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Resistive transition and fluctuations of the conductivity in $YBa_2Cu_3O_7$, $EuBa_2Cu_3O_7$ and $GdBa_2Cu_3O_7$ superconductors
Effect of inhomogeneities

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Systematic resistivity measurements in polycrystalline samples of the high-T_c oxide superconductors $RBa_2Cu_3O_7$ (R = Y, Eu, Gd) are performed with several (low) current densities. Special attention is devoted to the temperature range close to the superconducting transition. The data allows the determination of temperature derivatives of the resistivity, which reveal the occurrence of a two-step transition. This feature is typical of a granular system. Two scaling regimes for the fluctuation conductivity are also identified. Near the temperature where the grains become superconducting, the enhancement of the conductivity follows a power law with sample dependent exponents. Analysis of this result on the basis of the Aslamazov–Larkin theory indicates that a fractal topology might be adequate to describe the inhomogeneous superconducting state. In the second scaling regime, near the zero-resistance temperature, an apparently universal exponent is observed.

1. Introduction

Since the early stages of the experimental work on high-T_c oxide superconductors it has been recognized that the resistivity as well as the specific heat close to the transition towards the superconducting state display rounding features which strongly suggest the occurrence of enhanced thermodynamic fluctuations in the normal state [1]. It is also largely accepted that these systems, by many of their properties, may be characterized as inhomogeneous superconductors, even when a single phase is present. For instance, in polycrystalline samples the magnetic properties clearly reveal effects of disorder and frustration [2]. Also transport properties, in particular the critical current [3], and experiments in bi-crystals [4], unequivocally show that weak links exist inside the material.

It is now clear that extremely short and anisotropic coherence lengths are the distinctive property underlying the peculiar phenomenology of high-T_c superconductors [5,6]. A short coherence length should reinforce thermodynamic fluctuations of the order parameter, which are hardly observable in bulk, homogeneous, low-T_c superconductors [7]. On the other hand, the short coherence length renders the superconducting order parameter very sensitive to microscopic defects [6] as, e.g. local variations of oxygen concentration. This could result in a complex topology for the spatial modulations of the order parameter.

Although the enhanced fluctuation regime as well as the inhomogeneous characteristic of the superconductivity in the oxide superconductors have been recognized, little has been said about the possible interplay between these two aspects. In particular, most of the experimental results obtained so far on the fluctuation conductivity of high-T_c systems have been analyzed in a perspective of homogeneous behavior. In the case of the Y–Ba–Cu–O system, a consequence of this (a priori) assumption may be the lack of consensus regarding the relevant dimensionality of the superconducting fluctuations. Claims are evenly divided between two-dimensional (2D) [8–10) and three-dimensional (3D) [1,11,12] behavior, with reports on a crossover between these two limiting regimes [13,14].

In this work, we investigate the resistive transition

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of a number of polycrystalline samples of the superconductors $YBa_2Cu_3O_7$, $EuBa_2Cu_3O_7$ and $GdBa_2Cu_3O_7$. The experimental procedures for sample preparation and resistivity measurements are described in section 2. Similarities and differences among the studied samples are discussed in section 3 in connection with the behavior of the resistivity and its temperature derivatives close to T_c. Evidence is then presented for a general picture of a global inhomogeneous structure of superconducting grains connected by weak links. The same samples have been previously investigated for their magnetic properties, which reveal effects of the inhomogeneous character of their superconducting state [15]. In order to study possible effects of these inhomogeneities on the fluctuation conductivity as well as the nature of the transition to zero resistance, we perform a detailed analysis of the resistivity data both near the onset temperature (section 4) and near the zero-resistance temperature (section 5). Scaling behavior is observed in both regions, and the exponents obtained are discussed in the light of existing models. A summary of the main results of the paper is presented in section 6.

2. Experimental

For this study, we have prepared three polycrystalline samples of $YBa_2Cu_3O_7$, labelled YBaCuO(I), (II) and (III), one of $EuBa_2Cu_3O_7$, labelled EuBaCuO, and one of $GdBa_2Cu_3O_7$, labelled GdBaCuO. The usual solid state reaction technique [16] was employed. Calcination was done at 950°C, under a flow of oxygen, in Pt or Al_2O_3 crucibles. The resulting pellets were finely powdered, pressed into disks of about 2 mm thickness and 9 mm in diameter. Sintering was performed at 950°C in O_2 atmosphere for one day. For the YBaCuO samples, the cooling process followed two different routes. While samples YBaCuO(I) and (II) were furnace cooled, sample (III) was slowly cooled in a controlled way, specially in the interval between 800°C and 450°C, in order to provide for its full oxygenation. The EuBaCuO and GdBaCuO samples were simply furnace cooled. An O_2 atmosphere was kept throughout the heat treatment. X-ray analysis revealed the expected orthorhombic phase, and the mass densities ranged between 72% and 86% of the ideal values.

