Critical-temperature inhomogeneities and resistivity rounding in copper oxide superconductors

J. Maza and Félix Vidal

Laboratorio de Física de Materiales, Facultad de Física, Universidad de Santiago, 15700 Santiago, Spain

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By using effective-medium approaches, we obtain the onset of the electrical-resistivity rounding, above the normal-superconducting transition, associated with inhomogeneities of the mean-field critical temperature T_{c0} at scales larger than the superconducting correlation length. These results are compared with available data in single-crystal and single-phase (to within 4%) polycrystalline $YBa_2Cu_3O_{7-\delta}$ samples. This comparison shows that the measured resistivity rounding cannot be explained by these types of local T_{c0} inhomogeneities. Complementarily, our calculations allow us to check some proposals on T_{c0} inhomogeneities associated with local sample strains or oxygen-content variations. The interplay between T_{c0} inhomogeneities and superconducting order-parameter fluctuations (SCOPF) leads to the conclusion that in the mean-field-like region (MFR) above the superconducting transition, the T_{c0} inhomogeneity contribution to the measured resistivity rounding in high-quality (single-phase) cuprate oxide superconductors is negligible. In contrast, our analysis confirms that in the MFR these effects may be explained quantitatively on the grounds of the Lawrence-Doniach theory for SCOPF.

I. INTRODUCTION

In summarizing, in 1978, the effects of fluctuations on the measured electrical resistivity $\rho^M(T)$ above the superconducting transition in metallic films—effects which have been actively studied for the last 10 years—Kosterlitz and Thouless concluded that the onset of the observed rounding of $\rho^M(T)$ "may alternatively be a result of film inhomogeneities."[1] However, no quantitative or qualitative justification of that alternative was presented then. In fact, in conventional low-temperature superconductors (LTSC's), these possible inhomogeneity effects on $\rho^M(T)$ *above* T_{cI}, the temperature at which $\rho^M(T)$ around the transition has its inflexion point (see below), have received relatively little attention, although they are often invoked in many works on the critical behavior around T_{cI}. This is in contrast with the continued attention to the interplay between other superconducting aspects and inhomogeneities in LTSC's, including the behavior of the $\rho^M(T)$ offset (*below* T_{cI}).[2,3]

In high-temperature copper oxide superconductors (HTSC), the dilemma between sample inhomogeneities and thermodynamic fluctuations *above* T_{cI} was stated by Bednorz and Müller in their seminal work,[4] although they formulated the alternative a way opposite to that done by Kosterlitz and Thouless for LTSC's: After indicating that the observed rounding of $\rho^M(T)$ above T_{cI} in La-Ba-Cu-O compounds may be of percolative nature, Bednorz and Müller conclude that "the onset [of the $\rho^M(T)$ drop] can also be due to fluctuations in the superconducting wave functions." Since then, the rounding of $\rho^M(T)$ above T_{cI} in HTSC's has been measured in a wide variety of polycrystals, films, and single-crystal samples, and the results are fairly well explained in terms of fluctuations of the superconducting order-parameter amplitude (SCOPF) in layered superconductors.[5,6] However, as is still the case for LTSC's, very often it is suggested that inhomogeneities may play an important role in $\rho^M(T)$ rounding, mainly in polycrystalline samples. In fact, because of the smallness of the superconducting-correlation-length amplitude $\xi(0)$ of HTSC's, on the order of interatomic distances, all the magnitudes may be sensitive near T_{cI} to different types of inhomogeneities, even when these inhomogeneities exist at small scales. Indeed, as $\xi(0)$ in HTSC's is typically two orders of magnitude smaller than in LTSC's, SCOPF effects will be correspondingly much more important in the former materials.[5-7] It thus seems evident that the interplay between inhomogeneities and SCOPF effects is a topic of considerable interest, the resistivity above T_{cI} being probably one of the best magnitudes to probe such an interplay.

To the best of our knowledge, until now the inhomogeneity influence on $\rho^M(T)$ above T_{cI} in HTSC's only has been quantitatively studied in an important but particular case:[5,6] the spatial inhomogeneities at scales larger than $\xi(T)$ (here with its geometrical meaning) associated with the orientational mismatch between sample domains (for instance, grains, polycrystallites, or untwinned regions) or with the presence of nonsuperconducting domains (for instance, due to compositional inhomogeneities or even sample porosity). In the mean-field-like region (MFR) above T_{cI}, where the analysis was done, the characteristic length of these domains was supposed to be much larger than $\xi(T)$ and also *temperature independent.* These effects lead to an enhanced apparent resistivity (or, equivalently, to a reduced cross-section area of the sample) and, consequently, strongly modify the amplitude of the ρ^M rounding effects, characterized by the excess or paraconductivity $\Delta\sigma$ (see below). In contrast, this type of inhomogeneity does not affect, at least in the MFR, the temperature behavior of $\Delta\sigma$. These temperature-independent inhomogeneities explain very well the $\Delta\sigma$

differences between polycrystalline and single-crystal samples.[5,6]

