Magnetic field for the onset of resistivity: Angular dependence and temperature-induced dimensional crossover in Bi-Sr-Ca-Cu-O

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The temperature-induced crossover from a two-dimensional (2D) to 3D behavior found in 2:2:1:2 Bi-Sr-Ca-Cu-O is studied by means of a large set of measurements of the magnetic field H^* for the onset of dissipation. Some interesting features of the angular dependence near the crossover temperature are found; in particular, the H^* values perpendicular to a-b planes lie on the irreversibility line. The angular behavior of H^* is analogous to that of the upper critical field in conventional layered superconductors. A tentative explanation is given.

I. INTRODUCTION

High-T_c copper oxides are compounds that consist of CuO_2 layers alternating with other layers: in particular, Y, Ba, and CuO layers in $YBa_2Cu_3O_7$; Ca, Sr, and BiO layers in $Bi_2Sr_2CaCu_2O_8$; and Ca, Ba, and TlO layers in $Tl_2Ba_2CaCu_2O_8$. The CuO_2 layers are superconducting below the transition temperature, whereas the contribution to superconductivity of planes BiO and TlO has not been yet clarified. Planes Y, Ca, Sr, and Ba, which show insulating behavior, increase the distance between the superconducting layers and, in this way, are responsible for the strong anisotropy of these compounds.

To describe the anisotropy quantitatively, it has sometimes been found useful to make use of an anisotropic elliptical effective-mass tensor in the Ginzburg-Landau theory.[1] However, this model is not appropriate for superconductors with a high degree of anisotropy[2] such as Bi and Tl compounds, for which the ratio ρ_z/ρ_{ab} (ρ_z and ρ_{ab} are the normal-state resistivities, respectively, along and perpendicular to the c axis) can be as large as 10^5.[3] Because of the small zero-temperature coherence length $\xi_z(0)$ along the c axis compared with that of conventional superconductors, $\xi_z(0)$ may be smaller than the spacing s between adjacent superconducting layers. Therefore, models that take into account the quasi-two-dimensional structure of these compounds are required. Also, since in all superconductors the coherence length $\xi_z(T)$ diverges as the temperature T approaches the transition temperature T_c, in high-T_c copper oxides some crossover from a two-dimensional (2D) (or quasi-two-dimensional) to an anisotropic 3D regime should occur below T_c. In other words, a crossover temperature T^* that separates the two regimes should be detectable. The extent to which T^* is close to T_c depends on the degree of anisotropy.

The crossover reduced temperature $t^*=T^*/T_c$ may be estimated considering that the crossing point demarking the quasi-2D from the 3D behavior is determined by the condition[4] $\xi_z(t^*)=s/\sqrt{2}$. For Bi 2:2:1:2, assuming the extrapolated zero-temperature coherence length to be $\xi_z(0)\simeq 1$ Å (Refs. 5 and 6) and $s\simeq 15$ Å for the spacing between the double-CuO_2 planes,[7] one should find $t^*=0.99$ taking the usual expression $\xi_z(t^*)=\xi_z(0)(1-t^*)^{-1/2}$. In an analogous way, for Y 1:2:3 [$\xi_z(0)\simeq 3$ Å (Ref. 8) and $s\simeq 12$ Å (Ref. 7)], one should find $t^*=0.88$.[9]

Two models are available in literature that have been shown to be capable of explaining the properties of layered superconductors. The first one, proposed by Lawrence and Doniach,[10] assumes that the superconducting order parameter in adjacent layers is coupled by Josephson tunneling, which occurs when the coherence length is larger than the layer spacing [$\xi_z(T)>s$, Lawrence and Doniach 3D regime]. The second one, proposed by Tinkham,[11] considers the layers to be decoupled [$\xi_z(T)<s$, 2D regime]. Both models make use of the upper critical field to describe the anisotropy. The equation for these two models are, for the 3D regime,

$$\left[\frac{H_{c2}(\vartheta)\sin\vartheta}{H_{c2\perp}}\right]^2+\left[\frac{H_{c2}(\vartheta)\cos\vartheta}{H_{c2\parallel}}\right]^2=1\ , \quad (1)$$

and for the 2D regime,

$$\left|\frac{H_{c2}(\vartheta)\sin\vartheta}{H_{c2\perp}}\right|+\left[\frac{H_{c2}(\vartheta)\cos\vartheta}{H_{c2\parallel}}\right]^2=1\ , \quad (2)$$

where ϑ is the angle between the external magnetic field $\mathbf{H}$ and the superconducting layers (planes a-b in the case of high-T_c copper oxides), while $H_{c2\perp}$ and $H_{c2\parallel}$ are the upper critical field for $\mathbf{H}$, respectively, applied perpendicular and parallel to the layers.

