Fluctuation-induced in-plane conductivity, magnetoconductivity, and diamagnetism of $Bi_2Sr_2CaCu_2O_8$ single crystals in weak magnetic fields

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We report detailed experimental results on the fluctuation-induced in-plane conductivity $\Delta\sigma_{ab}$, magnetoconductivity $\Delta\tilde{\sigma}_{ab}$, and diamagnetism $\Delta\chi_{ab}$, of high-quality $Bi_2Sr_2CaCu_2O_8$ crystals. The data were obtained with magnetic fields H applied perpendicularly to the superconducting (CuO_2) planes and up to $\mu_0H=5$ T, which not too close to the transition [for reduced temperatures $\varepsilon\equiv(T-T_{C0})/T_{C0}\gtrsim10^{-2}$] may be considered in the weak magnetic field limit. In the mean field region (MFR) above the transition, these data are analyzed in terms of thermal fluctuations of the superconducting order parameter amplitude (OPF), on the grounds of the existing theoretical approaches for layered superconductors that take into account the presence of two superconducting layers in the layer periodicity length, s, which for these compounds is equal to one-half the crystallographic unit-cell length in the c direction. These results show that, due to its strong ε dependence, $\Delta\tilde{\sigma}_{ab}$ is dramatically affected by the presence of small T_C inhomogeneities, associated with small oxygen content inhomogeneities uniformly distributed in the crystals. These inhomogeneity effects are taken into account, consistently with our $\Delta\sigma_{ab}$ and $\Delta\chi_{ab}$ results, by using an effective medium approach proposed by Maza and Vidal. In this way, the amplitude and the ε behavior of the three observables studied here are explained in terms of the direct OPF effects, at a quantitative level, confirming then the absence of appreciable indirect contributions [as, for instance, the Maki-Thompson and the density-of-states (DOS) terms]. These last results may suggest unconventional (non $^1s_0$), pair breaking, wave pairing in these compounds, as first proposed from OPF analyses by Veira and Vidal. The resulting values of the in-plane and out-of-plane coherence length amplitudes are, respectively, $\xi_{ab}(0)=(0.9\pm0.1)$ nm and $\xi_c(0)\lesssim0.05$ nm. These coherence length amplitudes are consistent with the values that we have obtained before for other Bi-based crystals by analyzing the effects of the vortex position fluctuations on the magnetization below the transition. These results also confirm at a quantitative level that in Bi-2212 compounds the effective number of fluctuating CuO_2 planes per periodicity length above the superconducting transition is $N_e\approx2$ and that the OPF's are essentially two dimensional over the entire MFR. [S0163-1829(96)07833-2]

I. INTRODUCTION

One of the striking features of the Bi-based high-temperature copper-oxide superconductors (HTSC's), first observed through measurements of the paraconductivity in polycrystalline $Bi_2Sr_2CaCu_2O_8$ (Bi-2212) samples, is the strong two-dimensional (2D) character of their thermal fluctuations of the superconducting order-parameter amplitude (OPF) in the mean-field region (MFR) above the superconducting transition.[1] As earlier stressed in Refs. 1 and 2, this 2D behavior of the OPF contrasts with the one observed in some other HTSC's, as for instance, the $YBa_2Cu_3O_{7-\delta}$ (Y-123) compounds, for which the OPF in the MFR above the transition are essentially 3D. These differences were consistent with the much stronger anisotropy of the Bi-based compounds, the anisotropy factor γ, being $\gamma=100$–200 for Bi-2212 and $\gamma=5$–10 for Y-123. Moreover, these differences, which manifest themselves also in the thermal fluctuation effects below the superconducting transition,[3] have enhanced the interest of the OPF above the transition in Bi-based HTSC, and in the last years an appreciable number of works have addressed the study of these fluctuation effects above the transition on various observables in these compounds, as the electrical resistivity,[2,4–13] the magnetic susceptibility,[5,14–17] and the magnetoconductivity.[7,11,13] However, in spite of these efforts, at present some of the central aspects of the OPF effects above the transition in Bi-based HTSC are still open or are controversial. In fact, these different works only agree in the confirmation of the 2D character of the OPF in the MFR above the transition. Also, in the case of the electrical conductivity there is some consensus about the absence of appreciable indirect (in particular, Maki-Thompson) OPF effects in these compounds, as first proposed explicitly in Refs. 2 and 5. However, there are important discrepancies among the values obtained by different authors[1,2,4–17] of the two basic characteristic lengths of these OPF effects: the in-plane, $\xi_{ab}(0)$, and the transversal, $\xi_c(0)$, superconducting coherence length amplitudes (at $T=0$ K). The disagreements concern also the periodicity length, s, of the superconducting CuO_2 planes, or the effective number, N_e, of fluctuating planes in s. In the case of the fluctuation-induced magnetoconductivity, there are also striking discrepancies among the amplitudes measured by different authors,[7,11,13] which in turn always disagree, by 1 or 2 orders of magnitude, with the amplitudes that may be deduced from the theoretical approaches.[18–24] In addition, there is no consensus at all on the reasons for these last disagreements, the proposed explanations including sample inhomogeneities,[13] anomalous high $\xi_{ab}(0)$ values[7] or even the nonapplicability of the currently

TABLE I. Values of the characteristic parameters for the fluctuation-induced conductivity, $\Delta\sigma$, magnetoconductivity, $\Delta\tilde{\sigma}$, and diamagnetism, $\Delta\chi$, above T_{C0} in Bi-2212 samples determined in this work and some results from the literature. The values into brackets were obtained by the corresponding authors from the analysis of other quantities.

Ref.	Sample	T_{C0} (K)	Quantity	MFR	N_e	s (nm)	$\xi_{ab}(0)$ (nm)	$\xi_c(0)$ (nm)
This work	Single crystal Bi1	89.1	$\Delta\sigma_{ab}, \Delta\tilde{\sigma}_{ab}, \Delta\chi_{ab}$	$0.02\lesssim\varepsilon\lesssim0.1$	2	1.54	0.85	$\lesssim$0.04
This work	Single crystal Bi2	87.3	$\Delta\sigma_{ab}, \Delta\tilde{\sigma}_{ab}, \Delta\chi_{ab}$	$0.02\lesssim\varepsilon\lesssim0.1$	2	1.54	0.90	$\lesssim$0.05
4	Single crystal	79	$\Delta\sigma_{ab}$	$0.02\lesssim\varepsilon\lesssim0.15$	1	3.02	(3.01)	(0.57)
6	Thin films	~80	$\Delta\sigma_{ab}$	$0.02\lesssim\varepsilon\lesssim0.13$	1	1.0		→0
7	Single crystal (Pb doped)	92	$\Delta\sigma_{ab}, \Delta\tilde{\sigma}_{ab}$	$0.05\lesssim\varepsilon\lesssim0.3$	1	1.56	3.8	0.1
8	Polycrystal (Ag doped)	~80	$\Delta\sigma$	$0.03\lesssim\varepsilon\lesssim0.4$	1	3.06		0.16
9	Single crystal	82	$\Delta\sigma_{ab}$	$0.03\lesssim\varepsilon\lesssim2$	1	1.26		0.04
10	Thin films	87	$\Delta\sigma_{ab}$	$0.03\lesssim\varepsilon\lesssim0.3$	1	~1.5		0.1
11	Thin films	84	$\Delta\sigma, \Delta\tilde{\sigma}$	$0.01\lesssim\varepsilon\lesssim0.15$	1	1.0	1.3	→0
12	Single crystal	86.5	$\Delta\sigma_{ab}$	$0.02\lesssim\varepsilon\lesssim0.4$	1	1.5	(1.3)	~0.1
14	Single crystal	84	$\Delta\chi_{ab}$	$0.04\lesssim\varepsilon\lesssim0.5$	2	1.54	1.09	→0
14	Polycrystal (Pb doped)	91.1	$\Delta\chi_{ab}$	$0.18\lesssim\varepsilon\lesssim0.8$	2	1.54	2.04	0.03

accepted theoretical approaches to the Bi-based HTSC.[11] This quite confused situation is illustrated in Table I, where we have summarized some of the values proposed by various groups for the characteristic parameters of the OPF above the transition in Bi-2212 compounds.

