Gaussian, three-dimensional-*XY*, and lowest-Landau-level scalings in the low-field fluctuation magnetoconductivity of $Bi_2Sr_2CaCu_2O_8$

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Systematic measurements of low-field fluctuation magnetoconductivity in a single crystal of $Bi_2Sr_2CaCu_2O_8$ are reported. Gaussian, critical, and lowest-Landau-level scalings are observed. In the Gaussian regimes, large intervals corresponding to low-dimensional fluctuations are evidenced. Far above T_c, effects of disorder produces a fluctuation spectrum characterized by a fractal topology. Decreasing the temperature, at first a homogeneous two-dimensional behavior is observed. Then, near T_c a crossover occurs to a narrow three-dimensional (3D) mean-field regime. Still closer to T_c, a scaling consistent with the predictions of the full dynamic 3D-*XY* universality class is clearly evidenced. This genuine critical regime is destroyed upon the application of magnetic fields above a few mT. For fields above a certain limit and in large temperature intervals, fluctuation magnetoconductivity scales as predicted by the lowest-Landau-level approximation of the Ginzburg-Landau theory. [S0163-1829(97)03641-2]

The effect of applied magnetic fields on the large temperature intervals dominated by thermal fluctuations in the high-temperature superconductors (HTSC's) has been the subject of many recent investigations.[1–5] An important and controversial point is related to the interplay between genuine critical fluctuations, which are observable in the presence of zero or very small fields,[3–5] and the lowest-Landau-level (LLL) scaling which should prevail at high enough fields.[2,5,6] Some authors claim on the relevance of the three-dimensional (3D)-*XY* thermodynamics to describe the critical phenomenology of the HTSC's in fields up to 10 T and in temperature intervals about 5 K above and below T_c,[4,7] while others find good agreement of data in these field and temperature ranges with the LLL type of scaling.[2,5,6]

In this report we present low-field fluctuation magnetoconductivity measurements in a single-crystal sample of $Bi_2Sr_2CaCu_2O_8$ (Bi-2212). Far from T_c, our results at zero and very low fields show the occurrence of large temperature intervals dominated by low-dimensional Gaussian fluctuations, as found earlier.[8,9] These regimes are unstable upon the application of magnetic fields and are markedly affected by disorder. Very close to T_c we clearly identify a genuine critical fluctuation region with an exponent consistent with the predictions of the full dynamic 3D-*XY* model.[10] This regime is destroyed by quite small fields and is confined to a temperature interval of ~ 0.1 K above T_c. When the applied field exceeds a value of a few mT, we identify a single LLL fluctuation regime in a large temperature interval above T_c.

The single crystal of Bi-2212 was grown in a rotatory gold crucible, according to details given in Ref. 11. Resistivity measurements were performed with a low-frequency–low-current ac method using a lock-in amplifier as a null detector. During the resistivity measurements, uniform magnetic fields in the range 0–50 mT were applied either parallel or perpendicular to the Cu-O planes of the layered Bi-2212 structure. For the in-plane geometry, the current was kept at right angle with the field direction. Temperatures were determined with a Pt sensor having an accuracy of 1–2 mK. Data points were recorded while increasing or decreasing the temperature in sweeping rates of 3 K/h, or smaller, near the transition. A large number of closely spaced points were collected in order to allow the numerical determination of the temperature derivative of the resistivity, $d\rho/dT$, in the interval encompassing the transition temperature.

For analyzing the results we adopt the simplest approach, which assumes that the fluctuation magnetoconductivity diverges as a power law:

$$\Delta\sigma(T,B)=A\epsilon^{-\lambda}, \tag{1}$$

where $\epsilon=[T-T_c(B)]/T_c(B)$ is the field-dependent reduced temperature, λ is the critical exponent, and A is a constant. As usual, the fluctuation magnetoconductivity is obtained from $\Delta\sigma=\sigma-\sigma_R$, where $\sigma=\sigma(T,B)$ is the measured magnetoconductivity and σ_R is the regular term extrapolated from the high-temperature behavior.

