Critical and Gaussian conductivity fluctuations in $YBa_2Cu_3O_{7-\delta}$

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We report on systematic conductivity fluctuation measurements on three different samples of $YBa_2Cu_3O_{7-\delta}$. We show, using the temperature derivative of the resistivity and the logarithmic derivative of the conductivity with respect to temperature, that the transition is a two-step process. In the normal phase, contributions from Gaussian and critical fluctuations are clearly evidenced. Far from T_c, the Gaussian exponents indicate that a fractal topology might be adequate to describe the space dimensionality of the fluctuation spectrum. Closer to T_c we observe a crossover to a three-dimensional (3D) homogeneous Gaussian regime. Still closer to T_c we unambiguously identify the exponent $\lambda_{cr} \sim 0.33$, predicted by the simplest full dynamic scaling theory of critical superconducting fluctuations. The obtained exponent is consistent with a 3D, two-component, order parameter. Near the zero-resistance state, the temperature dependence of our data is rather consistent with power-law behavior, suggesting the occurrence of a phase-transition phenomenon related to the percolation granular network.

I. INTRODUCTION

The extremely small coherence length and the strong anisotropy are among the most distinctive properties of the high-temperature cuprate superconductors. A major consequence of these characteristics is the occurrence of large regions where effects of thermal superconducting fluctuations are visible in several of their temperature-dependent properties. Since the early stages in the experimental work, this raises the question of observing or not the scaling regimes dominated by genuine critical fluctuations.[1] Specifically concerning the electrical conductivity, however, up-to-date the most systematic reports available in the literature just evidence the regimes dominated by Gaussian fluctuations, either in $YBa_2Cu_3O_{7-\delta}$ (Refs. 2–5) and $Bi_2Sr_2CaCu_2O_8$.[5,6] This is in contrast with recent results on the specific-heat anomaly near T_C, which are better described by supposing critical, as opposed to Gaussian, fluctuations.[7,8] Results concerning the upper critical field[9] and the Ettingshausen effect[10] were also interpreted in terms of critical fluctuations. As known, the experimental access to the critical region gives information not only on the degree of anisotropy of the superconductor, but also on the symmetry of the order parameter, which is important for modeling the pairing interaction.

In this paper we study carefully the resistive transition of three independent samples of polycrystalline $YBa_2Cu_3O_{7-\delta}$. We show that the transition proceeds as a two-step process. Using a simple but reliable method of analyzing the fluctuation conductivity results, we unambiguously identify a fully dynamical critical regime with the expected exponent for a 3D-*XY* transition. Moreover, we characterize the regime dominated by Gaussian fluctuations and discuss their interplay with structural inhomogeneities. We also briefly present results near the zero resistance state.

II. EXPERIMENT

We have prepared in different times three polycrystalline samples of $YBa_2Cu_3O_{7-\delta}$ following the standard powder solid-state reaction technique. Care was taken to obtain well oxygenated and high-density sintered pellets. Two samples labeled I and II were measured soon after preparation. The third sample (sample III) was first deoxygenated to $\delta \simeq 0.15$ in vacuum at 450 °C. After 60 days approximately, sample III was reoxygenated back to $\delta \simeq 0$. Then the present measurements were taken. Although restoring the behavior of the normal resistivity, the above procedure enlarges specifically the contribution of weak links to the width of the transition.

Resistivity measurements were performed using a low-frequency–low-current ac technique. A variable decade transformer and a lock-in amplifier were employed in a compensating circuit and as null detector, respectively. Relative sensitivities of 10^{-5} were easily attained. Temperatures were determined with a Pt sensor with an accuracy of 1–2 mK. Data points were recorded while increasing or decreasing temperature in sweeping rates of about 2 K/h. The large number of closely spaced points allowed us to numerically determine the temperature derivative of the resistivity near T_c.

