Fluctuational dissipation in $YBa_2Cu_3O_{7-\delta}$ in tilted magnetic fields

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(Received 2 December 1996; revised manuscript received 24 March 1997)

We recently showed through angular measurements that in a wide range of temperature across T_c the resistivity of twinned films of $YBa_2Cu_3O_{7-\delta}$ can be consistently described in terms of fluctuational conductivity. Comparison with data taken on untwinned samples reveals that the upper part of the transition is identical for films and single crystals, and that the same theory works well in both cases. In addition, pure flux flow may describe the data in an appreciable region of H and T in the crystal only. We conclude that in a wide portion of the H-T plane the dissipation is due solely to intrinsic properties (order-parameter fluctuations with a possible flux-flow contribution in the crystal), while only at lower temperatures does the pinning become relevant, as supported by the breakdown of the angular scaling. [S0163-1829(97)06330-3]

High-temperature superconductors (HTC's) are known to present a broad transition in the presence of magnetic fields even in pure samples. It is generally believed that this feature is mainly due to the effects of the order parameter fluctuations. Fluctuations are particularly enhanced in HTC's, due both to the high critical temperature and to the short coherence lengths, in the (a,b) planes as well as along the c axis. Fluctuations are also thought to extend their influence onto the resistive properties below the critical temperature, giving rise to a nonzero dissipation also below T_c. While the region for T sufficiently higher than T_c can be understood in terms of Aslamazov-Larkin (AL) fluctuation theory[1] (even though better results are obtained for the $H=0$ case), the region across and below T_c is still a matter of discussion.

In the presence of magnetic fields, the experimental approach to the fluctuation-induced dissipation in the temperature region across T_c has been mainly devoted to the identification of some scaling properties,[2] letting T_c and/or H_{c2} be scaling parameters. This approach has been recently questioned: Indeed, it has been shown that more than one scaling theory can be made to fit the data at once,[3] thus raising doubts on the reliability of the conclusions that can be drawn by such analysis. It should be stressed, however, that the scaling study of the magnetization has been demonstrated to be a powerful tool, essentially because explicit expressions for the scaling functions could be written down.[4]

In the region well below T_c one should recover the predictions of the mean field theory[5] (that is, in the absence of disorder, the flux-flow regime), but if (and how) this limit is reached is still an open question. Moreover, the complex structure of flux lines and its evolution as a function of T and H, together with the presence of disorder, enormously affect the motion of the flux lines: Flux lattice melting,[6] fluxon decoupling,[7] viscous motion,[8] vortex-glass phases,[9] all are prominent features in the dissipative properties of HTC's. Those aspects, together with the absence of a pronounced feature separating flux motion from fluctuations, complicate the description of the dissipative regimes.

The current understanding of the fluctuation contribution to the dissipation is then limited by several factors. We have previously shown[10] that one can get noticeable enlightenment on the role of the fluctuation-induced resistivity from the analysis of the dependence of the resistive transitions on the orientation of the applied magnetic field. In fact, according to theoretical predictions,[11] in the vicinity of T_c the field and angular dependences of the fluctuational conductivity are not independent, but follow the rule $\Delta\sigma(H,\vartheta)=\Delta\sigma[H/H_{c2}(\vartheta)]$. Similar scaling is predicted for all the scalar thermodynamic quantities,[12] in the absence of disorder or in the presence of isotropic disorder. Oriented defects, such as twins, columnar defects, or intrinsic pinning by the (a,b) planes, are expected to modify the angular dependence of the flux-motion-related resistivity, and they might suppress the angular scaling. The role of defects can be further elucidated by a detailed comparison of the resistivity between untwinned crystals, where pinning is either absent or isotropic, and twinned films. This comparison is one of the main points of this paper and leads to results consistent with the angular investigations.

The sample under study is a c-axis-oriented $YBa_2Cu_3O_{7-\delta}$ (YBCO) film grown by laser ablation.[13] The θ-2θ rocking curve had a full width at half maximum (FWHM) of 0.4°. The film is about 1000 Å thick. It was patterned in a 2-mm-long, 100-μm-wide strip by ion milling. The resistive transition width in zero field (90%–10% criterion) is $\Delta T_c=0.8$ K. The resistance midpoint temperature is 90.5 K. Details about the resistivity measurements are reported in Ref. 10. Measurements were taken at various angles ϑ between the magnetic field and the (a,b) planes, as a function of the temperature at a fixed applied field, $\rho_H(T;\vartheta)$, and as a function of the field (field sweeps) at fixed temperature, $\rho_T(H;\vartheta)$.

