Scaling behavior of conductivity and magnetization in high-temperature superconductors

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(Received 24 June 1996; revised manuscript received 18 October 1996)

Through magnetization and conductivity measurements, the effect of dimensionality on the superconducting fluctuations has been investigated for $Tl_2Ba_2CaCu_2O_8$ (Tl-2212), $YBa_2Cu_3O_7$ (YBCO), and $(Tl,Bi)Si_2CaCu_2O_7$ (Tl-1212). Our results show that the bilayered thallium compound (i.e., Tl-2212 which is the most anisotropic compound) is clearly two-dimensional (2D) while a 3D-2D crossover is evidenced for Tl-1212 and YBCO. This crossover occurs through an intermediate region between two asymptotic behaviors: 3D near the transition and 2D at higher temperatures. [S0163-1829(97)01906-1]

I. INTRODUCTION

One of the most important features in the high-temperature superconductors (HTSC's) is the large width of the temperature window in which the fluctuations are important. This is due to their very short coherence lengths which determine the unit volume of the fluctuations and the high operating temperatures because each fluctuation mode is associated with the energy $\sim k_B T$. In addition, the layered structure of the HTSC effectively reduces the dimensionality of the fluctuations.

These fluctuations in the HTSC have been observed in magnetization, conductivity, and specific-heat measurements among others. Usually, the analysis of the fluctuations is carried out through scaling laws because of the lack of any general expression applicable in both the pure three-dimensional (3D) or two-dimensional (2D) case for the whole temperature range. Recently, on the basis of this scaling approach, numerous experimental papers[1–5] have succeeded in discussing the phenomenon of the critical fluctuations in terms of the lowest Landau level (LLL) approximation,[6,7] which holds in a region of the phase diagram close to a renormalized $H_{C_2}(T)$. The relevance of a scaling behavior exhibited by physical properties within this approximation has been presented for many types of HTSC's.[8,4,5] Through such an analysis it is then possible to study the influence of the dimensionality effects on the fluctuations. These dimensionality effects are directly related to the degree of anisotropy of the system which increases from $YBa_2Cu_3O_7$ to thallium-based compounds such as $Tl_2Ba_2CaCu_2O_8$ (Tl-2212). The thallium system is of great interest because many phases having intermediate anisotropy are available. Thus, one can compare the behavior of phases such as Tl-2212, considered as anisotropic as $Bi_2Sr_2CaCu_2O_8$ (Bi-2212), and (Tl, $BiSr_2CaCu_2O_7$ (Tl-1212) which is structurally and physically very close to $YBa_2Cu_3O_7$.

In this paper, we report on magnetization measurements on Tl-2212 and Tl-1212 single crystals in magnetic fields applied parallel to the c axis. By analyzing the data through the LLL scaling, we have concluded to a two-dimensional (2D) behavior for Tl-2212 whereas the results for Tl-1212 suggest a three-dimensional (3D) description. In order to be more explicit in our conclusions, we have carried out conductivity measurements on the Tl-1212 and YBCO samples. (This latter compound is used as a reference.) We finally find that the fluctuations for both compounds are three dimensional near the transition with a crossover to 2D away from the transition.

II. EXPERIMENT

Details on the preparation of $Tl_2Ba_2CaCu_2O_8$ and $(Tl,Bi)Sr_2CaCu_2O_7$ single crystals are given elsewhere.[9,10] The $YBa_2Cu_3O_7$ sample was processed using a MTG technique. Its complete preparation description is described in Ref. 11.

The magnetization measurements with the field parallel to the c axis were carried out using a SQUID magnetometer (Quantum design MPMS). The data $M(T,H)$ ($1<H<5$ T) were recorded following the procedure given in Ref. 4. In our resistive measurements, the magnetic field ($1<H<7$ T) was applied parallel to the c axis and the current was injected perpendicular to the field direction in the (ab) planes of the samples.