We performed several resistivity measurements, using an AC lock-in technique in the temperature interval from the superconducting transition to room temperature. Various (low) current densities were used. The uncertainties in the absolute values of the resistivities were about 10%, since geometrical factors were not precisely known. No corrections for porosity were attempted. The accuracy in relative values of the resistivities was about a few parts in 10^5 and was essentially limited by the noise level in the copper–beryllium pressure contacts. The temperature was determined by a Pt sensor with an accuracy of 1–2 mK. A large number of closely spaced data points allowed us to numerically determine temperature derivatives of the resistivity near T_c, using a procedure that has been described in ref. [17].

3. The resistive transition

It has been already pointed out [17–19] that the temperature derivative of the resistivity, $d\rho/dT$, close to T_c gives interesting information about the superconducting transition in the high-T_c oxides. We have found a fairly general picture for the five samples studied in this work, with minor qualitative changes occurring upon variation of the current across a given sample. Some of our present results are shown in figs. 1–3. From those figures one concludes that, quite generally, the transition to the zero resistance state is achieved in two steps. In most cases $d\rho/dT$ shows a two-peak structure. A pronounced maximum is followed, at a slightly lower temperature, by a second peak before the resistivity goes to zero. An inhomogeneous, granular-like model for the superconductivity may be used to interpret the data. The higher temperature peak should then correspond to the superconducting transition occurring inside the grains, while the current dependent (and sometimes not well defined) low temperature peak would indicate the establishment of long-range order through the weak links.

Figure 1 shows $d\rho/dT$ close to the superconducting transition for the most resistive sample, YBaCuO(I). When the measurement was performed with a current density $j = 92$ mA/cm^2, the two-peak structure was clearly visible. However,

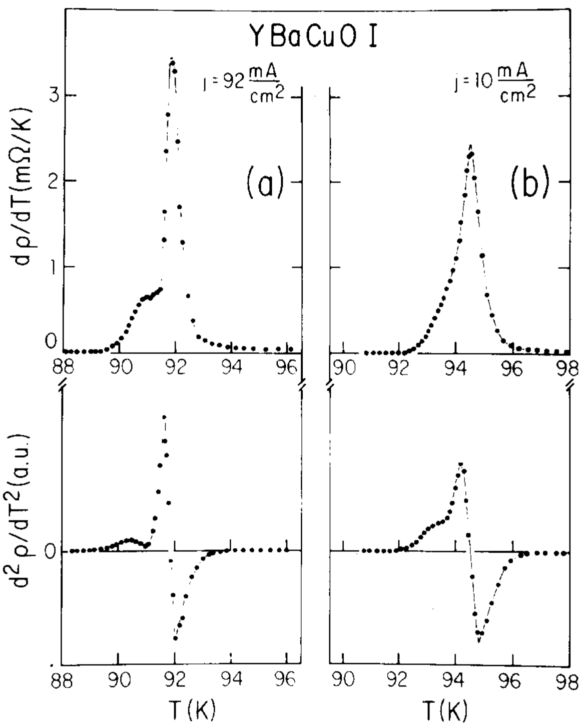

Fig. 1. First and second derivatives of the resistivity near T_c for the YBaCuO(I) sample, described in the text and in tables 1 and 2. Measurements were performed with current densities of (a) $j=92$ mA/cm^2 and (b) $j=10$ mA/cm^2.