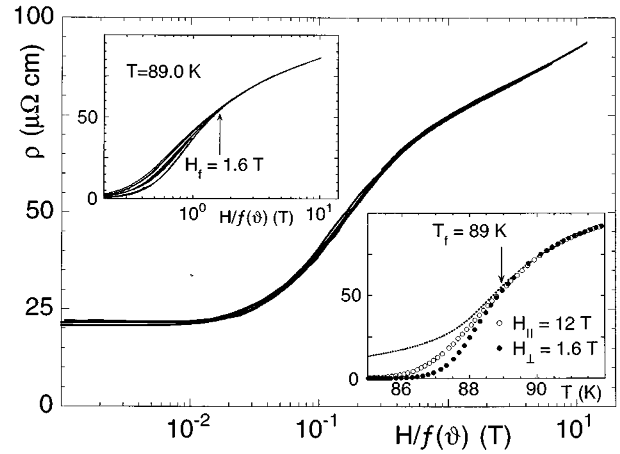

FIG. 1. Main panel: magnetic field sweeps data for the resistivity in the YBCO film, at $T=90.3$ K, plotted as ρ vs the experimentally rescaled field $H/f(\vartheta)$. The figure demonstrates the full collapse of the data taken at several angles ($\vartheta=0°,1°,5°,15°,60°,90°$). Upper inset: same measurements, taken at $T=89.0$ K, from Ref. 10: The scaling is obtained only above $H_f=1.6$ T (arrow). Lower inset: collapsing from above T_c down to a characteristic temperature $T_f=89.0$ K of the resistive transitions in a 12 T parallel and 1.6 T orthogonal field. Dashed line is the fit with the fluctuational conductivity theory (Ref. 15).

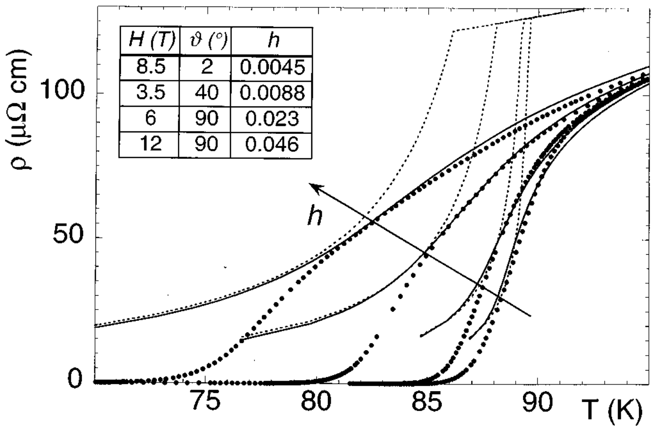

FIG. 2. Resistive transitions of the YBCO film, taken at different field strengths and orientations (solid circles, experimental data). Solid lines are the fits using the excess conductivity as given by the interacting fluctuations theory (Ref. 15), and dotted lines are the Bardeen-Stephen free flux flow. $\rho_n=(8.0+1.3T)$ $\mu\Omega$ cm.