There exists another important class of inhomogeneity that may also affect the electrical resistivity near the superconducting transition: the compositional or structural inhomogeneities [also at any scale larger than $\xi(0)$] which, in contrast with those alluded to above, may modify spatially the *local* mean-field critical temperature T_{c0}. By local we mean a sample domain with a characteristic dimension larger than the superconducting-correlation-length amplitude in the mean-field region, where our results will be applied, and smaller than any morphological or structural macroscopic dimension as, for instance, the grain size (in polycrystalline samples) or the untwinned domain size. One of the most common and perhaps well-known sources of critical-temperature inhomogeneity is the presence of local strains. In the case when the whole sample is under an external uniform pressure, the dependence of the critical temperature on strain was first observed by Kammerling Onnes and coworkers.[8] The T_{c0} dependence on local strains was later invoked by Testardi as a possible alternative mechanism to fluctuations for explaining the observed rounding of $\rho^M(T)$ in LTSC films.[9] As noted before, HTSC's should exhibit enhanced sensitivity to localized inhomogeneities because of their short coherence lengths. In this regard, it has been recently proposed, for instance, that when dealing with local strains modifying the Cu-O_2 interplane spacing, such as lattice dislocations, the local T_{c0} enhancement can be of the order of T_{c0} itself both in Y- and La-based compounds.[10] Another possible source for a spatially varying T_{c0} is stoichiometric inhomogeneity. For instance, since the oxygen-vacancy content has an effect upon T_{c0},[11] variations in the oxygen-vacancy ordering may lead, as suggested by different authors,[12] to an inhomogeneity in T_{c0}.

In this paper we will use the mean-field approaches of the effective-medium theories (EMT's) to determine the onset of the rounding of the sample average resistivity associated with inhomogeneities of the critical temperature in HTSC's. These results will be confronted with available experimental data on the resistivity rounding in either single-crystal or polycrystalline $YBa_2Cu_3O_{7-\delta}$ samples in order to check (i) if *any* Gaussian T_{c0} inhomogeneity *alone* may explain the observed rounding of $\rho^M(T)$, (ii) if the proposed T_{c0} inhomogeneities, associated with local sample strains or local oxygen content, are compatible with the measured $\rho^M(T)$ rounding, and (iii) the interplay between SCOPF (an intrinsic effect always present) and T_{c0} inhomogeneities (a nonintrinsic effect) at scales larger than $\xi(T)$, and their relative contribution to the measured paraconductivity.[13]

II. RESISTIVITY ROUNDING ASSOCIATED WITH A T_{c0} GAUSSIAN DISTRIBUTION

In this section, we will calculate the rounding of the effective (sample average) resistivity $\rho^e(T)$ associated with the presence of spatial inhomogeneities of the normal-superconducting transition temperature. These inhomogeneities may be characterized through the *local* mean-field-like critical temperature T_{c0}. As noted in the Introduction, by local we understand here fixed-volume regions of the sample with characteristic dimensions larger than $\xi(T)$, but smaller than the typical sample domains (grains, twinnings, etc.). T_{c0} may be defined through the *local* resistivity $\rho(T)$ by

$$\rho(T_{c0})=0 \ , \tag{1}$$

in the *absence of fluctuation effects.* Note that even in the case of homogeneous samples (the same T_{c0}), we do not have a direct experimental access to T_{c0},[5] but its use facilitates the formulation of the interplay between inhomogeneities and fluctuations effects.

The main hypothesis of our mean-field approach is to assume a spatial Gaussian distribution of T_{c0}, characterized by the mean value of the critical temperature $\overline{T}_{c0}$ and by the standard deviation ΔT_{c0}: At a sample temperature T around $\overline{T}_{c0}$, there will be a volume fraction $P(T)$ of the material which has become a superconductor (the corresponding local T_{c0} is above T), given by

$$P(T)=\frac{1}{2}\left[1\mp\operatorname{erf}\left[\frac{|T-\overline{T}_{c0}|}{\Delta T_{c0}}\right]\right] . \tag{2}$$

In this equation, erf is the error function, and the minus (plus) sign is for $T>\overline{T}_{c0}$ ($T<\overline{T}_{c0}$). Note that $P(\overline{T}_{c0})=\frac{1}{2}$; i.e., at $\overline{T}_{c0}$ half of the sample has become a superconductor.

At this point it will be useful to relate $\overline{T}_{c0}$, a nondirectly measurable temperature, to some accessible characteristic temperature of the $\rho^M(T)$ behavior. As noted in the Introduction, we may use T_{cI}, the "geometrical" temperature where $\rho^M(T)$ around the transition has its inflexion point, i.e., is defined by[5]

$$\frac{d^2\rho^M(T_{cI})}{dT^2}=0 \ . \tag{3}$$

To relate T_{cI} and $\overline{T}_{c0}$, we must realize that the main drop in $\rho^M(T)$ will occur when there exists a superconducting percolative path through the sample. For a three-dimensional (3D) continuum system, this percolation threshold corresponds to a volume, here superconducting, fraction close to 15%.[14] We can then introduce the percolative critical temperature T_{cp} by $P(T_{cp})=0.15$. The important point is that since $T_{cI}\simeq T_{cp}$, we get, from Eq. (2),

$$0.15\simeq\frac{1}{2}\left[1-\operatorname{erf}\left[\frac{|T_{cI}-\overline{T}_{c0}|}{\Delta T_{c0}}\right]\right] , \tag{4}$$

