Fluctuation magnetoconductivity in $YBa_2Cu_3O_7$: Gaussian, three-dimensional XY, beyond three-dimensional XY, and lowest-Landau-level scaling

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Systematic measurements of the in-plane fluctuation magnetoconductivity in a $YBa_2Cu_3O_7$ single crystal are presented. Fields between 0 and 14 T were applied either parallel or perpendicular to the Cu-O atomic planes. The data reveal the occurrence of a large Gaussian regime in the normal phase. Far above T_c, the mean-field fluctuation spectrum is effectively two dimensional. Decreasing the temperature towards T_c, a crossover to a three-dimensional (3D) Gaussian regime is seen at low applied fields. The analysis of these results allows the estimation of the coherence length perpendicular and parallel to the Cu-O planes, and reveals that superconductivity in $YBa_2Cu_3O_7$ is characterized by a double planar periodicity. The c lattice parameter is the relevant periodicity length of the 2D behavior, whereas the smallest distance between the double Cu-O layers plays an important role in the 3D fluctuation spectrum. In fields above 5 T applied parallel to the c axis, the fluctuation magnetoconductivity scales as predicted by the 3D lowest-Landau-level approximation of the Ginzburg-Landau theory. Very close to T_c, and for quite low values of the applied field, the results clearly show the occurrence of a genuine critical regime, where the exponent is consistent with the predictions of the full dynamic 3D XY universality class. Still closer to T_c, evidence is found for a fluctuation regime beyond 3D XY scaling. This new scaling raises the interesting possibility for the ultimate weakly first-order character of the superconducting transition in $YBa_2Cu_3O_{7-\delta}$. The whole set of data is condensed on H-T diagrams, which display the regions of stability for the observed fluctuation regimes, in fields oriented parallel or perpendicular to the Cu-O layers.

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I. INTRODUCTION

Thermodynamic fluctuations are observed in equilibrium and transport properties of the high-T_c cuprates (HTSC's) in large temperature ranges above and below the normal-superconductor transition.[1] The study of Gaussian fluctuations, which are observed far above T_c, has been useful for obtaining informations on the effective dimensionality of superconductivity in the HTSC materials.[2,3] Moreover, it provides a method for determining quantitatively the anisotropic Ginzburg-Landau (GL) coherence length.[4,5]

Recently, accurate specific-heat[6] and electrical-conductivity[7] measurements very close to T_c revealed the effects of genuine critical fluctuations, which belong to the three-dimensional (3D) XY universality class. One important related question, which has been addressed by several authors,[8–10] concerns the robustness of the 3D XY scaling upon the application of a magnetic field. Indeed, in high enough fields, the superconducting transition should be described by the lowest-Landau-level (LLL) approximation of the GL theory.[11,12] However, for $YBa_2Cu_3O_7$ (YBCO), controversy remains about the magnitude of the field and the width of the temperature interval that delimit the regions of stability of the 3D XY thermodynamics. Some authors claim relevance of the 3D XY critical phenomenology in fields up to 10 T and in temperature ranges about ± 5 K around T_c,[8,13] while others find good agreement of specific-heat and magnetization data with the LLL type of scaling in these field and temperature ranges.[9,10,14]

Most of the experimental work performed with the purpose of studying 3D XY or LLL scalings consists of specific-heat and magnetization measurements. However, conductivity experiments in applied magnetic fields (magnetoconductivity) are also interesting, since fluctuation effects are huge in this case, and accurate measurements can be easily done. These experiments give quantitative information that should be useful for clarifying some of the controversial aspects related to field effects on regimes dominated by thermal fluctuations in YBCO. In addition, fluctuation-conductivity measurements in the critical region allow the determination of the dynamical exponent z. This is also a controversial subject since certain data are interpreted by assuming a relaxation dynamics with $z=2$,[15] while other workers suggest[7,16] the model-E value[17] $z=1.5$, even in the presence of an applied magnetic field.[18]

In this article we report field-dependent fluctuation conductivity measurements in a YBCO single crystal. Fields up to 14 T were applied either parallel ($H\|ab$) or perpendicular ($H\|c$) to the Cu-O atomic planes. In the normal phase, far from T_c, we observe a large Gaussian regime that is dominated by two-dimensional (2D) fluctuations. This regime is stable up to the highest applied field when $H\|ab$ but it is rounded off in fields above 1 T for the $H\|c$ configuration. Decreasing the temperature towards T_c, and in fields below 1 T for both orientations, a crossover to a 3D Gaussian regime is seen. This study of the 3D Gaussian regime allows us to estimate the coherence length along the c axis. We also obtain the field dependence of the mean-field critical temperature, from which we calculate the in-plane coherence length. In fields above 5 T applied along the c axis, the fluctuation conductivity scales according to the 3D LLL theory[12] in a broad temperature range around the transition. In very low applied fields and in a narrow temperature range about 0.5 K above T_c, we observe a genuine critical regime, where the exponent is consistent with the predictions for the full dynamic 3D XY universality class.[19] Still closer to T_c, our results reveal a scaling regime beyond 3D XY fluctuations, which has been first reported in Ref. 20. The origin of this new fluctuation regime is still unknown, but the very low value found for the corresponding exponent suggests its interpretation as precursor of an ultimate weakly-first-order pairing transition in YBCO. The whole set of data is condensed in H-T diagrams showing the regions of validity of the various fluctuation regimes observed for fields oriented parallel and perpendicular to the Cu-O atomic planes.

II. EXPERIMENTAL DETAILS AND METHOD OF ANALYSIS

A. Sample preparation and measurement techniques

A single crystal of YBCO was grown by a self-flux method in a yttria-stabilized zirconia (YSZ) crucible. Oxygenation was performed for 6 days at 500 °C. The crystal is uniformly microtwinned and has an oxygen content between 6.90 and 6.92. Further details on the sample preparation and characterization may be found in Ref. 21.

In-plane resistivity measurements were performed with a low-frequency low-current ac technique that employs a lock-in amplifier as null detector. Four in-line electrical contacts were painted silver on one sample surface. Contact resistances below 1 Ω could be obtained. During the resistivity measurements, uniform magnetic fields in the range 0–14 T were applied parallel or perpendicular to the Cu-O layers. For the in-plane configuration, the field was applied either parallel or at a right-angle to the current direction. The misalignments are estimated to be below 3°. Temperatures were determined with a Pt sensor that has an accuracy of 1–2 mK and was corrected for magnetoresistance effects. Data points were recorded while increasing or decreasing the temperature in rates of 3 K/h or smaller. A large number of closely spaced points were recorded in order to allow the numerical determination of the temperature derivative of the resistivity, $d\rho/dT$, in the temperature range encompassing T_c.