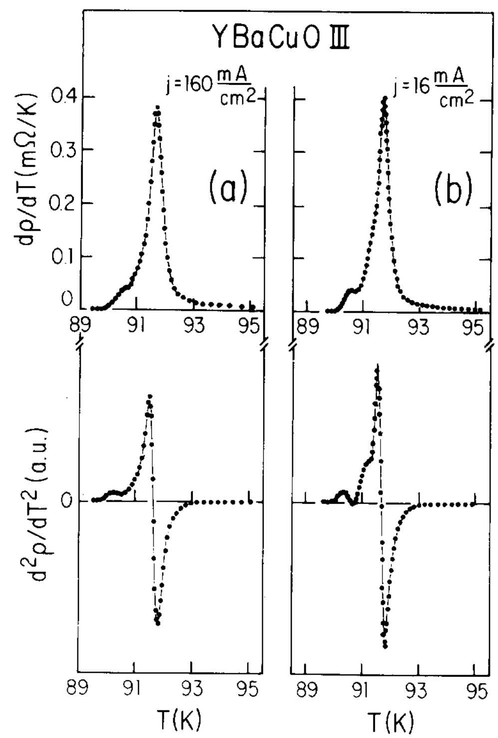

Fig. 2. The same as fig. 1, but for the YBaCuO(III) sample. Current densities are (a) $j=160$ mA/cm^2 and (b) $j=16$ mA/cm^2.

when the current was decreased to $j=10$ mA/cm^2, the whole transition was displaced to higher temperatures. The lower peak, which became no longer visible in $d\rho/dT$, actually merged partially into the main peak, as shown by the second derivative, also displayed in the figure. The second derivative shows that, in fact, lowering the current does not change the two stage character of the transition. Figure 2 shows the behavior of $d\rho/dT$ for the YBaCuO(III) sample, which has the lowest resistivity. In this case, the decreasing of current, instead of apparently suppressing the secondary peak, makes it clearer. Figures 3(a) and (b) show the results for the EuBaCuO and GdBaCuO samples, respectively. In some sense these are extreme cases. The width of the transition in the EuBaCuO sample is rather large (~ 10 K), and the two peaks in $d\rho/dT$ are similar in size. In contrast, for the GdBaCuO sample we observe at most a slight asymmetry in a single maximum. Nevertheless, the two-peak structure is clearly resolved in the second derivative, also shown in fig. 3 (b).

These observations are, as a whole, consistent with the picture of a weak-linked granular superconducting network. When the input current is lowered, both peaks are displaced to higher temperatures, but not on an equal footing. The secondary peak shifts in a larger extent, indicating that, at a given temperature, some of the junctions which are unable to superconduct when the current is high, can support a lower supercurrent.

It is important to notice that *granularity* here should not be confused with *poly-crystallinity*. Throughout this paper, granularity refers exclusively to superconducting properties. Since the spatial variations of the superconducting order parameter are probably related to variations in oxygen concentration, the relation between the superconducting inhomogeneities and the metallurgical grains may be highly non-trivial. In connection to this, it is worth noticing that inhomogeneous behavior has often been reported in single-crystal samples [20]. Indeed, the

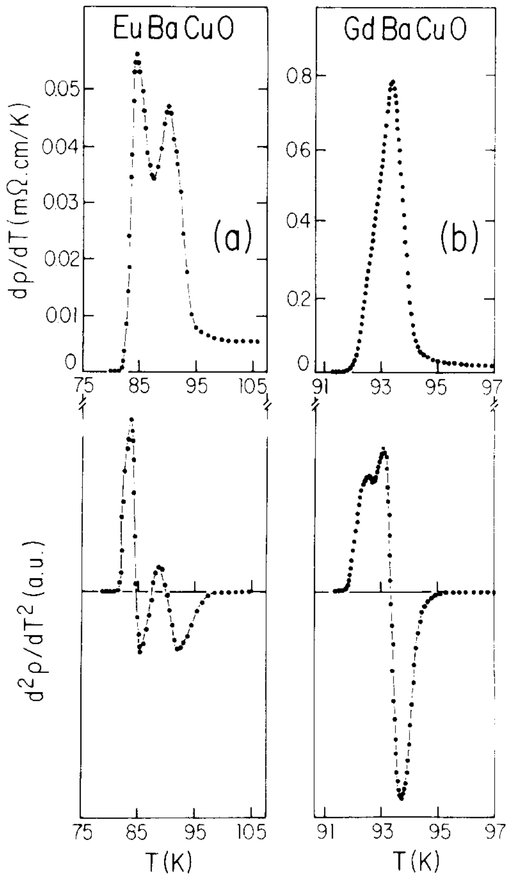

Fig. 3. The same as fig. 1, but for the (a) EuBaCuO and (b) GdBaCuO samples.

two-step transition in YBaCuO superconductors is likely to be a general property. Friedmann et al. [14] observed a double-peak structure in $d\rho/dT$ close to the sharp transition in a measurement of the resistivity parallel to the a–b plane in a single-crystal sample. The two maxima were also observed in the broad transition of an intentionally deoxygenated sample [21]. This two-step character of the resistive transition n YBaCuO was also recognized and extensively discussed by Rosenblatt and coworkers [22].