or, equivalently,

$$T_{cI}-\overline{T}_{c0}\simeq 0.6\,\Delta T_{c0} \ . \tag{5}$$

Note that if T_{c0} inhomogeneities are neglected ($\Delta T_{c0}\simeq 0$), we obtain $T_{cI}\simeq T_{c0}$, as first proposed in Ref. 5. Indeed, this conclusion must be seen as an approximation, since T_{c0} is never experimentally accessible directly. Moreover, we have checked that for any T_{c0} inside $T_{cI}\pm\Delta T_{cI}$, the main conclusions of this paper remain the same. Here ΔT_{cI}, the upper half-width of the resistive transition, is defined by $d\rho/dT(T_{cI}+\Delta T_{cI})=\frac{1}{2}d\rho/dT(T_{cI})$. Note also that both T_{c0} and T_{cI} may strongly differ from T_c, the temperature at which resistivity becomes nonmeasurable, i.e., $\rho^M(T_c)\simeq 0$. This is so because, whereas T_{cI} and T_{c0} concern individual grains, twin domains, etc., T_c concerns the overall sample and, therefore, may be highly sensitive to intergrain or interdomain links.

Equation (5), which imposes a constraint between $\overline{T}_{c0}$ and ΔT_{c0}, can be used to make some very useful order-of-magnitude estimates of the possible T_{c0} enhancements. For instance, assuming $\overline{T}_{c0}\simeq 90$ K and $\Delta T_{c0}\approx\overline{T}_{c0}$, as proposed in Refs. 10 and 12 for Y-based compounds, Eq. (5) yields $T_{cI}\approx 150$ K. This is obviously against experimental evidence. Assuming again $\overline{T}_{c0}\simeq\Delta T_{c0}$ and imposing $T_{cI}=90$ K for Y-based compounds, we obtain $\overline{T}_{c0}\simeq 55$ K. No bulk measurements (such as heat capacity or magnetic susceptibility) have ever shown such low bulk critical temperatures with respect to the resistive ones for $YBa_2Cu_3O_{7-\delta}$ compounds. These qualitative estimates suggest that on the grounds of our plausible assumptions, the local T_{c0} enhancements induced by strains or variation in composition are much weaker than has been put forward. These estimates do not rule out the possibility of T_{c0} inhomogeneities playing an important role on $\rho^M(T)$ above T_{cI}. To check this possibility quantitatively, we must first obtain the sample average resistivity $\rho^e(T)$ from the local T_{c0} distribution and a given profile for the local resistivity $\rho(T)$ and then compare it with $\rho^M(T)$. In Secs. II A and II B, we are going to analyze two different cases: the presence or not, simultaneously with the T_{c0} inhomogeneities, of an intrinsic ρ-rounding effect, such as that associated with SCOPF's.

A. Resistivity rounding due to T_{c0} inhomogeneities alone

If the only rounding mechanism is a T_{c0} inhomogeneity, then the *local* resistivity will only take the values $\rho=0$ [for a volume fraction $P(T)$] or $\rho=\rho_B$ [for a volume fraction $1-P(T)$], where ρ_B is the normal-state resistivity. The effective resistivity of the sample will be calculated using the mean-field approaches of the effective-medium theories (EMT's). Their use requires $P(T)$ in Eq. (2) to be far from the percolation threshold. As a representative EMT, we shall use the symmetrical Bruggeman's model,[15] which in our case yields

$$\rho^e=\rho_B(T)[1-3P(T)] \ . \tag{6}$$

It is worth remarking that provided $\rho^e\gtrsim 0.6\rho_B$, the differences in $\rho^e(T)$ given by other EMT's, like the Claussius-Mossotti model,[15] are only a few percent. In fact, the above constraint on the resistivity values will be taken here as a practical criterion for the low-temperature limit of the applicability of the above model [Eq. (6)]. Note again that Eqs. (2) and (6) contain two main parameters, namely, $\overline{T}_{c0}$ and ΔT_{c0}. Both are, in principle, unknown, but must, however, be correlated by Eq. (5). The possibility of a T_{c0} spatial inhomogeneity explaining by itself the resistivity behavior in the MFR amounts to checking whether Eqs. (2) and (6) fit the measured resistivity with $\overline{T}_{c0}$ and ΔT_{c0} as free parameters but with the constraint of Eq. (5). This comparison is done in Sec. III.

B. Resistivity rounding due to the simultaneous presence of T_{c0} inhomogeneities and SCOPF

We now deal with the simultaneous presence of an intrinsic rounding effect, i.e., thermodynamic fluctuations of the superconducting order-parameter amplitude (SCOPF), and a nonintrinsic effect, i.e., a spatial variation of T_{c0}. Note here that the interest of this scenario is not only due to its implications on the $\rho^M(T)$ rounding above T_{cI} in HTSC's, but also because it concerns the general topic of the interplay between intrinsic and nonintrinsic rounding effects near critical phenomena.[16] Since the T_{c0} inhomogeneities studied here act at scales larger than the correlation length, we will assume that they do not change the nature of SCOPF's themselves. (A different case is, for instance, two-media materials in which the superconducting medium is near and above the percolation threshold, and where the structure of SCOPF's with wave vectors larger than the percolation length is modified.[17]) As our approach will be applied to copper oxide superconductors, which are layered materials, we introduce the SCOPF through the Lawrence-Doniach (LD) approach,[18] which we have recently shown to be very well adapted to these materials.[5,6] Introducing the excess conductivity $\Delta\sigma$ by

$$\sigma=\sigma_B+\Delta\sigma \ , \tag{7}$$

where σ_B is the background or noncritical part of the conductivity ($\sigma_B=1/\rho_B$), LD theory gives, for the fluctuation-induced excess conductivity in the CuO_2 layers (*ab* planes),[18]

$$\Delta\sigma_F=\frac{A_{\rm LD}}{\epsilon}\left[1+\frac{B_{\rm LD}}{\epsilon}\right]^{-1/2} \ . \tag{8}$$