B. Method of analysis

For analyzing the results we adopt the simplest approach, which assumes that the field-dependent fluctuation conductivity diverges as a simple power law,

$$\Delta\sigma(T,H)=A\varepsilon^{-\lambda}. \quad (1)$$

In the above equation, $\varepsilon\equiv[T-T_c(H)]/T_c(H)$ is the field-dependent reduced temperature, λ is the critical exponent, and A is a constant. The fluctuation magnetoconductivity is obtained from $\Delta\sigma=\sigma-\sigma_{\mathrm{R}}$, where $\sigma=\sigma(T,H)$ is the measured conductivity and σ_{R} is the regular term extrapolated from the high-temperature behavior,

$$\sigma_{\mathrm{R}}=(a+bT)^{-1}, \quad (2)$$

where a and b are phenomenological constants that depend weakly on the applied field.

In analogy with the Kouvel-Fisher method[22] for the analysis of critical phenomena, we determine numerically

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

Using Eq. (1), we deduce that

$$\chi_\sigma^{-1}=\frac{1}{\lambda}(T-T_c). \quad (4)$$

Thus, the simple identification of a linear temperature behavior in plots of χ_σ^{-1} versus T allows the simultaneous determination of T_c and λ. With the definition of the temperature region in which scaling is observed, the amplitude A may be easily calculated from Eq. (1) by substituting in it the values of T_c and λ previously determined.

The quantity χ_σ^{-1} may also be used to verify the applicability of the Lawrence-Doniach (LD) approach[23] to the regimes dominated by Gaussian fluctuations in HTSC's. According to that theory, which is relevant for layered superconductors, a crossover occurs from a 3D fluctuation regime near T_c to an effectively 2D decoupled regime in temperatures far above T_c. The critical temperature, however, remains the same for both asymptotic regions. Within this approach the quantity χ_σ^{-1} is written as

$$\chi_\sigma^{-1}=\frac{2T_c\varepsilon(\varepsilon+\alpha)}{2\varepsilon+\alpha}, \quad (5)$$

where $\alpha\equiv[2\xi_c(0)/s]^2$, $\xi_c(0)$ is the amplitude of the GL coherence length perpendicular to the layers, and s is the spacing between the layers.[23]

As an example of our method of analysis, in Fig. 1 we show the resistive transition of our YBCO sample at zero field. In panels (a) and (b), ρ and $d\rho/dT$ results are plotted, respectively. In panel (c), the transition is shown as χ_σ^{-1} versus temperature. The slope of the straight line on the figure gives the exponent $\lambda=0.17$, which corresponds to a new critical fluctuation regime, as discussed in Sec. IV B 1. Also signaled in Fig. 1 is the temperature of maximum $d\rho/dT$, denoted as T_p. In low and moderate applied fields this temperature is a useful parameter since it represents a lower limit for observing fluctuation regimes in the normal phase. It can also be a good approximation for the critical temperature in studies of conductivity fluctuations in the mean-field region.[3]

The numerical procedure to determine χ_σ^{-1} and the extrapolation to estimate σ_R introduce uncertainties in the values obtained for the critical exponents. However, these errors tend to become small near T_c, since a large fraction of the total conductivity in this temperature region is due to fluctuations. In order to minimize uncertainties, we performed at least two measurements of ρ versus T for a given applied

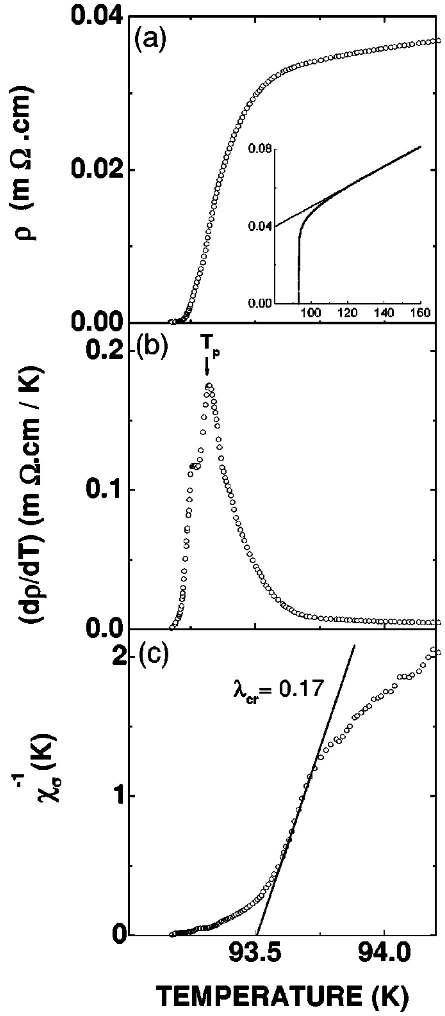

FIG. 1. Superconducting transition in YBCO at zero field plotted as (a) resistivity versus *T*, (b) $d\rho/dT$ versus *T*, and (c) inverse logarithmic derivative of the conductivity, χ_σ^{-1}, versus *T*. The temperature range is the same for the three plots. The exponent quoted in panel (c) is obtained from the slope of the fitted straight line.

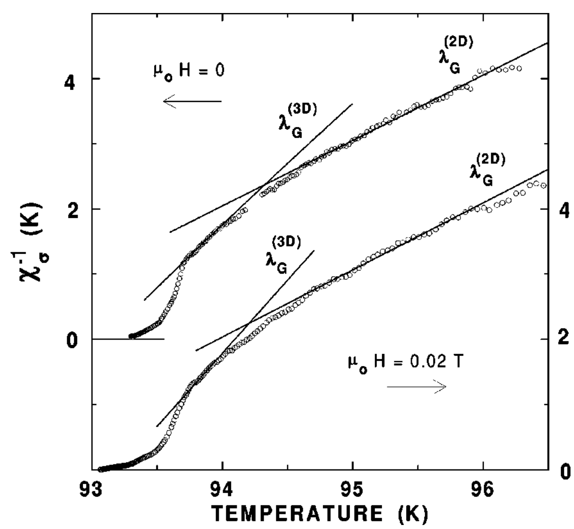

FIG. 2. Representative plots of χ_σ^{-1} as a function of *T* for YBCO. Results are obtained in zero applied field, and in $\mu_0 H = 0.02$ T ($H \| ab$). The straight line labeled by the exponent $\lambda_G^{(2D)}$ ($=1.0 \pm 0.1$) is a fit to Eq. (4), and corresponds to a 2D Gaussian fluctuation regime. The line labeled by $\lambda_G^{(3D)}$ ($=0.50 \pm 0.04$) is also a fit to Eq. (4), and represents a 3D Gaussian regime.

field. Four or more of these independent runs were performed in several cases in order to check the exponent values, to estimate their uncertainties, and to obtain a better definition of the temperature ranges relevant for the various scaling regimes observed. In such cases, the reported exponents are average values over the runs.