In analogy with the Kouvel-Fisher method of analysis of critical phenomena,[12] we determine numerically

$$\chi_\sigma=-(d/dT)\ \ln\Delta\sigma. \tag{2}$$

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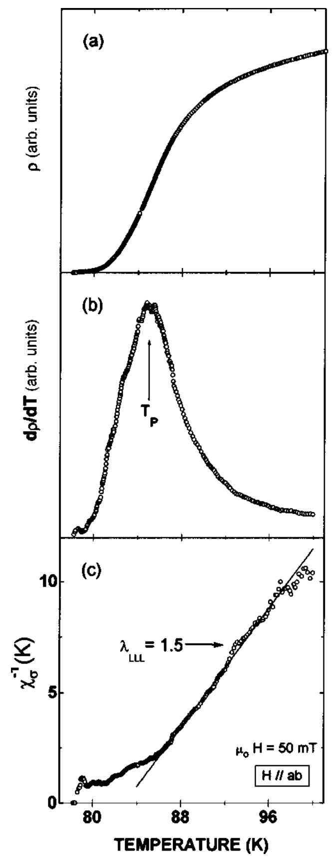

FIG. 1. Superconducting transition in Bi-2212, measured in $\mu_0 H = 50$ mT applied parallel to the ab planes and determined as (a) resistivity versus T, (b) $d\rho/dT$ versus T, and (c) the inverse of the logarithmic derivative of the conductivity χ_σ^{-1} versus T. The temperature interval is the same for the three plots. The exponent quoted in panel (c) is obtained from the slope of the fitted straight line. Its value is typical of LLL scaling, as discussed in the text.

Using Eq. (1), we obtain

$$\chi_\sigma^{-1} = (1/\lambda)(T - T_c). \tag{3}$$

Thus, simple identification of linear temperature behavior in plots of χ_σ^{-1} versus T allows simultaneous determination of T_c and λ. Once defined the temperature interval where the scaling is observed, the constant A may be calculated by substituting the values of T_c and λ in Eq. (1).

The quantity χ_σ is also useful to verify if the Lawrence-Doniach (LD) approach[13] is adequate to describe the regimes dominated by Gaussian fluctuations in Bi-2212. This theory, which is relevant for layered superconductors, predicts the occurrence of a crossover from a 3D-fluctuation regime near T_c to an effectively 2D-decoupled regime in temperature intervals farther from T_c. The critical temperature, however, remains the same for both asymptotic regions, and the inverse T-logarithmic derivative is written as

$$\chi_\sigma^{-1} = 2T_c\epsilon(\epsilon + \alpha)/(2\epsilon + \alpha), \tag{4}$$

where $\alpha = [2\xi_c(0)/s]^2$, $\xi_c(0)$ is the amplitude of the Ginzburg-Landau (GL) coherence length perpendicular to the planes, and s is the spacing between the layers.[13]

As an example of our method of analysis, in Fig. 1 we show the resistive transition of our sample, measured in

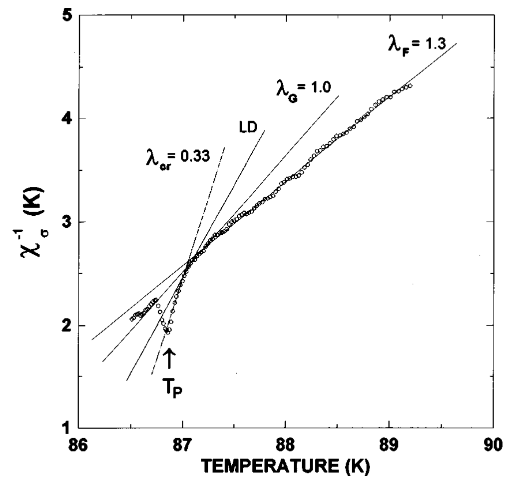

FIG. 2. Representative plot of χ_σ^{-1} as a function of T in Bi-2212 at $\mu_0 H = 1$ mT applied parallel to the Cu-O planes. Straight lines are fits to Eq. (3) with the quoted exponents or to Eq. (4) (labeled LD). The temperature T_P corresponds to the maximum of $d\rho/dT$.

$\mu_0 H = 50$ mT applied parallel to the Cu-O planes. In panels (a) and (b), resistivity and $d\rho/dT$ results are plotted, respectively. In panel (c), the transition is shown as χ_σ^{-1} versus T in the same temperature interval. In this panel, the slope of the straight line gives the exponent $\lambda = 1.5$, which is typical of LLL scaling. Also indicated in Fig. 1 is the temperature T_P which signals the maximum of $d\rho/dT$. This is an useful parameter since it gives a lower bound for observing fluctuations in the normal phase.

