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Uniaxial anisotropic flux trapping in Y-Ba-Cu-O and Bi-Sr-Ca-Cu-O single crystals

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Measurements of the angular dependence of the remanent magnetization of Y-Ba-Cu-O and of Bi-Sr-Ca-Cu-O single crystals reveal uniaxial anisotropy for flux trapping; the anisotropy axis is the crystalline **c** axis. The amount of trapped flux is determined by the component of the field **H** along **c**. For flux trapping with **H** in the *a-b* plane, we observe unidirectional anisotropy; the anisotropy direction is defined by **H** during the cooling process.

Magnetic techniques have been used extensively to probe anisotropic features[1-4] which characterize all known high-temperature superconductors (HTSC). Intrinsic anisotropic features in HTSC have quite frequently been blurred[5] by flux trapping and flux creep, which are known to be strongly anisotropic.[2,6,7] Moreover, it is very probable that anisotropic flux trapping is related to intrinsic features such as the anisotropic coherence length.[8] Most studies of anisotropic properties have concentrated on the behavior for directions along the principal crystallographic axes. Only recently, Farrell *et al.*,[9] following a suggestion made by Kogan,[10] have presented angular dependence torque measurements on grain-aligned HTSC and interpreted the results in terms of the intrinsic transverse magnetization. A detailed study of the angular dependence of flux trapping in oriented samples is still lacking.

In the present paper we demonstrate the existence of *uniaxial* anisotropy of flux trapping in *single crystals* of Y-Ba-Cu-O and Bi-Sr-Ca-Cu-O by a *direct* measurement of the angular dependence of the remanent magnetization. In these measurements the sample is cooled in a field, the field is then turned off, and the remanent magnetization is measured while the sample is rotated relative to the original direction of the field around a principal crystalline axis. We have already described[11] similar measurements for ceramic HTSC, demonstrating the existence of *unidirectional* anisotropy where the direction is defined by the external field. For single crystals, the results are completely different and much more complicated. In particular, the nature of the anisotropy depends on the axis of rotation. Trapped flux in the *a-b* plane exhibits *unidirectional* features when the sample is rotated around the **c** axis. These results are very similar to those observed[11] for ceramic HTSC. However, for transverse rotations, i.e., for the axis of rotation perpendicular to **c** (hereafter arbitrarily referred to as the **a** axis), we detect a clear *uniaxial* anisotropy; the anisotropy axis coincides with the crystallographic **c** axis.

In Refs. 12 and 13 we describe details of the sample preparation. Low-field (50 Oe) magnetic measurements yield a superconducting transition temperature T_c of only 84 K for the $4\times3\times0.3$-mm^3 Y-Ba-Cu-O sample, probably due to the diffusion of a small amount of Mg from the crucible which was used for this particular batch. The width of the transition is of order 1 K. Scanning electron microscope (SEM) pictures show smooth and uniform surfaces. For the $5\times3\times0.075$-mm^3 Bi-Sr-Ca-Cu-O sample, $T_c=84$ K and the width of the transition (in a field of 50 Oe) is about 4 K. SEM pictures show uniform surfaces only in the *a-b* plane. Stacking of numerous layers of nonuniform widths is observed in the edges perpendicular to the *a-b* plane.

Magnetic measurements were done on a vibrating sample magnetometer (VSM) which enables one to rotate the sample relative to the external field. The experimental procedure is as follows. The sample is cooled in a field H ($500\ \text{Oe}\le H\le 15$ kOe) to a low temperature T. The "cooling angle" ϕ is the angle between **H** and the **c** (**a**) axis. The field is turned off (zero nominal field $\simeq$20 Oe) and the "initial remanent magnetization" $M^i_{\rm rem}$ is measured. The sample is then rotated relative to **H**; the axis of rotation is parallel to **a** (**c**). During the rotation, the remanent magnetization $M_{\rm rem}$ is measured as a function of the angle θ between **H** and **c** (**a**). Note that in $M_{\rm rem}$ measurements the demagnetization correction is negligible and the results are simpler to interpret. We therefore focus here on these measurements and describe similar measurements of the angular dependence of the zero-field-cooled and field-cooled magnetization in a future publication.