III. RESULTS

In Fig. 2 we show measured values of χ_σ^{-1} versus T in a large temperature range above T_c, both in zero applied field and in $\mu_0 H = 20$ mT ($H \| ab$). These results are representative of the behavior of this quantity in low applied fields, $\mu_0 H \leqslant 100$ mT for $H \| ab$ and $\mu_0 H \leqslant 10$ mT for $H \| c$. Far above T_c, and in a large temperature range, we obtained fits of χ_σ^{-1} to Eq. (4) with the exponent $\lambda_G^{2D} = 1.0(\pm 0.1)$, for both measurements in Fig. 2. This behavior is indicative of two-dimensional Gaussian fluctuations. Decreasing the temperature towards T_c we notice a smooth crossover to another power-law regime, characterized by the exponent $\lambda_G^{2D} = 0.50 \pm 0.03$. This is a three-dimensional Gaussian regime, which is unaffected by magnetic fields in the ranges $\mu_0 H \leqslant 1$ T ($H \| ab$) and $\mu_0 H \leqslant 0.1$ T ($H \| c$). Further decreasing the temperature, but still in the normal phase (above T_p), we observe a marked crossover to power-law regimes characterized by small exponents. This indicates the breakdown of the mean-field description for the fluctuation conductivity in our YBCO crystal. In Figs. 3, 4, and 5 we show expanded views of representative results for χ_σ^{-1} versus T in the close vicinity of T_c. In Fig. 3, data for several fields applied parallel to the ab plane are shown. The obtained scalings are indicative of genuine critical conductivity fluctuations. Just below the Gaussian region, we notice a regime labeled by the exponent $\lambda_{cr}^{(1)} = 0.33 \pm 0.02$. At very low fields, this regime holds in a temperature range smaller than 0.1 K, and may be discerned only when a given experiment is individually analyzed, as done in Fig. 5, and in Fig. 2 of Ref. 20. In plots like those of Figs. 3 and 4, the $\lambda_{cr}^{(1)}$ regime may be visualized above a certain value of the applied field. In very low fields, as shown in Figs. 3 and 4, the asymptotic power-law regime in the fluctuation conductivity of our YBCO crystal corresponds to an exponent $\lambda_{cr}^{(2)} = 0.17 \pm 0.01$. This regime is rounded off in very small magnitudes of the applied field (approximately 5 mT when $H \| ab$). At fields around 50 mT ($H \| ab$) or 10 mT ($H \| c$), a crossover regime with $\overline{\lambda} \simeq 0.24$ is observed, as represented in the figures. When the field attains 100 mT ($H \| ab$) or 20 mT ($H \| c$), the only power law observed in the critical region corresponds to the $\lambda_{cr}^{(1)}$ exponent. Above $\mu_0 H \simeq 150$ mT ($H \| ab$) and $\mu_0 H \simeq 40$ mT ($H \| c$) the regime $\lambda_{cr}^{(1)}$ is also rounded off. The ultimate critical regimes observed are those corresponding to $\lambda_{cr}^{(1)}$ and $\lambda_{cr}^{(2)}$. When the temperature is further decreased towards T_p, χ_σ^{-1}

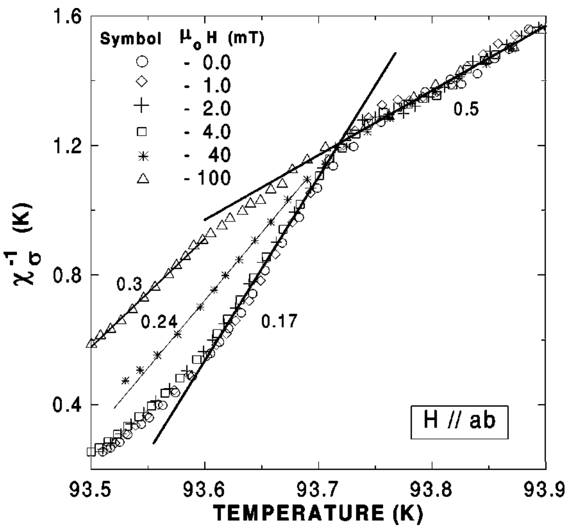

FIG. 3. Expanded view of χ_σ^{-1} versus T in the critical-fluctuation region. Results for several (low) fields applied parallel to the ab planes are shown. The straight line labeled by the exponent $\lambda_{cr}^{(2)}=0.17$ correspond to a regime beyond the 3D XY fluctuations, which is observable in very low values of the field. Larger fields tend to suppress this behavior, and stabilize a regime with an exponent close to $\lambda_{cr}^{(1)}=0.33$, which corresponds to critical 3D XY-E fluctuations.

becomes rounded, and no power-law behavior can be systematically identified.

For the geometry $H\|ab$, we observe in χ_σ^{-1} a power-law regime with exponent $\lambda_G^{2D}=1$ up to the highest studied field and for both field-current configurations ($H\|j$, $H\perp j$). However, the 3D Gaussian regime is rounded off above $\mu_0 H=1$ T, independently of the field orientation in the ab plane. When $H\|c$, we observe a 2D Gaussian region in fields up to 1 T, whereas the 3D Gaussian regime is discerned only up to $\mu_0 H=0.1$ T. For this field orientation, and for field magnitudes above 2.5 T, no single power law in χ_σ^{-1} could be

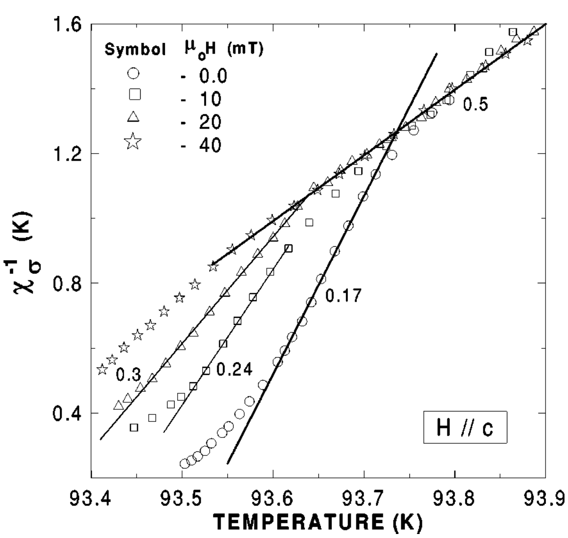

FIG. 4. The same as Fig. 3, but for fields oriented parallel to the c axis. In this case, fields below $\mu_0 H=10$ mT could not be applied.

