) is found in YBCO samples of different kinds (single crystals, sintered bulk samples and thin films) prepared with different techniques.

(ii) $D=3$. The agreement of the linear behavior predicted by Aslamazov-Larkin with the experimental $\delta\sigma^{-2}$ curves of Fig. 5(a) is even less convincing in comparison with the previous case: the linear section of the curves is very narrow (≈ 2 K) and we exclude the possibility that it is due to three-dimensional fluctuations. It corresponds rather to the inflexion point between the section of the curves at high temperatures with upward curvature and the section close to the transition and downward curvature. An additional argument supports our conclusion: the out-of-plane coherence length $\xi_{\perp,0}$ estimated from the theoretical curve would be 0.5–1 nm, i.e., significantly larger than the estimates reported so far based on different techniques.[16–18]

(iii) $D=1$. In $\delta\sigma^{-2/3}$ curves [see Fig. 5(b)] no indication of linear behavior is found: a marked downward curvature is present in the whole temperature range below ≈ 100 K.

C. Predictions of mean-field theory: Maki-Thompson term

We recall that the so-called Maki-Thompson (or "indirect") contribution to the conductivity is positive as is the Aslamazov-Larkin contribution and takes into account the interactions of the normal carriers with fluctuating Cooper pairs. The result is conveniently expressed by introducing the reduced temperature $\varepsilon\equiv 8(T-T_c)/\pi$ and the pair-breaking parameter $\delta\equiv T_c^*-T_c$. T_c^* represents the value of T_c in the absence of pair breaking. It is obtained:[38]

$$\delta\sigma_{(\mathrm{MT})}^{(3D)}=\frac{\pi e^2}{4h\xi_0}t^{-1/2}\frac{1}{1+\sqrt{\delta/\varepsilon}}\ , \tag{2a}$$

$$\delta\sigma_{(\mathrm{MT})}^{(2D)}=\frac{\pi e^2}{4hd}t^{-1}\frac{\varepsilon}{\varepsilon-\delta}\ln\left[\frac{\varepsilon}{\delta}\right]\ , \tag{2b}$$

$$\delta\sigma_{(\mathrm{MT})}^{(1D)}=\frac{\pi^2 e^2\xi_0}{2hS}t^{-3/2}\frac{\sqrt{\varepsilon/\delta}}{1+\sqrt{\delta/\varepsilon}}\ . \tag{2c}$$

The verification of the above predictions is less straightforward in comparison with the case of the Aslamazov-Larkin predictions because α depends on the pair-breaking parameter δ and not only on the dimensionality. The importance of the Maki-Thompson contribution increases with temperature and/or with decreasing values of δ. It gives a larger contribution in comparison with the Aslamazov-Larkin term, since the prefactors of Eqs. 2(a)–2(c) are four times larger in three and one dimensions and two times larger in two dimensions. It follows that α is expected to progressively decrease with respect to the Aslamazov-Larkin predictions as the Maki-Thompson term becomes important. In $\delta\sigma^{-1}$ curves this would correspond to an increasing downward curvature as temperature increases.[36] Since it is experimentally observed to be the opposite, we exclude the relevance of the Maki-Thompson contribution in our case. As an additional argument, we note that if we assume the validity of the Maki-Thompson expression in three dimensions (2a), the estimated value of $\xi_{\perp,0}$ would be four times larger in comparison with our previous estimate based on the Aslamazov-Larkin formula. Depending on the sample, we would obtain $\xi_{\perp,0}=2-4$ nm which is much larger than any other estimate reported in the literature and would even contradict the experimental evidence for the anisotropicity of the superconducting state of YBCO.