The relevant feature that distinguishes the two models, when the anisotropy is strong, lies in the behavior of the derivative for ϑ close to zero ($\mathbf{H}$ parallel to the layers). Indeed, we have from Eq. (1)

$$\left|\frac{dH_{c2}}{d\vartheta}\right|_{\vartheta=0}=0\ , \quad (3)$$

so that the curve $H_{c2}(\vartheta)$ displays a round maximum at $\vartheta=0$ and, from Eq. (2),

$$\left|\frac{dH_{c2}}{d\vartheta}\right|_{\vartheta=0}=\frac{H_{c2\parallel}^2}{2H_{c2\perp}}\neq 0\ , \quad (4)$$

which corresponds to a cusp at $\vartheta=0$.

The two models have been successfully applied to the artificially prepared layered superconductors, in particular, Nb/Ge,[12] Nb/Cu,[13,14] and V/Ag (Ref. 15) systems. In these systems, a clear dimensional crossover between the two regimes was observed, because the measurements of the upper critical field showed that the curve $H_{c2}(\vartheta)$ had a cusplike behavior around $\vartheta=0$ for the coherence length ξ in the range $d<\xi<s$ (where d and s were, respectively, the thicknesses of the superconducting layer and nonsuperconducting interlayer), and a round maximum for $\xi>s$.

Now, considering that in the high-T_c copper oxides the coherence length $\xi_z(T)$ can cross the two regimes by varying the temperature T, the previous models should be found to hold also in these high-T_c superconductors by direct measurement of the upper critical field. Unfortunately for these superconductors, the field H_{c2}, especially $H_{c2\parallel}$, is experimentally detectable only for T close to T_c. However, partial results have been obtained. Naughton *et al.*[6] show that for $T=84.5$ and 89 K the behavior of $H_{c2}(\vartheta)$ in Y 1:2:3 single crystal is Lawrence-Doniach 3D, while for Bi 2:2:1:2 single crystal at $T=80.4$ K the behavior is 2D (cusplike). Analogous measurements carried out by Palstra *et al.*[5] in Bi 2:2:1:2 single crystals in the temperature range 75–85 K do not have an angular resolution high enough to discriminate between the two models. Therefore, the direct approach seems to be impractical, because of the extremely high values of H_{c2}.

In order to get over this difficulty, various indirect methods of searching for anisotropy have been employed. The lower critical field H_{c1} should show an angular dependence as well as H_{c2};[2] however, the data of H_{c1} obtained from the measurements of the magnetic penetration depth[16] have not been devoted to investigating the possible existence of a dimensional crossover. The measurements of critical current j_c in epitaxial films of Y 1:2:3 (Ref. 17) and of Bi 2:2:1:2 (Ref. 18) show a pronounced anisotropy. For Bi 2:2:1:2 at 70 K the behavior of $j_{c\perp}(H)$ seems to be consistent with a 2D model, while at higher temperatures a 3D model is more suitable to qualitatively explain an additional dissipation present in the experimental results. Measurements of both j_c (Ref. 19) and magnetoresistance[20] in Bi 2:2:1:2 films do not allow one to choose between the two models, because of the poor angular resolution. The experimental results, obtained by means of simultaneous measurements of the longitudinal and transverse components of the equilibrium magnetization in Y 1:2:3 and Bi 2:2:1:2 single crystals, only seem to suggest a generic agreement with a 3D anisotropic theory.[21] However, as the authors claim, there is no theory that explicitly accounts for magnetization in this regime. Torque measurements by means of a high-resolution torque magnetometer in Y 1:2:3 single crystals[22] show that a crossover should be present in the range 75–80 K between 3D and 2D behavior, when the temperature is lowered.