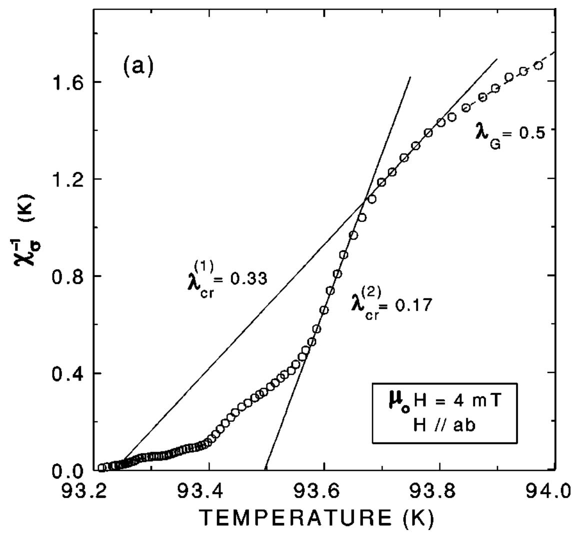

FIG. 5. Representative run of χ_σ^{-1} versus T in the critical region, allowing the observation of the narrow regime characterized by the exponent $\lambda_{cr}^{(1)}=0.33$ (3D XY-E), which is located between the Gaussian and the asymptotic $\lambda_{cr}^{(2)}=0.17$ regimes.

identified. However, for $\mu_0 H=5$ T and above, the fluctuation magnetoconductivity data could be reasonably fitted to the 3D LLL scaling theory, as discussed in Sec. IV D.

We remark, from the results in Figs. 1–5, that the extrapolated critical temperatures are slightly different for the various scaling regimes observed. This fact, which becomes evident in our method of analysis, in which T_c is not considered as a unique fitting parameter, is indeed expected on physical grounds. For instance, the critical temperature relevant for a mean-field Gaussian fuctuation regime should not be exactly coincident with the one characterizing a genuine critical regime.

IV. DISCUSSION

A. Fluctuation-conductivity exponent

The contribution of fluctuations to the electrical conductivity of superconductors may be estimated from the Drude kinetic formula,[24]

$$\Delta\sigma \cong (2e^2/m)n_s\tau, \tag{6}$$

where n_s is the density of Cooper pairs, τ is the lifetime of the evanescent superconducting droplets, and e and m are the electron charge and mass, respectively. In the critical region, n_s varies as the order-parameter correlation function, that is,[25]

$$n_s(\xi)\sim\langle\psi(\xi)\psi(0)\rangle\sim\xi^{2-d-\eta}, \tag{7}$$

where ξ is the correlation length, d is the dimensionality of the fluctuation spectrum, and η is a critical exponent. On the other hand, according to the dynamical scaling theory,[17] $\tau\sim\xi^z$. Thus, we expect that the fluctuation conductivity diverges at T_c with the exponent

$$\lambda=\nu(2-d+z-\eta), \tag{8}$$

where ν is the critical exponent for the correlation length.

B. Gaussian fluctuations

1. 2D and 3D regimes

The mean-field GL theory predicts that $\nu=1/2$, $z=2$, and $\eta=0$. Thus, as shown by Aslamasov and Larkin (AL),[26] the Gaussian exponents depend on the dimensionality as

$$\lambda_{\rm G}=2-\frac{d}{2}. \tag{9}$$

As depicted in Fig. 2, a Gaussian fluctuation regime corresponding to $d=2$ describes our results in the reduced temperature range extending from $\varepsilon=0.04$ down to $\varepsilon=0.014$. Decreasing the temperature towards T_c, our χ_σ^{-1} results cross over to a power-law behavior governed by 3D Gaussian fluctuations. However, the observed 2D-3D crossover cannot be described by Eq. (5), which is deduced from the LD model, and the fluctuation results in the Gaussian region are better interpreted using the framework of the AL theory. According to this theory, the critical amplitudes are given by

$$A_{\rm 2D}=\frac{e^2}{16\hbar s} \tag{10a}$$

and

$$A_{\rm 3D}=\frac{e^2}{32\hbar\xi(0)} \tag{10b}$$

in the 2D and 3D cases, respectively. In Eq. (10a), s is the relevant layer thickness for the 2D fluctuation system, whereas $\xi(0)$ in Eq. (10b) is the amplitude of the GL coherence length. For a planar anisotropic system, as described by the LD model, the critical amplitude is also given by Eq. (10b), but $\xi(0)$ should be interpreted as the coherence length perpendicular to the layered structure, $\xi_c(0)$.

Substituting the experimental critical amplitude in Eq. (10b), we estimate the coherence length $\xi_c\simeq0.115$ nm. This value is in rather good agreement with determinations from other authors.[4,5,27] We list in Table I the values calculated for ξ_c at various applied fields. There, it appears that this parameter is rather insensitive to the field orientation and magnitude within the ranges of observation. On the other hand, fitting our χ_σ^{-1} results to Eq. (5) in the same temperature range, we obtain the parameter $\alpha=0.43$. Combining this result with the determined ξ_c, we deduce that $s\simeq0.35$ nm. This value for s is of the order of the distance between the pair of dimpled Cu-O_2 layers,[28] characteristic of the YBCO unit cell. However, one can expect that this layered system effectively decouples when $\xi_c(T)$ becomes smaller than the separation between the double-layer structures, which is $\delta\simeq0.83$ nm.[28] Then, the fluctuation spectrum would acquire a 2D character in a reduced temperature much smaller than that expected from the LD model, in accordance to our experimental observations. A verification of this hypothesis is obtained by replacing the experimental amplitude, A_{2D}, for the 2D Gaussian regime in Eq. (10a) and computing the effective thickness s. As listed in Table I, we find the field-independent value $s=1.0\pm0.1$ nm, which is indeed close to δ and to the lattice constant c. An additional check comes from the estimation of the temperature-dependent GL coherence length at the lower reduced-temperature limit for the 2D Gaussian region. Consistently, we obtain $\xi_c\simeq0.9$ nm.

TABLE I. Values obtained in various applied fields for the coherence length $\xi_c(0)$ and the thickness s by substituting the experimental amplitudes for the 3D and 2D Gaussian fluctuation conductivities in Eqs. (10a) and (10b), respectively. Also listed are the amplitudes for the critical regimes characterized by the exponents $\lambda_{\rm cr}^{(1)}=0.33$ and $\lambda_{\rm cr}^{(2)}=0.17$.