We first focus our attention on the angular scaling properties of the field-dependent resistivity in YBCO. We have previously demonstrated[10] the angular scaling property of the resistivity (that is, the field and angle dependence can be expressed through a rescaled field $H/f(\vartheta)$, $\rho(H,\vartheta)=\rho[H/f(\vartheta)]$) in a limited temperature and magnetic field range. The insets of Fig. 1 summarize this feature. The upper inset shows how an entire set of field sweeps, $\rho_T(H;\vartheta)$, taken at fixed temperature (89.0 K) and various angles, collapses onto a single curve when plotted against a properly rescaled field $H/f(\vartheta)$, where $f(\vartheta)$ is defined as the number that, at every angle, makes the data better collapse onto the orthogonal-field curve [thus defining $f(0°)=1$]. Using the experimentally obtained $f(\vartheta)$, the scaling can be checked also on the transitions, $\rho_H(T;\vartheta)$, since for two orientations ϑ_1 and ϑ_2 one obtains the scaling if the fields are chosen as $H_1/f(\vartheta_1)=H_2/f(\vartheta_2)$. This is exemplified in the lower inset of Fig. 1, where we report the resistive transitions taken at $\vartheta=0°$ and $H=12$ T and at $\vartheta=90°$ and $H=1.6$ T, corresponding to $f(0°)=7.5$. In Ref. 10 the scaling function has been successfully identified with the anisotropic three-dimensional (3D) law. The anisotropy ratio is directly measured as $\varepsilon_{\rm exp}=f(0°)=7.5$. From the insets it is readily seen that the scaling applies only above a field-dependent temperature $T_f(H)$ or, equivalently, a temperature-dependent field $H_f(T)$ (arrows): In the high-H, high-T region of the resistive transitions, the data can be made to scale, while at low temperatures and low fields the angular scaling breaks down.

These findings are here extended at a different temperature (Fig. 1, main panel). The resulting $f(\vartheta)$ coincides within the experimental error with that obtained previously.[14] We note that in this case, due to the higher temperature ($T=90.3$ K), the scaling is fullfilled also at low fields.

From these sets of data, we thus demonstrate that an angular scaling takes place at high fields and temperatures. We also identified the angular scaling function with the anisotropic 3D expression for $H_{c2}(\vartheta)/H_{c2}(90°)$. In particular, the anisotropy ratio $\varepsilon=f(0°)$ is directly measured. As noted before, this scaling is expected if pinning phenomena are not relevant, so that it is possible to identify $T>T_f$ as the region where order parameter fluctuations, insensitive to pinning, are dominant.

To support this hypothesis and to extend the obtained results to higher fields, where the angular scaling cannot be verified due to the experimental limitations in the value of the field in the parallel orientation, we compared the obtained data with the predictions of the interacting-fluctuations theory developed by Ikeda *et al.*[15] This theory takes into account the characteristic features of high-T_c superconductors in a high magnetic field: small coherence length (which implies large fluctuations, and a relevant role of the non-Gaussian terms), high temperature, and the layered structure. It is worth noting that the theory is based on a Landau level (LL) expansion, which is not appropriate at very low magnetic fields. Deviations are thus expected in the low-field region. Once the normal-state resistivity has been set, the theory contains a small number of parameters: λ_{0ab}, ξ_{0ab}, ξ_{0c}, and T_{c0}. In addition, it is usually allowed to introduce a slowly field-dependent prefactor $C(H)$, of order unity.[15] So-obtained fits usually follow the data only down to a typical temperature, which we have shown to coincide with T_f (Fig. 1, lower inset, and Ref. 10).

In the present analysis of the data, we hold $C(H)$ fixed. We thus obtain only slightly worse fits, but the correct low-temperature limit is recovered (see below). The results of the fit demonstrate that the data can be suitably described by the theory. In Fig. 2 we present some of the experimental resistive transitions, taken at various fields and angles. From the fits, we obtained $\lambda_{0ab}=1010$ Å, $\xi_{0c}=1.43$ Å, in agreement with reported values,[16] and $T_{c0}=90.0$ K, according to the resistive transition in zero field. The experimental result for the anisotropy ratio, $\varepsilon_{\rm expt}=7.5$, fixes the value for ξ_{0ab}

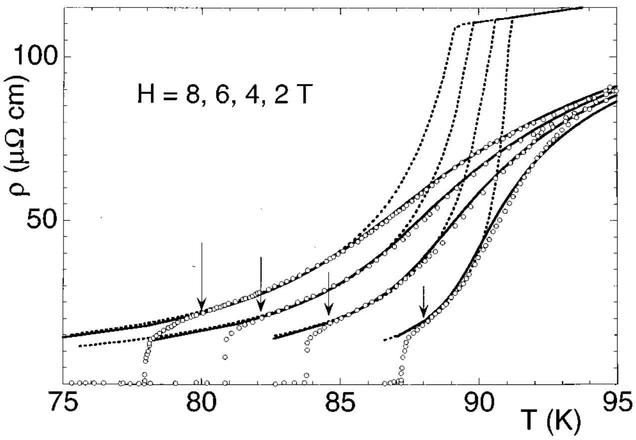

FIG. 3. Resistive transitions of the untwinned YBCO crystal (data digitized from Ref. 18) at different field strengths ($\vartheta=90°$). Solid lines are the fits using the excess conductivity as given by the interacting fluctuations theory (Ref. 15), and dotted lines are the Bardeen-Stephen free flux flow. In this case, a region exists where the BS flux-flow expression fits the data. $\rho_n=(7.0+1.1T)$ $\mu\Omega$ cm. Arrows mark $T_f(H)$.