III. RESULTS AND DISCUSSION

A. Temperature derivative of the resistivity

Figure 1 shows $d\rho/dT$ as a function of temperature for samples I and III close to T_c. The determination of $d\rho/dT$ is a simple procedure for magnifying details of the transition.[11,12] The asymmetric peak structure observed in Fig. 1 occurs systematically in polycrystalline samples[13] and may be discerned in some single-crystal data.[14] This indicates that the transition in $YBa_2Cu_3O_{7-\delta}$ is a two-step process, a feature which should be properly taken into account when analyzing fluctuation conductivity data. The position T_{cp} of the sharp maximum in $d\rho/dT$ corresponds approximately to the bulk critical temperature. Above T_{cp} the transition is dominated by superconducting fluctuations in the normal phase. In the low-temperature side of the $d\rho/dT$ maximum of sample I, in Fig. 1(a), one may discern a faint hump which develops

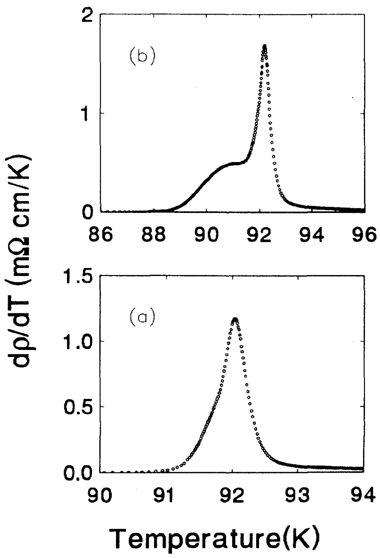

FIG. 1. Temperature derivative of the resistivity near T_c for samples I (panel a) and III (panel b) described in the text.

into a secondary and rounded peak in sample III. This feature is current dependent[13,15] and is related to a thermally controlled percolation-type process, which is strongly dependent on the meso- and macroscopic inhomogeneities affecting superconductivity in $YBa_2Cu_3O_{7-\delta}$.[13,16]

B. Method of analysis

We analyze our data by adopting the simplest approach where fluctuation conductivity, or paraconductivity, diverges as a power law of the type[17]

$$\Delta\sigma = A\varepsilon^{-\lambda} , \tag{1}$$

where $\varepsilon=(T-T_c)/T_c$ is the reduced temperature, λ is the critical exponent, and A is a constant. $\Delta\sigma=\sigma-\sigma_R$ is obtained from the measured σ by subtracting the regular conductivity σ_R. As commonly done, σ_R is calculated from extrapolations of the high-temperature behavior:

$$\sigma \cong \sigma_R = \frac{1}{\rho_R}, \quad \rho_R = \rho_0 + \frac{d\rho_R}{dT} T , \tag{2}$$

where ρ_0 and $d\rho_R/dT$ are constants. In our samples, the linear resistivity behavior holds above 150 K, approximately. Instead of analyzing our results directly with Eq. (1) we determine the logarithmic derivative of $\Delta\sigma$ from the experiment and define

$$\chi_\sigma = -\frac{d}{dT}\ln(\Delta\sigma) . \tag{3}$$

Using Eq. (1) we obtain

$$\frac{1}{\chi_\sigma} = \frac{1}{\lambda}(T-T_c) , \tag{4}$$

which is formally analogous to a Curie-Weiss susceptibility in a ferromagnet, with the critical exponent playing the role of the Curie constant. Thus, simple identification of linear temperature behavior in plots of $1/\chi_\sigma$ versus T allows the determination of T_c and λ. The amplitude A remains undetermined. However, as far as the absolute values of the intrinsic conductivity are not accurately known, A is a less useful parameter.

The main source of uncertainty in our analysis comes from the extrapolation procedure to estimate ρ_R near T_c, as in most paraconductivity studies. Errors introduced by the numerical calculation of the derivative

$$-\frac{d}{dT}(\Delta\sigma) = \frac{1}{\rho^2}\frac{d\rho}{dT} - \frac{1}{\rho_R^2}\frac{d\rho_R}{dT} \tag{5}$$

are partially compensated because the term involving ρ_R in Eq. (5) is small compared to the term containing the total resistivity ρ near the transition.