Our conclusion on the absence of the Maki-Thompson contribution in YBCO is in agreement with earlier reports[1,4,9,13] and with the general argument that the Aslamazov-Larkin term dominates under ordinary conditions. As an additional argument in favor of our conclusion, it was pointed out by some authors that pair breaking by disorder and thermal phonons should be large in all cuprates because of the high density of defects[2] and the high transition temperature,[47] respectively. The latter point has also been previously raised for amorphous superconductors.[48,30] Experimental evidence for strong pair breaking in YBCO has indeed been reported by Matsuda, Hirai, and Komiyama.[16] There are reports on YBCO single crystals which support[10] or do not exclude[5] the relevance of the Maki-Thompson contribution. A possible reason for this discrepancy is that in single crystals the lower density of defects in comparison with epitaxial films could significantly reduce the relevance of pair breaking. In all cases, no quantitative agreement is found between the theoretical curves of Maki-Thompson and our experimental curves.

D. Predictions of mean-field theory: Lawrence-Doniach model

Friedmann *et al.*,[5] Gasparov,[49] and Baraduc *et al.*[41] reported on Lawrence-Doniach behavior of the in-plane paraconductivity of YBCO according to the expression[39]

$$\delta\sigma_{\parallel}=\frac{\pi e^2}{8h}\frac{1}{dt}\left[1+\left[\frac{2\xi_{\perp,0}}{d}\right]^2\frac{1}{t}\right]^{-1/2}\ , \tag{3}$$

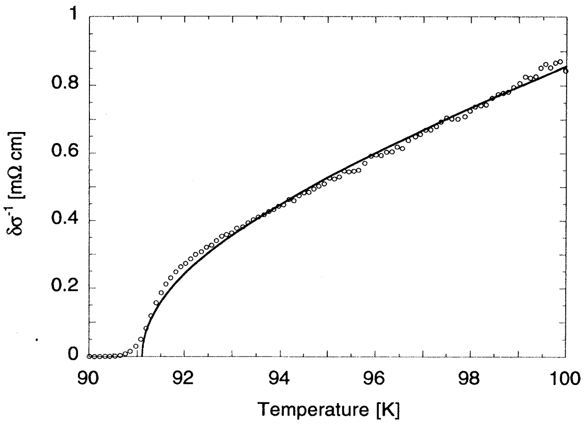

FIG. 6. Example of analysis of the data with the Lawrence-Doniach Eq. (3). The predicted crossover from linear to square-root temperature dependence of $\delta\sigma^{-1}$ is too smooth to account for the rapid downturn of the experimental curve near the transition.

where d is the distance between two adjacent superconducting planes.

In agreement with Hagen, Wang, and Ong,[4] we have found that the above expression accounts only qualitatively for the experimental behavior of our data (see Fig. 6). In particular, the predicted crossover from $\alpha=1$ to $\alpha=1/2$ is too smooth to explain quantitatively the abrupt downturn observed near the transition in the experimental $\delta\sigma^{-1}$ curves. The behavior predicted by Eq. (3) shows a downward curvature in the whole fluctuation region, whereas our experimental curves are linear for some samples while others even exhibit an upward curvature.

E. Summary of the data analysis within conventional theories

Our analysis of in-plane paraconductivity data on several YBCO films indicates that, in the *whole* fluctuation region $0.1 \gtrsim t \gtrsim 5\times10^{-3}$, the experimental temperature dependence of the critical exponent α deviates markedly from the universal predictions of both mean-field and scaling theories. In particular, we have noted that α is sample dependent. This is evident in $\delta\sigma^{-3}$ curves [see Fig. 5(b)] where the curvature changes sign in some temperature range, being positive (negative) in films with more (less) linear temperature dependence of the resistivity. This variability implies that *the critical exponent does not exhibit any universal behavior* in the fluctuation region accessible to the experiment. Since we have observed that the degree of linearity of the resistivity scales with the degree of lattice order,[29] we also conclude that the deviations of the critical exponent from universal predictions are influenced by lattice order.

Since we have found no evidence for critical fluctuations, we have concluded that mean-field fluctuations dominate. We therefore attempt to explain our data within a generalized mean-field approach presented in the next section.