The structure in $d\rho/dT$ allows us to characterize two regimes in the resistive transition. The first one refers to fluctuation effects above the higher temperature maximum. We identify the position of this peak as the bulk (intra-grain) critical temperature, T_c. The second regime concerns the approach to the zero resistance state. The experimentally determined temperature T_{c0} at which this state is reached is chosen as the appropriate critical temperature in this case.

4. Fluctuations of the conductivity above T_c

In this section we are concerned with the analysis of our resistivity data in the range $T \gtrsim T_c$. Following the common interpretation, we ascribe the enhancement of the conductivity in this temperature range to fluctuations of superconducting pairs in the normal state. This *paraconductivity* [7], is obtained from the experimental data by considering

$$\Delta\sigma = \sigma - \sigma_r\,, \tag{1}$$

where σ and σ_r are the measured and regular conductivities respectively. Usually $\Delta\sigma$ is analyzed in comparison to the Aslamazov–Larkin (AL) theory [23], which studies the effect of Cooper pair formation in temperatures above T_c, taking into account gaussian fluctuations around the minimum of the Ginzburg–Landau free energy. This theory predicts that

$$\Delta\sigma = \frac{A_{AL}}{\lambda}\,\epsilon^{-\lambda}\,, \tag{2}$$

where $\epsilon = (T - T_c)/T_c$ is the reduced temperature and

$$\lambda = 2 - \frac{d}{2}\,, \tag{3}$$

d being the dimension of the system. Equations (2) and (3) reveal one of the main interests of studying the fluctuation conductivity in high-T_c compounds, as one may expect to obtain relevant information about the controversial issue of the dimensionality of these systems. Several experiments are reported in the literature [1,8–14]. However, particularly for the YBaCuO system, a general agreement has not yet been achieved.

We center our analysis not directly on eq. (2), but rather on the temperature derivative of the paraconductivity, which may be written as

$$-\frac{d(\Delta\sigma)}{dT} = \frac{1}{\rho^2}\frac{d\rho}{dT} - \frac{1}{\rho_r^2}\frac{d\rho_r}{dT} + \frac{A}{T_c}\,\epsilon^{-(\lambda+1)}\,, \tag{4}$$

where ρ_r is the regular resistivity. An analysis based on eq. (4) presents an advantage with respect to direct fits to eq. (2). Errors originated in the subtraction of the regular part from the raw data are minimized, as the term in which this contribution appears in eq. (4) is small compared to the one involving the total resistivity. As commonly done, we determine ρ_r for temperatures near T_c by extrapolating the high temperature behavior. This, except for the EuBaCuO system, is quite accurately described by an expression of the type

$$\rho = \rho_0 + \rho_1 T \,, \qquad (5)$$

where ρ_1 does not depend on temperature and ρ_0 is the residual resistivity extrapolated to $T=0$.

When analyzing fluctuation conductivity data, authors in general *choose* a fixed exponent in the AL expression, eq. (2), and define the reduced temperature with respect to a mean-field critical temperature, which is determined through a best fit procedure. The overall quality of the fitting is then judged by comparing the results for different exponents (dimensions). Our approach is based on a completely distinct philosophy. We determine the *actual* critical temperature T_c as discussed in the previous section, and define the reduced temperature ϵ with respect to this T_c. We then proceed to logarithmic plots such as those of fig. 4 for small values of ϵ, searching for scaling regimes from which exponents can be extracted. Finally, the obtained exponents are compared with model theoretical predictions.

In the representative data shown in fig. 4, one generally observes a crossover from a higher temperature power law regime, which we label by the exponent λ_2, to a regime closer to T_c, described by the exponent λ_1. Still closer to T_c, rounding effects probably due to finite grain size become dominant. Such a qualitative picture seems to be universal. It was first pointed out explicitly by Ausloos and Laurent [8], and may be discerned in results as those of Vidal et al. [12] and in the single-crystal data of Friedmann et al. [14].