Finally, measurements of the angular dependence of the magnetic field H^* for the onset of the dc resistivity (briefly, *onset field* H^*) have been carried out by us in Bi 2:2:1:2 films. The first experimental results obtained by us[23–25] have shown that H^* worked as the upper critical field H_{c2}: below a certain temperature T^*, the data in the angular dependence of H^* (ϑ dependence) was well fitted for small angles around $\vartheta=0$ by Eq. (2) and above T^* by Eq. (1). Therefore, temperature T^* could be assumed to be the crossover temperature from 2D to 3D regime. The fact that field H^* for the onset of resistivity may substitute for field H_{c2} in Eqs. (1) and (2) is still now unexplained. However, the result is relevant and a correlation of experiment and theory should be found. A hint at explaining the analogy between H^* and H_{c2} will be given in Sec. IV.

To clarify the crossover from 2D to 3D behavior, in this paper we present a large set of measurements of the onset field H^* at various temperatures and for different angles around $\vartheta=0$ in Bi 2:2:1:2 films, grown on different substrates. The experimental results confirm the data previously found[23–25] and show additional features. In particular, $H_\perp{}^*$ is located on the irreversibility line and the crossover from 2D (cusplike) to 3D (round maximum) behaviors occurs in a narrow range of temperature.

The experimental results are presented in Sec. III and discussed in Sec. IV.

II. EXPERIMENTAL SETUP AND SAMPLES

The samples are highly c-axis-oriented epitaxial films of Bi 2:2:1:2 grown on $LaGaO_3$ and $NdGaO_3$ substrates. The mosaic spread is less than 0.15°.[26] The films are about 1 μm thick, 6 mm long, and 2 mm wide. For comparison, measurements have also been taken on a sputtered Bi 2:2:1:2 film and on a Y 1:2:3 granular sample.

The sample holder, placed on the top of a cold finger of a cryogenerator, was adjusted and fixed so that the a-b plane lay in a vertical plane. The magnetic field, supplied by a 2-T traditional electromagnet, could rotate in a horizontal plane. The rotation angle ϑ was measured to be accurate to 0.1°. In such an arrangement, the tilting of the cold finger could generate some misorientation of the apparatus when the field is perpendicular to the surface of the film, i.e., some deviation from strict orthogonality could occur. On the contrary, the possibility of reaching the strict parallel configuration was only limited by the angular resolution of the rotation of the magnet, and did not depend on an eventual deviation of the film surface from the vertical.

The temperature could be varied between 30 K and room temperature, and stabilized within 0.02 K. It was measured by means of a platinum thermometer, for which no magnetic correction has been necessary within 0.02 K, up to a field of 2 T.

A lock-in version of the four-probe technique for the measurements of the resistance has been used. The frequency of the measurement has been chosen to be as low as 20 Hz, in order to avoid inductive effects in the conduction and 50 Hz noise. Contacts were made by pressing the probes over a gold evaporation on the sample, and covering the contact points with small amounts of silver paint. The contact resistance was always lower than 10 Ω. The current was kept as low as 20 μA, to prevent possible local heating of the sample. We observed local heating effects only for currents higher than 1 mA. The sensitivity was 5 nV, so that resistances of the order of 10^{-4} Ω could be detected.

The zero-resistance temperatures at $H=0$ for the epitaxial films are 79.1 K (sample I) and 80.4 K (sample II). The normal-state dc resistivity at the onset of the transition is of the order of $\rho_n = 10^2$ μΩ cm. The transition widths (10–90 %) are 4 K (sample I) and 7 K (sample II).

III. EXPERIMENTAL RESULTS

We carried out measurements of the resistance as a function of the applied magnetic field H for several angles ϑ between the magnetic field and the (a,b) planes, at different temperatures. The analysis has been essentially made on the epitaxially grown films, because the other samples were not sufficiently well oriented. In Fig. 1 the typical response of the three kind of samples to the magnetic field is shown. Only the epitaxial films exhibit a sharp onset of the resistivity at a well-defined magnetic field H^* (indicated by an arrow in the figure), while the resistance in the sputtered film and the granular sample is developed immediately upon application of the field. This is an indirect check of the orientation of the sample; only the best-oriented films exhibit an onset field. In the following, we will take H^* as the relevant experimental parameter, and confine ourselves to the investigation of epitaxial films only.