III. FLUCTUATION CONDUCTIVITY AND MAGNETIZATION

The contribution to the enhancement of conductivity and susceptibility are known to arise from Cooper pairs that begin to form, even for $T>T_c$, due to thermal fluctuations.[12] The expressions for the excess of conductivity and susceptibility, as obtained in a Gaussian fluctuation regime for a three-dimensional system,[13] predict an unobserved divergence of conductivity and susceptibility as $T\rightarrow T_c$. Such a deviation results from entering the critical region where correction terms of higher order in the superconducting order parameter Ψ, are not negligible in the Ginzburg-Landau (GL) free energy. In the Gaussian approximation, individual fluctuations are considered and only the $|\Psi|^2$ terms are included. The lack of any experimental evidence for such a divergence from the Gaussian fluctuation theory has led to the development of a theory[14–16] that goes beyond the Gaussian approximation. For instance, the Kyoto group[15,16] has calculated the fluctuation conductivity based on the model of Lawrence and Doniach by including the $|\Psi|^4$ term with the renormalization effect due to interactions between fluctuations. Ullah and Dorsey[14] have included this quartic term within the Hartree approximation and showed that experimental results for transport properties, including electrical conductivity due to the fluctuations, are in quantitative agreement with their calculation. In either two or three dimensions, they found, for various thermodynamic properties, scaling forms which are valid only under strong magnetic fields where electrons are confined to the Landau levels due to the orbital motion around an axis along the field direction. This limits the spatial correlation transverse to the field direction and, thus, the effective dimension is reduced because the only free motion available is along the field direction.

The scaling forms for magnetization (M) and conductivity (σ) are given by

$$\Theta = \left(\frac{T^2}{H}\right)^{1/3} F_{3\mathrm{D}}\left(A\,\frac{1}{(HT)^{2/3}}\,\varepsilon_H\right) \quad \text{for 3D}, \tag{1}$$

$$\Theta = \left(\frac{T}{H}\right)^{1/2} F_{2\mathrm{D}}\left(B\,\frac{1}{(HT)^{1/2}}\,\varepsilon_H\right) \quad \text{for 2D}, \tag{2}$$

with $\varepsilon_H = T - T_c(H)$. Here, the Θ represents the measured quantities: M/H or σ. The values A and B are appropriate constants characterizing the materials and $F_{3\mathrm{D}}$ and $F_{2\mathrm{D}}$ are the scaling functions.

According to this model any physical properties, including magnetization and conductivity, will follow the same scaling behavior. The plot $\Theta(H/T)^{1/2}$ vs $[\varepsilon_H/(HT)^{1/2}]$ for 2D, and its respective plot for 3D, will determine the dimensionality of the fluctuation mode. The difficultly lies in the fact that the dimensionality of the scaling is set for the whole range of studied temperature.

The parameter $T_c(H)$, in Eqs. (1) and (2), is the mean-field transition temperature in the presence magnetic fields. It is determined by optimizing the scaling using linear and nonlinear $T_c(H)$ curves. If we set the linear approximation for the upper critical field line,

$$T_c(H) = T_{c_0} + H\left(\frac{dH_{c_2}}{dT}\right)_{T_{c_0}}, \tag{3}$$

the determination of T_{c_0} can well define $dH_{c_2}/dT|_{T_{c_0}}$, the upper critical field slope.

A. Magnetization measurements

In this section, we present magnetization measurements in the critical region for Tl-2212 and Tl-1212, analyzed through the scaling behavior predicted by Ullah and Dorsey.[14] In addition, we compare our results for Tl-1212 with the data available in the literature for $YBa_2Cu_3O_7$.

Figure 1 shows the temperature dependence of the magnetization at various magnetic fields for Tl-2212. We observe here a temperature T^* where all the $M(T)$ curves registered for different magnetic fields cross at a single point. This phenomenon has often been observed in bismuth- and thallium-based compounds[15–18,4] and is considered as a manifestation of critical superconducting fluctuations in Josephson coupled layered superconductors.

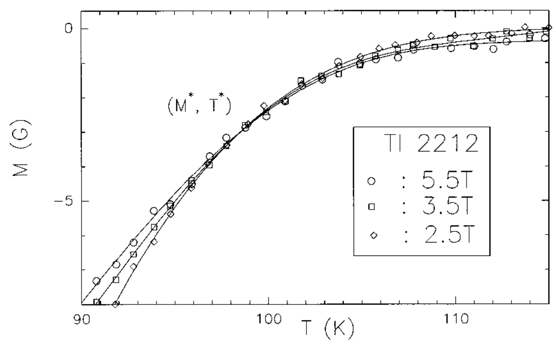

FIG. 1. Temperature dependence of the magnetization at various magnetic fields (5.5, 3.5, and 2.5 T) for Tl 2212.