$=\varepsilon_{\rm expt}\xi_{0c}$. The normal-state resistivity has been chosen as $\rho_n=A+BT$, and results in a value slightly above the experimental one. This behavior is always observed when calculating the fluctuation conductivity[17] and has not received up to now an explanation. With the same set of parameters we fit *all* the resistivity curves *together*, at all the magnetic fields and angles (see also Fig. 2 in Ref. 10). In Fig. 2, the reduced field $h=H/H_{c2}(\vartheta)$ ranges from 4.5×10^{-3} to 4.6×10^{-2}.

Since the fluctuation theory we applied was developed for defect-free superconductors, similar results should be recovered in pure samples. To check this suggestion, we fitted published data of resistive transitions of an untwinned YBCO crystal[18] with the interacting fluctuations theory. The

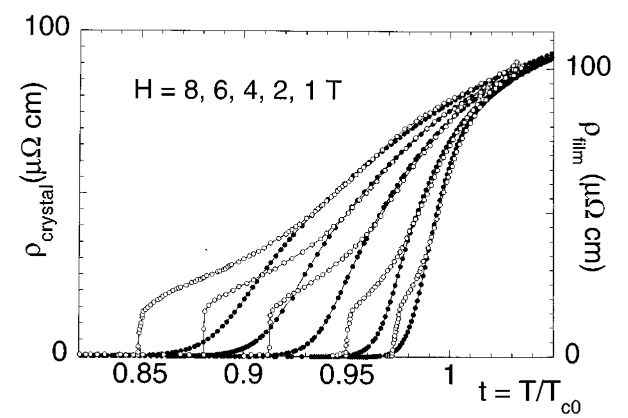

FIG. 4. Resistive transitions of the untwinned crystal (open circles, left scale, data from Ref. 18) and of our film (solid circles, right scale), as a function of the reduced temperature (T_{c0} is obtained from the fluctuative fits). Different vertical scales reflect slightly different normal state resistivity. The disordered (film) and the pure (untwinned crystal) samples behave identically in the high part of the transition, indicating that in this region the dissipation is due to intrinsic properties only. Data taken in the $\vartheta=90°$ orientation.