The measurement process was as follows: the temperature at a fixed value T was stabilized within 0.02 K; then, for a chosen angle ϑ, the measurement of the resistance $R(H)$ as a function of the magnetic field H (sweeping in the range 0–2 T), was performed. From the curve R vs H the field H^* for the onset of the resistance was determined. Typical results at 78.00 K are shown in Fig. 2 for sample I. As is immediately apparent, H^* rises as the field direction becomes closer to the parallel orientation.

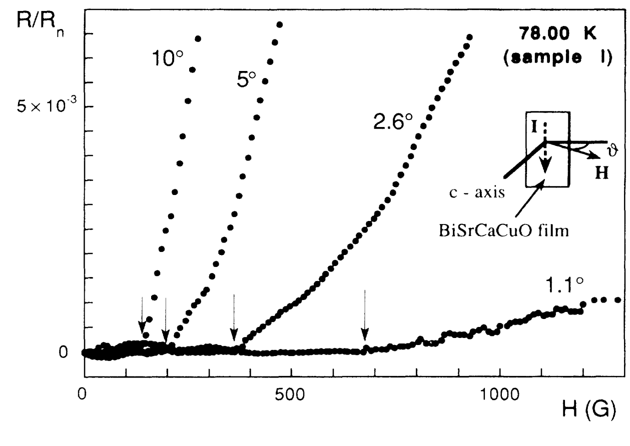

FIG. 2. Normalized resistance R/R_N vs magnetic field H at a fixed temperature and various angles ϑ between the field direction and the a,b planes (sample I). The onset field H^* increases as the field orientation becomes parallel to the a,b planes. The sample arrangement with respect to the magnetic field H and the probing current I is also sketched.

In Fig. 3 we show a complete plot of H^* as a function of ϑ at a given temperature. It is to be stressed that during each angular set of measurements the temperature had to be kept fixed (within 0.02 K). Because of the compressed scale the figure seems to show that the behavior is cusplike at $\vartheta=0$, but it is not possible to discriminate between cusp and round maximum in such a scale. In fact, the same data exhibit a round maximum when observed on a suitably enlarged scale (Fig. 4).

The entire collection of angular data, the main experimental result of this paper, is presented on a small angular range around $\vartheta=0$ in Figs. 4 and 5. As is apparent, the behavior is cusplike for temperatures up to 76.80 K (sample I, Fig. 4) and 78.70 K (sample II, Fig. 5); on the contrary, from 77.65 K (sample I) and 80.10 K (sample

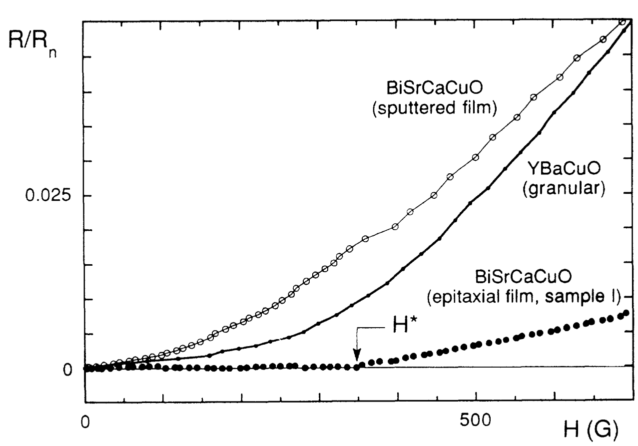

FIG. 1. Typical curves of the normalized resistance R/R_N vs the applied magnetic field H for three different samples. Only the epitaxial film exhibits an onset field H^* (indicated by an arrow in the figure). In the others, the dissipation is developed immediately upon the application of the field.

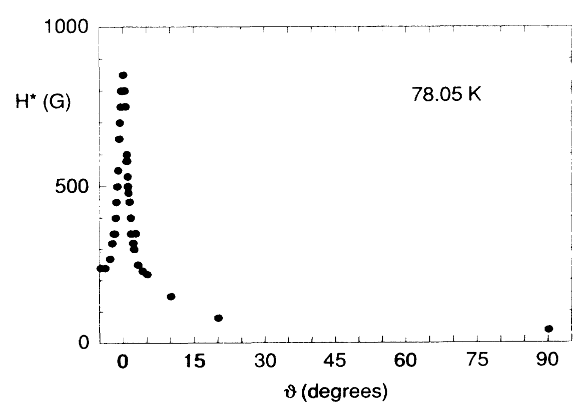

FIG. 3. ϑ dependence of the onset field H^* at a fixed temperature over the entire angular range (sample I). On this scale, the behavior would seem to be cusplike at $\vartheta=0$. An enlargement near $\vartheta=0$ is reported in Fig. 4.