Among other compounds, we have recently reported for Tl-2212 that the 2D scaling form works much better than the 3D one for which the data never collapse onto a single curve whatever the values of $T_c(H)$ chosen (see Ref. 4). Within the framework of this 2D analysis, we have obtained $-(dH_{c_2}/dT)_{T_{c_0}} = 2.6 \pm 0.2$ T/K with $T_{c_0} = 103$ K.

Moreover, the 2D nature of the superconducting transition for Tl-2212 and Tl-2223 has been confirmed in Ref. 4 by using the Tesanovic *et al.*[6] function. These latter authors have obtained an explicit form of the scaling function for the fluctuation's contribution to thermodynamic quantities in two-dimensional (2D) superconductors on the basis of the lowest Landau level approximation. In addition, in bismuth-based superconductors, Li *et al.*[17,18] have also successfully analyzed the fluctuation magnetization in high magnetic fields using the above 2D analysis. For these very anisotropic compounds, there is indeed no difficulty to account for the experimental magnetization data by assuming a bidimensionality on the whole range of temperature.

Let us now turn to the Tl-1212 sample. This compound exhibits the double advantage to belong to the thallium system, so that is shows a marked layered structure, and to be, structurally speaking, very close to the $YBa_2Cu_3O_7$ (the Tl in Tl-1212 replaces the Cu in the square coordination of $YBa_2Cu_3O_7$). Thus, it is interesting to understand how the fluctuation phenomenon adapts to this peculiar characteristic.

We present in Fig. 2 the temperature dependence of the magnetization at different applied fields for Tl-1212. We observe, once again, the existence of the crossing point (M^*, T^*) discussed above. Figures 3 and 4 show the data scaled by the 3D and 2D scaling forms, respectively. From the magnetization measurements, no distinction could be made between the 3D and 2D plots. The upper critical field slope corresponding to Figs. 2 and 3 are the same, i.e., $-dH_{c_2}/dT = 2.2 \pm 0.2$ T/K with $T_{c_0} = 86$ K. This behavior illustrates the difficulty existing for the less anisotropic compounds to account for experimental data by assuming a fixed dimensionality.

Indeed, a similar feature has already been encountered for $YBa_2Cu_3O_7$ by Welp *et al.*[5] and Wilkin *et al.*[19] For this compound, these authors could hardly determine the more appro-

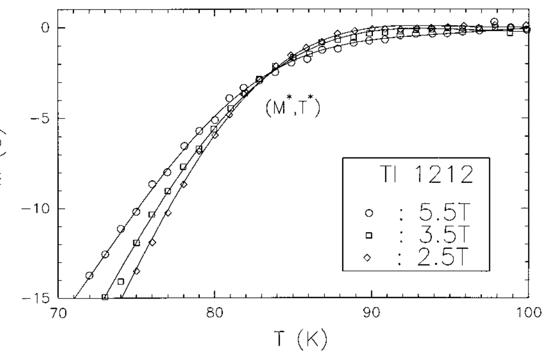

FIG. 2. Temperature dependence of the magnetization at various magnetic fields (5.5, 3.5, and 2.5 T) for Tl 1212.

priate scaling form, the two plots being very similar. Nevertheless, they have finally estimated that the three-dimensional mode is more satisfactory near the transition while, at higher temperatures, $YBa_2Cu_3O_7$ cannot be accurately treated as a continuum and the vestiges of its microscopic layered structure has to be considered by using the 2D form. This appears to agree with recent experimental data of Pierson *et al.*[20] These authors have measured the specific heat of $YBa_2Cu_3O_7$ and $LuBa_2Cu_3O_7$ in magnetic fields. They found that the scaling is, as a whole, clearly better for the 3D case than for the 2D one. Nevertheless, Pierson *et al.*[20] have found, once again, some evidence for a 2D behavior away from the transition. Indeed, the scaling behavior on the high-temperature side is a little better for 2D. At the sight of our magnetization data for Tl-1212, such a distinction between two temperature ranges where the 3D and 2D scaling forms would successively work is not evidenced.