$\mu_0H\Vert ab\perp j$ (T)	$\xi_c(0)$ (nm)	s (nm)	$A_{0.33}$ (mΩ cm)	$A_{0.17}$ (mΩ cm)
0	0.12	1.0	0.76	0.33
0.001		1.0	0.79	0.35
0.002	0.11	1.0	0.77	0.35
0.004	0.11	1.1	0.79	0.34
0.008	0.11	1.0	0.79	0.34
0.01	0.12	1.0	0.75	0.34
0.02	0.11	1.1	0.79	
0.04	0.11	1.1	0.76	
0.06	0.12	1.0	0.73	
0.08	0.12	1.0	0.76	
0.10	0.11	1.1	0.75	
0.50	0.11	0.9		
1.0	0.10	1.1		
$\mu_0H\Vert c$ (T)	$\xi_c(0)$ (nm)	s (nm)	$A_{0.33}$ (mΩ cm)	$A_{0.17}$ (mΩ cm)
0	0.12	1.0	0.76	0.33
0.01	0.12	1.0	0.75	
0.02	0.12	1.0	0.77	
0.04	0.11	1.1	0.67	
0.06	0.12	1.0		
0.08	0.11	1.0		
0.10	0.11	1.1		

2. Second critical field

Although the Gaussian critical amplitudes are unaffected by the magnetic field, the extrapolated mean-field critical temperatures are field dependent. In Figs. 6(a) and 6(b) we show the critical temperatures for the 3D Gaussian and for the critical regimes as functions of the applied field in the cases $H\Vert c$ and $H\Vert ab$, respectively. These temperatures are obtained by extrapolating each fluctuation regime to $\chi_\sigma^{-1}=0$ with the help of Eq. (4).

The slopes $dT_c^{\rm 3D-G}/dH$ for the mean-field critical temperatures of the 3D Gaussian regime are different for the two field directions. We obtain 1.16 K/T and 0.07 K/T for $H\Vert c$ and $H\Vert ab$, respectively. From these slopes and the expressions for the anisotropic second critical field in a layered superconductor,[29]

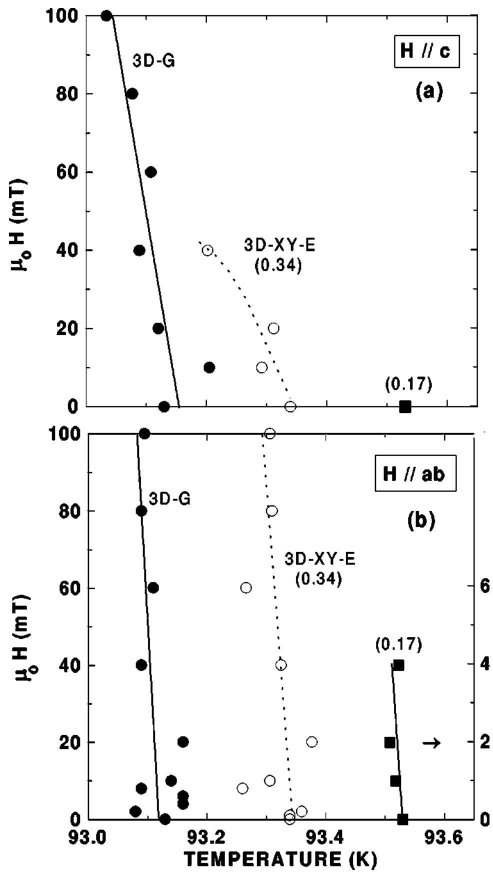

FIG. 6. Field dependence of the critical temperatures obtained from extrapolations to $\chi_\sigma^{-1}=0$ of the power-law fluctuation regimes fitted to Eq. (4). Black dots correspond to the mean-field critical temperatures for the 3D Gaussian regime. Open circles denote $T_c(H)$ for the critical 3D XY-E regime, and the black squares give $T_c(H)$ for the regime described by the exponent $\lambda_{cr}^{(2)}=0.17$. Panel (a) presents results for $H\|c$, and panel (b) refers to $H\|ab$.

$$H_{c2}^{(c)}(T)=\frac{\phi_0}{2\pi\xi_{ab}^2(T)} \text{ and } H_{c2}^{(ab)}(T)=\frac{\phi_0}{2\pi\xi_{ab}\xi_c}, \quad (11)$$

where (c) and (ab) mean parallel to the c axis and ab plane, respectively, and ϕ_0 is the quantum of flux, we may estimate the coherence lengths parallel and perpendicular to the Cu-O planes. Assuming that the coherence length depends on the temperature as in the GL theory, $\xi(T)=\xi(0)\varepsilon^{-1/2}$, we calculate $\xi_{ab}(0)=2.0\pm0.4$ nm and $\xi_c(0)=0.13\pm0.03$ nm. The value for $\xi_{ab}(0)$ is in reasonable agreement with estimations from susceptibility[5] and second critical field[30,31] measurements. The value found for $\xi_c(0)$ agrees with our estimations from the fluctuation conductivity results. This finding is interesting since it represents a criterion of self-consistency for our analysis of the Gaussian contribution to the fluctuation conductivity in our YBCO crystal.

C. 3D XY and beyond 3D XY scalings

As shown in Figs. 3, 4, and 5 (and in the H-T diagrams of Figs. 8 and 9), the critical-fluctuation region for our sample presents an *internal structure*. Decreasing the temperature towards T_c, we first observe a fluctuation-conductivity regime described by a power law with exponent $\lambda_{cr}^{(1)}=0.33$. This is very close to the predicted value of 0.32, obtained from Eq. (8) with the full dynamic 3D XY model,[15] for which[32] $\nu=0.67$, $\eta=0.03$, and[17,33] $z=3/2$. This scaling behavior, which we call 3D XY-E because of the model-E dynamics,[17] was first observed in YBCO polycrystalline samples,[7] then in single crystals of YBCO (Refs. 16 and 18) and $Bi_2Sr_2Ca_2CuO_8$ (Ref. 34). For the specific sample being studied here, the width of the 3D XY region is very small. It is almost unnoticeable in the zero-field plots of Figs. 3 and 4, and is slightly better defined in the plot shown in Fig. 5.

In our sample, when the temperature is further decreased towards T_c, a new scaling regime is observed within the critical region. This inner region corresponds to a power law with exponent $\lambda_{cr}^{(2)}$.

As shown in the H-T diagrams of Figs. 8 and 9, all of these critical-fluctuation regimes are destroyed upon the application of low magnetic fields. The 3D XY-E scaling is the most robust against a magnetic field, and its upper temperature limit is about 0.5 K above T_c, as formerly observed.[7] This value is in agreement with estimations of the Ginzburg number for YBCO.[35]

The observation of the regime beyond 3D XY-E scaling was first reported in Ref. 20. Its interpretation is still unclear. In Ref. 20 we suggested that the $\lambda_{cr}^{(2)}$ regime might be precursor to a weak first-order pairing transition. A first-order transition occurs when the absolute minimum of the Ginzburg-Landau free-energy F switches discontinuously from the high-temperature position, $|\psi|=0$, to the one with nonzero $|\psi|$. One can expect that above but in close vicinity to T_c, the system is allowed to fluctuate between the two free-energy minima because of the low height of the barrier that separates them. This could affect the system dynamics, modifying the effective value of z. According to this picture, the weak-first-order transition could be approached from above roughly within the static 3D XY scheme, but with a gradual evolution in its dynamics. For instance, the value $\lambda_{cr}^{(2)}\simeq0.17$ may be reproduced if $z\simeq1.28$ in Eq. (4). In principle, the description proposed above does not preclude the observation, in very clean samples, of crossover regimes with exponents smaller than $\lambda_{cr}^{(2)}$, since the limit of discontinuous first-order behavior would correspond to an effective value $\lambda=0$.