Here $\epsilon\equiv(T-T_{c0})/T_{c0}$, $B_{\rm LD}\equiv[2\xi_c(0)/d_e]^2$, d_e is the *effective* distance between adjacent *ab* superconducting layers, and $\xi_c(0)$ is the amplitude of the superconducting correlation length in the *c* direction. In the original LD theory, $A_{\rm LD}\equiv e^2/16\hbar d_e$, where e is the electron charge and $\hbar$ is the reduced Planck's constant. In more recent versions of LD theory, the amplitude $A_{\rm LD}$ may depend not only on an effective interlayer distance, but also on the interplane coupling,[19,20] or even on the number of components, n, of the order parameter.[21] For instance, in the version of Ref. 21, $A_{\rm LD}\equiv(e^2/16\hbar d_e)rn$, where r is a factor associated with pair-breaking effects, which equals 1 for *s*-wave pairing. It is worth remarking that in this approach, for $n=2$ the amplitude $A_{\rm LD}$ is twice the original LD value. Let us also remember here that our previous analysis of the paraconductivity in HTSC's strongly suggests that one other possible *intrinsic* rounding effect on $\rho^M(T)$, that associated with the scattering of normal excitations by SCOPF's, is negligible.[6] This is also found in the theoretical treatment of Ref. 21. Thus we will use the LD SCOPF effects as the only intrinsic $\rho^M(T)$ rounding.

Because of the simultaneous presence of intrinsic and nonintrinsic rounding effects, there will be, at a given temperature, a continuum of conductivity values. In order to treat quantitatively this situation, we need a generalization of Eq. (6) which is valid for a medium having only two possible values of electrical conductivity, $\rho=0$ and ρ_B. For that purpose we shall use the generalized Bruggeman's EMT formula[15]

$$\int \frac{\sigma-\sigma^e}{\sigma-2\sigma^e} Q(\sigma,T) d\sigma = 0 , \tag{9}$$

where σ^e is the effective conductivity ($\sigma^e=1/\rho^e$) and $Q(\sigma,T)$ is the local conductivity distribution; i.e., $Q(\sigma,T)d\sigma$ is the volume fraction of the sample having an electrical conductivity between σ and $\sigma+d\sigma$ at a sample temperature T. Since we have assumed a Gaussian distribution for T_{c0}, we simply get, for the conductivity distribution,

$$Q(\sigma,T)=\frac{2}{\sqrt{\pi}\Delta T_{c0}} \exp\left[-\left[\frac{T_{c0}(\sigma,T)-\bar{T}_{c0}}{\Delta T_{c0}}\right]^2\right] , \tag{10}$$

where $T_{c0}(\sigma,T)$ is now the relationship between conductivity and critical temperature as given by the fluctuation mechanism, i.e., Eqs. (7) and (8). For computational purposes it is better to recast Eq. (9) into the equivalent iterative form

$$\sigma^e = \int \sigma Q(\sigma) d\sigma + \int \frac{(\sigma-\sigma^e)^2}{2\sigma^e-\sigma} Q(\sigma) d\sigma . \tag{11}$$

It is worth noting that in first order in $(\sigma-\sigma^e)/\sigma^e$, the effective conductivity is simply, as one would expect, the volume-weighted average of the local conductivity. In order to carry out the integrals in Eq. (11), we need at any sample temperature, as singled out in Eq. (10), the local critical temperature for a given local conductivity. Since the fluctuation mechanism [Eqs. (7) and (8)] gives directly the conductivity for a given critical temperature, the above integrals are worked out more easily by summing up in T_{c0} instead of σ. Thus, in particular, Eq. (9) becomes

$$\int \frac{\sigma(T_{c0},T)-\sigma^e}{\sigma(T_{c0},T)-2\sigma^e} \frac{2}{\sqrt{\pi}\Delta T_{c0}} \times \exp\left[-\frac{(T_{c0}-\bar{T}_{c0})^2}{\Delta T_{c0}^2}\right] dT_{c0} = 0 , \tag{12}$$

where $\sigma(T_{c0},T)$ is the conductivity as directly given by Eqs. (7) and (8).

In sum, we have obtained the proper expression for the effective electrical conductivity, namely, Eq. (12), which contains in the MFR both the intrinsic rounding due to SCOPF's and that due to a Gaussian distribution of local T_{c0} values. This formula is used in the next section for estimating the transition-temperature inhomogeneities in real samples from resistivity data.