II) the data show a round maximum at $\vartheta=0$. The field $H^*_{\parallel}$ diminishes as the temperature increases (note the different vertical scales in the figures). In the intermediate temperature range a different phenomenon appears: in the data at 77.30 and 77.50 K in sample I a "shoulder" is present: H^* seems to level off to a round maximum (data up to $\pm 0.4°$ at 77.30, $\pm 0.2°$ at 77.50 K), but presents a sharp enhancement (quasicusp-like) strictly close to the parallel orientation. We will give a tentative explanation in Sec. IV. In sample II this effect is less evident, but the data at 78.80 K do not allow one to discriminate between a cusp or a round maximum.

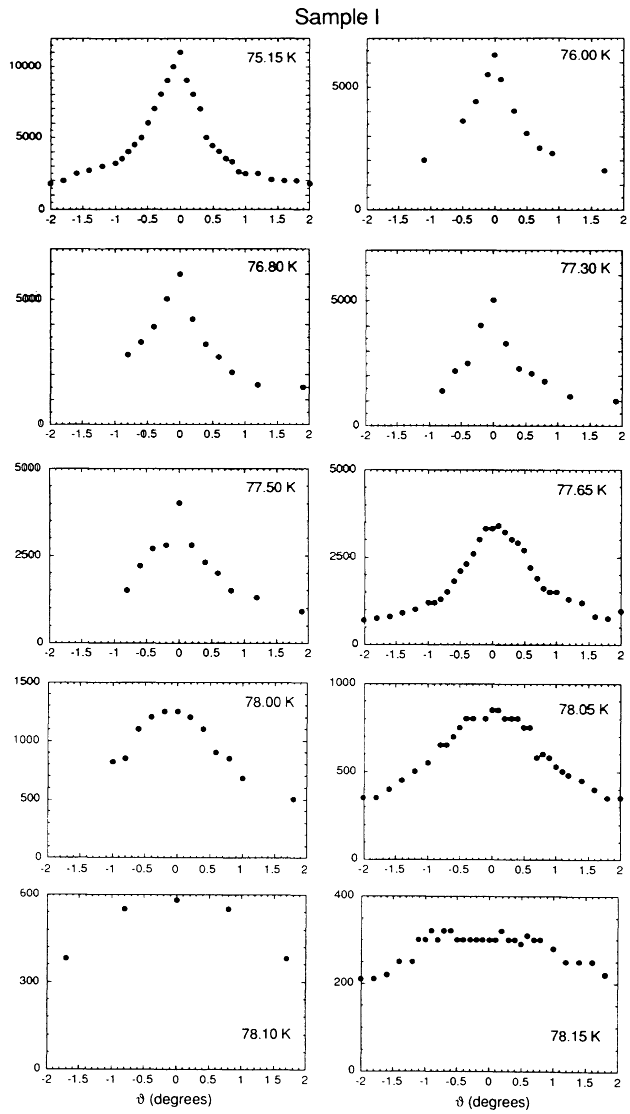

FIG. 4. ϑ dependences of H^* at several temperatures for sample I in a narrow angular range around $\vartheta=0$ (compare the data at 78.05 K in this scale with those of Fig. 3). It is clearly apparent that an evolution of the ϑ behavior from a cusplike maximum to a round one occurs by increasing the temperature. The data at 77.30 and 77.50 K present an intermediate behavior (see text).