We start with results of measurements of $M_{\rm rem}$ for rotations around an axis parallel to **a**. Figures 1(a) and 1(b) exhibit the angular dependence of the remanent magnetization as a function of the rotation angle θ, for various cooling angles ϕ, for Y-Ba-Cu-O [Fig. 1(a)], and Bi-Sr-Ca-Cu-O [Fig. 1(b)]. In these figures the sample is cooled to 4.2 K in 1 kOe. The remanent magnetization which is obtained when the field is turned off is indicated by an arrow. The angular dependence data, obtained dur-

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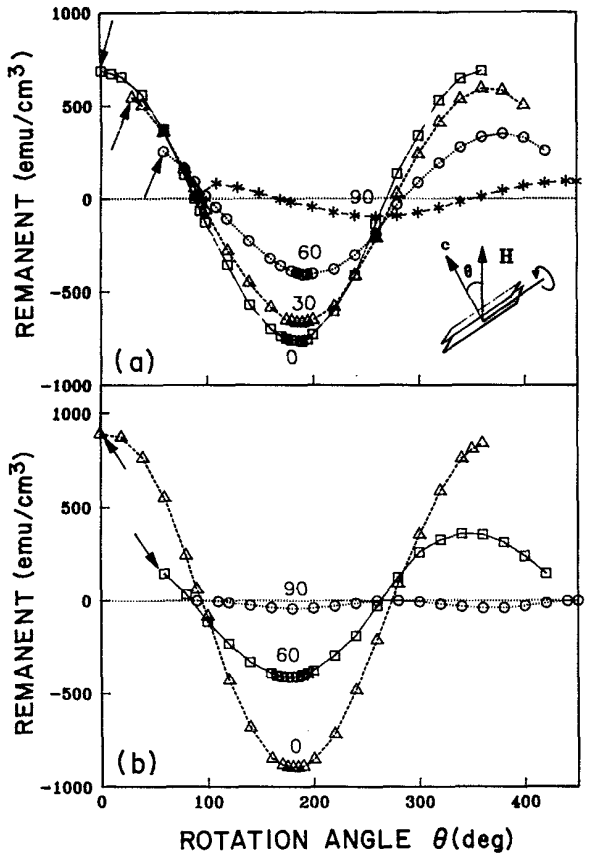

FIG. 1. Angular dependence of the remanent magnetization for the indicated cooling angles at 4.2 K and a cooling field of 1 kOe for (a) Y-Ba-Cu-O and for (b) Bi-Sr-Ca-Cu-O crystals. Arrows denote the initial remanent values. Diagram in (a) sketches the orientation of the samples relative to the applied field during the rotation experiment.

ing the rotation of the sample in zero field, fit perfectly to a $\cos\theta$ expression with an amplitude which decreases with ϕ. The data presented in these figures are reversible, namely, by reversing the sense of the rotation, we trace back the original values on the time scale of this experiment ($\simeq$4 min). The dominant features in these figures are the pronounced minima at a fixed angle $\theta=180°$, *independent* of the initial cooling angle ϕ [except for ϕ close to 90° where the minimum is shifted towards 270°; see Fig. 1(a)]. The fixed location of the minima is in very sharp contrast to the results of a similar experiment on ceramic materials where the minima always occur at 180° relative to the direction of the cooling field. We also note that the amount of trapped flux decreases gradually with ϕ; for $\phi=90°$ the trapping is quite low, being practically zero when compared to the trapping for $\phi=0°$. Another interesting feature of these figures, related to the above-mentioned "zero" trapping, is the crossing of all the curves at $\theta=90°$ and 270°. The value of the remanent moment at these angles is near zero.