As a further contribution to the understanding of the OPF effects above the superconducting transition in Bi-based HTSC, in this paper we present detailed experimental data of the fluctuation-induced in-plane conductivity $\Delta\sigma_{ab}$, magnetoconductivity $\Delta\tilde{\sigma}_{ab}$, and diamagnetism, $\Delta\chi_{ab}$, of two Bi-2212 single crystals. In the case of $\Delta\tilde{\sigma}_{ab}$ and $\Delta\chi_{ab}$, the measurements were performed for magnetic fields H applied perpendicularly to the ab planes and up to $\mu_0H=5$ T, that corresponds to the so-called low magnetic field limit, even for reduced temperatures $\varepsilon\equiv(T-T_{C0})/T_{C0}$, of the order of $\varepsilon\approx0.01$, T_{C0} being the mean-field transition temperature for $\mu_0H=0$. In the case of the fluctuation-induced diamagnetism, we have presented already some results obtained in other Bi-2212 crystals.[16,17] However the interest of the new $\Delta\chi_{ab}$ data presented here is enhanced by the fact that they correspond to the crystals on which we have also measured the paraconductivity and the fluctuation-induced magnetoconductivity and, therefore, these data will allow a simultaneous, quantitative and consistent analysis of the three quantities, all of which depend on the same characteristic lengths. Two basic and new aspects of this analysis are (i) whereas the effective mean-field critical exponent, x, of the paraconductivity and of the fluctuation-induced diamagnetism is of the order of $x\approx-1$, it is $x\approx-3$ for the fluctuation-induced magnetoconductivity in the weak magnetic field limit.[18–24] As a consequence of such a stronger ε-dependence, $\Delta\tilde{\sigma}_{ab}(\varepsilon,H)$ could be very appreciably affected by the presence in the sample of small T_C inhomogeneities, associated with small stoichiometric (oxygen content) inhomogeneities. These nonintrinsic effects on $\Delta\tilde{\sigma}_{ab}(\varepsilon,H)$ are going to be estimated at a quantitative level and consistently with the $\Delta\sigma_{ab}$ and $\Delta\chi_{ab}$ results (see also the footnote of Ref. 13) by using an effective-medium approach proposed by Maza and Vidal.[25] In fact, we will see here that the important discrepancies mentioned above among the different $\Delta\tilde{\sigma}_{ab}$ measurements may be in part explained in terms of these nonintrinsic inhomogeneity effects. (ii) The analysis of the three quantities will be performed on the grounds of the theoretical approaches that take into account the presence of two CuO_2 layers in s, the periodicity length associated with these superconducting layers.[17,19,21,22,24,26] Together with the important corrections associated with the inhomogeneities, the influence of the two superconducting layers in s will be crucial to explain simultaneously and consistently both the reduced temperature behavior and the amplitude of the three quantities studied here.

II. EXPERIMENTAL DETAILS AND RESULTS

A. Sample preparation and measurement techniques

The Bi-2212 single crystals used in this work were grown from stoichiometric mixtures of Bi_2O_3, $Sr(OH)\cdot8H_2O$, $CaCO_3$, and CuO by using a flux-growth technique previously described, together with their structural characterization, in Ref. 27. Let us just note that these mixtures were heated in alumina crucibles at 780 °C, ground and then heated again at 840 °C for 12 h and examined by x-ray powder diffraction as pure polycrystalline 2212. Then, the product was transferred to a rotary conical gold crucible, melted at 980 °C in 6h 15m and kept at this temperature for 2 h. The melt was cooled to 870 °C at 0.5 °C h^{-1} and, once crystallized, to 600 °C at 25 °C h^{-1} and, finally, to room temperature by turning off the furnace power. No traces of other phases than Bi-2212 were found when performing x-ray dif-

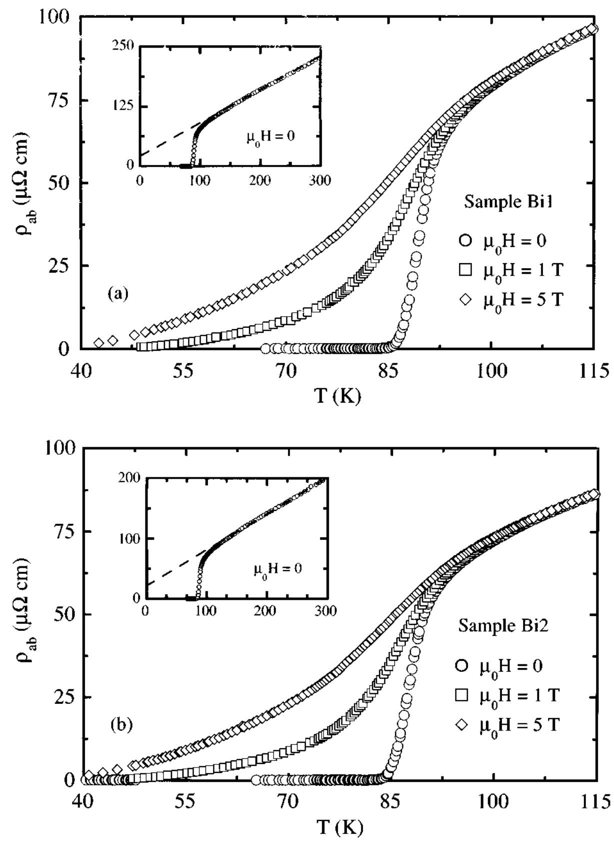

FIG. 1. (a) and (b). Temperature dependence around the transition of the in-plane resistivity of the two crystals studied here, in presence of an external magnetic field, H, applied perpendicularly to the CuO_2 planes. A general view of $\rho_{ab}(T)$ is shown in the corresponding insets.

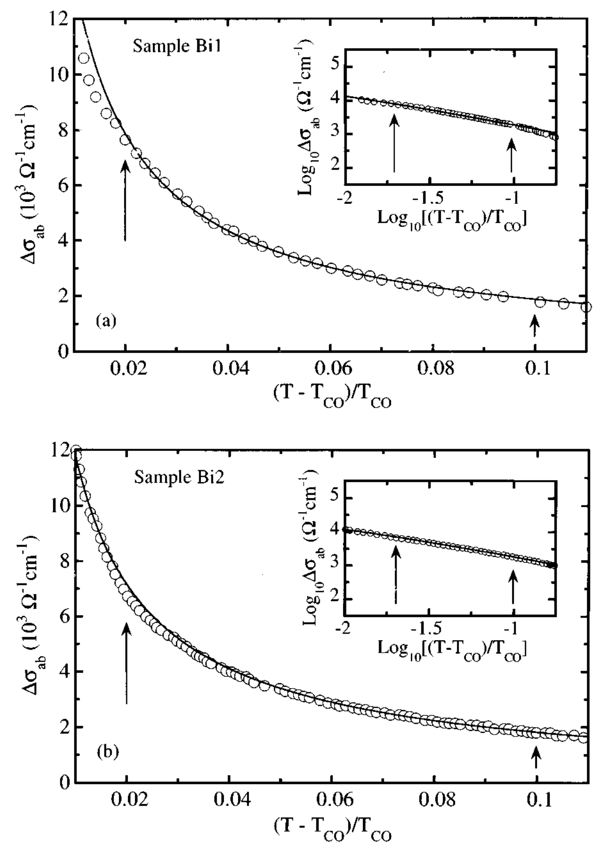

FIG. 2. (a) and (b). Reduced temperature dependence of the in-plane paraconductivity of the two crystals studied here. The reduced temperature was defined here by using T_{CI}, extracted from the $\rho_{ab}(T,0)$ curves, as T_{C0}. A log-log representation of $\Delta\sigma_{ab}(\varepsilon)$ for both crystals is shown in the corresponding insets. The solid lines are the best fits of Eq. (9) to the experimental data in the region bounded by the arrows. See main text for details.

fraction. Also, the oxygenation of these crystals was found to be homogeneous to within 4%, the resolution of our x-ray measurements. However, it is now well established that the presence of oxygen content inhomogeneities well to within a few percentage of the total oxygenation may appreciably affect the local transition temperature of the crystals.[28,29] We will see here that, in turn, these small T_{C0} inhomogeneities do not appreciably affect $\Delta\sigma_{ab}(\varepsilon)$ but they deeply affect $\Delta\widetilde{\sigma}_{ab}(\varepsilon)$, due to its stronger ε dependence near the average T_{C0}.