Table 1 collects the data obtained from our paraconductivity experiments. There one observes that both exponents λ_1 and λ_2 are *sample dependent*, and so are the respective amplitudes A_1 and A_2, though neither of them depend on the current density. Concerning specifically the YBaCuO system, one also observes that when the normal resistivity decreases

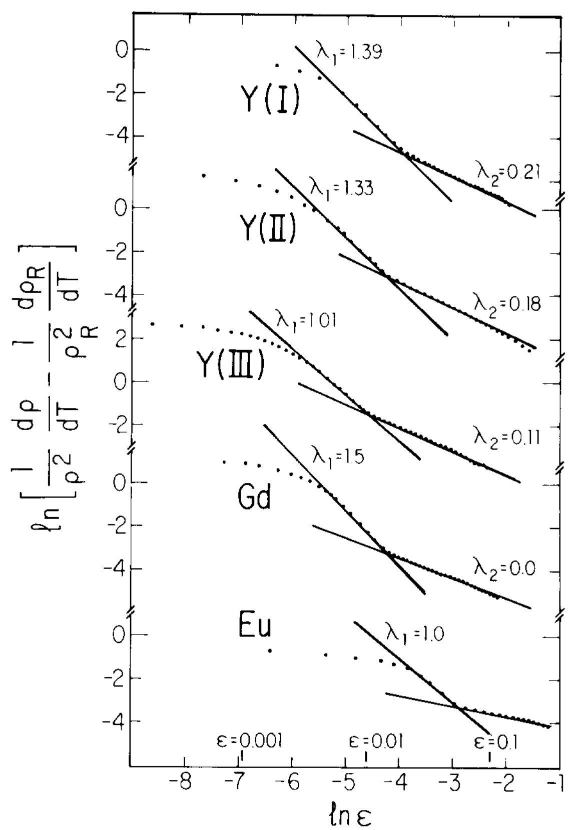

Fig. 4. Representative logarithmic plots of the derivative of the conductivity, measured in mΩ cm/K, as a function of the reduced temperature $\epsilon = (T - T_c)/T_c$. Straight lines describe power law regimes with the quoted λ_1 and λ_2 exponents. These data are summarized in table 1.

(let us say, the *quality* of the sample increases) the exponent λ_1 approaches the value predicted by the 2D Aslamazov–Larkin theory, according to eqs. (2) and (3). The same holds for the EuBaCuO sample, which also has low resistivity, although in this case we were unable to determine ρ_r, for the resistivity curve bends downward at temperatures as high as 300 K. Thus, experiments indeed show that for low resistance samples the conductivity fluctuations are indicative of layered superconductivity in these high-T_c oxides. In order to explain the departure from this in the high resistance samples, we point out that the totality of our results in the λ_1 regime can still be understood in the framework of the AL theory if we assume that the superconducting state *inside* the grains presents a *fractal topology*. Then, as shown by

Table 1
Data concerning conductivity fluctuations above T_c. Measurements are performed with the quoted current densities. T_c is determined as the position of the high temperature maximum of $d\rho/dT$. The power law regimes, obtained from fits to eq. (4), are described by the exponents λ_1 and λ_2, and respective amplitudes A_1 and A_2

Sample	j (mA/cm^2)	T_c (K)	λ_1	$10^5 A_1$ (mΩ cm)$^{-1}$	λ_2	$10^3 A_2$ (mΩ cm)$^{-1}$
YBaCuO(I)	92	91.76	1.39±0.04	7±3	0,21±0.03	8.5±0.9
	31	93.43	1.39±0.07	8±2	0.21±0.02	7.8±0.4
	10	94.47	1.43±0.01	5±3	0.19±0.04	7±1
YBaCuO(II)	80	91.76	1.33±0.03	22±4	0.18±0.02	27.1±0.06
YBaCuO(III)	160	91.60	0.97±0.03	340±20	0.12±0.02	141±3
	65	91.60	1.02±0.02	240±60	0.11±0.03	140±10
	16	91.645	1.05±0.03	190±20	0.09±0.02	151±10
	8	91.665	1.01±0.02	230±20	0.11±0.01	141±7
EuBaCuO	119	90.08	1.02±0.1	960±200		
GdBaCuO	180	93.34	1.53±0.06	8.5±4	−0.03±0.04	70±7

Char and Kapitulnik [24], eq. (3) should be written as

$$\lambda=2-\frac{\tilde{d}}{2}, \quad (6)$$

where $\tilde{d}$ is the fracton, or spectral dimension [25] of the fractal structure. It is important to emphasize that we are studying the regime where *intra-grain* fluctuations are dominant. In this length scale fractality should result from short range inhomogeneities, probably related to local departures from oxygen stoichiometry and to the defect structure of the sample.