As experimentally observed in Figs. 1 and 2, an interesting feature of the Josephson coupled layered superconductors is the existence of a field-independent magnetization point at a temperature T^*.[4,6,17,18] This peculiar behavior is usually explained by the vortex fluctuations effect, i.e., the entropy contribution to the free energy due to the thermal distortions of two-dimensional vortex pancakes as suggested by Bulaevskii *et al.*[21]

In this model, the field-independent magnetization is defined as

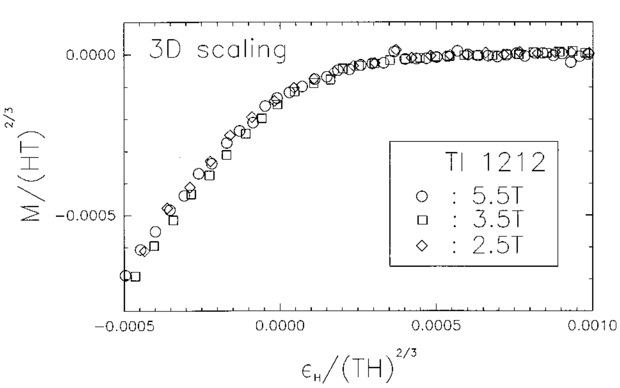

FIG. 3. 3D scaling of the magnetization data based on Eq. (1) for Tl-1212. The units of the variables $M/(HT)^{2/3}$ and $\varepsilon_H/(HT)^{2/3}$ are $G^{1/3}\,K^{2/3}$ and $G^{-2/3}\,K^{1/3}$, respectively.

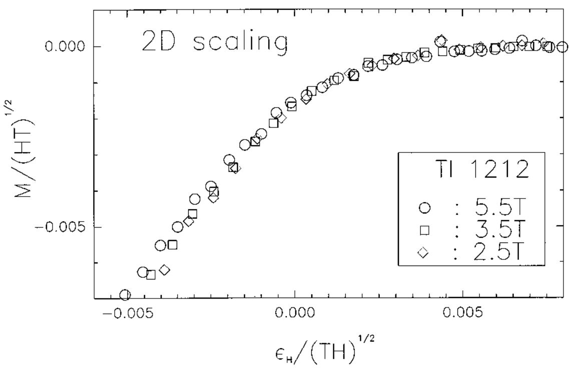

FIG. 4. 2D scaling of the magnetization data based on Eq. (2) for Tl-1212. The units of the variables $M/(HT)^{1/2}$ and $\varepsilon_H/(HT)^{1/2}$ are $G^{1/2}\,K^{-1/2}$ and $G^{-1/2}\,K^{1/2}$, respectively.

$$-M(T^*) = -M^* = \frac{k_B T^*}{l\phi} \ln \frac{\eta\alpha}{\sqrt{e}}. \tag{4}$$

In quasi-2D systems, the fluctuations of the order-parameter amplitude has been considered by Tesanovic *et al.*[6] In the framework of a high-field scaling theory, these authors predict the same relation without the ln factor, i.e., $\ln(\eta\alpha/\sqrt{e})=1$. Although the reliability of such an assumption remains unclear (see, for instance, Refs. 4 and 22), we consider that it holds in our case. As emphasized by Pierson *et al.*,[20] the length l describes a length scale in the c direction of the crystal and is frequently associated with the thickness of the superconducting planes within a unit cell.[17,18]

In our case, for Tl-1212, we have $l_{1212}\cong 50$ Å. This value has to be compared with $l_{\mathrm{YBCO}}\cong 55$ Å obtained by Pierson in $YBa_2Cu_3O_7$ from the data of Ref. 23. The fact that l_{1212} appears large compared to the periodicity of the structure $c\cong 12$ Å, obtained from x-ray-diffraction data,[10] leads to the conclusion that the sample is not close to a pure 2D system and that a 3D anisotropic description does not have to be left out.