The resistivity at zero magnetic field $\rho_{ab}(T,0)$, and the magnetoresistivity $\rho_{ab}(T,H)-\rho_{ab}(T,0)$, were measured by using a conventional lock-in amplifier phase-sensitive technique previously described.[2,30,31] The relative ac voltage resolution was better than 0.05 μV, whereas the relative magnetoresistivity accuracy $[\rho_{ab}(T,H)-\rho_{ab}(T,0)]/\rho_{ab}(T,0)$, was 5×10^{-4}. Before performing the magnetoresistivity measurements, the magnetic susceptibilities of the crystals χ_c and χ_{ab}, for H parallel and, respectively, perpendicular to the ab planes, were measured in the low magnetic field limit with a SQUID based-magnetometer (Quantum Design), following a procedure similar to that previously used in other experiments and described in detail in Refs. 5 and 32.

B. Results

Some examples of the in-plane magnetoresistivity $\rho_{ab}(T,H)$, measured in the two crystals studied here (noted samples Bi1 and Bi2) are shown in Figs. 1(a) and 1(b). In these examples, the external magnetic field, H, was applied perpendicularly to the ab (CuO_2) planes. The dashed lines in the insets of both figures correspond to the fitting, in the normal region bounded by $150\leqslant T\leqslant250$ K, of $\rho_{abB}(T)=\rho_{abB}(0)+(d\rho_{abB}/dT)T$, with $\rho_{abB}(0)$ and $(d\rho_{abB}/dT)$ as temperature-independent free parameters. The values of these parameters, together with other general characteristics of the resistivity of the two samples used in this work are summarized in Table II. The low rms errors of the fits (of the order of 0.2%) confirm the adequacy of such a linear dependence and provide a first indication of the good quality of our crystals. Note that the obtained values are similar to the lowest values reported by other authors in Bi-2212 samples,[33–35] and also to the values usually reported for high-quality single crystals of other HTSC families as, for instance, Y-123 compounds (see, e.g., Ref. 30 and references therein).

The temperature T_{CI} for which $d\rho_{ab}/dT$ has its maximum is 89.1 K for sample Bi1, whereas it is 87.3 K for sample Bi2. As it is shown in Table II, both temperatures are similar, to within the experimental uncertainties, to the corresponding $T_{C\chi}$, the magnetic-susceptibility transition temperature (see below). Such an agreement suggests then that these temperatures must be close to T_{C0}, the mean-field critical tem-

TABLE II. Values of some of the parameters, of the two Bi-2212 crystals studied here, obtained from their in-plane resistivity and magnetic susceptibility. These parameters are defined in the main text.

Sample	Dimensions (mm^3)	T_{CI} (K)	ΔT^{+}_{CI} (K)	ΔT^{-}_{CI} (K)	$d\rho_{abB}/dT$ ($\mu\Omega$ cm/K)	ρ_{abB} (0 K) ($\mu\Omega$ cm)	$T_{C\chi}$ (K)	10^5 χ_{abB}	10^5 χ_{cB}
Bi1	1.15×0.35×0.16	89.1	0.30	0.35	0.68	24.5	88.9	2.2	−0.8
Bi2	0.95×0.72×0.13	87.3	0.40	0.35	0.59	22.9	87.1	1.9	−1.2

perature. Another noteworthy aspect to be commented on here is the half width of the resistive transition, ΔT_{CI}, defined by

$$\left(\frac{d\rho_{ab}(T)}{dT}\right)_{T_{CI}\pm\Delta T^{\pm}_{CI}}=\frac{1}{2}\left(\frac{d\rho_{ab}(T)}{dT}\right)_{T_{CI}}, \tag{1}$$

where + or − corresponds to, respectively, the upper and lower half width. The values of $\Delta T^{\pm}_{CI}$ quoted in Table II reveal a relatively broad transition which, together with the slightly high values for $\rho_{abB}(0)$, provides already an indication of the possible presence of small stoichiometric (oxygen content) inhomogeneities in the crystals, as indicated above.

The in-plane paraconductivity, $\Delta\sigma_{ab}(\varepsilon)$, of the two Bi-2212 crystals are presented in Figs. 2(a) and 2(b). As usually, $\Delta\sigma_{ab}(\varepsilon)$ was defined by

$$\Delta\sigma_{ab}(\varepsilon)\equiv\frac{1}{\rho_{ab}(\varepsilon)}-\frac{1}{\rho_{abB}(\varepsilon)}, \tag{2}$$

where $\rho_{ab}(\varepsilon)$ is the measured resistivity, $\rho_{abB}(\varepsilon)$ is the bare or background resistivity (i.e., the resistivity the samples would have in absence of OPF effects), and $\varepsilon\equiv(T-T_{C0})/T_{C0}$ is the reduced temperature for $\mu_0H=0$. These $\Delta\sigma_{ab}(\varepsilon)$ data were extracted from the zero-magnetic field results of Figs. 1(a) and 1(b) by using T_{CI} as T_{C0}. As $\rho_{abB}(\varepsilon)$ we have used the linear extrapolation of $\rho_{ab}(\varepsilon)$ measured between 150 and 250 K. Some comments on these results are in order here. Note first the excellent agreement between the paraconductivities measured in the two samples, mainly in the mean-field-like region [the ε region bounded by the arrows in Figs. 2(a) and 2(b)], where the agreement is well within the experimental resolution (of the order of 10%). This result is a first direct indication that the paraconductivity is not appreciably affected by the small stoichiometric and structural inhomogeneities of the two crystals. When compared with the $\Delta\sigma_{ab}(\varepsilon)$ data measured by other authors in different Bi-2212 crystals[4,7,9,12] and films,[10,11] we observe also a similar ε behavior (the corresponding critical exponent in the MFR is close to −1, see next section). However, there are appreciable, although relatively small (up to 50%), amplitude differences, probably associated with a lower quality of the samples used in those works, which always have $d\rho_{abB}/dT$ and $\Delta T^{\pm}_{CI}$ values higher than those of the two crystals studied here.

Some examples of the reduced temperature dependence of the in-plane fluctuation-induced magnetoconductivity $\Delta\tilde{\sigma}_{ab}(\varepsilon)_H$, measured in the two crystals studied here, are presented in Figs. 3(a) and 3(b). In ε, we have used the T_{CI} extracted from $\rho(T,H=0)$ as T_{C0}. These data correspond to μ_0H equal to 1 or 5 T, and they were obtained by applying the usual definition,

$$\Delta\tilde{\sigma}_{ab}(\varepsilon,H)\equiv\frac{1}{\rho_{ab}(\varepsilon,H)}-\frac{1}{\rho_{ab}(\varepsilon,0)}, \tag{3}$$

to the data points of Figs. 1(a) and 1(b). Although these data are going to be analyzed and compared with the theoretical approaches in the next section, it will be useful to comment already here two aspects of these data. Note first that the theoretical in-plane fluctuation-induced magnetoconductivity is usually defined as[18–24]

$$\Delta\tilde{\tilde{\sigma}}_{ab}(\varepsilon,H)\equiv\Delta\sigma_{ab}(\varepsilon,H)-\Delta\sigma_{ab}(\varepsilon,0). \tag{4}$$

So, $\Delta\tilde{\sigma}_{ab}(\varepsilon,H)$ and $\Delta\tilde{\tilde{\sigma}}_{ab}(\varepsilon,H)$ will coincide only if $\sigma_{abB}(\varepsilon,0)\approx\sigma_{abB}(\varepsilon,H)$, i.e., if the normal magnetoresistivity is negligible even through the transition. Our results in the normal region well above T_{C0} confirm that such an approximation [also used by most of the authors which have measured $\Delta\tilde{\sigma}_{ab}$ (Refs. 4, 6–13, and 30)] is reasonable and, therefore, we are going to note hereafter by $\Delta\tilde{\sigma}_{ab}(\varepsilon,H)$ both the measured and the calculated in-plane fluctuation-induced magnetoconductivity. Moreover, these theoretical approaches assume also the so-called weak magnetic field limit, which may be characterized by[17]

$$l_H\equiv\left(\frac{\hbar}{2e\mu_0H}\right)^{1/2}\gg\xi_{ab}(\varepsilon), \tag{5}$$

where l_H is the so-called magnetic length, e is the electron charge, $\hbar$ is the reduced Planck constant, and $\xi_{ab}(\varepsilon)=\xi_{ab}(0)\varepsilon^{-1/2}$ is the superconducting coherence length in the ab plane. Taking into account that in Bi-2212 crystals $\xi_{ab}(0)\approx0.9$ nm (see later), even for $\mu_0H=5$ T one may expect deviations of the weak-magnetic field OPF behavior only for $\varepsilon\lesssim10^{-2}$, which is less than the expected Ginzburg reduced temperature.[17] Note, finally, the striking differences between the $\Delta\tilde{\sigma}_{ab}(\varepsilon)_H$ data for the two crystals studied here [compare the results for $\mu_0H=1T$ in Figs. 3(a) and 3(b)]. These differences, which contrast with the excellent agreement commented before between their paraconductivities (see Fig. 2), provide another indication of the presence in these crystals of small T_C inhomogeneities: As was already stressed in Ref. 25, due to the strong ε dependence of $\Delta\tilde{\sigma}_{ab}$, these T_C inhomogeneities will affect much more this quantity than $\Delta\sigma_{ab}$. We will see in the next section that these nonintrinsic effects may easily explain the huge differences between the experimental results for $\Delta\tilde{\sigma}_{ab}$ and the theory for ideal crystals (dashed lines).