To understand the physics beyond these observations, we recall that in a VSM the measured magnetization is *only* the component of **M** along the magnetic field. Each of the curves in Figs. 1(a) and 1(b) (except for those close to 90°) is dominated by a $\cos\theta$ term. This suggests that **M** is fixed in the crystal frame of reference and rotates with the sample. This is very plausible; $M_{\rm rem}$ results from trapped flux and the pinning forces are strong enough, at least at low temperatures, to overcome the small torque which is applied by the small remanent field ($\simeq$20 Oe) during the rotation. The fact that the location of the minima always occurs at $\theta=180°$ indicates that **M** is parallel to **c** independent of the cooling angle. Thus, the crystallographic **c** axis defines the anisotropy direction. In contrast to this behavior, in ceramic samples $M_{\rm rem}$ is created in the direction of the cooling field; rotation would yield a minimum at an angle 180° relative to the initial orientation.

It is apparent from Figs. 1(a) and 1(b) that the initial values of the remanent magnetization $M^i_{\rm rem}$ (denoted by arrows in the figures), as well as the values M_π of the remanent magnetization after rotation to $\theta=180°$, depend on the initial conditions, namely, on the angle ϕ between **H** and **c** during the cooling process. The angular dependence of the initial values (Fig. 2) exhibits a dominant $\cos^2\phi$ term. In fact, the solid lines in this figure describe an excellent fit to

$$M^i_{\rm rem}=M^i_{\rm rem}(0)\cos^2\phi+\text{const}. \qquad (1)$$

It will become apparent in a later section that the constant terms (100 and 17 emu/cm^3 for the "Y" and "Bi" samples, respectively) are associated with the flux trapped in the *a-b* plane. In any case, the coefficients $M_{\rm rem}(0)$ (585 and 890 emu/cm^3) are much larger than the constant terms and thus the general shape of $M^i_{\rm rem}$ is governed by a $\cos^2\phi$ term. Recalling again that a VSM measures only the component of **M** along the magnetic field, it is apparent that the actual initial remanent moments scale as $\cos\phi$.

The measured values of M_π also scale in a very simple manner. Figure 3 exhibits the values of M_π for various ϕ values for one of the crystals (Bi-Sr-Ca-Cu-O). Using the same parameters as in Eq. (1), the data fit nicely to

$$M_\pi=M_\pi(0)\cos\phi+\text{const}. \qquad (2)$$

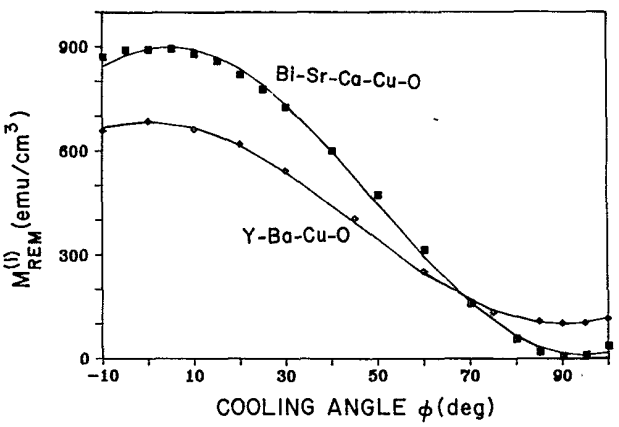

FIG. 2. The initial value of the remanent magnetization as a function of the cooling angle ϕ for Y-Ba-Cu-O and for Bi-Sr-Ca-Cu-O. Solid lines are fitted to Eq. (1); see text.