V. THE CUTOFF APPROACH

The universal mean-field predictions considered in the previous section are derived in the limit $\xi \gg \tilde{\lambda}$. As mentioned before, the deviations of these predictions from the experimental behavior discussed above in the case of YBCO are not peculiar to cuprate superconductors. Similar deviations were also observed in the paraconductivity of amorphous superconductors[30,33] and in the fluctuation-induced diamagnetism of Tl-doped Pb.[50] These deviations were ascribed to the expected breakdown of the approximation $\xi \gg \tilde{\lambda}$ at high temperatures and/or in the case of short coherence length. The simplest generalization proposed by Levanyuk[14] and later by Patton, Ambegaokar, and Wilkins[51] consists of the explicit introduction of a short-wavelength cutoff $\tilde{k}=2\pi/\tilde{\lambda}$ in the mean-field fluctuation spectrum. The application of this approach to the Aslamazov-Larkin theory consists of the calculation of the integral[15]

$$\delta\sigma \sim \int_{k\le\tilde{k}} \frac{(\mathbf{ku})^2}{[1+(\xi k)^2]^3}\frac{d^Dk}{(2\pi)^D}\ , \qquad (4)$$

where $\mathbf{u}$ is the unit vector along the electric-field vector. We recall that the conventional Aslamazov-Larkin result [(1a) and (1b)] was originally obtained by extending the integral of Eq. (4) to infinity, which is a valid approximation if $\xi \gg \tilde{\lambda}$.

Analysis of the data within the cutoff approach

The generalized Aslamazov-Larkin expression (4) with cutoff included was first used to account for the deviations of experimental data on amorphous alloys[33] from the predictions of the conventional expression (1a) and (1b). As mentioned in Sec. III, these deviations arise from the characteristic s-shaped temperature dependence of the paraconductivity in logarithmic plots, that was also observed in YBCO (see Fig. 3) and other cuprates. This dependence is in clear contrast to the linear dependence predicted by Eqs. (1a) and (1b); it consists of a downturn at $0.1 \gtrsim t \gtrsim 0.01$ followed by an upturn at lower temperatures. The same cutoff approach was applied more recently to experimental data on YBCO.[1,13] In the high-temperature range $0.1 \gtrsim t \gtrsim 0.01$, corresponding to the downturn to the paraconductivity in Fig. 3, the quantitative agreement between the generalized expression (4) and experimental data was satisfactory for amorphous alloys, while the agreement was only qualitative for YBCO. In the low-temperature range ($t \lesssim 0.01$), corresponding to the upturn of the paraconductivity in Fig. 3, the agreement was neither quantitative nor qualitative in both cases. It was argued that such disagreement at low temperatures is of no importance, since the dependence of the paraconductivity at these temperatures is affected by sample inhomogeneities[30] and is sensitive to the choice of T_c.[13] As mentioned in Sec. III, the same characteristic temperature dependence of the paraconductivity has been systematically found in samples prepared with different techniques of several compounds belonging to two different classes of short-coherence-length superconductors. This characteristic dependence is therefore not accidental and requires a detailed quantitative analysis, which is presented in this section. It is based on a closed form of the Aslamazov-Larkin integral (4) that has been derived previously[24] [see Eqs. (5a) and (5b)], in contrast to the numerical methods adopted in other previous work.[33,1,13] A second advantage of our analysis is that only the angular average of the cutoff $\tilde{k}$ and not its angular dependence enters into the closed form [(5a) and (5b)] of the integral (4). Finally, in previous work it was assumed that cutoff effects are relevant only at high temperatures and that the conventional Aslamazov-Larkin universal behavior is found when sufficiently close to the transition. We note that this is a misleading assumption, since the numerical treatment of the integral (4) hides the possibility that cutoff effects can also be relevant close to the transition, and this is immediately noted by studying the exact result [(5a) and (5b)].[24,52] Indeed, mean-field theory *implicitly* takes into account cutoff effects, as pointed by Levanyuk[14] and in the classic textbook by Landau and Lifshitz.[25] Therefore, it is correct to state that the universal predictions derived from mean-field theory fail if the approximation $\xi \gg \tilde{\lambda}$ is not valid, *independent* of the temperature. These deviations are larger at higher temperatures, since ξ is short; nevertheless they can be significant in the whole fluctuation region. This statement is in agreement with a theoretical result obtained with the renormalization-group method by Ivanchenko and Lisyansky[53] and is confirmed in the case of YBCO by the analysis presented in the previous section which shows that the dimensionality of the fluctuation spectrum is *not* related to the critical exponent, even close to the transition. The conclusions on the validity of the Aslamazov-Larkin result in some temperature ranges reported in previous works are simply due to the arbitrary determination of the critical temperature and the use of logarithmic plots. This explains the controversy in the literature mentioned in the Introduction.

