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Vortex bending in a tilted $YBa_2Cu_3O_{7-\delta}$ crystal

I. M. Obaidat, S. J. Park,* H. Safar, and J. S. Kouvel
Department of Physics, University of Illinois, Chicago, Illinois 60607-7059

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Magnetization-vector measurements were made on a $YBa_2Cu_3O_{7-\delta}$ crystal, initially cooled to 4.2 K in an external field $\mathbf{H}_e$ parallel to the c axis. With $\mathbf{H}_e$ fixed, the crystal was then tilted, such that the angle θ between the c axis and $\mathbf{H}_e$ was gradually raised to 90° and lowered back to zero. Our results reveal that all the vortex flux remains parallel to the c axis until the tilt angle θ reaches a threshold value (close to 15° for $H_e \leqslant 500$ Oe). As θ exceeds this value, the vortex flux in the ab plane rises rapidly from zero, and it appears to derive solely from a bending of the vortices initially directed along c. This whole process is fairly consistent with theoretical predictions, and it is found to be essentially reversible with the cycling of θ at low H_e. The hysteresis that develops at higher H_e rises and approaches the conventional hysteresis measured along ab after zero-field cooling. Comparison is also made with a cross-flux experiment, which is seen to be only superficially equivalent to the crystal-tilt experiment. [S0163-1829(97)51234-3]

The configurational structure of Abrikosov vortices in single crystals of the layered cuprate superconductors, such as the classic $YBa_2Cu_3O_{7-\delta}$ (YBCO), has been much studied and largely elucidated experimentally and theoretically.[1] Particular attention has been given to the symmetrical case where the vortices are oriented with their magnetic flux along the c axis normal to the CuO_2 layers and, as such, are believed to have a ‘‘pancake’’ structure lying in these layers.[2] These vortex pancakes are seen[3] to form lines along the c axis when extended defects, such as the a-b twin boundaries prevalent in as-grown crystals,[4] are present. Although there has been theoretical consideration,[5] it still remains to be explored experimentally as to when and how vortices deviate from this orientation when the crystal sample is tilted in a fixed magnetic field directed initially along the c axis.

We have been carrying out this sample tilting experiment with a YBCO crystal in various fields applied along c during cooling to 4.2 K and then held fixed. As reported in this paper, our results are revealing that the vortex flux remains parallel to c until the crystal tilt angle θ reaches a critical value θ_c, above which the vortex flux in the ab plane rises rapidly and appears to derive from a bending of the vortices originally oriented along c. This whole process, which is fairly consistent with recent theoretical predictions,[5] is found to be essentially reversible with cycled θ at low fields. The small hysteresis that develops at higher fields (and interferes with the critical threshold behavior) will be compared with that of various conventional measurements.

Our sample was a heavily twinned YBCO crystal platelet, ~1.5 mm in diameter in the ab plane and ~0.1 mm thick along the c axis, which had been carefully prepared by standard flux-melt growth techniques by Lisa Paulius of Western Michigan University. The crystal was mounted in our cryogenic vibrating-sample magnetometer (VSM) such that it could be tilted about an axis in the ab plane. In our VSM system, two sets of pickup coils are arranged in quadrature, allowing us to measure both M_L and M_T, the longitudinal and transverse components of the sample magnetization vector relative to the fixed external field $\mathbf{H}_e$ in the plane normal to the tilt axis.

The geometry in the crystal tilt plane is exhibited in Fig. 1(a), where the c axis is shown tilted by angle θ relative to $\mathbf{H}_e$. With reference to this figure, the measured M_L and M_T were converted to B_{ab} and B_c, the vortex flux densities parallel to the ab plane and the c axis, by means of the following equations:

$$B_{ab}=(H_e+\alpha_{ab}M_L)\sin\,\theta-\alpha_{ab}M_T\,\cos\theta \tag{1}$$

and

$$B_c=(H_e+\alpha_c M_L)\cos\theta+\alpha_c M_T\,\sin\theta, \tag{2}$$

where $\alpha_{ab}=4\pi-D_{ab}$ and $\alpha_c=4\pi-D_c$. The demagnetization factors, $D_{ab}=0.61$ and $D_c=4\pi-2D_{ab}=11.35$, were

