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Anisotropic vortex cross-flux effects in grain-oriented $YBa_2Cu_3O_7$

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After cooling to 4.2 K in a field $\mathbf{H}_{cool}$ parallel (or normal) to the c axis and then removing $\mathbf{H}_{cool}$, the sample was subjected to an increasing field **H** normal (or parallel) to c and the longitudinal and transverse magnetizations relative to **H** were measured simultaneously. The vortex flux produced by $\mathbf{H}_{cool}$ along c persists and inhibits the creation by **H** of vortex flux in the a-b plane. However, the creation of the latter does not require a threshold value of **H**. The vortex flux produced by $\mathbf{H}_{cool}$ in the a-b plane diminishes rapidly with increasing **H** along c, and there are essentially no cross-flux effects. Thus, these effects are largely governed by the strength of the initial flux pinning, which is highly anisotropic.

The pronounced crystallographic asymmetry of the CuO_2-layered superconducting compounds (e.g., $YBa_2Cu_3O_7$) is clearly manifested in strong anisotropies of their physical properties. These especially include various anisotropic magnetic properties associated with the vortex state. For external magnetic fields **H** applied parallel or perpendicular to the c axis of a $YBa_2Cu_3O_7$ crystal, striking differences are seen in the lower critical field (H_{c1}),[1-5] the values of H_{c1} at all temperatures below T_c being much larger for **H** parallel to c. Moreover, in an untwinned $YBa_2Cu_3O_7$ crystal, the upper critical field (H_{c2}) was found to be almost isotropic within the basal (a-b) plane, but much lower along c.[6] Thus, the principal anisotropy is with regard to the orientation of vortex lines relative to the c axis normal to the CuO_2 layers, and it is evident that the pinning forces are strongest for the vortex lines aligned parallel to c. The same conclusion concerning the magnetic anisotropy was also reached from direct measurements of vortex-flux trapping in a $YBa_2Cu_3O_7$ crystal that was cooled in fields along different crystallographic directions and then rotated in a small fixed field **H**.[7] The latter experiments, though well designed, were limited conventionally to measurements of the sample magnetization parallel to **H**.

In our own rotational experiments on field-cooled $YBa_2Cu_3O_7$, which were similarly motivated in part, simultaneous measurements were made of the sample magnetization components parallel and perpendicular to **H** by means of a vibrating-sample magnetometer with two sets of pickup coils mounted in quadrature.[8] Our sample was a thin disk (5 mm diameter, 0.5 mm thick) cut from a boule prepared at the Los Alamos National Laboratory, in which small crystallites of $YBa_2Cu_3O_7$ in an epoxy matrix had been field oriented such that their c axes were coaligned, with the a and b axes randomly oriented in the basal plane. The collective c axis lies in the plane of the sample disk, which was rotated about its axis in a fixed **H** (in the disk plane), allowing us to study the effects of the principal anisotropy on the rotating magnetization vector **M**.

As in our previous rotational measurements on polycrystalline samples of elemental Nb (Ref. 9) and of $YBa_2Cu_3O_7$ (Ref. 10), we found that the total measured **M** at 4.2 K was readily decomposed into a diamagnetic (shielding) component $\mathbf{M}_D$, which stays fixed and equals $\chi_0\mathbf{H}$ (χ_0 being the initial susceptibility after zero-field cooling) even for H well above H_{c1}, plus a penetrating

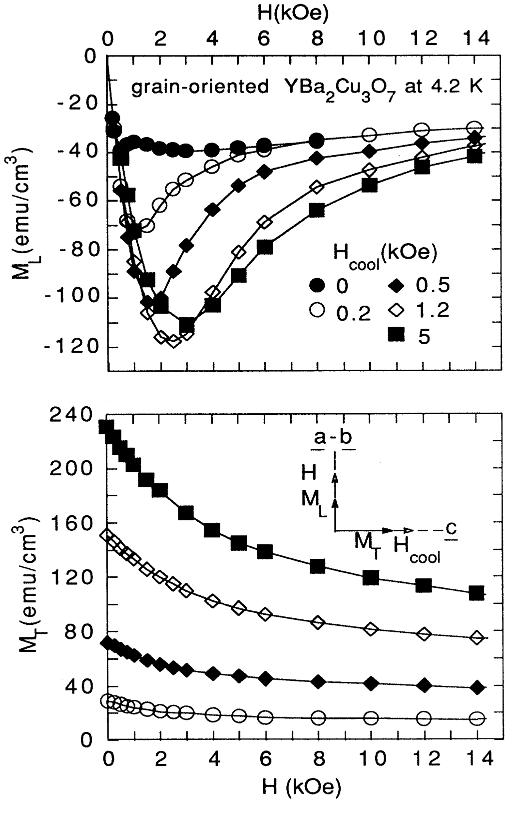

FIG. 1. Grain-oriented $YBa_2Cu_3O_7$ at 4.2 K. Longitudinal and transverse magnetizations (M_L, M_T) relative to **H** applied in the a-b plane plotted vs H for different values of $\mathbf{H}_{cool}$ applied along c during cooling, as indicated in the vector diagram.