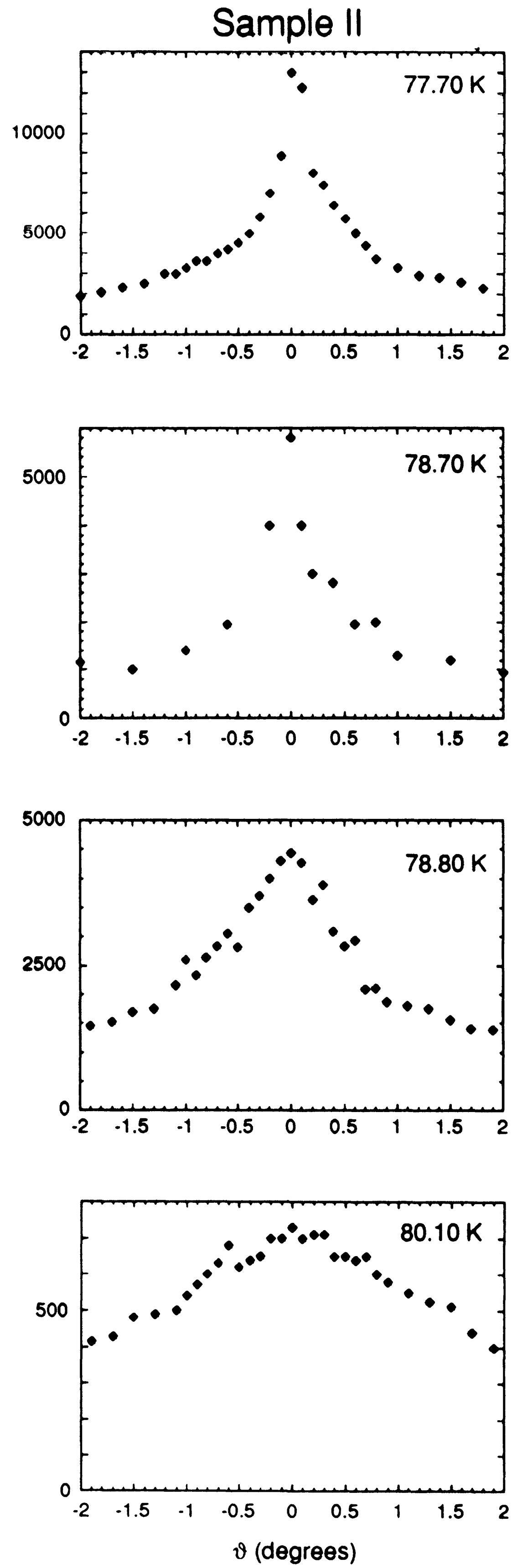

FIG. 5. Same as in Fig. 4, but for sample II.

IV. DISCUSSION

We will divide the discussion of the experimental data to two main parts: comments on the evidence of a dimensional crossover, and tentative explanations for the phenomena not contained in the "classical" theories of anisotropic superconductors.

As one can clearly see from Figs. 4 and 5, the angular behavior of H^* presents a round or cusplike maximum, depending on the temperature. In other words, we have, for both samples, $|dH/d\vartheta|_{\vartheta=0}\neq 0$ for low temperatures and $|dH/d\vartheta|_{\vartheta=0}=0$ for higher temperatures. This behavior is exactly the one expected and found[12-14] for H_{c2} in layered conventional superconductors as the coherence length becomes longer than the interlayer spacing. Because of the analogous behavior of H^* (in our measurements) and H_{c2} (in layered conventional superconductors), we will assume for the moment that the angular behavior of H^* reflects that of H_{c2}, and we will interchange $H_{c2}(\vartheta)$ with $H^*(\vartheta)$ in the fit of the data.

In Fig. 6 the fits for $H^*(\vartheta)$, obtained using formulas (1) and (2), are shown. It is immediately apparent that not only the qualitative behavior (i.e., a cusp or a round maximum), but also a quantitative fit (in which the only parameter that can be poorly adjusted is $H_\perp^*$, because of the possibility of a small misalignment in the orthogonal configuration) is in good agreement with the predictions of the 2D and 3D models. We stress that, as is evident from the figure, it is not possible to satisfactorily fit the small-angle data at lower temperature with a Lawrence-Doniach 3D model [continuous line in Fig. 6(a)], just as it is impossible to fit the higher-temperature data with a 2D Tinkham model [dashed lines in Fig. 6(c)]. The best obtainable fits are also reported in Fig. 6 for comparison. Analogous fits have been obtained in all the measurements reported here, for temperatures outside the ranges 77.30–77.65 K (sample I) and 78.70–78.80 K (sample II). In this temperature ranges it is not clear whether a 2D or a 3D model takes place, as shown in Fig. 6(b). It is important to stress that our fits for H^* in Bi-Sr-Ca-Cu-O are as good as, or better than, the fits for H_{c2} in traditional layered superconductors (see, e.g., Fig. 6 of Ref. 14).