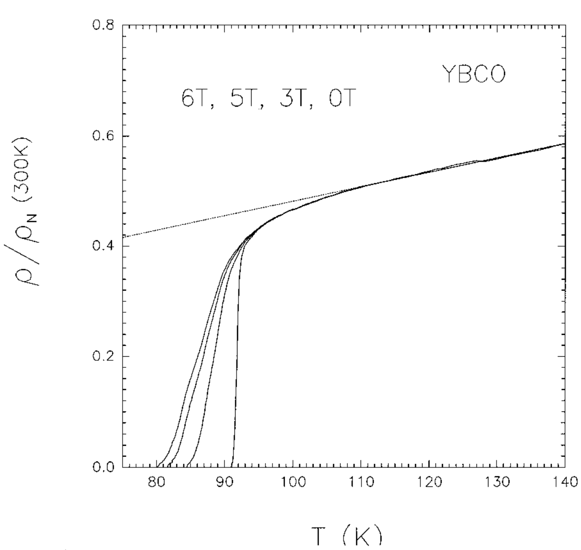

FIG. 5. Resistive transitions for $YBa_2Cu_3O_7$. The dashed line represents the linear background obtained by the high-temperature resistivity.

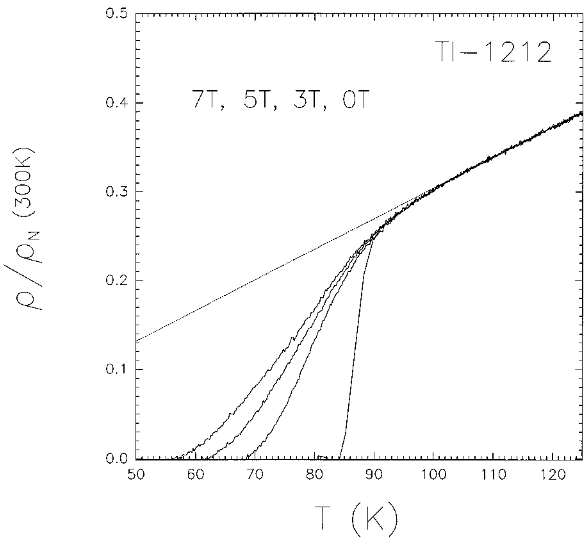

FIG. 6. Resistive transitions for Tl-1212. The dashed line represents the linear background obtained by the high-temperature resistivity.

To summarize, our magnetization analysis has shown that the Tl-1212 is not clearly 2D contrary to Tl-2212 and Tl-2223. Indeed, the behavior of the Tl-1212 seems to be quite close to the one of $YBa_2Cu_3O_7$, at least in a restricted range of temperature. Moreover, through this study, we have enlightened the great influence of the layered structure on the dimensionality of the fluctuation mode. We started with a 2D description for Tl-2212 (characterized by a double thallium layer imposing a weak coupling) to come to an intermediate 2D-3D description for Tl-1212 (which contains a single thallium layer). This latter feature is developed in the following by considering transport measurements in $YBa_2Cu_3O_7$ and Tl-1212.

B. Conductivity measurements

The fluctuation conductivity was just determined by subtracting the normal-state conductivity from the total conductivity. The linear background is obtained by extrapolation of the high-temperature resistivity. Typical resistive transitions are shown for $YBa_2Cu_3O_7$ and Tl-1212 in Figs. 5 and 6.

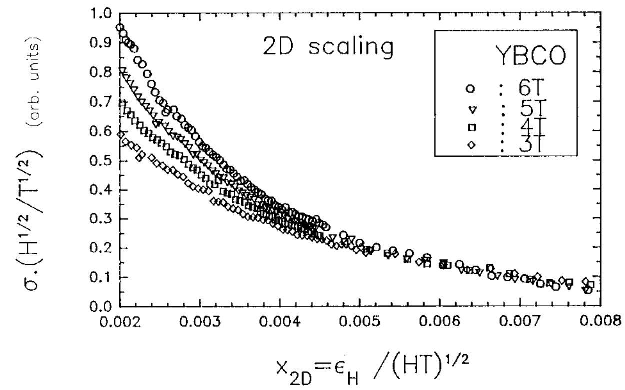

FIG. 8. 2D scaling of the conductivity data based on Eq. (2) for $YBa_2Cu_3O_7$. As can be seen, the scaling is very good away from T_c and the observed conductivity deviates from the scaling behavior more and more as the temperature approaches T_c (as x approaches 0).