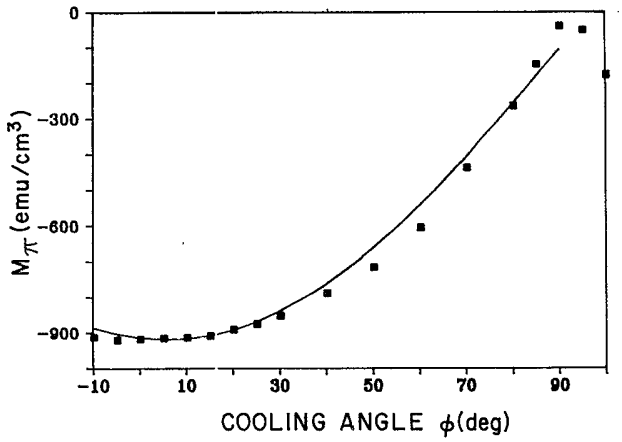

FIG. 3. The minima values M_π as a function of the cooling angle ϕ for Bi-Sr-Ca-Cu-O. The solid line represents a fit to Eq. (2).

The data described in Figs. 1–3 may be summarized by

$$M_{\rm rem} = M^0_{\rm rem} \cos\phi \cos\theta + \text{const}\,, \tag{3}$$

where $M^0_{\rm rem}$ is the remanent for $\phi=0$ at $\theta=0$. Note that for $\theta=\phi$ and for $\theta=0$, Eq. (3) reduces to Eqs. (1) and (2), respectively.

This simple result suggests the following scenario for the organization of the vortex lines: During the cooling process the vortex lines are aligned parallel to the magnetic field. However, trapping is extremely anisotropic; thus, when the field is turned off only the components $\cos\phi$ of the total flux (i.e., current loops in the *a-b* plane) are trapped. Qualitatively, the anisotropy we find for flux trapping is consistent with the reported anisotropy of the critical currents J_c in HTSC.[1,7] Preferred flux trapping for magnetic fields along the c axis is equivalent to larger J_c in the *a-b* plane. However, the anisotropy ratio is larger in our experiment (7:1 and 50:1 for the Y and Bi crystals, respectively) than for the reported values for J_c.

So far we have discussed data for a cooling field of 1 kOe at 4.2 K. Figure 4 demonstrates that the qualitative features of the angular dependence of $M_{\rm rem}$ are independent of the cooling field for fields between 0.5 and 14 kOe. In Fig. 4, we present $M_{\rm rem}(\theta)$ data for various fields for Bi-Sr-Ca-Cu-O for $\phi=0$ and we note the similarity among the curves and, in particular, the pronounced minima at $\theta=180°$. Similar features are obtained for other ϕ values not shown here. (The inset to Fig. 4 which shows the field dependence of $M_{\rm rem}$ for $\phi=0$ demonstrates that the saturation in $M_{\rm rem}$ is obtained for fields well below our highest field of 14 kOe.) Also, temperature has no noticeable effect on these features. Note, however, that temperature in this experiment is limited to a narrow range ($T<25$ K) where $M_{\rm rem}$ is reversible, at least in the time window of the experiment. At higher temperatures we observe irreversible effects which apparently blur the information; these data are not discussed here.

We have already mentioned that the anisotropic features which are described in Figs. 1–4 for HTSC crystals are very different from those observed in polycrystalline materials. This behavior is also in contrast to what is ob-

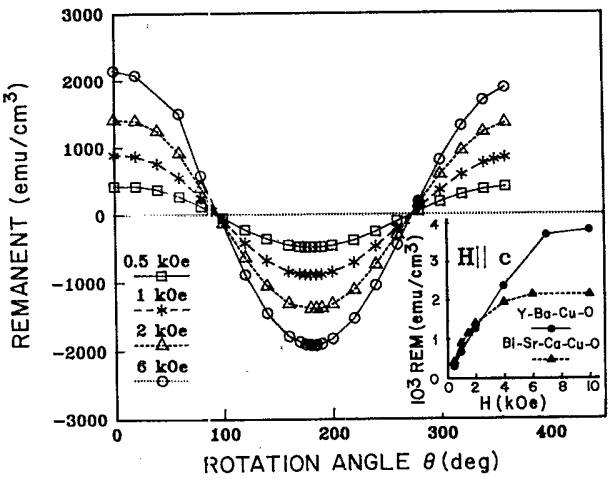

FIG. 4. Angular dependence of the remanent magnetization at 4.2 K for the indicated cooling fields for Bi-Sr-Ca-Cu-O. Inset: Field dependence of the remanent for Y-Ba-Cu-O and for Bi-Sr-Ca-Cu-O.