An alternative description that does not involve changes in the dynamics was also proposed in Ref. 20 with its basis on the scaling analysis presented by Fisher and Berker[36] for a first-order transition driven by the temperature. This theory predicts that the coherence-length critical exponent is given by $\nu=1/d$, which, for $d=3$, would correspond to approximately one-half of its value for the 3D XY model. Then, keeping the 3D XY-E values for z and η in Eq. (8), one would calculate $\lambda\simeq0.16$, which is in agreement with the experimental value for $\lambda_{cr}^{(2)}$.

An additional indication of the ultimate first-order character of the pairing transition in YBCO is the increase (see Figs. 3–6) in the extrapolated critical temperature for the $\lambda_{cr}^{(2)}$ regime when compared to that obtained for the 3D

XY-E scaling. In a second-order phase transition, T_c is reached when F flattens out around the equilibrium point. If the transition is weakly first order, F would appear as effectively flat at a higher temperature, when the minimum at nonzero $|\psi|$ starts to appear, yielding a higher extrapolated value of T_c with respect to one that would be obtained if the transition remained strictly second order. This effect accounts for the somewhat paradoxical results of Fig. 3, where critical fluctuations seem to shift T_c upwards with respect to its mean-field value.

If the pairing transition in YBCO is indeed of first order, the mechanism that drives this is still unclear. Halperin, Lubensky, and Ma,[37] many years ago proposed that coupling of the order parameter to fluctuations of the electromagnetic field may drive the superconducting transition into a weakly first-order one. However, their theory predicts that first-order effects would occur in a reduced-temperature range too narrow to be observed in an extreme type-II superconductor as YBCO. In Table I we list the amplitudes of the 3D XY-E and the $\lambda_{\rm cr}^{(2)}$ critical scalings, and in Figs. 6(a) and 6(b) we show the field dependence of the extrapolated critical temperatures for these regimes.

D. Lowest-Landau-level scaling

For the $H\|c$ configuration, the Aslamazov-Larkin fluctuation regimes are observed only up to $\mu_0H=1$ T in our sample. This fact raises the possibility for describing the superconducting transition in YBCO in terms of the LLL approximation for applied fields above this limit applied along the c axis. Indeed, the critical and LLL scalings cannot coexist in the same region of the H-T plane, and the issue of critical versus LLL interpretation for magnetic-field effects on the fluctuation regimes of the HTSC has been the subject of intense controversy.[8,10,13,14]

Within the LLL approximation, physical properties scale with the variable $t_{\rm LLL}=[T-T_c(H)]/(TH)^{2/3}$, in a 3D system.[12,38] The relevant equation for analyzing the excess of conductivity is[12]

$$\Delta\sigma=\left(\frac{T^2}{H}\right)^{1/3}f(t_{\rm LLL}), \tag{12}$$

where f is an unknown scaling function. Thus, plotting $\Delta\sigma(H^{1/3}/T^{2/3})$ versus $t_{\rm LLL}$, one should obtain a single curve, independent of H. In Fig. 7 we show such a plot for our $\Delta\sigma$ results in fields of 1, 5, 10, and 14 T applied along the c axis. There one observes that, except for the case $\mu_0H=1$ T, the data collapse reasonably well onto a single curve. This indicates that the 3D LLL approximation describes correctly the fluctuation conductivity in our sample in fields higher than $\mu_0H=5$ T applied perpendicular to the Cu-O planes. These results are in agreement with fluctuation analysis of transport properties,[38] magnetization,[10,38] and specific heat[10,14] in YBCO. The only discrepancy between the scalings reported in different works concerns the value of the minimum field required to stabilize the 3D LLL state. Some authors[10,14] claim that good LLL scaling is already possible for $\mu_0H=1$ T, while others[13] find it possible only for fields above 6 T, which is closer to our estimation.

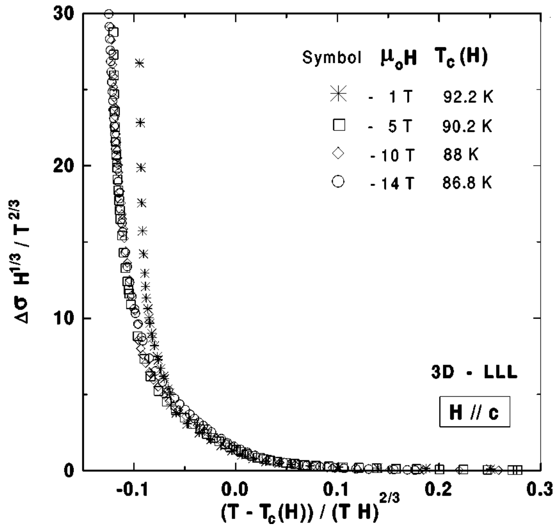

FIG. 7. Lowest-Landau-level scaling for fluctuation magnetoconductivity in YBCO in fields $\mu_0H=1$, 5, 10, and 14 T applied along the c axis. The fitting parameters $T_c(H)$ are quoted on the figure.

E. *H-T* diagrams

The whole set of our measurements is used to sketch H-T diagrams where the domains of validity for each type of scaling may be visualized. Figure 8 shows a log-log representation of the diagram obtained when $H\|ab$ $(H\|j)$. We choose $T_p(H)$ as the parameter to which the reduced temperatures refer, since each fluctuation regime represented in the diagram has its own extrapolated critical temperature.