The closed form of the integral (4) that we use for our analysis reads as follows in the case of in-plane paraconductivity of isotropic planes in three and two dimensions:[24]

$$\delta\sigma_{\parallel}^{(3D)} = \frac{e^2}{8h}\frac{1}{\xi_{\perp,0}}\frac{1}{\sqrt{t}}\left[\arctan\tilde{u}_{(1)} - \frac{\tilde{u}_{(2)}}{1+\tilde{u}_{(2)}^2} - \frac{2}{3}\frac{\tilde{u}_{(3)}^3}{(1+\tilde{u}_{(3)}^2)^2}\right], \tag{5a}$$

$$\delta\sigma_{\parallel}^{(2D)} = \frac{\pi e^2}{8hd}\frac{1}{t}\left[1 - \frac{1}{1+\tilde{u}_{(1)}^2} - \frac{\tilde{u}_{(2)}^2}{(1+\tilde{u}_{(2)}^2)^2}\right], \tag{5b}$$

where d is a characteristic thickness of the two-dimensional system and the adimensional quantity $\tilde{u} \equiv \tilde{u}_0/\sqrt{t} \equiv \xi\tilde{k} \equiv \xi_0\tilde{k}/\sqrt{t}$ plays the fundamental role. In Eqs. (5a) and (5b), $\tilde{u}_{(1)}$, $\tilde{u}_{(2)}$, and $\tilde{u}_{(3)}$ are angular averages of $\tilde{u}$ calculated for each one of the three (two) different terms in the squared bracket. In the limit $\tilde{u} \gg 1$, the conventional result [(1a) and (1b)] is obtained. This limit is valid in the whole mean-field region $t \ll 1$ if ξ_0 is long or at temperatures sufficiently close to the transition point if ξ_0 is small. To give a quantitative criterion, one must take into account that thermal energy cannot activate fluctuations with wavelength shorter than the range a of the interatomic forces. Thus one must have $\tilde{\lambda} = 2\pi/\tilde{k} \gg a$ for all cases. Hence, as a rule of thumb, the approximation $\tilde{u} \gg 1$ holds in the whole mean-field region ($t \ll 1$) if $\xi_0 \gtrsim 10$ nm. For example, Johnson and Tsuei[30] and Johnson, Tsuei, and Chaudhari[33] reported the experimental evidence for cutoff effects at $t \gtrsim 0.1$ in amorphous alloys with $\xi_0 \approx 4-7$ nm. Therefore, these effects are expected in a larger temperature interval in the cuprates, since $\xi_{\perp,0} = 0.1-0.3$ nm in these superconductors. If $\tilde{u} \lesssim 1$ the Aslamazov-Larkin contribution is reduced in comparison with the previous case because the large-k section of the fluctuation spectrum does not contribute. The reduction of the paraconductivity for $\tilde{u} \lesssim 1$ is evident. In this case *the temperature dependence of the paraconductivity exhibits no definite power-law behavior, independently of the dimensionality of the system.*

In what follows we shall apply the foregoing qualitative analysis to our experimental data in the quantitative form. The anisotropy of YBCO complicates the analysis, since $\tilde{u}$ becomes angular dependent. Therefore, in the analysis of our data with Eqs. (5a) and (5b), we must leave $\tilde{u}_{(1)}$, $\tilde{u}_{(2)}$, $\tilde{u}_{(3)}$, and $\xi_{\perp,0}$ as free parameters. $\tilde{u}_{(1)}$, $\tilde{u}_{(2)}$, and $\tilde{u}_{(3)}$ would be fixed if the angular dependence of $\tilde{u}$ was known. The value of the mean-field critical temperature T_c was kept fixed within ± 0.2 K. This narrow range is determined by the width of the resistive transitions, which is 1–1.5 K in the films measured, and is further limited by the requirement that, in any case, T_c must be larger than T_{c0}, as stated before.