The critical exponent for the fluctuation conductivity is given by[10]

$$\lambda = \nu(2 + z - d + \eta), \tag{5}$$

where ν is the critical exponent of the correlation length, z is the dynamical exponent, d is the dimension of the system, and η is a small exponent. The GL theory predicts that $\nu = 1/2$, $z = 2$, and $\eta = 0$. Thus, the Gaussian exponents depend solely on the dimensionality as $\lambda_G = 2 - d/2$.[14]

Figure 2 shows a plot of χ_σ^{-1} versus T, obtained for $\mu_0 H = 1$ mT applied parallel to the Cu-O planes, in an extended temperature interval which is mainly dominated by contributions from mean-field fluctuations. We identify three power law regimes in this Gaussian region, which are represented by continuous lines in the figure. As seen in the expanded view of Fig. 3, in a narrow temperature interval (approximately 0.1 K) close to T_c, we obtain $\lambda_G \cong 0.50$, which is the value expected for homogeneous 3D Gaussian fluctuations. Increasing the temperature, a crossover occurs to a regime described by the exponent $\lambda_G \cong 1.0$. This corresponds to 2D mean-field fluctuations, which are indeed expected to occur in an anisotropic layered system as Bi-2212 and are effectively observed by several other authors.[8,9,15] However, the 3D-2D crossover cannot be reproduced by the LD theory. Fitting the χ_σ^{-1} results to Eq. (4) in the 3D asymptotic limit (line labeled LD in Fig. 2), we obtain the parameter $\alpha = 0.40$. Using the value $\xi_c \cong 0.1$ nm,[16] we calculate $s \cong 0.3$ nm. This value for s is of the order of the distance between the sheets in the double Cu-O layers characteristic of the Bi-2212 structure. However, one may expect that when $\xi_c(T)$ becomes

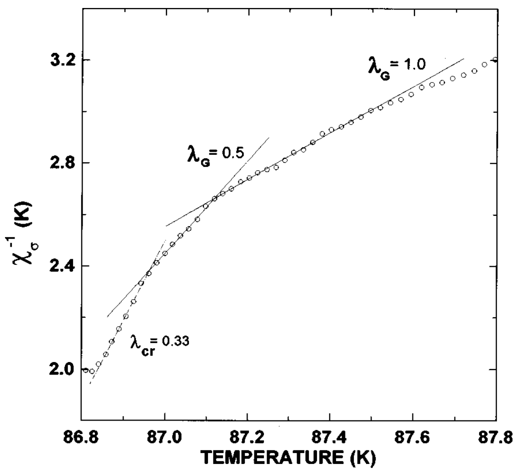

FIG. 3. Expanded view of the χ_σ^{-1} plot in Fig. 2 showing the power-law regimes in the vicinity of T_P.

smaller than the separation between the double-plane structures, which is $c/2 \cong 1.5$ nm, the layered system would effectively decouple. Then, the fluctuation spectrum acquires a 2D character, with a mean-field critical temperature smaller than that extrapolated from the 3D regime. From the reduced temperature where the 3D-2D crossover occurs in our sample, we estimate $\xi_c(T) \cong 1.4$ nm, which is indeed of the order of $c/2$.

Farther from T_c, we observe in Fig. 2 a large power-law regime corresponding to the exponent $\lambda_F = 1.30(\pm 0.07)$. This value may be understood within the Gaussian approach if fluctuations develop in a fractal space. Then, as shown by Char and Kapitulnik,[17] the exponent for fluctuation conductivity is $\lambda = 2 - \tilde{d}/2$, where $\tilde{d}$ is the spectral dimension for the fluctuation network. The obtained value for λ_F is consistent with $\tilde{d} \cong 4/3$, which is the well-known spectral dimension for the percolation problem.[18] Several reports claim on the relevance of fractality for explaining noninteger exponents in fluctuation conductivity in both Bi-based[19] and Y-based[20] superconductors. In the case of our single-crystal sample, disorder is likely to come from oxygen nonstoichiometry and other microscopic and mesoscopic defects which are known to occur in Bi-2212 superconductors.