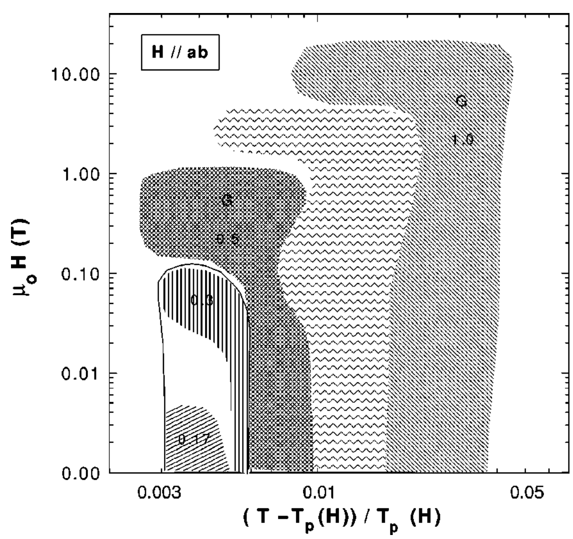

FIG. 8. H-T diagram showing the regions of dominance of Gaussian and critical scalings in the normal phase of YBCO. The regions are labeled by the observed exponents. The reduced temperatures are referred to $T_p(H)$, which is the maximum of $d\rho/dT$, and the field is applied parallel to the Cu-O planes. The location of the critical regimes is marked by a continuous contour.

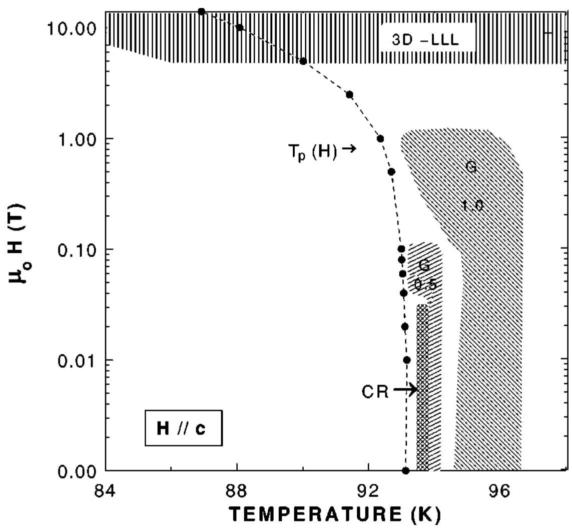

FIG. 9. The same as Fig. 8, but for the $H\|c$ configuration. In this case a region dominated by LLL fluctuations is identified.

The boundaries delimiting the regions of dominance of the various scaling behaviors are determined with considerable experimental uncertainty, and should not be regarded as sharply defined. For instance, we notice the large crossover region separating the 2D from the 3D Gaussian regimes. Noticeable also is the internal structure of the critical regime, which is encircled by a continuous line in Fig. 8.

The diagram obtained for the configuration $H\|ab$ $(H\perp j)$ is quantitatively similar to that of Fig. 8. This indicates that there is no appreciable anisotropy concerning the relative orientation of the field and current for the in-plane fluctuation conductivity in the normal phase of YBCO. Figure 9 shows the diagram obtained when $H\|c$. In this case, the limiting fields for the critical regimes are scaled down by some anisotropy factor. We notice that the limiting field for the $\lambda_{cr}^{(2)}$ regime is below 10 mT, which is the minimum field value that we could apply for the configuration $H\|c$. The LLL scaling describes the data in a large temperature range both above and below $T_p(H)$ for fields above $\mu_0 H = 5$ T in this configuration.

It is interesting to observe in Figs. 8 and 9 that, as discussed in Sec. IV B 1, the 3D XY-E scaling is stable only when rather small fields are applied. This observation is in contrast with some field-dependent specific-heat results,[8,13] where the 3D XY scaling is reported to hold up to 6 T and above.

V. FINAL REMARKS AND CONCLUSIONS

Our in-plane fluctuation-magnetoconductivity results in YBCO reveal the occurrence of Gaussian regimes in a large temperature range whose lower limit is about 0.5 K above the value of T_c extrapolated from the genuine critical regime. Farther from the critical temperature, the fluctuation spectrum is effectively two dimensional, but a crossover to a 3D behavior is observed when the temperature comes close enough to T_c. Although the Lawrence-Doniach theory describes correctly the 3D limit of the Gaussian regime, it fails to reproduce the observed 3D-2D crossover. Indeed, the 2D Gaussian regime extrapolates to a mean-field critical temperature which is smaller than the corresponding T_c^{MF} for the 3D Gaussian region. This behavior shows that YBCO is a superconductor characterized by a double planar periodicity.[39] The distance between the Cu-O layers within the double-sheet structures controls the 3D fluctuation spectrum, whereas the decoupling to an effectively 2D regime occurs when $\xi_c(T)$ decreases to a value slightly smaller than the lattice constant c, which is the periodicity length associated with the double Cu-O planes. The same kind of double planar periodicity underlies the behavior of fluctuation conductivity in Bi-2212 (Ref. 34).

The critical amplitude for the 3D Gaussian fluctuation magnetoconductivity and the corresponding field-dependent critical temperature allow us to estimate the isotropic GL coherence length. We obtain $\xi_c(0) = 0.1$ nm and $\xi_{ab}(0) = 2$ nm. From the lower-temperature limit for the 3D Gaussian scaling, and from the respective mean-field critical temperature extrapolated from the χ_σ^{-1} data, we estimate the Ginzburg number Gi $= 0.005$ at low applied fields for both field orientations.

We remark that we were able to describe consistently our conductivity-fluctuation results in the mean-field regime without considering additional contributions as the Maki-Thompson (MT) term.[40] In fact, there exists some consensus about the absence of appreciable MT effects on the fluctuation conductivity of the HTSC.[2,4,7,41] The reason that makes the MT contribution negligible is still unclear. For instance, it could result from strong pair-breaking effects or from the unconventional nature of superconductivity in these compounds.

The Gaussian regimes are moderately robust against the application of magnetic fields. For the orientation $H\|ab$, the 3D Gaussian scaling is observed up to $\mu_0 H = 1$ T, and the 2D Gaussian scaling up to the highest studied field, $\mu_0 H = 14$ T. When $H\|c$, the 3D Gaussian regime holds up to $\mu_0 H = 0.1$ T, whereas the 2D Gaussian regime is valid up to $\mu_0 H = 1$ T. For fields equal and above $\mu_0 H = 5$ T applied along the c-axis, our results could be scaled according to the predictions of the 3D lowest-Landau-level theory.

Genuine critical behavior is clearly identified in our low-field measurements. The critical region has an internal structure, and two power-law regimes are observed in sequence when T approaches T_c from above. The corresponding critical exponents are $\lambda_{cr}^{(1)} = 0.33 \pm 0.04$ and $\lambda_{cr}^{(2)} = 0.17 \pm 0.01$. The value of the exponent $\lambda_{cr}^{(1)}$ is consistent with the predictions for the 3D XY universality class with the model-E dynamical exponent $z = 3/2$.[17,33] This observation points to a simple description of the superconducting transition in YBCO, where the symmetry of the GL order parameter is given by the O(2) rotation group.[19] The observed 3D XY-E scaling is essentially a zero-field one, since for $\mu_0 H \geqslant 0.1$ T $(H\|ab)$ or $\mu_0 H \geqslant 0.04$ T $(H\|c)$ criticality is rounded off. A clear interpretation of the regime beyond 3D XY-E scaling is still lacking. An interesting possibility deserving further investigation is the hypothesis that the $\lambda_{cr}^{(2)}$-regime is precursor to an ultimate weakly-first-order pairing transition in YBCO.