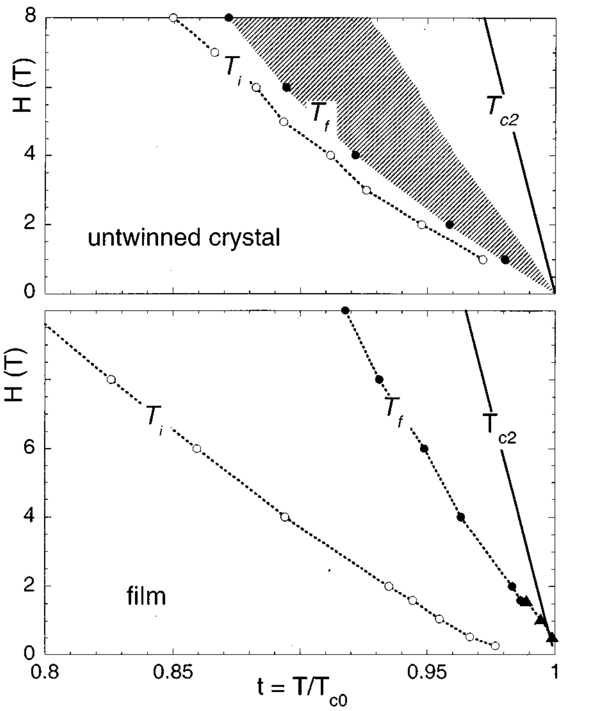

FIG. 5. H-T phase diagrams as obtained from the data and the interpretation here given, in the crystal (upper panel) and in the film (lower panel). Above $T_f(H)$ (as determined from the failure of the fluctuative fits, solid circles, and from the breaking of the angular scaling, solid triangles), only intrinsic properties contribute to the dissipation. Below $T_i(H)$, open circles, the resistivity becomes unmeasurably small, and the flux lines tend to freeze. In the region between T_i and T_f the dissipation is ascribed to (disorder-influenced) motion of flux lines. In the shaded region we cannot distinguish between free-flux-flow and order-parameter fluctuations. $H_{c2}(T)$ (solid lines) is that determined from the fits. Dotted lines are guides for the eye.

results are presented in Fig. 3: The field spans the 2–8 T range, and it is directed only perpendicular to the (a,b) planes. Thus ε is not measured and it must be left as additional parameter. It is seen that the results are very convincing, as usual only above a field-dependent temperature $T_f(H)$. Again, the obtained parameters are very reasonable: $\lambda_{0ab}=1000$ Å, $\xi_{0c}=1.43$ Å, $T_{c0}=91.8$ K, and $\varepsilon=7.5$.

From the fact that the same theory describes equally well the resistive transitions either in the twinned and untwinned samples, we have a strong indication that intrinsic properties are dominant on the dissipative processes in the upper part of the transitions. Putting forth this indication, we argue that when the microscopic parameters $(\xi,\varepsilon,\lambda)$ attain the same value, the same behavior of the resistivity should be obtained. Considering that the fit parameters are almost the same for our twinned thin film and for the Argonne's untwinned crystal, we plot in Fig. 4 the resistive transitions of the two samples at same magnetic fields vs the reduced temperature $t=T/T_{c0}$. The coincidence of the data in the upper part of the transition is outstanding, giving confidence on the irrelevance of defects on the dissipation close to T_c. This interpretative framework is supported by other experiments showing that near T_c the resistivity in YBCO is not affected either by different concentration of impurities[19] or by the enhancement of pointlike defects due to electron irradiation.[20] Moreover, it seems very unlikely that a distribution of T_c's, often invoked for the broadening of the transition in HTC's, could exist in the film, as opposed to the ''pure'' T_c in the crystal.

Other sources of dissipation are expected to be present in type-II superconductors, connected to the vortex motion. From the comparison of our data on the twinned film with those on untwinned crystals, it is clear that the low part of the transition is heavily affected by the structural features of the sample, which can dictate the type of vortex transformation (vortex glass-liquid or melting transition, decoupling, thermal activation, etc.). It is not the aim of this paper to study this dissipation region. Instead, we show in the following how the data can support a connection between the fluctuational and the free flux-flow (in absence of disorder) regimes.

The fluctuation theories that extend the treatment below T_c should have[5] as a low-temperature limiting form the simple Bardeen-Stephen (BS), flux-flow expression $\rho = \rho_n H/H_{c2}$. It is then interesting to look if this limit is reached in HTC's, also because it is known that this simple expression hardly describes the data on HTC's (Ref. 21) (where special techniques are needed in order to observe the free flow of vortices[22]). We note that the BS expression contains only ρ_n and H_{c2} as parameters, which have been already obtained in the fluctuation analysis, and so it is straightforward to check if and when it applies to the data. Dotted lines in Figs. 2 and 3 are given by the BS expression. The flux-flow curves lead to several considerations. Before commenting on the results, we remark that the BS expression coincides with the fluctuation theory at low temperatures, giving confidence in the numerical procedure followed to evaluate the theoretical fluctuational conductivity.

Let us consider first the data on twinned films. It is apparent that the BS behavior is almost never followed in this sample: The high density of defects substantially affects the vortex motion, and pinning features become prominent on the intrinsic ones. This is strikingly different from what is observed in untwinned crystals: After a very steep rise, the resistivity follows the BS behavior within a well-detectable temperature range and then approaches T_c according to the pure fluctuation contribution.