C. Fluctuations in the normal phase

Figures 2 and 3 show representative results for $1/\chi_\sigma$ as a function of temperature for samples I and III, respectively. Results for sample II look very similar to those for sample I. The measurements were repeated from 5 to 8 times for each sample, under variation of conditions as the sense of the temperature drift or the current density.

From Figs. 2 and 3 it is clear that the transition is a two-step process, which should be described by different phenomenologies above or below T_{cp}. Above T_{cp}, detailed inspection reveals that the best description of $1/\chi_\sigma$ is given by successive straight lines which can be fitted to limited but reproducible temperature ranges. In the majority of measurements we could fit four power-law regimes, corresponding to different exponents. These are labeled by the indices λ_1, λ_2, λ_3, and λ_{cr}, as shown in Figs. 2 and 3 and Table I.

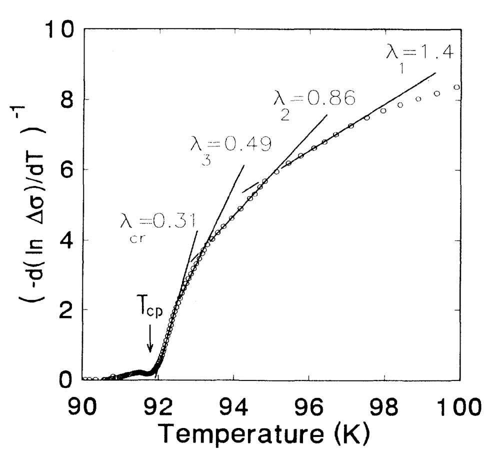

FIG. 2. Representative plot of the logarithmic T derivative of the paraconductivity as a function of T for sample I. Straight lines correspond to fits to Eq. (4). The respective exponents are quoted. T_{cp} indicates the maximum of $d\rho/dT$.

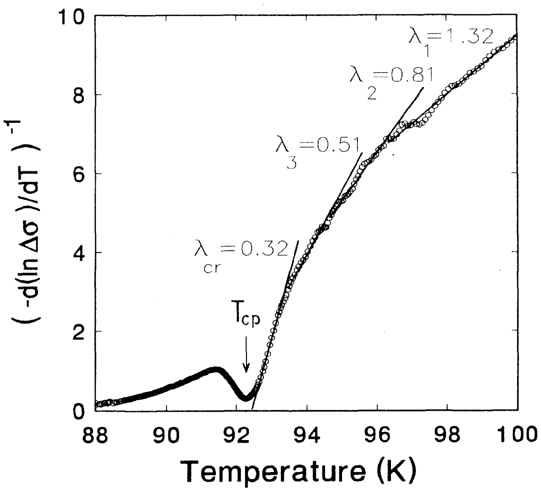

FIG. 3. The same as Fig. 2 but for sample III.

1. *Gaussian fluctuations*

The regimes farther from T_c, λ_1 to λ_3 are dominated by Gaussian fluctuations. The regime λ_1, well above T_c, is the most affected by experimental errors and uncertainty in ρ_R. However, by performing averages over the several measurements, we obtain the mean value of the characteristic exponent, $\lambda_1=1.32\pm0.15$. The second power-law regime is characterized by the exponent $\lambda_2=0.85\pm0.09$. Closer to T_c, the third Gaussian regime is described by the exponent $\lambda_3=0.51\pm0.06$.