III. COMPARISON WITH THE EXPERIMENTAL DATA IN THE MEAN-FIELD REGION

In order to compare the expressions obtained above with the experimental results, we shall use as examples published resistivity data of one polycrystalline sample,[5] single phase to better than 4%, and a single crystal in the *ab* plane,[22] both of nominal composition $YBa_2Cu_3O_{7-\delta}$. A general view of their electrical resistivity is plotted in Fig. 1, circles and squares corresponding to, respectively, the polycrystal and single crystal in the *ab* plane. Note that two samples differ largely both in the absolute values of the resistivity and the temperature slope. Our purpose here is, therefore, to compare the expressions we have obtained for the effective ρ^e in the mean-field region, in which we have included the eventual presence of T_{c0} inhomogeneities with and without SCOPF's, with the measured resistivity ρ^M. As said in the Introduction, ρ^M may be also affected by the mismatch between grains or untwinned regions or even the presence of nonsuperconducting domains. These effects must then be "added" to ρ^e in order to obtain a proper comparison with ρ^M. Following the empirical picture described in detail in Refs. 5 and 6, in the presence of the temperature-independent inhomogeneities, ρ^M is related to ρ^e (which contains the T_{c0} inhomogeneities and/or the SCOPF effects) by

$$\rho^M = \frac{1}{p}\rho^e + \rho_c , \tag{13}$$

where p ($0<p<1$) is associated with the effective cross-section data of the sample (and, indeed, also with the path lengthening due to the random orientation of the *ab* planes) and ρ_c accounts for the contact resistance between different sample domains (grains, untwinned domains, etc.). *Above* T_{c0}, both p and ρ_c are assumed to be temperature independent in the MFR (and, of course, at higher temperatures). To extract p and ρ_c from the ex-

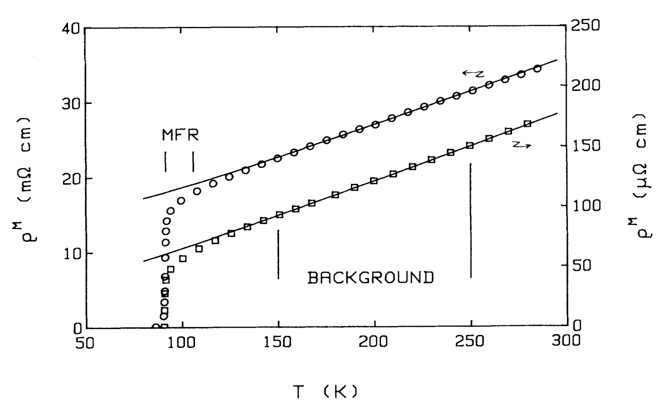

FIG. 1. Temperature behavior of the electrical resistivity of the two samples used here as typical examples. The squares correspond to the resistivity in the *ab* plane of a single crystal measured by Hikita and Suzuki (Ref. 22). The circles correspond to a granular sample (Ref. 5). The background resistivity is shown (solid lines), as well as the mean-field region (MFR) where our results are applied.

perimental data, the important point is the fact that far away from the transition (background region) neither any eventual T_{c0} smearing nor SCOPF's will be relevant, and so ρ^e can be identified with the ideal resistivity of that type of compound in the *ab* plane, i.e., that measured in high-quality single crystals in the *ab* plane. Other details of the p and ρ_c extraction procedure may be seen in Refs. 5 and 6, but we just state that (i) For the ideal background resistivity in the *ab* plane, we have used the Zou-Anderson functional form, namely, $\rho_B^i = C_1/T + C_2 T$. C_1 and C_2 are obtainable by fitting this expression of ρ_B to the experimental data in the temperature interval 150–250 K. (ii) The ideal temperature slope of resistivity has been taken as $C_2 = 0.6\ \mu\Omega\,\mathrm{cm}$, in accordance with measurements on high-quality single crystals.[22,23] (iii) The mean-field-like region for either EMT or LD theory is taken as the temperature interval $0.1 < [\rho_B(T) - \rho^e(T)]/\rho_B(T_{cI}) < 0.4$. Some of these features may be seen in Fig. 1. When this analysis is applied to the two aforementioned samples, one obtains $p \simeq 1$, $\rho_c \simeq 0$ for the single crystal, and $p = 6.6\times10^{-3}$, $\rho_c = 7.8\ \mathrm{m}\Omega\,\mathrm{cm}$ for the polycrystal. These values of the parameters associated with the *temperature-independent* structural inhomogeneities show that, as expected, our two representative examples correspond to two very different cases: an almost ideal single crystal and a granular sample having strong long-scale *temperature-independent* inhomogeneities. For the remainder of this section, we shall compare the measured resistivity rounding of these two samples with the theoretical ρ^M, obtained by combining Eq. (13) with ρ^e given by Eq. (6) or (12) and using for p and ρ_c the values indicated above.