(vortex-flux) component $\mathbf{M}_P$, which turns rigidly with the sample for very small rotation angles (θ). After cooling the grain-oriented $YBa_2Cu_3O_7$ sample to 4.2 K in a field ($\mathbf{H}_{cool}$) along the c axis, our rotational measurements showed that $\mathbf{M}_P$ continues to turn rigidly with the sample for θ up to 360°, with little change in magnitude. This behavior was observed even in fields up to 1 kOe, indicating that the vortex lines along c are strongly pinned and, moreover, that their persistence inhibits the field in producing new vortex lines in the a-b plane. Contrastingly, when $\mathbf{H}_{cool}$ was applied in the a-b plane, the vortex lines were seen to move readily with respect to the rotating sample. The results of these rotational measurements, which will be reported fully in a future paper, suggested a simpler related experiment whose results will be presented forthwith in this paper.

In this experiment, our grain-oriented $YBa_2Cu_3O_7$ sample was cooled to 4.2 K in $\mathbf{H}_{cool}$ of various amplitudes applied along c or a-b. After $\mathbf{H}_{cool}$ was removed, the sample was turned by 90° and its longitudinal and transverse magnetization components ($\mathbf{M}_L$, $\mathbf{M}_T$) relative to an increasing external field $\mathbf{H}$ (along a-b or c) were measured simultaneously. In Fig. 1, our results for $\mathbf{M}_L$ and $\mathbf{M}_T$ vs H are displayed for the case where $\mathbf{H}_{cool}$ was applied along c and $\mathbf{H}$ was then applied in the a-b plane. (In all cases, the measured magnetizations were normalized to the volume of the crystallites by assuming that χ_0 after zero-field cooling has the perfect-shielding value of $-1/4\pi$, modified by demagnetization effects.) It is immediately evident from Fig. 1 that while M_T is gradually diminishing with increasing H from its original thermoremanence (TRM) value for each H_{cool}, M_L decreases to a minimum value that becomes considerably more negative with increasing H_{cool}—and thus with increasing M_T. (For $H_{cool}=5$ kOe, the TRM is saturated, and both M_T and M_L vs H remain unchanged for further increases of H_{cool}.)

The effect of a persistent M_T on the behavior of M_L is seen more meaningfully if the latter is decomposed into its diamagnetic shielding and penetrating vortex-flux parts ($M_D^{(L)}$ and $M_P^{(L)}$, respectively). Regarding $M_D^{(L)}$, our rotational measurements (described earlier) have shown that up to at least $H=4$ kOe, $M_D^{(L)}$ closely equals $\chi_0 H$, where χ_0 equals the initial slope of the M_L-vs-H curve for zero H_{cool} in Fig. 1. Hence, for each H, we can subtract the negative $\chi_0 H$ from the measured (less negative) M_L and obtain $M_P^{(L)}$. Also, since M_D is entirely longitudinal, the measurement M_T corresponds to $M_P^{(T)}$, the transverse vortex-flux magnetization.

The values of $M_P^{(L)}$ and $M_P^{(T)}$, thus derived from the data in Fig. 1, are plotted in Fig. 2(a) over a more restricted range of H. It is clear that as H_{cool} is raised and $M_P^{(T)}$ rises accordingly, $M_P^{(L)}$ is increasingly suppressed at all but low H. This cross-flux effect is brought out pictorially in Fig. 2(b), where the $\mathbf{M}_P$ vectors at $H=0$, 1, and 2 kOe are drawn for $H_{cool}=0$ (dashed lines) and 0.5 kOe (solid lines). The components parallel to $\mathbf{H}$ of the latter