On the basis of the Aslamozov-Larkin theory[17] for fluctuation conductivity, one should expect exponents given by

$$\lambda=2-\frac{d}{2}\,, \tag{6}$$

where d is the dimension of the fluctuation system. Our exponents λ_1 and λ_2 do not correspond to integer dimensionality. Nevertheless, we may reconcile these results with the Gaussian theory by supposing that fluctuations develop in a space having fractal topology. In this case, as shown by Char and Kapitulnik,[18] the conductivity exponent should be written as

$$\lambda=2-\frac{\tilde{d}}{2}\,, \tag{7}$$

where $\tilde{d}$ is the fracton dimension of the fluctuation network. It is indeeded known that inhomogeneities in the microscopic and mesoscopic scales strongly affect several properties of the high-T_c superconductors. Concerning paraconductivity in particular, claims for fractality have been reported in the Bi-based systems[5,19,20] and $YBa_2Cu_3O_{7-\delta}$.[13,21] The third Gaussian exponent, λ_3, corresponds to a homogeneous 3D regime, according to Eq. (6).

In the following discussion we assume that the coherence length varies as in the Ginzburg-Landau theory, $\xi(T)=\xi(0)\varepsilon^{-1/2}$, and all the anisotropy is contained in $\xi(0)$. Then, using the value[9] $\xi_{ab}(0)\cong13$ Å, we obtain that in the quasifilamentary λ_1 regime, the length of the superconducting droplet ranges about 50–70 Å. This is a rather short-range scale, where fractality should come from microscopic defects as oxygen vacancies. Dominance of the 1D character could indicate some role of the Cu-O chains along the b axis. In spite of the large error bar we note that the average value of λ_1 is consistent with $\tilde{d}\approx\frac{4}{3}$, which is the well-known fracton dimensionality of the percolation network.[22]

The exponent λ_2 corresponds to a crossover regime between 2D and 3D geometry. Using[9] $\xi_c(0)\simeq2$ Å, one calculates that the superconducting droplet reaches about 12–16 Å along the c direction in this temperature range, showing that fractality in this case could result mainly from imperfect coupling between superconducting planes. It is noticeable that the value $\lambda_2\simeq0.85$ corresponds to $\tilde{d}\simeq2.3$, which is close to $1+\frac{4}{3}$, a value already found by Ausloos *et al.*[5] in a Bi-based compound. Thus, the quasi-2D λ_2 fluctuations might be roughly visualized as homogeneously planar in the ab plane and percolation structured perpendicular to the plane.

The exponent $\lambda_3\simeq0.5$ is just the predicted one for homogeneous three-dimensional fluctuations. In the corresponding temperature range, the droplet would reach sizes of 100–150 Å in the plane and 17–24 Å in the c direction. In this length scale fractality becomes unobservable probably because the superconducting coherence length ξ becomes larger than the percolation coherence length, ξ_p. Indeed a crossover from the fractal regime ($\xi<\xi_p$) to a homogeneous regime ($\xi>\xi_p$) would be expected for bulk intragranular fluctuations, as in this case the percolation backbone would be linked to the defect structure, which gives a ξ_p essentially temperature independent.[5]

2. *Critical fluctuations*

The fourth power-law regime in Figs. 2 and 3 and Table I is labeled by the exponent λ_{cr}. This corresponds to genuine critical fluctuations which were predicted to occur by Lobb[1] but was not unambiguously identified in previous fluctuation conductivity results in $YBa_2Cu_3O_{7-\delta}$. Figure 4 is an expanded view of the critical regime for sample I.

In the critical region, the full dynamical scaling theory[23] predicts that the paraconductivity diverges at T_c as

$$\Delta\sigma\sim\varepsilon^{-\nu(2+z-d+\eta)}\,, \tag{8}$$

where ν is the coherence length critical exponent, z is the dynamical critical exponent, and $\eta\approx0$ describes the departure from the Ornstein-Zernike behavior in the order parameter correlation function. The simplest description of the superconducting transition supposes that the Ginzburg-Landau order parameter is just described by the O(2) rotation group.[24] This means that the thermodynamic properties of superconductor in the critical region are the same as a 3D-XY model.[24] Then, as done by Lobb,[1] one should substitute $\nu\simeq\frac{2}{3}$, $z\simeq\frac{3}{2}$, and

TABLE I. Exponents that characterize conductivity fluctuations in the normal phase of $YBa_2Cu_3O_{7-\delta}$. Values are obtained from fits of experimental data to Eq. (3) (see text). The reduced temperatures indicate the range of validity of each regime.