The zero-field-cooled (ZFC) and the field-cooled (FC) in-plane magnetic susceptibility, χ_{ab}, of sample Bi1 are shown in Fig. 4. These data were already corrected from demagnetization effects (which may be important when the magnetic moment is large), by assuming the ellipsoidal approximation, which leads to a demagnetization factor of the order of 0.8.

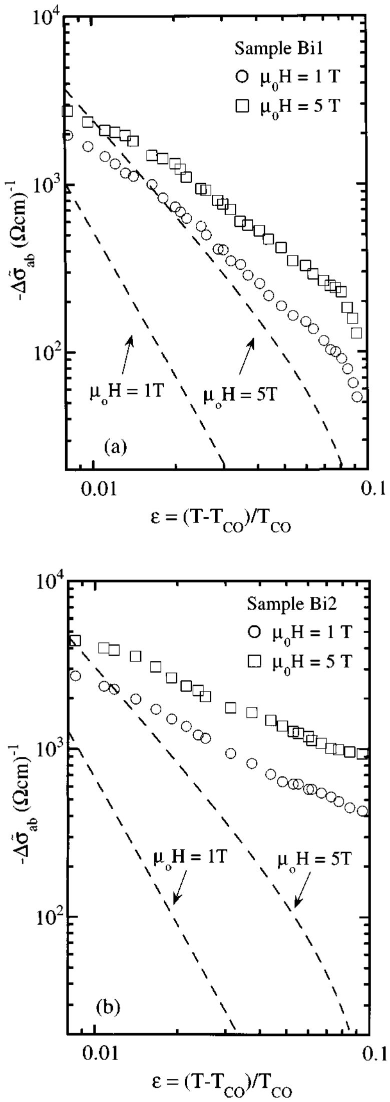

FIG. 3. (a) and (b). Fluctuation-induced magnetoconductivity in the ab plane vs reduced temperature of Bi1 and of Bi2 crystals, for $\mu_0H=1$ T and $\mu_0H=5$ T. The dashed lines are the corresponding direct OPF (or Aslamazov-Larkin) contributions to $\Delta\widetilde{\sigma}_{ab}(\varepsilon,H)$, calculated through Eq. (12) by using the values of Table III. The reduced temperature was defined here by using T_{CI}, extracted from the $\rho_{ab}(T,0)$ curves, as T_{C0}. The dramatic disagreement between the theoretical results for an ideal (homogeneous) crystal and the experimental data is not mitigated by the inclusion of other (indirect) OPF effects. Such a disagreement strongly suggests the presence in our samples of small T_{C} inhomogeneities. See main text for details.

As it can be seen in Fig. 4, the low-temperature susceptibility saturates well to about $\chi\approx-1$. This provides a direct indication of the excellent quality of this sample, which must have then only a quite small proportion of nonsuperconducting phases. Some examples of $\chi_{ab}(T)$ and $\chi_c(T)$ above T_{C0}, measured in the two crystals studied here, are presented in Figs. 5 and 6. In making these measurements, we have followed the same procedure we have previously used to determine the OPF effects on the susceptibility in $YBa_2Cu_3O_{7-\delta}$ crystals. Such a procedure has been detailed in Ref. 32. Let us just note here that these data were already corrected for a small Curie-Weiss-like contribution. The dashed lines represent the constant normal-state background for both field orientations, respectively, χ_{abB} and χ_{cB}. The corresponding temperature-independent values are summarized in Table II. The comparison of the results of Figs. 5(b) and 6 shows that the rounding effects on $\chi_{ab}(T)$ above T_{C0} are quite similar in both crystals. This provides a first direct indication that these rounding effects are due to intrinsic OPF effects and

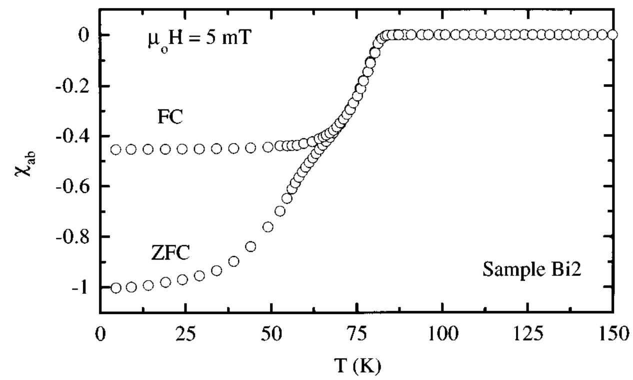

FIG. 4. Temperature dependence of the zero-field-cooled (ZFC) and field-cooled (FC) in-plane magnetic susceptibility χ_{ab} of sample Bi2, measured with a magnetic field of $\mu_0H=5$ mT applied perpendicularly to the ab planes.

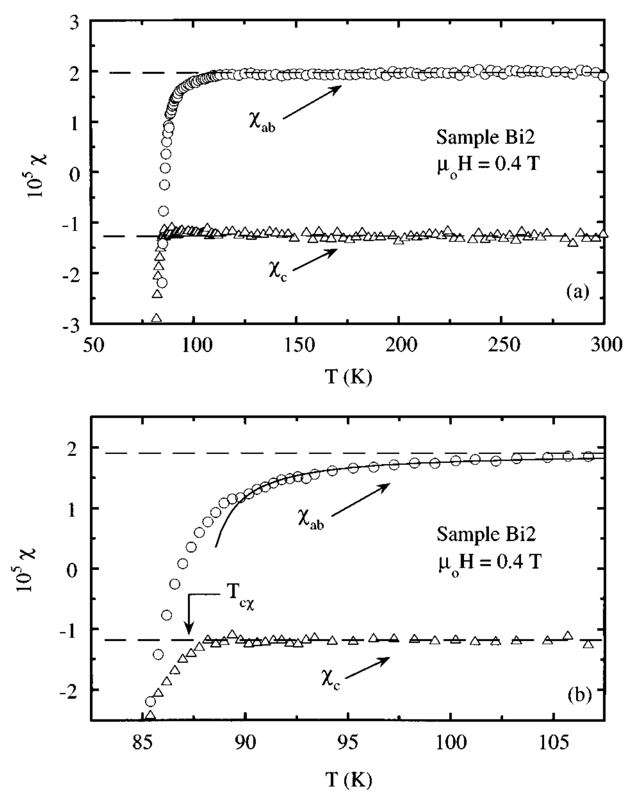

FIG. 5. (a) Temperature behavior of the magnetic susceptibility of sample Bi2 for $\mu_0H=0.4$ T, with H perpendicular (circles) and parallel (triangles) to the ab plane. The dashed lines are extrapolations of the normal-state susceptibilities. (b) Detailed view around the transition. The so-called magnetic-susceptibility transition temperature, $T_{C\chi}$, corresponds to the temperature where $\chi_c(T)$ separates from its behavior in the normal state. The solid line is the mean-field-like prediction in the mean-field region.