We have, then, experimentally shown that the angular behavior of the onset field H^* in Bi-Sr-Ca-Cu-O is completely analogous to that of $H_{c2}(\vartheta)$ in conventional layered superconductors, for temperatures lying outside a narrow range.

Assuming that the behavior of $H^*(\vartheta)$ reflects that of $H_{c2}(\vartheta)$, that is, that the cusp or round maximum is due to the different dimensionality of the superconducting system, we turn now to a tentative explanation of the shoulder present in our H^* data for the intermediate temperature range between cusplike and round maximum behaviors. As previously described, it seems that H^* lies in a round-maximum region, but when the magnetic field is applied strictly parallel to the layers, it presents a sharp (cusp) enhancement. Taking into account the anisotropic 3D model, we note that in this model the superconducting planes are (weakly) coupled via Josephson interaction, and this coupling is always supposed to exist. However, the magnetic field can destroy the Josephson coupling when the flux through the junction plane becomes sufficiently high. In the case under study, the junction plane is perpendicular to the superconducting layers, so that the flux of the magnetic field through the junction is at a maximum when H is parallel to the planes. For temperatures far enough below the transition temperature, the coupling is stronger at higher temperatures, because of the divergence of the coherence length $\xi_\perp$: the shorter $\xi_\perp$, the weaker the coupling. If we suppose that only

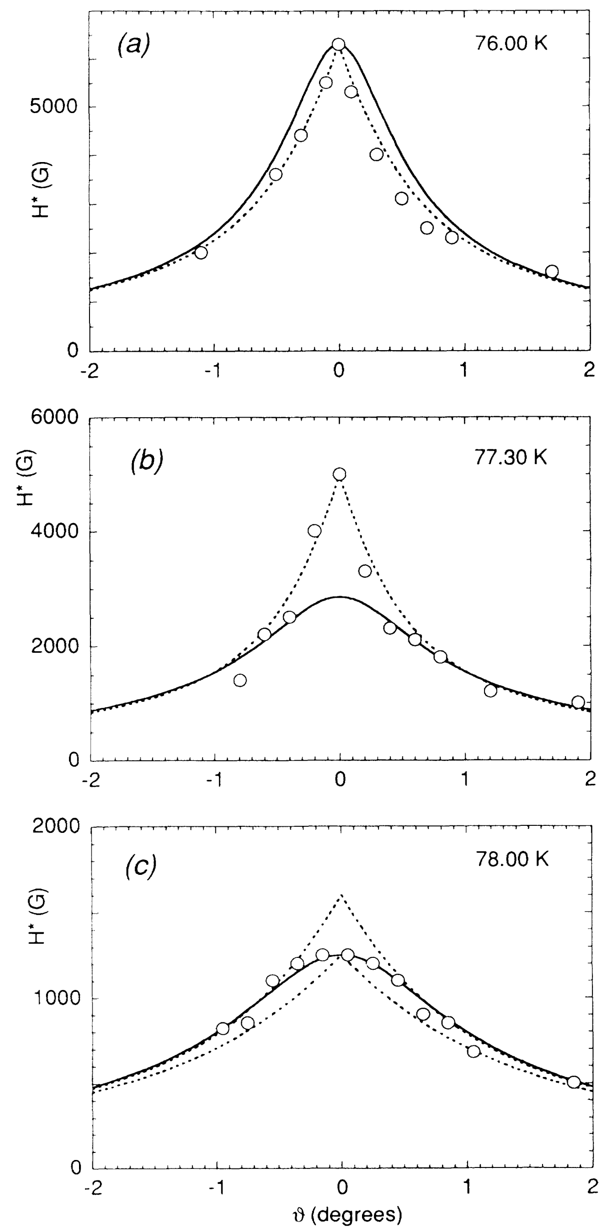

FIG. 6. Typical fits of H^* by means of 3D [Eq. (1), full lines] and 2D models [Eq. (2), dashed lines] (a) At low temperatures the data are well fitted by a 2D model only, (c) at higher temperature by a 3D one. In the intermediate range (b) a satisfactory fit is not obtainable. In (c) two different 2D fits are shown, none of which is satisfactory. The reason for substituting H_{c2} with H^* in Eqs. (1) and (2) are explained in the text.