It turns out that the three-dimensional Eq. (5a) accounts for the experimental data of all films analyzed within the experimental error. The opposite result is obtained by using the two-dimensional Eq. (5b). We conclude that the superconducting fluctuations of our YBCO films are three dimensional. The results of our analysis with Eq. (5a) are reported for four films in Table II.

Some curves taken from Table II and the corresponding experimental data are shown in linear and logarithmic scales in Figs. 7(a) and 7(b). We put into evidence the quantitative agreement of Eq. (5a) with the experimental

TABLE II. Results of the analysis of the in-plane paraconductivity data of four YBCO films with Eq. (5a). It is noted that $\tilde{u}_{(i),0} \sim 0.1$ for all cases. We note that larger values of $\tilde{u}_{(i),0}$ correspond to more disordered films, as discussed at the end of Sec. V A.

Film number	379S1	354S1	37S2	52S2
T_{c0} (K)	90.2	90.5	87.8	89.3
ρ (300 K) ($\mu\Omega$ cm)	275	270	325	270
T_c (K)	90.93	91.13	89.30	90.57
$\xi_{\perp,0}$ (nm)	0.08	0.10	0.11	0.11
$\tilde{u}_{(1),0}$	0.35	0.40	0.57	0.24
$\tilde{u}_{(2),0}$	0.05	0.05	0.06	0.04
$\tilde{u}_{(3),0}$	0.10	0.10	0.13	0.09

data in Fig. 7(a) and the deviation of these data from the universal predictions of Table I in Fig. 7(b). We note that Eq. (5a) accounts for the experimental data only in the interval $T^* \approx 100$ K $\gtrsim T \gtrsim T^{**} \approx T_c + 0.5$ K, as it should if this interval is expected to represent the mean-field region. The deviation of the theoretical curve from the data below T^{**} is ascribed to the beginning of the tail of the transition. However, we cannot exclude that this deviation might be due to the crossover to critical fluctuations. In this case, T^{**} would correspond to the Ginzburg temperature t_G and we would estimate $t_G \approx 5 \times 10^{-3}$, in agreement with independent estimates reported in the literature. From Eq. (5a) we obtain $\xi_{\perp,0} = 0.08-0.11$ nm. Also this value falls in the range of estimates reported in the literature.[16–18]

From Table II, one notes that the cutoff parameters $\tilde{u}_{(1),0}$, $\tilde{u}_{(2),0}$, $\tilde{u}_{(3),0}$ are different one from another. Each one of these parameters has the physical meaning of the angular average of the cutoff function $\tilde{u}$ for each one of the three terms in the bracket of Eq. (5a). This means that the cutoff $\tilde{u}$ is anisotropic in YBCO, as expected. The precise angular distribution of $\tilde{u}$ remains to be investigated; it would reflect the anisotropy of the Fermi velocity and of the order parameter. Therefore, fluctuation measurements could be correlated and compared with electron, optical, and tunneling spectroscopies.