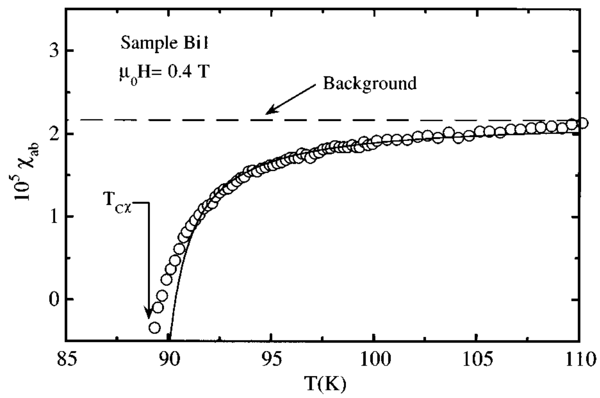

FIG. 6. Detailed view around the transition of the temperature behavior of the magnetic susceptibility of sample Bi1 for $\mu_0 H = 0.4$ T, with H perpendicular to the ab planes. The dashed line is the normal-state susceptibility. $T_{C\chi}$ is the magnetic-susceptibility transition temperature and the solid line is the mean-field-like prediction in the mean-field region.

that, therefore, the extrinsic effects associated with possible sample inhomogeneities remain small also for this observable. In addition, these results are relatively similar to those obtained by other authors in other good Bi-2212 single crystals, the differences being well to within 25%.[14] Finally, Fig. 5(b) illustrates the definition of $T_{C\chi}$, the temperature where $\chi_c(T)$ presents the sharp deviation from its normal-state behavior. As it may be seen in Table II, $T_{C\chi}$ agrees, to within ΔT^+_{CI}, with T_{CI}, defined through Eq. (1).

The fluctuation-induced diamagnetism, for a weak magnetic field applied perpendicular to the ab planes, $\Delta\chi_{ab}$, is obtained from the above $\chi_{ab}(T)$ data by using

$$\Delta\chi_{ab}(\varepsilon) \equiv \chi_{abB}(\varepsilon) - \chi_{ab}(\varepsilon), \tag{6}$$

where $\chi_{abB}(\varepsilon)$ is the background susceptibility. Here again we will use for χ_{abB} a linear extrapolation of the normal susceptibility measured between 150 and 250 K [dashed lines in Figs. 5(b) and 6]. The resulting $\Delta\chi_{ab}(\varepsilon)/T$ is presented in Figs. 7(a) and 7(b) for sample Bi1 and, respectively, Bi2. In Eq. (6), the reduced temperature is defined with $T_{C\chi}$ as T_{C0}. Let us stress here, however, that T_{CI} and $T_{C\chi}$ are so close to each other (see Table II) that the use of T_{CI} would not appreciably modify these $\Delta\chi_{ab}(\varepsilon)/T$ results. These results on $\Delta\chi_{ab}(\varepsilon)$ in both samples agree quantitatively with each other and, to within 25%, with the results previously reported by other groups in Bi-2212 single-crystal samples.[14] Let us already stress also here that the comparison of the $\Delta\chi_{ab}(\varepsilon)/T$ results of Figs. 7(a) and 7(b) with those of $\Delta\sigma_{ab}(\varepsilon)$ of Figs. 2(a) and 2(b) confirms that for both crystals these two observables have the same ε behavior for $\varepsilon \gtrsim 2\times10^{-2}$, a region of temperatures that will correspond to the so-called mean-field region. These results not only confirm the 2D character of the OPF in these compounds, but also it is a first indication of the absence of the indirect contributions to the OPF effects (see next section).

III. DATA ANALYSIS

It will be useful to summarize already here three aspects of the comparison between the experimental data presented

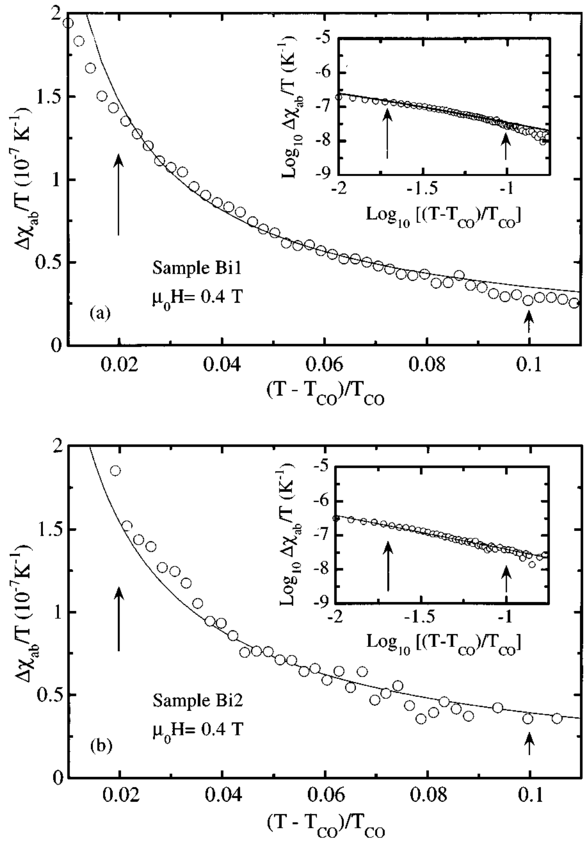

FIG. 7. Fluctuation-induced diamagnetism (over T) for H applied perpendicularly to the ab plane vs the reduced temperature for sample Bi1 (a) and sample Bi2 (b). In the insets a log-log representation is shown. The solid lines correspond to Eq. (10), with the parameters values given in Table III. See the main text for details.

in the preceding section and the available theoretical approaches. Note first that earlier results on the paraconductivity in Bi-based HTSC suggested that the so-called *indirect* OPF contributions (as for instance the so-called Maki-Thompson contribution) were negligible and that the *direct* OPF term (in this case the so-called Aslamazov-Larkin contribution) will suffice to account for the measurements.[1,2] This conclusion was since then confirmed, at least at a qualitative level, by different analyses of the paraconductivity[4–13] and of the fluctuation-induced diamagnetism[14–16] (see also Table I). So, in this paper we will analyze our experimental data, included those of the fluctuation-induced magnetoconductivity, in terms of the direct OPF contributions alone. In addition, it is also now well established that in these compounds one must take into account the presence of two superconducting CuO_2 planes in the layer periodicity length, $s = 1.54$ nm, (which is equal to $c/2$, where $c = 3.08$ nm is the crystallographic unit-cell length in the c direction).[14,17,24,26] We will see that our present analyses fully confirm the adequacy of such a procedure. Finally, we will see that the presence in our crystals of small critical temperature inhomogeneities, uniformly distributed in the samples, does not appreciably affect our $\Delta\sigma_{ab}(\varepsilon)$ and $\Delta\chi_{ab}(\varepsilon)/T$ data. However, as already stressed in the Introduction, due to its much stronger ε dependence, these T_{C0} inhomogeneities dramatically affect the fluctuation-induced in-plane magnetoconductivity. So, in analyzing $\Delta\tilde{\sigma}_{ab}(\varepsilon,H)$ we are going to use an effective medium approach proposed by Maza and Vidal[25] (MV) to take into account these inhomogeneity effects. Moreover, as a crucial test of consistency, we are going to check that the corresponding inhomogeneity corrections will not appreciably affect the in-plane paraconductivity.

A. In-plane paraconductivity and fluctuation-induced diamagnetism

In layered superconductors with two superconducting layers per periodicity length, s, and with two different Josephson coupling strengths, γ_1 and γ_2, between adjacent layers, which in principle is the case well suited to the Bi-2212 crystals studied here, the direct contributions in the MFR to the in-plane paraconductivity and to the fluctuation-induced diamagnetism are given by[17,24]

$$\Delta\sigma_{ab}(\varepsilon,\gamma_1/\gamma_2)=N_e(\varepsilon,\gamma_1/\gamma_2)\,\frac{A_{\rm AL}}{\varepsilon}\left(1+\frac{B_{\rm LD}}{\varepsilon}\right)^{-1/2}, \tag{7}$$

and, respectively,

$$\frac{\Delta\chi_{ab}(\varepsilon,\gamma_1/\gamma_2)}{T}=N_e(\varepsilon,\gamma_1/\gamma_2)\,\frac{A_{\rm S}}{\varepsilon}\left(1+\frac{B_{\rm LD}}{\varepsilon}\right)^{-1/2}, \tag{8}$$