We summarize the previous considerations in Fig. 5, where we set up an H-T diagram. We define two characteristic temperatures: T_i, the temperature where the detected voltage is twice our sensitivity, gives an indication of the beginning of the vortex motion and can be a measure of the glass or melting transition, and T_f, the temperature below which the fluctuation–free-flow description fails [it is determined either by the temperature where an entire angular set of resistive transitions merges (see Fig. 1) or where the fit by interacting fluctuations theory departs from the data; where both definitions applies, it is a result that the two choices coincide]. This leads to three different regions from the dissipative point of view: Below T_i the resistivity is vanishingly small, and the vortex lattice (or glass) is frozen; between T_i and T_f, vortices do move, but due to the pinning their motion results in being highly viscous (it has been described in terms of ''glassy'' motion of the vortex system[8] or as a ''plastic'' motion of portions of the lattice[23]). Above T_f, one enters the free-flow–fluctuation regime. From Fig. 5 it is seen that the twinned film presents a wide region of pinning dominated flux motion, while in the untwinned crystal this region is rather narrow: Instead, in the crystal one observes BS flux flow, which is hampered by defects (most likely, twins) in the film. The upper critical field does not mark a sharp transition in the dissipative properties, neither in defective nor in pure samples.

We thank the CNR-IESS laboratory for help in sample patterning, V. Boffa for valuable discussions, and U. Baffi for help in the project and realization of the sample holder.

[1] W. Holm *et al.*, Phys. Rev. B **52**, 3748 (1995).

[2] S. Ullah and A. T. Dorsey, Phys. Rev. B **44**, 262 (1991); U. Welp *et al.*, Phys. Rev. Lett. **67**, 3180 (1991); S. Sarti *et al.*, Phys. Rev. B **52**, 3734 (1995).

[3] A. R. Junod, in *Studies of High-Temperature Superconductors*, edited by A. V. Narlikar (Nova Science, New York, 1996), Vol. 19, p. 1; M. Roulin, A. Junod, and E. Walker, Physica C **260**, 257 (1996).

[4] Z. Tesanovic *et al.*, Phys. Rev. Lett. **69**, 3563 (1992).

[5] D. J. Thouless, Phys. Rev. Lett. **34**, 946 (1975).

[6] W. K. Kwok *et al.*, Phys. Rev. Lett. **69**, 3370 (1992).

[7] L. I. Glazman and A. E. Koshelev, Phys. Rev. B **43**, 2835 (1991); C. J. van der Beek *et al.*, Physica C **195**, 307 (1992).

[8] M. Giura *et al.*, Phys. Rev. B **46**, 5753 (1992).

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

[10] S. Sarti, M. Giura, E. Silva, R. Fastampa, and V. Boffa, Phys. Rev. B **55**, 6133 (1997).

[11] R. Ikeda, Physica C **201**, 386 (1992).

[12] G. Blatter, V. B. Geshkenbein, and A. I. Larkin, Phys. Rev. Lett. **68**, 875 (1992); Z. Hao and J. R. Clem, Phys. Rev. B **46**, 5853 (1992).

[13] V. Boffa *et al.*, in *Proceedings of Fourth Euro-Ceramics*, edited by A. Barone, D. Fiorani, and A. Tampieri (Gruppo editoriale Faenza Editrice, Faenza, 1996), Vol. 7, p. 139.

[14] D. Neri, S. Sarti, and E. Silva, Nuovo Cimento D to be published (1997).

[15] R. Ikeda, T. Ohmi, and T. Tsuneto, J. Phys. Soc. Jpn. **60**, 1051 (1991).

[16] See, e.g., G. Blatter *et al.*, Rev. Mod. Phys. **66**, 1125 (1994).

[17] See, e.g., T. A. Friedmann *et al.*, Phys. Rev. B **42**, 6217 (1990).

[18] W. K. Kwok *et al.*, Phys. Rev. Lett. **72**, 1092 (1994).

[19] K. Semba *et al.*, Phys. Rev. B **49**, 10 043 (1994).

[20] J. A. Fendrich *et al.*, Phys. Rev. Lett. **74**, 1210 (1995).

[21] A. P. Malozemoff, MRS Bull. **15**, 50 (1990).

[22] M. N. Kunchur *et al.*, Phys. Rev. Lett. **70**, 998 (1993).

[23] W. K. Kwok *et al.*, Phys. Rev. Lett. **73**, 2614 (1994).