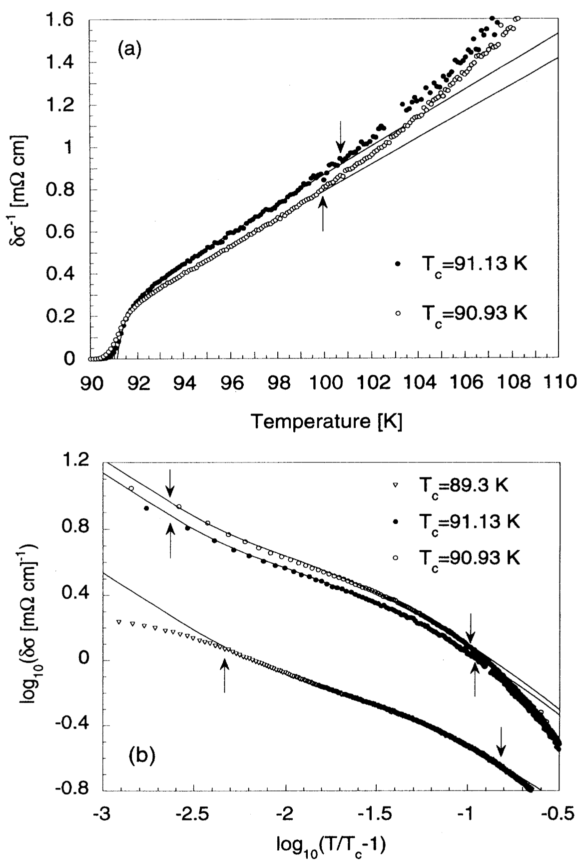

FIG. 7. The paraconductivity data of some films of Table II are plotted in linear (a) and logarithmic (b) scales. The curves obtained from Eq. (5a) are indicated by solid lines and agree within the experimental error bars between ≈ 100 K and $\approx T_c + 0.5$ K (indicated by arrows).

The values of $\tilde{u}_{(1),0}$, $\tilde{u}_{(2),0}$, $\tilde{u}_{(3)0}$, obtained from our analysis are of the order of ~ 0.1. This indicates that the fluctuation spectrum is dominated by components with $k \sim \tilde{k} \sim 1/\xi$ in the whole fluctuation region. This explains why the critical exponent α depends not only on the dimensionality of the spectrum but also on the spectral density of the fluctuations in the region $k \sim \tilde{k}$. We therefore conclude that the local character of the microscopic interactions leading to the superconducting instability manifests itself in the nonuniversality of the critical exponents.

It was previously noted that the temperature dependence of the paraconductivity is, to some extent, sample dependent. We also noted that this is related to the degree of linearity of the resistivity and to lattice disorder.[29] The foregoing quantitative analysis summarized in Table II gives evidence that the degree of lattice order scales as the cutoff parameter $\tilde{u}$. No correlation is found with the value of the out-of-plane coherence length, since the latter does not change appreciably. This implies the existence of a correlation between the degree of lattice disorder and $\tilde{\lambda}$. Further work is still needed on this point. We add that a correlation between deviations from the universal predictions of Aslamazov-Larkin and disorder was also observed in amorphous binary alloys.[30,33]

VI. SUMMARY AND CONCLUDING REMARKS

Our analysis of in-plane paraconductivity data on epitaxial YBCO films provides an explanation of the controversy found in the literature on the dimensionality and on the character of the thermal fluctuations of the conductivity of YBCO near the transition point. The main sources of controversy are the following.

(i) The variety of different methods used in the analysis of the data;

(ii) the complex temperature dependence of the paraconductivity that allows arbitrary conclusions to be made on the value of the critical exponent.

Our analysis indicates that such complex behavior does not follow *at any temperature* the simple universal laws predicted by both scaling and mean-field theories. We explain quantitatively our data by applying a generalized Aslamazov-Larkin result in three dimensions which includes an anisotropic short-wavelength cutoff in the spectrum of Gaussian fluctuations. The result of this analysis gives evidence for the relevance of fluctuations with short wavelength not only at high temperatures, as reported previously, but also very close to the transition point. This reveals the localized character of the superconducting state of YBCO, confirms its three-dimensional nature and explains the sensitivity of the fluctuation spectrum of this cuprate to the lattice disorder at the atomic scale.

Finally, the relevance of superconducting fluctuations with short wavelength implies that the conventional mean-field spectrum of the Ginzburg-Landau theory is no longer a valid approximation for YBCO. This implies that a modification of the effective Hamiltonian and, equivalently, of the microscopic BCS equations is necessary to properly describe the superconducting transition in the cuprates.

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