where $N_e(\varepsilon,\gamma_1/\gamma_2)$ is an effective number of independent fluctuating planes per periodicity length, $A_{\rm AL}\equiv e^2/16\hbar s$ is the Aslamazov-Larkin paraconductivity amplitude, $B_{\rm LD}\equiv[2\xi_c(0)/s]^2$ is the Lawrence-Doniach parameter which controls the OPF dimensionality in these layered materials, $A_{\rm S}\equiv\mu_0\pi k_B\xi^2_{ab}(0)/3\phi_0^2 s$ is the Schmidt diamagnetism, k_B is the Boltzmann constant, and $\phi_0=h/2e$ is the flux quantum. Mainly due to the presence of $N_e(\varepsilon,\gamma_1/\gamma_2)$, these expressions for $\Delta\sigma_{ab}(\varepsilon)$ and $\Delta\chi_{ab}(\varepsilon)/T$ could be quite complicated.[17,24] However, earlier results on $\Delta\chi_{ab}(\varepsilon)/T$ in HTSC strongly suggest that in these compounds the Josephson coupling strength between neighbor CuO_2 superconducting layers must be only slightly dependent of the interlayer distances, i.e., $\gamma_1/\gamma_2\approx 1$.[17,32] So, in this approximation, Eqs. (7) and (8) reduce to

$$\Delta\sigma_{ab}(\varepsilon)=\frac{2A_{\rm AL}}{\varepsilon}\left(1+\frac{4B_{\rm LD}}{\varepsilon}\right)^{-1/2} \tag{9}$$

and, respectively,

$$\frac{\Delta\chi_{ab}(\varepsilon)}{T}=\frac{2A_S}{\varepsilon}\left(1+\frac{4B_{\rm LD}}{\varepsilon}\right)^{-1/2}. \tag{10}$$

If, in addition, $B_{\rm LD}\ll\varepsilon$ [or equivalently, $\xi_c(\varepsilon)\ll s/2$] in the MFR, i.e., in the 2D limit and with $\gamma_1/\gamma_2\approx 1$, Eqs. (9) and (10) reduce to $\Delta\sigma_{ab}(\varepsilon)=2A_{\rm AL}/\varepsilon$ and $\Delta\chi_{ab}(\varepsilon)/T=2A_S/\varepsilon$. Note also that, with all generality, Eqs. (7) and (8) lead to (in MKSA units) (Refs. 17 and 36)

$$\frac{\Delta\chi_{ab}(\varepsilon)/T}{\Delta\sigma_{ab}(\varepsilon)}=2.79\times 10^5\,\xi^2_{ab}(0), \tag{11}$$

an ε-independent relationship and which allows a straightforward estimation of $\xi_{ab}(0)$. The presence in $\Delta\chi_{ab}(\varepsilon)$ and $\Delta\sigma_{ab}(\varepsilon)$ of indirect contributions would modify Eq. (11) which, in particular, will become ε dependent.[2,5,17] This

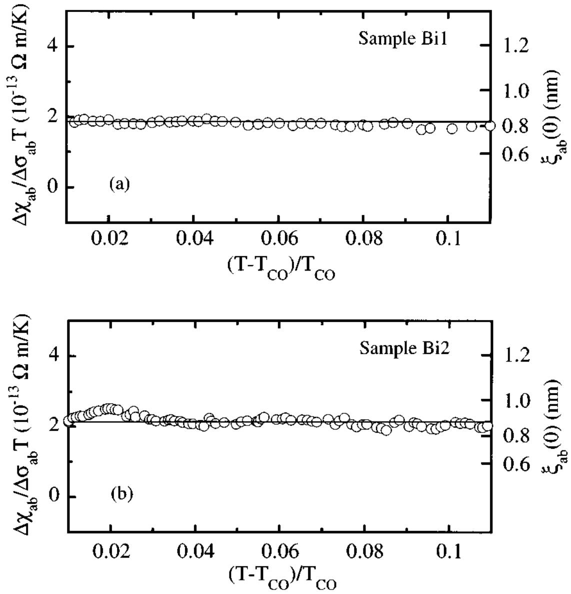

FIG. 8. Relationship between the in-plane fluctuation-induced diamagnetism over T and the in-plane paraconductivity for sample Bi1 (a) and sample Bi2 (b) vs reduced temperature. The solid lines are the best fits of Eq. (11), with $\xi_{ab}(0)$ as the unique free parameter. See the main text for details.

equation provides then a direct check of the possible relevance of these indirect terms in the MFR above T_{C0}.

The solid lines in Figs. 2(a) and 2(b) correspond to the best fits of Eq. (9) to the $\Delta\sigma_{ab}$ experimental data for the two samples, in the ε region bounded by the arrows, i.e., for $2\times 10^{-2}\lesssim\varepsilon\lesssim 10^{-1}$, with $\xi_c(0)$ as the unique free parameter. From these fits we obtained, $\xi_c(0)\lesssim 0.04$ nm for sample Bi1, and $\xi_c(0)\lesssim 0.05$ nm for sample Bi2, the rms error being in both cases of the order of 3%. These $\xi_c(0)$ values are much smaller than the periodicity length, s ($\sim$1.54 nm), confirming then at a quantitative level that in the MFR the OPF effects in the Bi-based compounds have a 2D-like behavior.[1,2] Also, these figures show that the agreement between experimental data and theory is excellent, and that without any indirect contribution. This last conclusion is confirmed by the results shown in Figs. 8(a) and 8(b).The solid lines in these figures are the best fits of Eq. (11), with $\xi_{ab}(0)$ as the unique parameter, to the experimental data. The resulting values are indicated in Table III. With these values for $\xi_{ab}(0)$ and the previously obtained one for $\xi_c(0)$, in Figs. 5(b), 6, 7(a), and 7(b) we have plotted Eq. (10) without any free parameter (solid lines). We found an excellent agreement between the theory and the experimental data (the rms

TABLE III. Superconducting coherence lengths and parameters characterizing the critical temperature inhomogeneity of the samples used in this work. These parameters are defined in the main text.

Sample	$\xi_{ab}(0)$ (nm)	$\xi_c(0)$ (nm)	$\overline{T_{C0}}$ (K)	$\Delta\overline{T_{C0}}$ (K)
Bi1	0.85	$\lesssim$0.04	88.9	0.6
Bi2	0.90	$\lesssim$0.05	86.6	1.1

error being of 5%), which shows at a quantitative level the adequacy of these theoretical approaches. These results also confirm the absence of appreciable indirect contributions to the fluctuation-induced diamagnetism in the MFR above T_{C0}.

B. Fluctuation-induced in-plane magnetoconductivity

In the MFR, the direct or Aslamazov-Larkin contribution to the fluctuation-induced magnetoconductivity, in the weak magnetic field limit and for $\gamma_1/\gamma_2=1$, is given by,[24,31]

$$\Delta\widetilde{\sigma}_{ab}(\varepsilon,H)=-\frac{A_{\rm AL}}{8}\left(\frac{\xi_{ab}(0)}{l_H}\right)^4\frac{[8\varepsilon(\varepsilon+B_{\rm LD})+3B_{\rm LD}^2]}{[\varepsilon(\varepsilon+B_{\rm LD})]^{5/2}}+\frac{A_{\rm AL}}{2}\left(\frac{\xi_{ab}(0)}{l_H}\right)^8\frac{1}{[\varepsilon(\varepsilon+4B_{\rm LD})]^{5/2}}\left[-15\left(1+\frac{2B_{\rm LD}}{\varepsilon}\right)^2+\frac{3}{2}\left(1+\frac{4B_{\rm LD}}{\varepsilon}\right)+\frac{35(1+2B_{\rm LD}/\varepsilon)^4}{2(1+4B_{\rm LD}/\varepsilon)}\right], \tag{12}$$

a result that may be directly obtained by just using $s/2$ instead of s in the original results of Hikami and Larkin[18] or of Maki and Thompson.[19] The other direct contribution to $\Delta\widetilde{\sigma}_{ab}(\varepsilon,H)$, the so-called Zeeman fluctuation-induced term (which reflects the Zeeman splitting effects), is not to be considered here because in HTSC this term is negligible in weak magnetic fields applied perpendicular to the superconducting layers.[31,37]

In Figs. 3(a) and 3(b) the dashed lines correspond to Eq. (12) with the $\xi_{ab}(0)$ and $\xi_c(0)$ values obtained above (see Table III) and for $\mu_0H=1$ T and, respectively, $\mu_0H=5$ T. These results show a very important disagreement between the theory and the experimental data, the differences at $\varepsilon\sim2\times10^{-2}$ being of 2 orders of magnitude. But, in addition, it is very easy to check that on the grounds of the theoretical OPF approaches summarized above it is not possible to simultaneously explain these $\Delta\widetilde{\sigma}_{ab}(\varepsilon,H)$ data together with those of $\Delta\sigma_{ab}(\varepsilon)$ and $\Delta\chi_{ab}(\varepsilon)/T$ measured in the same Bi-2212 crystals. This conclusion strongly suggests that due to its strong ε dependence, these $\Delta\widetilde{\sigma}_{ab}(\varepsilon,H)$ data may be very appreciably affected by the presence of small T_C inhomogeneities in our Bi-2212 crystals. In fact, the relatively large resistive transition (see Fig. 1 and Table II) makes such an explanation quite feasible. So, in the remaining part of this subsection we are going to use the effective-medium approach proposed by Maza and Vidal[25] (MV) to estimate how the presence in the samples of small T_C inhomogeneities, uniformly distributed in the crystals, could affect the *measured* (or effective) in-plane paraconductivity, $\Delta\sigma^e_{ab}$, and the *measured* in-plane fluctuation-induced magnetoconductivity, $\Delta\widetilde{\sigma}^e_{ab}$.