Turning now to the higher temperature regime, we observe that the values of λ_2 are quite small. This fact suggests that this regime may be dominated by a Maki-Thompson (MT) term in the fluctuation conductivity [26,27]. This term describes the contribution of normal quasi-particles resulting from the decay of fluctuating Cooper pairs in the presence of weak pair-breaking processes. In two dimensions, the MT term is logarithmically divergent as follows:

$$\Delta\sigma 2D/MT=\frac{A_{MT}}{\epsilon-\delta}\ln(\epsilon/\delta), \quad (7)$$

where δ is the pair-breaking parameter. However, in a fractal description of the inhomogeneous superconductors, modifications are expected in the strict logarithmic behavior [24]. This would be translated in effective λ_2 exponents somewhat different from zero in a power law-type fit.

Recently, Ausloos et al. [28] reported on observations similar to ours in one sample of $YBa_2Cu_3O_{7-y}$ and one of $Bi_{1.75}Pb_{0.25}Ca_2Sr_2Cu_3O_{10-y}$. For the YBaCuO sample they found the same crossover between MT and AL behavior, though with homogeneous exponents. Their analysis of the effect of inhomogeneities, which appears only in the Bi-based sample, also resort to a fractal description. However, they restrict the relevant fracton dimension to that of a surface-like percolation backbone. Our results for the 123-system suggest that, at least in this case, more general fractals may be useful to describe the fluctuation network.

Effects of fractal geometry were also reported by Giovannella [29] in connection with magnetic irreversibilities in sintered La-based and Y-based superconductors.

Another interesting aspect of our experimental results refers to the amplitudes A_{AL} and A_{MT} appearing in eqs. (2) and (7). For homogeneous systems in two dimensions the AL and MT theories predict that these amplitudes are

$$A^{2D}_{AL}=\frac{e^2}{16\hbar\ell} \quad \text{and} \quad A^{2D}_{MT}=\frac{e^2}{8\hbar\ell}, \quad (8)$$

where ℓ is the film thickness, which may be taken as the coherence length perpendicular to the Cu–O planes (ξ_c) in the high-T_c oxides [14]. However, in table 1 we observe that the amplitudes A_1 and A_2 are strongly sample dependent. Moreover, using for l the value $\xi_c \approx 7$ Å, obtained from magnetic measurements in single crystals of $YBa_2Cu_3O_7$ [30], we calculate a value for A_{AL}^{2D} in eq. (8) which is two orders of magnitude higher than the amplitude A_1 determined for our sample YBaCuO(III), which presented the exponent closest to the expected 2D value. From our results it is clear that the experimental amplitudes are strongly dependent on the inhomogeneities that also affect the normal electric conduction and define the fractal topology. Therefore, the inhomogeneous character of the samples has to be considered in a more fundamental way when comparing experimental and theoretical fluctuation amplitudes.

Before closing this discussion, it is worthwhile mentioning that one could also consider the occurrence of a true critical behavior (non Ginzburg–Landau) in the λ_1-regime. Such an interpretation would be strongly dependent on an estimate of the width of the critical region in the high-T_c superconductors, which is a matter of controversy. For instance, Quader and Abrahams [31], based on specific heat data, estimate that as long as $\epsilon > 0.001$ critical fluctuations are not important. This range is neatly below our λ_1-regime. On the other hand, Lobb [32] and Kapitulnik et al. [33] raise the possibility that breakdown of the Ginzburg–Landau theory may occur in a larger temperature range, possibly compatible with the crossover between our λ_1- and λ_2-regimes. However, in the presence of critical phenomena one would expect to observe universal behavior. The clearly revealed sample dependence of the fluctuation conductivity exponents, in both λ_1- and λ_2-regimes (the latter certainly *not* critical), leads one rather to consider inhomogeneity effects through the replacement $d \to \tilde{d}$.

5. The approach to the zero-resistance state

We turn now to the temperature range close to the zero-resistance temperature T_{c0}. Figure 5 displays representative resistivity data. The logarithmic plots show that a power law of the type