We will first compare the experimental data with the theoretical ρ^M due to either SCOPF or T_{c0} inhomogeneities *alone*. In Figs. 2(a) and 2(b), we display the results of this comparison. The experimental points correspond, respectively, to the single-crystal (squares) and granular (circles) samples of Fig. 1. The inflexion-point temperatures are, respectively, $T_{cI} = 90.86$ and 91.04 K. The two solid lines were obtained from Eqs. (7), (8), and (13), with the values of p and ρ_c indicated before and with A_{LD} and B_{LD} as free parameters (and $T_{c0} = T_{cI}$). The resulting values are, *in both cases,* $A_{\mathrm{LD}} = 310\pm50\ \Omega^{-1}\,\mathrm{cm}^{-1}$ and $B_{\mathrm{LD}} = 0.16\pm0.05$. These relatively important uncertainties are associated with the sample dimensions for both the single-crystal and granular samples, and the p and ρ_c extraction for the latter. The fact that the same A_{LD} and B_{LD}, within uncertainties, explain the resistivity rounding in single crystals and polycrystals in the MFR is a nice check of the consistency of our analysis procedure in terms of LD theory. On the grounds of the original LD approach, those values correspond to a correlation-length amplitude $\xi_c(0) = 1 \pm 0.3$ Å and an effective superconducting-layer spacing $d_e = 5\pm1$ Å. Note that the latter value is well between both CuO_2 plane spacings in $YBa_2Cu_3O_{7-\delta}$ compounds (3.3 and 8.4 Å). The above value for $\xi_c(0)$ is somewhat smaller than that currently found by measuring other properties, where $\xi_c(0) \approx 2$ Å.[24] In fact, this is the value we find, within the uncertainties, using for A_{LD} the expression proposed in Ref. 21 for *s*-wave pairing (and then $d_e = 10\pm2$ Å). However, the important point for the analysis in this paper is that in all the cases the functional form for $\Delta\sigma_F$ remains the same, and therefore our conclusions for the role of T_{c0} inhomogeneities in the presence of SCOPF's do not change.

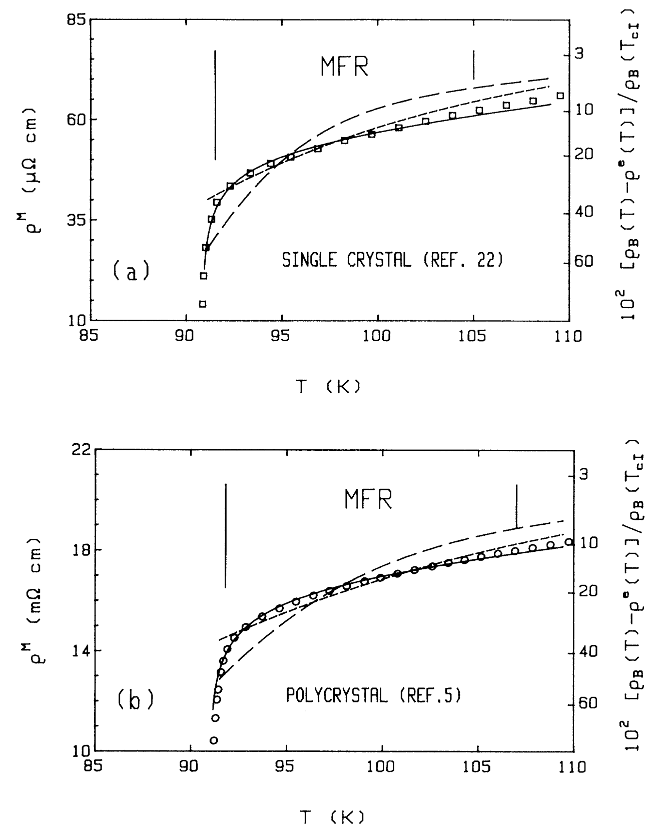

FIG. 2. Comparison between the measured resistivity in the MFR and different approaches for the resistivity rounding: Lawrence-Doniach theory alone (solid lines), with the best-fit values $A_{\mathrm{LD}} = 310\pm50\ \Omega^{-1}\,\mathrm{cm}^{-1}$ and $B_{\mathrm{LD}} = 0.16\pm0.05$; a best-fit Gaussian distribution of transition temperatures alone with $\overline{T}_{c0} = 70\pm5$ K and $\Delta T_c = 20\pm5$ K (short-dashed lines), and with the percolation constraint of Eq. (5) (long-dashed lines). The MFR is the region between 10 and 40 on the left axis.

The $\rho^M(T)$ rounding due to transition-temperature inhomogeneities *alone* is represented by the dashed lines in Figs. 2(a) and 2(b). The short-dashed lines represent Eqs. (2) and (6) with $\overline{T}_{c0}$ and ΔT_{c0} as free parameters. The best-fit values are $\overline{T}_{c0} = 70\pm5$ K and $\Delta T_{c0} = 20\pm5$ K for Figs. 2(a) and 2(b). Not only is the fit quality clearly worse than for LD theory alone, but the best-fit values are physically untenable. The long-dashed lines represent Eqs. (2) and (6), but with the constraint of Eq. (5). The disagreement with the experimental points rules out again the possibility, as one should expect, of a smearing of the transition temperature as the only driving mechanism for the rounding of the critical behavior near and above T_{cI}.