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[1] D. S. Fisher, M. P. A. Fisher, and D. A. Huse, Phys. Rev. B **43**, 130 (1991).

[2] P. P. Freitas, C. C. Tsuei, and T. S. Plaskett, Phys. Rev. B **36**, 833 (1987).

[3] M. Ausloos and Ch. Laurent, Phys. Rev. B **37**, 611 (1988).

[4] T. A. Friedmann, J. P. Rice, J. Giapintzakis, and D. M. Ginsberg, Phys. Rev. B **39**, 4258 (1989).

[5] W. C. Lee, R. A. Klemm, and D. C. Johnston, Phys. Rev. Lett. **63**, 1012 (1989).

[6] G. Mozurkewich, M. B. Salamon, and S. E. Inderhees, Phys. Rev. B **46**, 11 914 (1992).

[7] P. Pureur, R. Menegotto Costa, P. Rodrigues Jr., J. Schaf, and J. V. Kunzler, Phys. Rev. B **47**, 11 420 (1993).

[8] N. Overend, M. A. Howson, and I. D. Lawrie, Phys. Rev. Lett. **72**, 3238 (1994); I. D. Lawrie, Phys. Rev. B **50**, 9456 (1994).

[9] M. Roulin, A. Junod, and E. Walker, Physica C **260**, 257 (1996).

[10] O. Jeandupeux, A. Schilling, H. R. Ott, and A. van Otterlo, Phys. Rev. B **53**, 12 475 (1996).

[11] P. A. Lee and S. R. Shenoy, Phys. Rev. Lett. **28**, 1025 (1972).

[12] S. Ullah and A. T. Dorsey, Phys. Rev. Lett. **65**, 2066 (1990).

[13] N. Overend, M. A. Howson, I. D. Lawrie, S. Abell, P. J. Hirst, C. Changkang, S. Chowdhury, J. W. Hodby, S. E. Inderhees, and M. B. Salamon, Phys. Rev. B **54**, 9499 (1996).

[14] S. W. Pierson, T. M. Katona, Z. Tešanovic’, and O. T. Valls, Phys. Rev. B **53**, 8638 (1996).

[15] M. B. Salamon, J. Shi, N. Overend, and M. A. Howson, Phys. Rev. B **47**, 5520 (1993).

[16] W. Holm, Y. Eltsev, and Ö. Rapp, Phys. Rev. B **51**, 11 992 (1995).

[17] P. C. Hohenberg and B. I. Halperin, Rev. Mod. Phys. **14**, 435 (1977).

[18] J. Kim, N. Goldenfeld, J. Giapintzakis, and D. M. Ginsberg, Phys. Rev. B **56**, 118 (1997).

[19] C. J. Lobb, Phys. Rev. B **36**, 3930 (1987).

[20] R. Menegotto Costa, P. Pureur, M. A. Gusmão, S. Senoussi, and K. Behnia, Solid State Commun. **113**, 23 (1999).

[21] R. Gagnon, C. Lupien, and L. Taillefer, Phys. Rev. B **50**, 3458 (1994).

[22] J. S. Kouvel and M. E. Fisher, Phys. Rev. **136**, A1616 (1964).

[23] W. E. Lawrence and S. Doniach, in *Proceedings of the 12th International Conference Low Temperature Physics, Kyoto, 1970*, edited by E. Kanda (Keigaku, Tokyo, 1971), p. 361.

[24] A. Schmid, Z. Phys. **215**, 210 (1968).

[25] J. M. Yeomans, in *Statistical Mechanics of Phase Transitions* (Oxford University Press, Oxford, 1982).

[26] L. G. Aslamazov and A. I. Larkin, Fiz. Tverd. Tela (Leningrad) **10**, 1104 (1968) [Sov. Phys. Solid State **10**, 875 (1968)].

[27] C. Torrón, A. Díaz, J. Jegoudez, A. Pomar, M. V. Ramallo, A. Revcolevschi, J. A. Veira, and F. Vidal, Physica C **212**, 440 (1993).

[28] R. M. Hazen, in *Physical Properties of High Temperature Superconductors*, edited by D.M. Ginsberg (World Scientific, Singapore, 1990), Vol. II, p. 121.

[29] A. A. Abrikosov, *Fundamentals of the Theory of Metals* (North-Holland, Amsterdam, 1988).

[30] B. Oh, K. Char, A. D. Kent, M. Naito, M. R. Beasley, T. H. Geballe, R. H. Hammond, A. Kapitulnik, and J. M. Graybeal, Phys. Rev. B **37**, 7861 (1988).

[31] U. Welp, W.K. Kwok, G. W. Crabtree, K. G. Vandervoort, and J. Z. Liu, Phys. Rev. Lett. **62**, 1908 (1989).

[32] J. C. Le Guillou and J. Zinn-Justin, Phys. Rev. B **21**, 3976 (1980).

[33] J. Lidmar, M. Wallin, C. Wengel, S. M. Girvin, and A. P. Young, Phys. Rev. B **58**, 2827 (1998).

[34] R. Menegotto Costa, P. Pureur, L. Ghivelder, J.A. Campá, and I. Rasines, Phys. Rev. B **56**, 10 836 (1997).

[35] G. Blatter, M.V. Feigel’man, V. B. Geshkenbein, A. I. Larkin, and V. M. Vinokur, Rev. Mod. Phys. **66**, 1125 (1994).

[36] M. E. Fisher and A.N. Berker, Phys. Rev. B **26**, 2507 (1982).

[37] B. I. Halperin, T. C. Lubensky, and S. K. Ma, Phys. Rev. Lett. **32**, 292 (1974).

[38] U. Welp, S. Fleshler, W. K. Kwok, R. A. J. DoW. Crabtree, Phys. Rev. Lett. **67**, 3180 (1991).

[39] R. A. Klemm, Phys. Rev. B **41**, 2073 (1990).

[40] K. Maki and R. S. Thompson, Phys. Rev. B **39**, 2767 (1989).

[41] J. Vieira and F. Vidal, Phys. Rev. B **42**, 8748 (1990); D. H. Kim, A. M. Goldman, J. H. Kang, K. E. Gray, and R. T. Kampwirth, *ibid.* **39**, 12 275 (1989); Mi-Ock Mun, Sung-Ik Lee, Sung-Ho Suck Salk, H. J. Shin, and M. K. Joo, *ibid.* **48**, 6703 (1993).