$YBa_2Cu_3O_{7-\delta}$	Critical fluctuations	Gaussian fluctuations		
Exponents	λ_{cr}	λ_3	λ_2	λ_1
Reduced temperature	$0.0026<\varepsilon<0.0064$	$0.008<\varepsilon<0.015$	$0.016<\varepsilon<0.032$	$0.038<\varepsilon<0.07$
Sample I	0.30±0.04	0.55±0.09	0.85±0.07	1.4 ±0.1
Sample II	0.36±0.06	0.49±0.06	0.88±0.1	1.25±0.3
Sample III	0.32±0.01	0.49±0.04	0.81±0.1	1.32±0.06
Averages	0.33±0.03	0.51±0.04	0.85±0.05	1.32±0.11

$d=3$ in Eq. (8) to obtain $\Delta\sigma \approx (T-T_c)^{-0.33}$, which is expected to be valid very close to T_c, where dynamic scaling effects become dominant.[23] This is just the behavior observed in our samples, where we obtained $\lambda_{cr}=0.33\pm0.03$. Consequently, critical fluctuation conductivity in $YBa_2Cu_3O_{7-\delta}$ is consistent with the simplest superconductivity theory, corresponding to s-wave pairing, which has a single complex (two-component) order parameter.

From our results we may estimate the Ginzburg reduced temperature $\varepsilon_G=(T_G-T_c)/T_c$ below which mean-field theory ceases to be valid. We calculate a critical width, $T_c\varepsilon_G\simeq 0.6$ K, which falls in the range of other estimations in Ref. 25.

D. The approach to the zero resistance state

Decreasing the temperature below the minimum where T_{cp} is located we enter into a region where $1/\chi_\sigma$ goes to zero, as shown in detail in Fig. 5 for samples I and II. This regime is difficult to explain. Interpretations have been proposed in terms of dissipative flux motion, which are likely to be correct in the presence of strong magnetic fields.[26] On the contrary, some authors argue on a phase transition phenomenon involving quenched disorder.[21,27,28]

Most conventional flux-creep formulas do not describe results in Fig. 5. The simplest empirical description of these data is given by power laws of the type

$$\Delta\sigma \sim \varepsilon_o^s , \quad (9)$$

where the reduced temperature $\varepsilon_o=(T-T_{co})/T_{co}$ is related to another critical temperature, T_{co}, which is close to the so-called zero resistance temperature. We generally identify two straight lines in plots like those of Fig. 5, corresponding to exponents s_1 and s_2, displayed in Table II. Our exponents seem to be sample independent for a certain interval of (low) current density. This probably does not hold for large current variations.[15,27]

Power-law behavior is rather suggestive of a phase transition phenomenon. Indeed, the exponent $s_1\simeq 2.7$ have been encountered by Rosenblatt and co-workers[28] in granular superconductors constituted by assemblies of small metallic particles embedded in an insulating matrix, and in ceramic $YBa_2Cu_3O_{7-\delta}$ as well. Rosenblatt[29] proposes an interpretation based on a paracoherent-coherent transition of the granular array, where the fluctuating phase of the order parameter in each grain becomes long-range ordered as a consequence of activation of weak links between the grains.

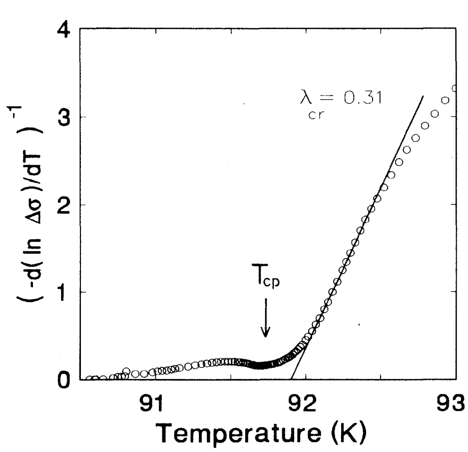

FIG. 4. Expanded view of data in Fig. 2 (sample I) near T_c. The power law denotes the critical regime with the quoted exponent (see Table I).