To relate the measured $\Delta\sigma^e_{ab}$ and $\Delta\widetilde{\sigma}^e_{ab}$ to the corresponding intrinsic observables, $\Delta\sigma_{ab}$ and $\Delta\widetilde{\sigma}_{ab}$, we start with the MV equation, based on the generalized Bruggeman's effective-medium-theory formula, which links the effective in-plane conductivity, $\sigma^e_{ab}(T,H)$, with the intrinsic one (the conductivity measured in an ideal, homogeneous, crystal), $\sigma_{ab}(T,H)$,[25]

$$\int_0^\infty \frac{\sigma_{ab}(T,H)-\sigma^e_{ab}(T,H)}{\sigma_{ab}(T,H)+2\sigma^e_{ab}(T,H)}\,Q(\sigma_{ab},T)d\sigma_{ab}=0, \tag{13}$$

where $Q(\sigma_{ab},T)$ is the local conductivity distribution, i.e., the volume fraction of the sample with a local conductivity between $\sigma_{ab}(T,H)$ and $\sigma_{ab}(T,H)+d\sigma_{ab}(T,H)$. (Let us note here that in the MV paper[25] the above equation contains a typographical error, a minus sign instead of the plus sign in the denominator.) This local or intrinsic conductivity, $\sigma_{ab}(T,H)$, may be written as the sum of the normal conductivity plus the corrections due to fluctuations,

$$\sigma_{ab}(T,H)=\sigma_{abB}(T,H)+\Delta\sigma_{ab}(T,0)+\Delta\widetilde{\sigma}_{ab}(T,H). \tag{14}$$

To approximate $Q(\sigma_{ab},T)$ in Eq. (13), we may note first that the basic effects of the stoichiometric inhomogeneities on $\sigma^e_{ab}(T,H)$, and therefore on $Q(\sigma_{ab},T)$, are due to the associated critical temperature inhomogeneities. For the corresponding distribution of T_{C0}'s, we will follow the MV procedure, which assumes a spatial Gaussian distribution characterized by the mean value of the critical temperature, $\overline{T}_{C0}$, and by the standard deviation $\Delta\overline{T}_{C0}$. Thus, the conductivity distribution may be written as

$$Q(\sigma_{ab},T)d\sigma_{ab}=\frac{2}{\sqrt{\pi}\Delta\overline{T}_{C0}}\exp\left\{-\left(\frac{T_{C0}-\overline{T}_{C0}}{\Delta\overline{T}_{C0}}\right)^2\right\}dT_{C0}. \tag{15}$$

As the exponential function in Eq. (15) is rapidly decreasing, to evaluate the integral in Eq. (13) we may change the integration limits to the interval $\overline{T}_{C0}\pm2\Delta\overline{T}_{C0}$. Then, Eq. (13) becomes

$$\int_{\overline{T}_{C0}-2\Delta\overline{T}_{C0}}^{\overline{T}_{C0}+2\Delta\overline{T}_{C0}}\frac{\sigma_{ab}(T,H)-\sigma^e_{ab}(T,H)}{\sigma_{ab}(T,H)+2\sigma^e_{ab}(T,H)}\,\frac{C}{\Delta\overline{T}_{C0}}\exp\left\{-\left(\frac{T_{C0}-\overline{T}_{C0}}{\Delta\overline{T}_{C0}}\right)^2\right\}dT_{C0}=0, \tag{16}$$

where $C=0.5448$ arises from normalization conditions. This expression links, therefore, the intrinsic and the effective conductivities through $\Delta \overline{T_{C0}}$, the standard deviation of critical temperatures due to the inhomogeneities. The corresponding effective paraconductivity and magnetoconductivity may be defined by just using $\sigma^e_{ab}(\overline{\varepsilon},H)$ given by Eq. (16) in Eqs. (2) and (3), i.e.,

$$\Delta\sigma^e_{ab}(\overline{\varepsilon},0)\equiv\sigma^e_{ab}(\overline{\varepsilon},0)-\sigma^e_{abB}(\overline{\varepsilon},0), \tag{17}$$

and

$$\Delta\tilde{\sigma}^e_{ab}(\overline{\varepsilon},H)\equiv\sigma^e_{ab}(\overline{\varepsilon},H)-\sigma^e_{ab}(\overline{\varepsilon},0), \tag{18}$$

where $\overline{\varepsilon}\equiv(T-\overline{T_{C0}})/\overline{T_{C0}}$ is the reduced temperature associated to the mean value $\overline{T_{C0}}$. Therefore, the central task here is now to calculate the $\Delta\overline{T_{C0}}$ leading $\Delta\sigma^e_{ab}$ and $\Delta\tilde{\sigma}^e_{ab}$ to agree with the measured quantities. Note already here that a crucial test of consistency will be the use of the same $\Delta\overline{T_{C0}}$ for both observables. The comparison between $\Delta\tilde{\sigma}^e_{ab}$ and the experimental data is showed in Figs. 9(a) and 9(b). The solid lines in these figures are the best fits to the experimental data of $\Delta\tilde{\sigma}^e_{ab}$, defined by Eq. (18) and calculated through Eq. (16), with $\overline{T_{C0}}$ and $\Delta\overline{T_{C0}}$ as free parameters. The corresponding $\sigma_{ab}(T,H)$ were obtained by imposing in Eq. (14) the values of $\xi_{ab}(0)$ and $\xi_c(0)$ obtained before (see Table III), i.e., without any other free parameter. The resulting fits are excellent, the rms error in the MFR being less than 10%, and the corresponding $\overline{T_{C0}}$ and $\Delta\overline{T_{C0}}$ being $\overline{T_{C0}}=88.9$ K and $\Delta\overline{T_{C0}}=0.6$ K for sample Bi1 and $\overline{T_{C0}}=86.6$ K and $\Delta\overline{T_{C0}}=1.1$ K for sample Bi2.

The above results show that by taking into account the presence of small T_C inhomogeneities in our crystals, it is possible to explain simultaneously and consistently the effects of the thermal fluctuations on the three observables measured here. In fact, it is the first time that the fluctuation-induced in-plane magnetoconductivity measured in Bi-2212 samples is explained at a quantitative level in terms of the existing theoretical approaches.[18–24] However, as the presence of inhomogeneities always introduces some additional uncertainties in the data analysis, it is crucial to provide here further checks on the goodness of our procedure. A first important check is to verify that the $\overline{T_{C0}}$ and $\Delta\overline{T_{C0}}$ values obtained before are consistent to each other and with the measured T_{CI}. Following the MV approach,[25] in the case of an inhomogeneous sample with a Gaussian distribution of critical temperatures, the relationship between T_{CI}, $\overline{T_{C0}}$, and $\Delta\overline{T_{C0}}$ may be approximated by taking into account that for $T\approx T_{CI}$ the inhomogeneous sample must be close to its percolation threshold, which for a three-dimensional continuum system will correspond to a superconducting fraction, $P(T)$, close to 15%. As $P(T)$ is given by[25]

$$P(T)=\frac{1}{2}\left[1-\mathrm{erf}\left(\frac{T-\overline{T_{C0}}}{\Delta\overline{T_{C0}}}\right)\right], \tag{19}$$

the relationship between T_{CI}, $\overline{T_{C0}}$, and $\Delta\overline{T_{C0}}$ may be approximated as

$$0.15\approx\frac{1}{2}\left[1-\mathrm{erf}\left(\frac{|T_{CI}-\overline{T_{C0}}|}{\Delta\overline{T_{C0}}}\right)\right], \tag{20}$$