when the coupling is very weak, i.e., only at the temperatures just above the uncoupled layers configuration, is the magnetic flux high enough to destroy the coupling itself, we have a straightforward explanation of the shoulder in our data; the coherence length is long enough to guarantee the coupling between the layers when the flux through the junction is low, but as the flux reaches a higher value, the planes decouple—magnetically—and a three-dimensional approach is no longer valid: H^* presents a cusp, but only when **H** is applied close to the parallelism.

As a summary of this first part of the discussion, we note that our results are all consistent with the assumption that H^* is the analog of H_{c2}. In this case, a dimensional crossover from two-dimensional to three-dimensional behavior occurs by increasing the temperature. We now discuss the nature of the onset field H^*.

H^* is not the upper critical field, at least in its common meaning. Being the onset field of the resistance in the presence of a magnetic field, it is strictly connected to the fluxon motion: H^* is the onset field for the motion of the fluxons. In this view, it must be related to the irreversibility line. To check this point, we performed a large set of measurements with $H \perp a,b$, as a function of the temperature. The resulting curve $H^*_\perp(T)$ lies on the irreversibility line coming from other authors and techniques,[27] as can be seen in Fig. 7.

The nature of the irreversibility line has been the subject of many papers; in particular, in a recent work Fisher, Fisher, and Huse[28] consider the irreversibility line as a vortex-glass to vortex-liquid transition. Moreover, in the same paper, it is argued that this line could represent a second-order transition, while the line dividing the normal state from the vortex-liquid state (i.e., the upper critical field line) would not be a true phase transition, but a continuous crossover. In this frame, it seems possible to match our two experimental results; (i) that the angular behavior of H^* is analogous to that of H_{c2} in traditional layered superconductors, and (ii) that the curve $H^*_\perp(T)$ lies on the irreversibility line, by assuming that the true critical field is the one described by the irreversibility line, which would represent a vortex-glass to vortex-liquid transition. This picture is by no means a complete explanation, nor an argument to give evidence that a glass transition exists; it is simply a speculative description of an assumption that would explain satisfactorily our experimental results. However, this hypothesis seems to find a clear confirmation when the experimental behaviors of the resistivity, as a function of both the magnetic field $\rho_T(H)$ and the temperature $\rho_H(T)$, are fitted by the theory.[29]

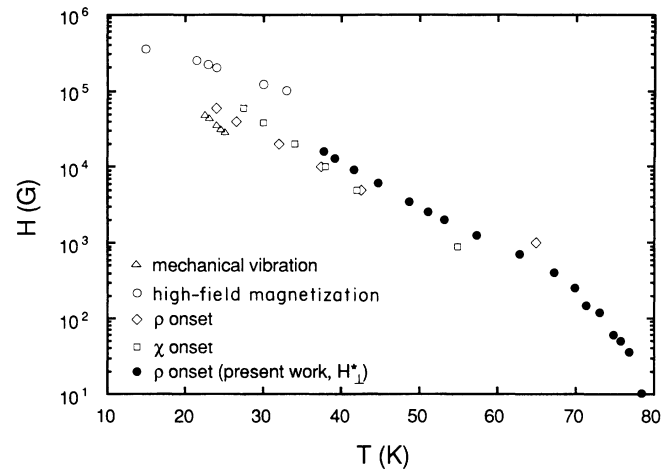

FIG. 7. Data corresponding to the irreversibility line as reported in Ref. 27 (open symbols) and $H^*_\perp$ data obtained from our measurements (full dots).

V. CONCLUSION

We have presented a large set of angular data for the onset field H^* of the dissipation in thin epitaxial films of Bi-Sr-Ca-Cu-O. The angular behavior is completely analogous to that already found and theoretically explained in conventional layered superconductors, including the existence of a temperature-induced dimensional crossover that occurs when the transverse coherence length crosses the interlayer spacing. The onset fields perpendicular to the a,b planes lie on the irreversibility line found by other authors. Under the assumption that the irreversibility line is a second-order transition line between a vortex glass and a vortex liquid our experimental results could find a satisfactory explanation.

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