We now turn to the issue of the interplay of T_{c0} inhomogeneities with SCOPF's in HTSC's. In other words, what will be the effect of T_{c0} inhomogeneities when $\rho^M(T)$ is already rounded by the intrinsic SCOPF mechanism? The answer can be easily obtained by using Eq. (12). For SCOPF's we will use the LD approach with $A_{LD}=370\ \Omega^{-1}\,cm^{-1}$ and $B_{LD}=0.2$. The T_{c0} Gaussian inhomogeneities will be characterized by its spread ΔT_{c0}. A typical example of the results of our calculations is shown in Fig. 3, where the difference in $\rho^M(T)$ is plotted, in this example for $T-\bar{T}_{c0}=4$ K, with and without T_{c0} inhomogeneities (but, we recall, always affected by SCOPF's), as a function of ΔT_{c0}. From this figure an important conclusion we can derive is the sensitivity of electrical resistivity as a probe to detect possible spreading in the transition temperature. In concrete terms, assuming a typical resistivity relative resolution of 2×10^{-3} (typically 0.1 over 50 $\mu\Omega$ cm), we see that one can resolve transition-temperature inhomogeneities of some tenths of kelvin, the precise amount depending on the absolute temperature within the MFR. This result admits also another reading: When interpreting the resistivity rounding onset (above T_{cI}) in terms of SCOPF's, transition-temperature inhomogeneities up to some tenths of kelvin (in fact, of the order of the observed width of the resistive transition) should affect very little the precise values of the critical exponents or amplitudes. It is clear, then, that T_{c0} inhomogeneities produce some kind of average of the critical magnitudes [see, for instance, Eq. (11)], but their effects on the resistivity will be relatively small because the latter is already rounded by SCOPF's. However, T_{c0} smearing effects may be appreciable when acting on magnitudes varying rapidly near the normal-superconducting transition. This may be, for example, the case of the resistivity itself, beyond the MFR closer to T_{c0}, where its temperature variation is steeper. This feature introduces additional difficulties in analyzing the paraconductivity results in the so-called "full critical" and crossover regions.[25] However, we remark that the

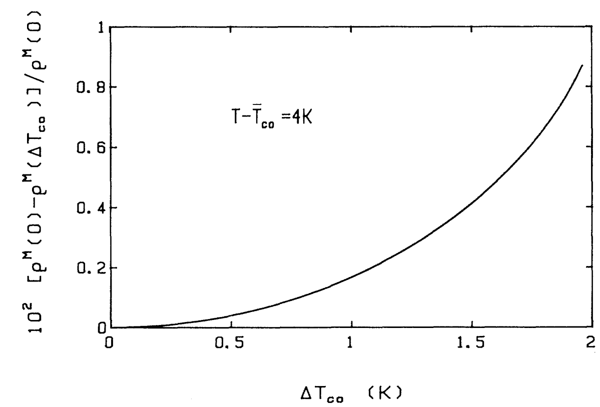

FIG. 3. Influence of a Gaussian T_{c0} inhomogeneity distribution on the electrical resistivity already rounded by thermodynamic fluctuations of the superconducting order-parameter amplitude (LD model). $\rho^M(0)$ and $\rho^M(\Delta T_{c0})$ are the measured resistivity, in this example at $T-\bar{T}_{c0}=4$ K (well within the MFR), without and with T_{c0} inhomogeneities, respectively, ΔT_{c0} is the spread of the Gaussian inhomogeneities.

observed $\Delta\sigma(\epsilon)$ behavior in the crossover region is very similar for all the Y-based samples we have studied and can be easily understood in terms of an intrinsic distinct dynamic regime for fluctuations, as first proposed in Ref. 25. Another example for the relative importance of T_{c0} inhomogeneities is the specific heat, for which it has been recently suggested that a T_{c0} inhomogeneity of some tenths of kelvin could have a dramatic effect on the analysis of its critical behavior.[26]

The above results may be confirmed by fitting Eq. (12) to the experimental data with A_{LD} and B_{LD} for SCOPF's, and $\bar{T}_{c0}$ and ΔT_{c0} for the T_{c0} inhomogeneity, as free parameters. In that case we find that the critical temperature spread ΔT_{c0} goes to negligible values (below 0.1 K), whereas the mean critical temperature $\bar{T}_{c0}$ falls very close to the inflexion-point temperature T_{cI}, consistent with Eq. (5). Indeed, we also find again the same values for A_{LD} and B_{LD} as quoted above. All the *single-phase* polycrystalline samples[5] submitted to the same analysis reproduce the same features. These results imply that in single-phase (better than 4%), either granular or single-crystal, samples, the T_{c0} inhomogeneities effects on the resistivity rounding in the MFR are negligible, their magnitude being less than our sensitivity threshold: some tenths of kelvin.

As remarked earlier, two main hypotheses on which our results rest are (i) a temperature-independent length scale of T_{c0} inhomogeneities. It should be of questionable validity if, close enough to $\bar{T}_{c0}$, the correlation length exceeds that length scale. At the lower temperature limit of the MFR, $T-T_{cI}\sim1$ K and so $\xi_{ab}\sim100$ Å. The procedure developed here can then be applied to probe eventual T_{c0} variations in grains or crystallites for polycrystals, or microtwins domain for crystals, caused, for instance, by different average oxygen content. At much shorter length scales, other inhomogeneities such as chemical defects or local variations in the oxygen-vacancy ordering might exist as well. This ordering is also shown to affect transition temperatures.[27] The treatment of these possible atomic-range inhomogeneities is outside our framework and should deserve further analysis. (ii) We have also assumed a Gaussian distribution of local T_{c0}'s. Of course, the actual distribution need not be Gaussian. In fact, assuming T_{c0} inhomogeneities as the only rounding mechanism, one can easily determine, for instance, by Eq. (6), an *ad hoc* superconducting fraction $P(T)$, i.e., the cumulative distribution that fits any resistivity data. Though this *ad hoc* distribution (obviously not necessarily Gaussian) can only be probed up to the percolation threshold ($\approx15\%$), we have checked that it is irregular in that it shows a kink coinciding with the shoulder of the resistivity curve. Moreover, when both SCOPF and T_{c0} inhomogeneity rounding effects are considered, the effective (average) conductivity [see Eq. (11)] should depend mostly on the distribution width and less on its finer details. We do not think, consequently, that the T_{c0} distribution (provided it is a regular one) choice is very sensitive for our main results.