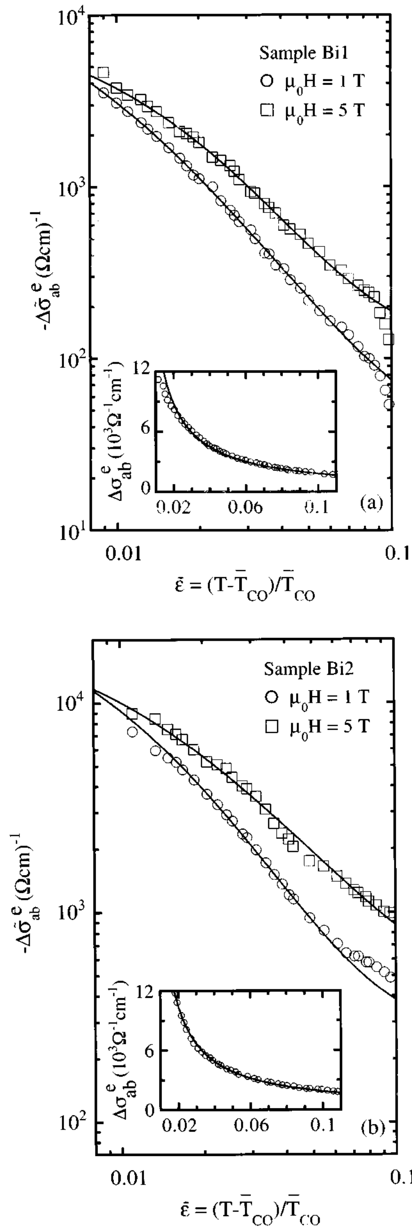

FIG. 9. (a) and (b). The same in-plane fluctuation-induced magnetoconductivity data as in Fig. 3 but as a function of the average reduced temperature, $\overline{\varepsilon}\equiv(T-\overline{T_{C0}})/\overline{T_{C0}}$. The solid lines are the best fits of the effective $\Delta\tilde{\sigma}^e_{ab}(\overline{\varepsilon},H)$, defined by Eq. (18) and calculated through Eq. (16), but with the $\xi_{ab}(0)$ and $\xi_c(0)$ values obtained before by analyzing $\Delta\sigma_{ab}$ and $\Delta\chi_{ab}$. The resulting $\overline{T_{C0}}$ and $\Delta\overline{T_{C0}}$ values are those presented in Table III. The insets show the comparison between the measured in-plane paraconductivity and $\Delta\sigma^e_{ab}(\overline{\varepsilon})$, calculated by using the same values of the different parameters as in $\Delta\tilde{\sigma}^e_{ab}(\overline{\varepsilon},H)$.

or, equivalently,

$$T_{CI}-\overline{T_{C0}}\approx 0.6\Delta\overline{T_{C0}}. \tag{21}$$

By using in Eq. (21) the $\overline{T_{C0}}$ and $\Delta\overline{T_{C0}}$ values obtained before (see Table III), we get $T_{CI}\approx 89.3$ K for sample Bi1, and $T_{CI}\approx 87.2$ K for sample Bi2, both calculated values being in excellent agreement with the measured ones (see Table II).

A second crucial test for our treatment of the inhomogeneity effects on $\Delta\tilde{\sigma}_{ab}(\varepsilon,H)$ is provided by the check of its compatibility with the two other observables measured here in the same crystals. In the case of the paraconductivity, the solid lines in the insets of Figs. 9(a) and 9(b) correspond to $\Delta\sigma^{e}_{ab}$, given by Eq. (18), with the values of all the involved parameters equal to the values obtained before for $\Delta\tilde{\sigma}^{e}_{ab}(\overline{\varepsilon,H})$ (those of Table III). As it can be seen in these insets, the agreement between $\Delta\sigma^{e}_{ab}(\overline{\varepsilon})$ and the measured in-plane paraconductivity is excellent. As we have stressed before, these results confirm at a quantitative level that due to its much weaker ε dependence, the paraconductivity is much less affected by the presence of small T_C inhomogeneities than the fluctuation-induced magnetoconductivity. In fact, the associated corrections remain well inside the experimental uncertainties of the data points (around 10% or less). This explains why in the preceding subsection we have found that the theoretical paraconductivity for homogeneous crystals was in excellent agreement with our MFR data (see also the footnote in Ref. 13). In the case of the fluctuation-induced diamagnetism, the main effect of the presence of inhomogeneities is the reduction of the superconducting fraction of the sample at a given temperature. This effect may be easily taken into account by introducing an adjustable constant in Eqs. (8) and (10). However, the small volume inhomogeneity needed to explain our $\Delta\tilde{\sigma}_{ab}$ results leads to an irrelevant correction for $\Delta\chi_{ab}$, in agreement with almost full flux expulsion showed at low temperature by the ZFC susceptibility (see Fig. 4). This is also consistent with the excellent agreement found before between the intrinsic $\Delta\chi_{ab}(\varepsilon)$ and our experimental data.

IV. CONCLUSIONS

We have presented in this paper detailed experimental data of the fluctuation-induced in-plane conductivity, magnetoconductivity, and diamagnetism of two Bi-2212 crystals. The structural, electric, and magnetic characterization of these crystals showed that they were of excellent quality, probably within the best Bi-2212 samples available until now.[27] However, our measurements also show that these samples are affected by small T_C inhomogeneities, associated with small oxygen content inhomogeneities (less than 1% of the total oxygenation) uniformly distributed in the crystals. These small T_C inhomogeneities (the corresponding $\Delta\overline{T_{C0}}$ is of the order of 1 K or less) do not appreciably affect $\Delta\sigma_{ab}$ and $\Delta\chi_{ab}$ in all the MFR but, due to its much stronger ε dependence, they severely affect $\Delta\tilde{\sigma}_{ab}$. So, in analyzing the intrinsic thermal fluctuation effects in terms of the available theoretical results for order-parameter fluctuations in layered superconductors,[17–24] we have used an effective-medium approach to also take into account the nonintrinsic effects associated with these inhomogeneities.[25] In this way, for the first time it was explained, consistently and simultaneously, $\Delta\sigma_{ab}$, $\Delta\tilde{\sigma}_{ab}$, and $\Delta\chi_{ab}$ measured in Bi-2212 compounds. Our analyses strongly suggest that the intrinsic OPF effects above T_{C0} are due only to the so-called direct contributions (the Aslamazov-Larkin terms in the case of $\Delta\sigma_{ab}$ and $\Delta\tilde{\sigma}_{ab}$, and the Schmidt term in the case of $\Delta\chi_{ab}$) and that, therefore, the so-called indirect contributions (as, for instance, the Maki-Thompson and the DOS terms) are not relevant in these compounds. These results confirm the possibility of unconventional (non-$^1s_0$), pair breaking,[38] wave pairing in these HTSC, as first suggested from OPF analyses in Ref. 2. The resulting values of the in-plane and out-of-plane coherence length amplitudes are, respectively, $\xi_{ab}(0)=(0.9\pm0.1)$ nm and $\xi_c(0)\lesssim0.05$ nm. These values agree with those that we have obtained before for other Bi-2212 crystals by studying the effects on the magnetization below T_{C0} of the fluctuations of the vortex positions.[16] These results also confirm at a quantitative level that in Bi-2212 compounds the effective number of fluctuating CuO_2 planes above the superconducting transition is $N_e\approx2$ and that the OPF are essentially two dimensional in all the MFR. Let us also stress here, finally, that our analyses of $\Delta\sigma_{ab}$ and $\Delta\tilde{\sigma}_{ab}$ in terms of T_{C0} inhomogeneities provide a simple and direct explanation of the until now controversial experimental results in Bi-2212 compounds.[4,6–12] But, in addition, our analyses may be easily extended to other $\Delta\tilde{\sigma}_{ab}$ results so far unexplained, as for instance those obtained in $Tl_2Ba_2CaCu_2O_x$ films.[39]

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