Decreasing the temperature towards T_c we observe in Figs. 2 and 3 a sharp crossover in the general χ_σ^{-1} versus T behavior. This denotes the breakdown of the mean-field description of the conductivity fluctuations in Bi-2212. A power law with exponent $\lambda_{cr} \cong 0.33$ could be fitted to the data in a temperature interval of about 0.1 K above T_P, as indicated by a dashed line in the figure. The obtained value for λ_{cr} is in agreement with the predictions of the full dynamic 3D-XY model,[10] for which $\nu = 0.669$, $\eta \cong 0$, and $z = \frac{3}{2}$.[21,22]

The application of rather small magnetic fields destroys the 3D-XY scaling. For instance, the scaling with exponent $\lambda_{cr} \cong 0.33$ breaks down when fields above 10 mT are applied parallel to the Cu-O planes. This characteristic field is as low as 0.3 mT for the $H \| c$ configuration.

Figure 1(c) shows a plot of χ_σ^{-1} versus T, where a single straight line could be fitted to a large portion of the fluctuation interval. The slope of this line gives the exponent $\lambda_{LLL} \cong \frac{3}{2}$, which is characteristic of lowest Landau level scaling.

TABLE I. Exponents that characterize magnetoconductivity fluctuations in the normal phase of Bi-2212. For each applied field, exponents are obtained from fits of experimental data to Eq. (3). At least two independent experimental runs were performed for each field value. The critical exponent is λ_{cr}. The Gaussian regimes are labeled by the exponents $\lambda_G^{(3D)}$, $\lambda_G^{(2D)}$, and λ_F. These correspond to homogeneous 3D, 2D, and fractal AL fluctuations, respectively. Also listed are the exponents λ_{LLL} that characterize fluctuations in the lowest Landau level regime.

$\mu_0 H \| c$	Critical		Gaussian		LLL
(mT)	λ_{cr}	$\lambda_G^{(3D)}$	$\lambda_G^{(2D)}$	λ_F	λ_{LLL}
0	0.33	0.53	1.06	1.29	
0.2	0.34	0.53	1.0	1.38	
0.3	0.33	0.42	1.0	1.39	
0.4		0.50	0.9	1.29	
0.5		0.56	1.15	1.39	
1.0			1.0	1.31	1.5
2.0					1.4
5.0					1.5
averages	0.33 ± 0.04	0.50 ± 0.06	1.01 ± 0.09	1.35 ± 0.06	1.5 ± 0.1
$\mu_0 H \| ab$	λ_{cr}	$\lambda_G^{(3D)}$	$\lambda_G^{(2D)}$	λ_F	λ_{LLL}
0	0.33	0.53	1.06	1.29	
1	0.30	0.47	1.0	1.24	
2	0.29	0.47	0.86	1.4	
3	0.34	0.41	0.91	1.3	
5	0.36	0.54	1.02	1.30	
7.5	0.39	0.61	1.2	1.22	
10		0.53	1.11	1.26	
20		0.47	1.11	1.39	1.6
35					1.5
50					1.5
averages	0.34 ± 0.04	0.50 ± 0.06	1.0 ± 0.1	1.30 ± 0.07	1.5 ± 0.1

When the field is strong enough to confine superconductivity in the LLL, the system would become effectively one dimensional, since the only degree of freedom left for fluctuations is along the field direction. In the Gaussian approximation,[23] the exponent would be $\frac{3}{2}$, as effectively observed. Lowest Landau level scaling is obtained in our sample when the field exceeds the characteristic values $\mu_0 H_{LLL}^{(\|)} \cong 1$ mT for $H \| c$ and $\mu_0 H_{LLL}^{(\perp)} \cong 30$ mT for $H \| ab$. These characteristic fields are rather small when compared to theoretical predictions indicating that below $H_{LLL} \cong 1$ T inter-LL interactions should be taken into consideration.[5,24] However, one could argue that, within the Gaussian approach and for any field above H_{c1}, the LLL scaling might be observable in a small temperature interval immediately above T_c, since these fluctuations would stabilize as vortices in the mixed state.