Finally, we want to comment briefly on a suggestive analogy with the case of a liquid ^{4}He sample placed near the λ line at a given temperature and in the presence of gravity. Here, because of the gravity-induced pressure gradient, each point of the sample is at a different reduced (critical) temperature. The analogy with a HTSC sample in which $T-T_{c0}$ varies locally is evident. When studying the propagation of first sound near the λ line, there are two simultaneous rounding effects on its velocity: (intrinsic) critical dispersion and (nonintrinsic) gravity-induced inhomogeneity. In that case it is also found that the nonintrinsic rounding effect is strongly attenuated with regard to the intrinsic one.[16]

IV. CONCLUSIONS

We have studied the presence of inhomogeneities of the mean-field transition temperature T_{c0} in HTSC's, caused, for instance, by local strains or oxygen-content variations, by using electrical resistivity as a probe property. To that end, we have obtained, by resorting to the effective-medium theories, pertinent expressions for the effective conductivity in the presence of a Gaussian distribution of transition temperatures, either with or without the additional presence of thermodynamic fluctuations. Order-of-magnitude estimates show that very general features of resistivity behavior near the transition temperature are incompatible with a transition-temperature spread of the order of the mean critical temperature itself.[10,12] Moreover, the observed resistivity behavior in the mean-field region cannot be explained solely by any T_{c0} inhomogeneity.

When considering the concurrent effect of thermodynamic fluctuations of the superconducting order-parameter amplitude (SCOPF), as given by LD theory and T_{c0} inhomogeneities, comparison with the experimental resistivity-rounding onset in *single-phase* (to better than 4%) $YBa_2Cu_3O_{7-\delta}$ samples leads to a negligible (below 0.1 K) T_{c0} spread. Since we have shown that a smearing of some tenths of kelvin will produce an effect comparable to the typical experimental uncertainties, that degree of smearing sets an upper limit for T_{c0} inhomogeneities in Y-based (single-phase) HTSC's. Answering the question first raised by Bednorz and Müller,[4] we may conclude, therefore, that transition-temperature inhomogeneities seem to play a negligible role in the electrical resistivity-rounding onset in HTSC's, even in (single-phase) polycrystalline samples. In contrast, our analysis confirms[5,6] that for either (single-phase) granular or single-crystal $YBa_2Cu_3O_{7-\delta}$ samples the rounding effects on the resistivity in the MFR can be explained *quantitatively* on the grounds of the Lawrence-Doniach theory for SCOPF's, with the same values for the correlation-length amplitude and the *effective* interlayer spacing. Although this work has focused on HTSC's, let us finish by noting that its qualitative aspects may also be applied to LTSC's. For instance, the presence of intrinsic SCOPF effects will also mitigate the relevance of possible nonintrinsic T_{c0} inhomogeneities. However, as the correlation-length amplitude is orders of magnitude larger than in HTSC's, SCOPF effects will be much smaller, relevant only very close to T_{c0}. Consequently, as stressed by Kosterlitz and Thouless,[1] the T_{c0} inhomogeneities may play a substantial role in the $\rho^M(T)$ rounding onset in LTSC's, in any case more important than in HTSC's. At a more quantitative level, because of the large magnitude of the correlation length in LTSC's, some of our simplifying assumptions, such as the existence of sample domains with a given local T_{c0} having a temperature-independent volume, may not be reasonable approximations in this case.[28]

Note added in proof. It has been suggested recently that the electrical resistivity along the *ab* plane in $YBa_2Cu_3O_{7-\delta}$ ($\delta<0.1$) in single crystals, and for $T\simeq 150$ K up to room temperature, follows a linear temperature dependence slightly better than the Zou-Anderson temperature dependence used in this work for the intrinsic background resistivity, ρ_B^i [see, e.g., Ref. 29]. However, as we have clearly pointed out earlier [Ref. 5, and in particular Fig. 1 therein], the use of either T dependence has a relatively small influence on the extracted paraconductivity. This is because when analyzing critical phenomena, the precise choice of the background should be of little relevance provided that a high-quality fitting in a wide T region is realized and also that the extrapolation through the transition is smooth [see e.g., Ref. 30 and references therein]. For instance, the intrinsic LD values for $YBa_2Cu_3O_{7-\delta}$ compounds obtained in this work by using the Zou-Anderson background, namely, $A_{LD}=310\pm50\ \Omega^{-1}\mathrm{cm}^{-1}$ and $B_{LD}=0.16\pm0.05$ only shift to $A_{LD}=380\pm70\ \Omega^{-1}\mathrm{cm}^{-1}$ and $B_{LD}=0.13\pm0.06$ when a linear temperature dependence for the background resistivity is used. The latter values, which comprise the scatter from sample to sample as well as all estimated uncertainties, are obtained by using $\rho_B^i(T)=C_1+C_2T$, with $C_1=5\ \mu\Omega\,\mathrm{cm}$ and $C_2=0.5\ \mu\Omega\,\mathrm{cm\,K}^{-1}$, which are well within the average values obtained in single-crystal samples [see the above-indicated references and also Ref. 31].

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