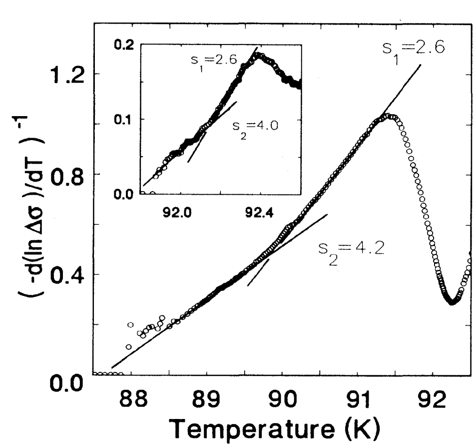

FIG. 5. Expanded view of data in Fig. 3 (sample III) in the regime approaching the zero-resistance state. Straight lines correspond to power-law behavior with the quoted exponents (see Table II). The inset shows similar results for sample II.

TABLE II. Exponents corresponding to power-law behavior in the regime approaching the $R=0$ state, Eq. (8). Values are obtained from fits of the experimental data to Eq. (3).

Exponents	s_2	s_1
Sample I	3.9 ± 0.6	$2.9\ \pm0.7$
Sample II	4.0 ± 0.9	$2.6\ \pm0.2$
Sample III	4.3 ± 0.6	2.59 ± 0.05
Averages	4.1 ± 0.4	$2.7\ \pm0.3$

The exponent $s_2 \simeq 4$ is harder to understand. This uncommon and rather high value might be consequence of fractal-related effects, in analogy to the case of intragrain fluctuations. For instance, certain physical fractals are more compact at short-length scales than in large aggregates.[30] This would imply a crossover in the appropriated fractal dimension as large clusters are coming into play closer to T_{co}. For the moment, because of the lack of an appropriate theory, we should not discard the possibility that the exponent s_2 refers to a noncritical effect. Clearly more detailed studies, either experimental and theoretical, are needed to clarify the behavior of the resistivity very close to the $R=0$ state in the high-T_c superconductors.

IV. CONCLUSIONS

We study experimentally the fluctuation conductivity and the nature of the resistive transition in three samples of polycrystalline $YBa_2Cu_3O_{7-\delta}$. Analysis of the temperature derivative of the resistivity near T_c reveals that the transition is a two-step process, a feature which should be properly taken into account when discussing fluctuation conductivity results. Using a method based on the determination of the logarithmic derivative of the conductivity, we are able to demonstrate the occurrence of Gaussian and critical conductivity fluctuations in the normal phase.

We identify three Gaussian regimes. Far from T_c, in the Gaussian region, the obtained exponents indicate that the fluctuation spectrum is defined in a space characterized by fractal topology. Specifically, the exponents correspond to the fracton dimension of a percolation network in the quasi-1D and in the quasi-2D geometries. Closer to T_c a crossover occurs to homogeneous and three-dimensional Gaussian fluctuations. Still closer to T_c, we observe a full dynamical regime dominated by genuine critical fluctuations. The value obtained for the exponent, $\lambda_{cr} \simeq 0.33$, is entirely consistent with a superconducting transition isomorphic to that of a 3D-XY model, in analogy to superfluidity in ^{4}He.[24] This means that the Ginzburg-Landau order parameter in $YBa_2Cu_3O_{7-\delta}$ has two components, as expected on the basis of simple s-wave pairing. We estimate a critical width of ~ 0.6 K above T_c.

In the regime approaching the zero-resistance state, the data are better described in terms of power-law behavior. This is rather suggestive of the occurrence of a phase-transition phenomenon involving the percolation granular arrangement, where the long-range ordering is achieved through activation of weak links between the grains.

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