Figures 7 and 8 show the scaled resistive transitions of YBCO for fields parallel to the c axis with the 3D and 2D scaling formulas, respectively. The two parameters used in Figs. 7 and 8 are $-dH_{c_2}/dT = 1.9 \pm 0.2$ T/K with $T_{c_0} = 92$ K. The value of the upper critical field slope agrees very well with the magnetization data of single crystals[24] and results of Ref. 5. The fluctuation conductivities have been analyzed in the same way for Tl-1212. The scaled data with the 3D and 2D scaling forms are exhibited in Figs. 9 and 10, respectively, with the parameters initially found in the magnetization analysis: $-dH_{c_2}/dT = 2.2 \pm 0.2$ T/K and $T_{c_0} = 86$ K. For both cases, YBCO and Tl-1212, it is shown that the higher the temperature is (i.e., $x > 0$; $x = 0$ for $T = T_c$, see Figs. 7–10), the better the conductivity data are scaled in terms of the 2D LLL variable. In contrast, when the temperature is decreasing near T_c, the data better scaled with the 3D variable. This phenomenon can be presented as evidence of a dimensional crossover, from 2D behavior away from T_c to 3D near it. This feature had already been reported in $YBa_2Cu_3O_7$.[3,20,25]

Indeed, for such compounds, we do not expect the effective interlayer coupling to be sufficiently strong to validate a full description in terms of 3D anisotropic homogeneous su-

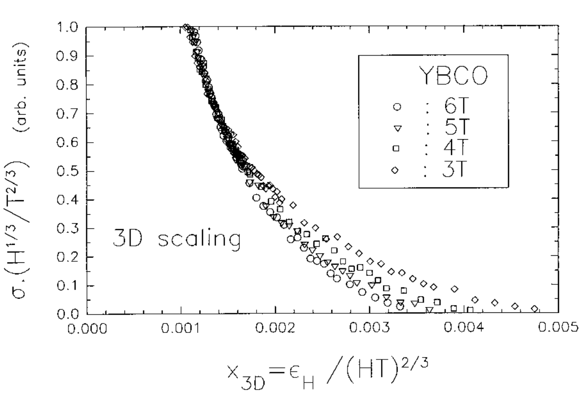

FIG. 7. 3D scaling of the conductivity data based on Eq. (1) for $YBa_2Cu_3O_7$. As can be seen, the scaling is very good near T_c (as x approaches 0) and the observed conductivity deviates from the scaling behavior more and more as the temperature increases.

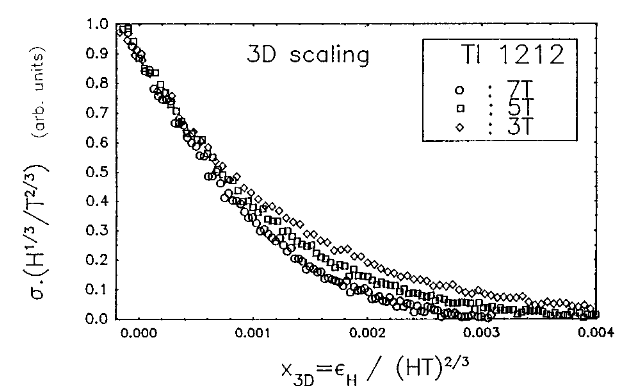

FIG. 9. 3D scaling of the conductivity data based on Eq. (1) for Tl-1212. As can be seen, the scaling is very good near T_c (as x approaches 0) and the observed conductivity deviates from the scaling behavior more and more as the temperature increases.

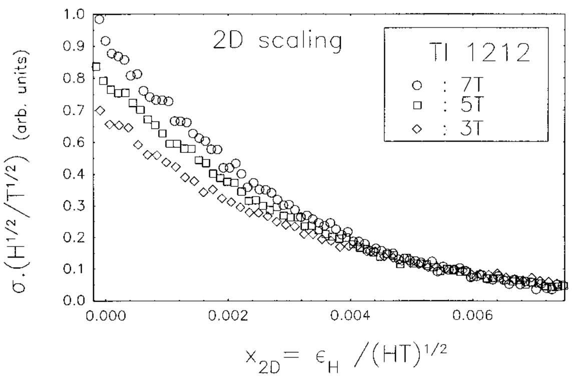

FIG. 10. 2D scaling of the conductivity data based on Eq. (2) for Tl-1212. As can be seen, the scaling is very good away from T_c and the observed conductivity deviates from the scaling behavior more and more as the temperature approaches T_c (as x approaches 0).