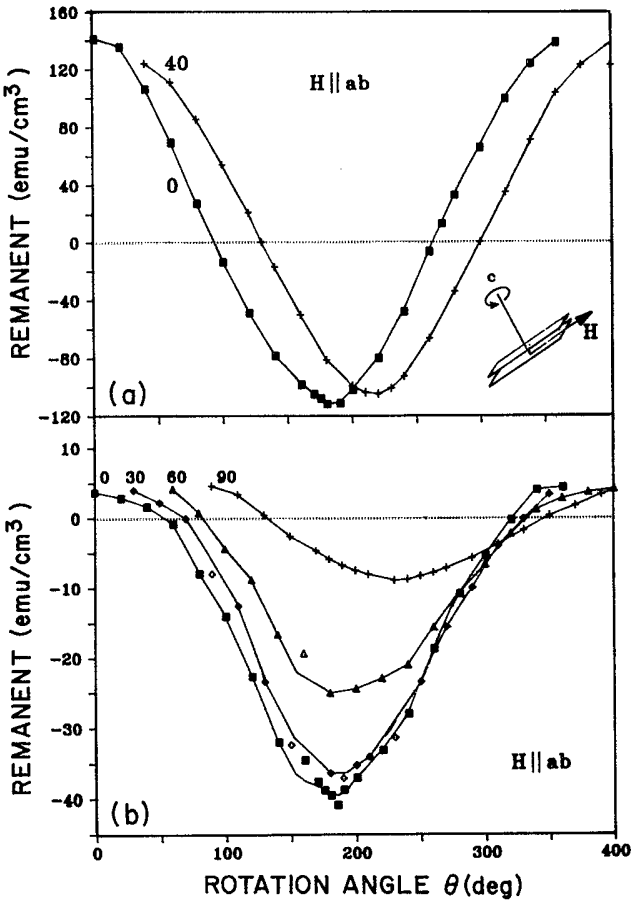

FIG. 5. Angular dependence of the remanent magnetization for the indicated cooling angles at 4.2 K and cooling field of 1 kOe for (a) Y-Ba-Cu-O and for (b) Bi-Sr-Ca-Cu-O crystals. Diagram in (a) sketches the orientation of the samples relative to the applied field during the rotation experiment.

served in the same Y-Ba-Cu-O crystal when the axis of rotation is perpendicular to the *a-b* plane; see Fig. 5(a). In Fig. 5(a) the angle θ is defined relative to the direction of the longest edge and the axis of rotation is parallel to the c axis. Figure 5(a) describes $M_{\text{rem}}(\theta)$ for different cooling angles. It is apparent that the minima are shifted and are always at 180° relative to the direction of the cooling field. Thus, the anisotropy is unidirectional and the anisotropic direction is defined by the direction of the field, just like the situation for ceramic materials. We may therefore conclude that in terms of flux trapping, the *a-b* plane in Y-Ba-Cu-O is isotropic. The results for the Bi-Sr-Ca-Cu-O crystal for similar rotations [see Fig. 5(b)] exhibit apparent uniaxial anisotropy. The amount of flux trapped in the *a-b* plane is only 4% of that trapped in the c direction. Therefore, we argue that the results of Fig. 5(b) reflect an artifact of the microstructure of the crystal in which nonparallel stacking of the *a-b* planes are observed. The remanent in this experiment is a result of trapping from transverse directions with dominant contributions from components of the field which are parallel to c. Note that the remanent values for a given θ for Y-Ba-Cu-O are larger than those for Bi-Sr-Ca-Cu-O. This observation, together with the uniform and parallel stacking in Y-Ba-Cu-O, explains the difference in behavior between Figs. 5(a) and 5(b).

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