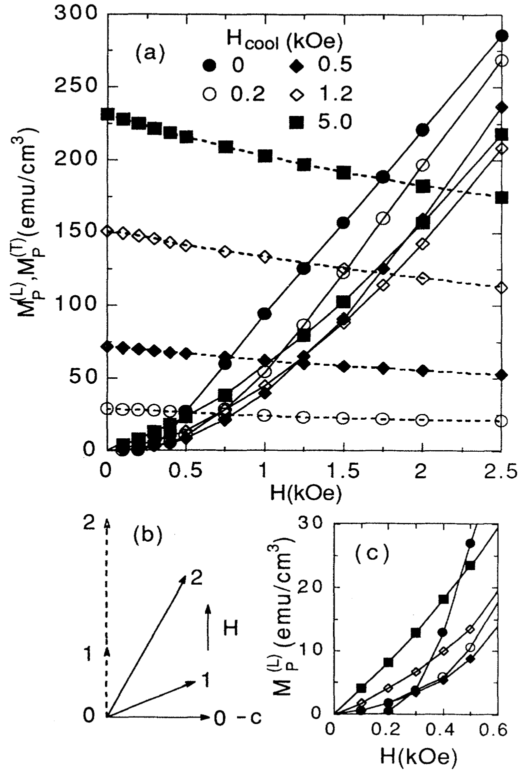

FIG. 2. (a) Longitudinal and transverse components of vortex-flux magnetization [$M_P^{(L)}$, solid curves; $M_P^{(T)}$, dashed curves] vs $\mathbf{H}$ applied in the a-b plane for different $\mathbf{H}_{cool}$ along c, as derived from the data in Fig. 1. (b) $\mathbf{M}_P$ vectors at $H=0$, 1, and 2 kOe for $H_{cool}=0$ (dashed lines) and 0.5 kOe (solid lines). (c) Detail of (a) at low H.

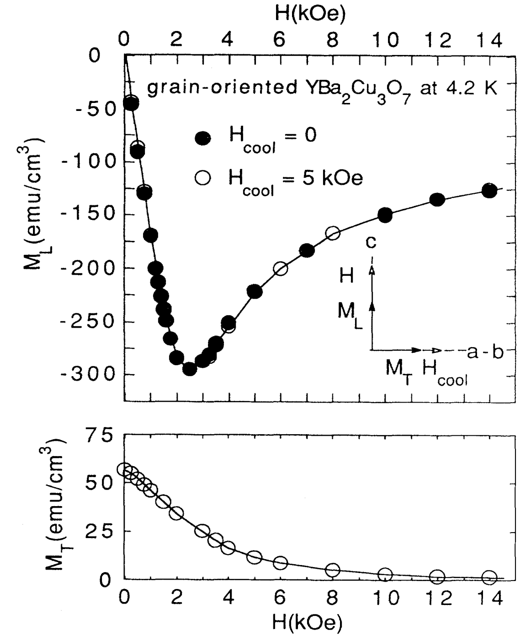

FIG. 3. Grain-oriented $YBa_2Cu_3O_7$ at 4.2 K. Longitudinal and transverse magnetizations (M_L, M_T) relative to $\mathbf{H}$ applied along c plotted vs H for different values of $\mathbf{H}_{cool}$ applied in the a-b plane during cooling, as indicated in the vector diagram.

vectors increase considerably more slowly than those of the former with increasing H. However, this is not so at much lower H, as evidenced in Fig. 2(c), where $M_P^{(L)}$ vs H near the origin has been expanded. We see that the curve for $H_{\text{cool}}=0$ rises from zero $M_P^{(L)}$ when H exceeds ~0.2 kOe (thus effectively defining H_{c1} in the a-b plane), whereas all the curves for nonzero H_{cool} rise immediately from the origin. Indeed, this countereffect grows with increasing H_{cool} to such an extent that for $H_{\text{cool}}=5$ kOe it prevails up to fairly high H, as is evident in Fig. 2(a).

In the second case, $\mathbf{H}_{\text{cool}}$ was applied in the a-b plane and $\mathbf{H}$ was then applied along c (i.e., the reverse of the first case) and the results for M_L and M_T vs H are displayed in Fig. 3. Only H_{cool} of zero and 5 kOe are represented, but they suffice to show that for any nonzero H_{cool}, the measured M_T diminishes very rapidly with increasing H and that M_L is essentially unchanged from its values for zero H_{cool}. Thus, it appears that the rapid expulsion of the vortex lines weakly pinned in the a-b plane precludes any suppression of vortex-line production along the c axis.

The marked contrast between these two cases (Figs. 1 and 3) demonstrates that the vortex cross-flux effects are highly anisotropic, reflecting to a large extent the anisotropy of the vortex-line pinning, which may well be intrinsic to the crystal structure.[11-13] However, interesting questions remain as to the detailed nature of the vortex lines under these cross-flux conditions. For instance, in the presence of vortex lines along c, does the inhibited field-induced vortex magnetization in the a-b plane represent the creation of new vortex lines in the plane or does it correspond to a canting of the original vortex lines? The canting possibility would involve a peculiar hybrid of vortex lines parallel and normal to c, which are known from direct observation[14] to have very different morphologies, as elucidated theoretically.[15,16] This question is presently being addressed by follow-up experiments in which we are measuring the cross-flux effects for various hysteretic changes of the external field.

Finally, we should point out that the M_L-vs-H curve for zero H_{cool} in Fig. 1 has an anomalous shallow minimum at ~2.8 kOe, which correlates with the location of the deep minimum in the corresponding curve in Fig. 3. This correlation suggests there may be a slight (~4%) misalignment of the crystallites in our sample or, more likely, that for the data in Fig. 1 the applied $\mathbf{H}$ was tilted slightly (~2°) out of the a-b plane. In either case, the effects on our data are not significant, except for very low H_{cool}.

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