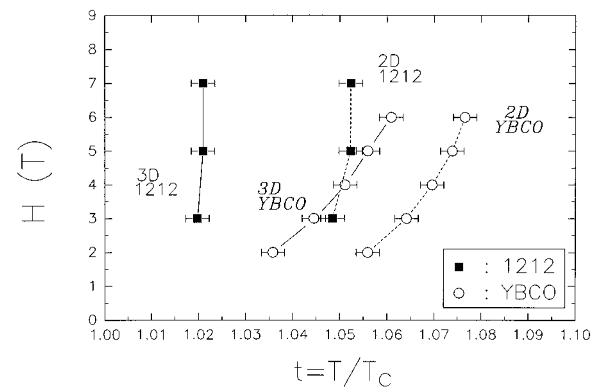

FIG. 11. Crossover lines determined from the points where the experimental conductivities deviate from the 2D and 3D scaling low. The full lines correspond to the limit of the 3D description and the dashed ones to the beginning of the 2D regime.

perconductors in the whole range of temperature. To understand this fundamental feature, it is important to take into account the very weak nature of the interlayer coupling in this highly anisotropic material and to picture their layered nature as a stack of Josephson junctions.[26] (It is well known as well that the presence of a magnetic field within a Josephson junction causes strong suppression of the Josephson currents across it because of its influence on the phase of the order parameter.[12]) Moreover, the two-dimensional behavior of those compounds at high temperatures means that the correlation length in the c direction (ξ_c) must be less than the spacing between the superconducting copper-oxide planes ($\cong$15 Å in the thallium bilayers), so that the layers are isolated and act independently. In this case, ξ_c represents the spatial extent of the superconducting coherence volume along the c axis.

In order to gain quantitative information, we have further investigated the location of those crossover lines at higher fields. If we define for Tl-1212 and $YBa_2Cu_3O_7$ x_{3D}^{cross} and x_{2D}^{cross}, the points where the 3D and 2D scaling, respectively, falls and succeeds, it is possible to determine, through Eqs. 1–3, the corresponding temperatures T_{3D}^{cross} and T_{2D}^{cross} associated to each value of the applied field. Thus, each pair (H, $x_{3D\text{ or }2D}^{cross}$) characterizes a point of the crossover lines. The latter are shown in Fig. 11.

We observe here that the different regimes do not overlap. This supposes a zone where the two compounds are truly in an intermediate case as regards the dimensionality of superconductivity: neither a pure 2D nor a pure 3D can describe the excess of conductivity in this zone of the critical fluctuations regime. This limitation comes from the fact that these scaling laws describing the critical fluctuations exist only for asymptotical regimes. Recently, Baraduc *et al.*[2] obtained a theoretical expression which was able to describe experimental data when the 2D and 3D scaling forms fall. However, this analysis is only valid for the Gaussian regime and does not take into account the critical regime.

Another important point concerning Fig. 11 is the relative width of the pure 3D and 2D regimes when one compares Tl-1212 and $YBa_2Cu_3O_7$: the pure 2D regime [i.e., the region above the line (H, T_{2D}^{cross})] is clearly larger for the Tl-1212 than for $YBa_2Cu_3O_7$. Such an observation is consistent with the weakly coupled behavior expected for this compound. Moreover, for Tl-1212, within the high-field range, the x_{2D}^{cross} and x_{3D}^{cross} become temperature independent and tend, within the experimental uncertainty, to the asymptotic values: $T_{2D}^{*cross}=90.5$ K and $T_{3D}^{*cross}=87.8$ K for the 2D and 3D crossover lines, respectively. The existing crossover lines predicted in the literature do not actually explain the existence of such a discontinuity in the dimensionality of the fluctuations (see, for instance, Ref. 27). Finally, it should be mentioned that the scaling analysis of the magnetization is mainly relevant at $T<T_c$, whereas the conductivity scaling only applies for $T>T_c$.

IV. CONCLUSION

In conclusion, we have studied the fluctuation magnetizations and conductivities for Tl-2212, Tl-1212, and $YBa_2Cu_3O_7$ using the LLL 2D and 3D scaling forms. For Tl-2212, the scaled magnetizations data have shown an unambiguously better agreement with the 2D scaling forms whereas no difference between the 3D and 2D description could be seen for Tl-1212. Although no general expressions are available for both the 2D and 3D regime, we have managed to gain quantitative information. Indeed, the scaled conductivities data of the Tl-1212 compound have allowed us to evidence two decoupling lines in the high-field regime.

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