Various measurements as those shown in Figs. 1–3 were performed. In Table I we list the exponents obtained in the critical, Gaussian, and LLL regimes at several values of the applied field and for two field-sample geometries. For each of these measurements, at least two independent runs were made. In several cases, where the exponent value or the interval of validity of a given scaling needed to be checked, the

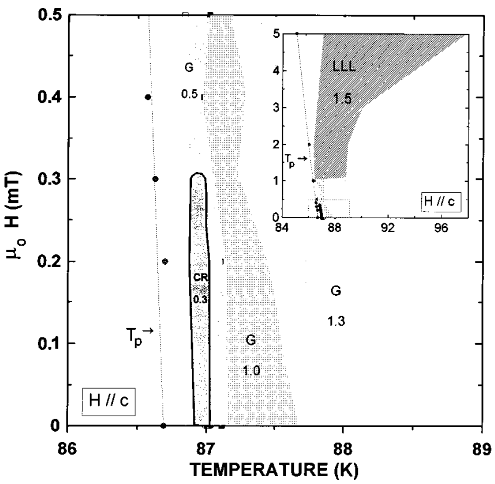

FIG. 4. H-T diagram showing the regions of dominance of Gaussian and critical scaling in the low-field limit of the $H\|c$ configuration. The regions are labeled by the observed exponents. The location of the 3D-XY regime is marked by a contour. The inset shows the large domain at higher fields where the LLL scaling is observed. The area limited by the dotted lines is enlarged in the main picture.

measurements were repeated four or more times. The whole set of results were used to draw H-T diagrams where the regions of dominance of each type of scaling are represented. An example is given by Fig. 4 which shows the low-field portion of the diagram obtained for the $H\|c$ configuration. In this diagram we encircle by a continuous line the narrow domain where 3D-XY fluctuations were observed. In the inset of this figure, data are presented for fields up to 5 mT. There one observes that above $\mu_0 H_{\rm LLL}^{\|} \cong 1$ mT, only LLL scaling could be identified.

In accordance with several reports,[8,9,15,16,18] our low field fluctuation magnetoconductivity results in Bi-2212 reveal the occurrence of large temperature intervals dominated by low-dimensional Gaussian fluctuations. However, when the temperature approaches T_c from above, we observe a crossover to an homogeneous 3D behavior. Our results indicate that although the LD theory describes correctly the 3D limit of the Gaussian regime, it fails to reproduce the observed 3D-2D crossover. This happens because Bi-2212 is a system with double planar periodicity:[25] the distance between Cu-O layers within the double-plane structures, $s \cong 0.3$ nm, controls the 3D fluctuation spectrum, whereas the decoupling to an effectively 2D fluctuation regime occurs when $\xi_c(T)$ decreases to about $c/2$, which gives the periodicity length associated with the double superconducting layers. We remark that the interpretation of our results in the mean-field region could be done without considering indirect contributions such as the Maki-Thompson term.[26]

Genuine critical behavior is clearly identified in our magnetoconductivity measurements. The obtained exponent is $\lambda_{\rm cr} = 0.33(\pm 0.04)$, which is entirely consistent with the predictions of the 3D-XY universality class with the model-F dynamical exponent $z = 3/2$.[22] This observation implies the validity of the simplest description of the superconducting transition, where the GL order parameter is described by the O(2) rotation group. In other terms, critical fluctuations of the conductivity indicate that a purely symmetric pairing state characterizes superconductivity in Bi-2212.

The critical temperature width at zero field is approximately 0.1 K, which is much smaller than that observed in $YBa_2Cu_3O_7$, where it amounts to about 0.5 K.[20] These numbers are in apparent contradiction with expectations based on the Ginzburg number, which is larger for Bi-2212 owing to its greater anisotropy. However, since the relevant critical thermodynamics is 3D, larger anisotropy just squeezes this regime to the very close vicinity of T_c.

The 3D-XY scaling is stable in the presence of magnetic fields up to $\mu_0 H_{XY}^{(\|)} \cong 0.3$ mT for $H\|c$ and $\mu_0 H_{XY}^{(\perp)} \cong 8$ mT for $H\|ab$. When the field exceeds $\mu_0 H_{\rm LLL}^{(\|)} \cong 1$ mT ($H\|c$) or $\mu_0 H_{\rm LLL}^{(\perp)} \cong 30$ mT ($H\|ab$), magnetoconductivity scales as expected from the lowest-Landau-level approximation of the GL theory.

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