$$\rho = B\epsilon_0^{s'} \tag{9}$$

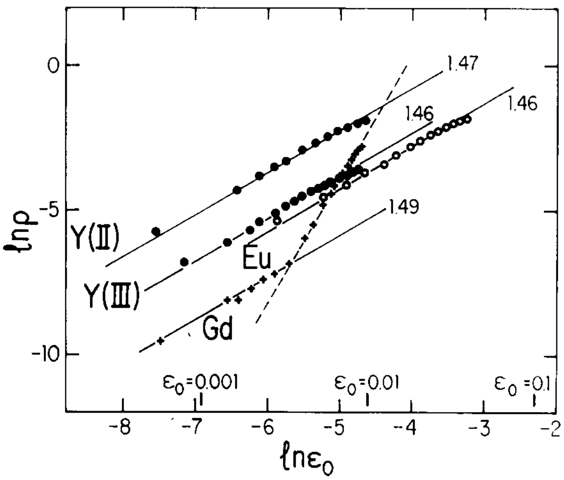

Fig. 5. Representative logarithmic plots of the resistivity, measured in mΩ cm, as a function of the reduced temperature $\epsilon_0 = (T - T_{c0})$, where T_{c0} is the zero resistance temperature. Full straight lines indicate power law behavior with the quoted exponents. The totality of these results is summarized in table 2.

is obeyed in all our samples for sufficiently low values of the reduced temperature $\epsilon_0 = (T - T_{c0})/T_{c0}$. This is in contrast to exponential activation laws [34] or Kosterlitz–Thouless behavior [10] sometimes referred to in the literature.

Table 2 summarizes the relevant data related to the experiments. There one observes that T_{c0} is close to 90 K for all samples except for EuBaCuO. Furthermore, T_{c0} increases with decreasing current density. For the high resistivity sample YBaCuO(I) the increment in T_{c0} is about 2.5 K when j decreases from 92 to 10 mA/cm^2. For the low resistivity sample YBaCuO(III) the corresponding increment is less than 0.2 K. However, in our point of view, the main result in table 2 concerns the apparent universality of the exponent s'. It can be seen that there is little variation around the average value

$$s' = 1.47 \pm 0.03$$

This exponent seems to be independent of the particular sample and of the current density, at least in the range observed here. The amplitude B in eq. (9) varies in a non-obvious way from sample to sample, but it is also independent of the current density. One also notes in fig. 5 that the data for the GdBaCuO sample departs earlier from the general trend. We believe that this is due to the close proximity of the

Table 2
Data concerning the transition to the zero resistance state. The studied samples are distinguished by their resistivities, whose values are quoted at 300 K and 0 K (linearly extrapolated). Measurements are performed with the indicated current densities. The values of T_{c0} are the zero resistance temperatures. The power law exponents s' and the amplitudes B are obtained from fits to eq. (9)

Sample	ρ(300 K) (ρ_0) (mΩ cm)	j (mA/cm^2)	T_{c0} (K)	s'	B (mΩ cm)
YBaCuO(I)	5.02	92	89.781	1.45±0.03	116±6
		31	90.56	1.5±0.4	
	(2.13)	10	92.35	1.47±0.1	
YBaCuO(II)	2.50				
		80	90.295	1.47±0.02	167±10
	(0.47)				
YBaCuO(III)		160	90.013	1.46±0.05	24±2
	0.89	65	90.030	1.47±0.05	19±7
	(0.09)	16	90.067	1.47±0.02	26±3
		8	90.187	1.46±0.03	32±4
EuBaCuO	1.26	119	82.28	1.5±0.1	16±8
	(—)	70	82.80	1.46±0.02	21±2
GdBaCuO	2.28				5±1
		180	91.67	1.49±0.06	
	(0.72)				

main transition in this case (see fig. 3).

The results in fig. 5 and table 2 are suggestive of a general behavior. Some insight on this phenomenon may be provided by percolation theory, which has been largely applied in analyzing the properties of inhomogeneous superconductors showing a smeared transition [35]. In a percolation-type interpretation the zero resistance state is achieved when superconducting grains become interconnected by Josephson or proximity effect. In the past, several authors [36] have proposed such a geometric approach for the transition in other inhomogeneous superconductors. However, in the majority of the cases, the results were interpreted according to the expression [37]

$$\rho \sim (x_c - x)^s , \qquad (10)$$

where x is the concentration of superconducting material and x_c is the critical percolation concentration, which is approached from below. Recent theoretical calculations [38] predict that $s \simeq 1.3$ in 2D percolation systems and $s \simeq 0.75$ in 3D. In contrast, in our experiment we observe a power law dependence with respect to the reduced temperature, as stated in eq. (9). Some authors have argued that the exponents s and s' should be approximately the same, with the assumption of a linear relationship between the superconducting volume fraction and the temperature [39]. However, we have obtained an exponent which is approximately twice the expected 3D value and is neatly higher than the expectation for two dimensions. Thus, if we assume a percolation-type interpretation for the results in fig. 5 and table 2, we have to consider a *non-linear relationship* between temperature and the relative concentration of superconducting material.

A more adequate interpretation is perhaps to suppose that percolation is accompanied by a genuine thermodynamic transition, where long range order is established among the superconducting grains as the phase of the order parameter locks collectively [40]. In this model, superconducting fluctuations across the inter-grain junctions are responsible for the power law behavior. The exponent is then $s' = \nu(4-d)$, where ν is the coherence length critical exponent ($\frac{1}{2}$ in the mean-field case), and the substitution $d \rightarrow \tilde{d}$ could again be considered as a means of introducing inhomogeneity effects. In relation to this, Gusmão and Mors [41] have shown that, by introducing a fractal geometry description for the superconducting grain network, the observed conductivity exponent near T_{c0} may be approached. In this case, our results indicate that a highly non-compact structure of weak-linked grains is formed just below T_c, which is consistent with the very low critical currents usually observed in ceramic samples.

An interesting explanation of the power law behavior close to T_{c0} was proposed by Rosenblatt [42], initially in relation to the behavior of artificial assemblies of superconducting grains. Recently the arguments were extended to ceramic superconductors [22,43]. The formal analogy between the pair tunnelling Hamiltonian of a granular superconductor and the X–Y spin model is used to predict the occurrence of a critical regime for the fluctuating phases of the order parameter associated to individual grains close to the zero resistance state. Within this scheme, s' should be equal to the susceptibility exponent γ. For a translationally invariant X–Y ferromagnet, renormalization group calculations [44] predict that $\gamma \approx 1.33$. However, disorder is expected to increase this value in a certain extent. Peyral et al. [43] have interpreted their results for YBaCuO within this approach, although they report an exponent $s' \simeq 2.7$, which is much higher than the value measured in our experiment. We believe that this discrepancy is due to the fact that they consider larger reduced temperature intervals. Farther from T_{c0}, in some cases, we have also found exponents higher than $s' = 1.47$ (see, for instance, the data for the Gd-based sample in fig. 5). We have noted, however, that these exponents may be current dependent.

6. Conclusions

In order to study the effects of inhomogeneities in the fluctuation conductivity as well as in the nature of the resistive transition in high-T_c oxide superconductors, we performed detailed resistivity measurements near T_c in several samples of polycrystalline $RBa_2Cu_3O_7$ (R = Y, Eu, Gd). Our main results are:

(1) Close to the transition, the temperature derivative of the resistivity, $d\rho/dT$, systematically shows a two-peak structure which resembles the behavior of a granular weak-linked superconductor, and is consistent with a two-step transition from the normal to the superconducting state. We identify two relevant temperatures: the intra-grain transition temperature T_c, where a first sharp peak appears in $d\rho/dT$, and the zero-resistance temperature T_{c0}, where long-range superconducting order is achieved.

(2) Above T_c, the conductivity enhancement due to superconducting fluctuations shows two scaling regimes, described by rather distinct and *sample dependent* exponents. For the regime farther away from T_c the exponent is close to zero, while near T_c a crossover is systematically observed to a regime in which the exponent ranges between 1.0 and 1.5. The observed non-universality may be reconciled with theoretical predictions for gaussian fluctuations of the conductivity if one assumes that the superconducting state develops in a fractal topology, and the fracton dimension, rather than the Euclidean dimension, governs the power law exponents.

(3) The approach to zero resistance is governed by another power law regime, with an exponent which is independent of the particular sample and of the measuring current. This may indicate that the resistive transition is dominated by a percolation phenomenon involving the weak-linked grain network, associated with thermodynamic fluctuations of the order parameter.

We believe that the above description of the superconducting state in the ceramic high-T_c oxides provides some improvement to the simplified granular picture often invoked to explain many properties of these systems. In addition to granularity, our results indicate that inhomogeneities affect the superconducting properties in a subgranular length scale, with the appearance of a superconducting state with fractal topology *inside* the grains. Of course, work on the same lines with single crystals is of definite importance to clarify such matters. The detailed geometric modelling of the system is beyond the scope of this work. However, simulation studies [41] with certain diffusion limited aggregates have shown to approximately reproduce the observed exponents.

To conclude, we are led to suppose that a mesoscopic defect structure probably presenting a fractal topology underlies the behavior of the electronic transport properties of the high-T_c oxide superconductors. Many other properties of these systems, as for instance the magnetic behavior, which is dominated by effects of disorder and frustration, are likely to be dependent on the same inhomogeneous arrangement.

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