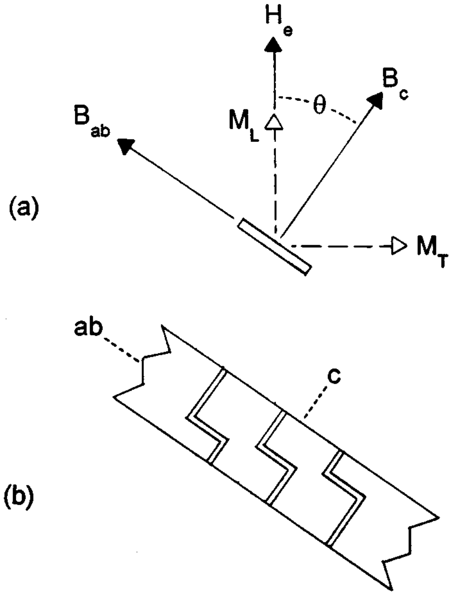

FIG. 1. (a) Geometrical arrangement of YBCO crystal platelet at tilt angle θ, whose flux density components, B_{ab} and B_c, are determined from measured magnetizations, M_L and M_T, parallel and perpendicular to external field H_e. (b) Detail of tilted crystal showing bent vortices with segments along ab plane.

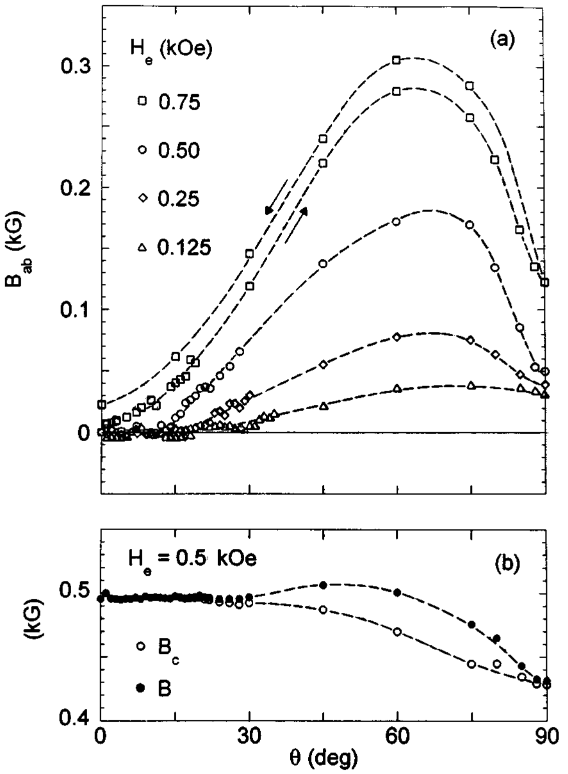

FIG. 2. (a) B_{ab} versus increasing tilt angle θ for various values of H_e at 4.2 K; plots for decreasing θ not shown for clarity, except for $H_e = 0.75$ kOe. (b) B_c and total flux density B versus increasing θ for $H_e = 0.5$ kOe.

determined from initial magnetization curves in the ab plane below H_{cl} ($\approx$40 Oe), assuming perfect Meissner shielding, and are consistent with the thin-platelet shape of the crystal. Typically, in all our tilting experiments, the YBCO crystal was initially cooled to 4.2 K from above T_c ($\approx$90 K) in a field $\mathbf{H}_e$ that was applied along c and subsequently held fixed. The crystal tilt angle θ between c and $\mathbf{H}_e$ was then increased in steps up to 90° and reduced in steps back to zero, with the flux density components B_{ab} and B_c determined at each step.

Our results for B_{ab} versus θ at several low fields are displayed in Fig. 2(a). For H_e up to 0.5 kOe, the variation with θ is essentially reversible, and we see that B_{ab} remains at zero (within the indicated scatter) until θ reaches a critical value (θ_c), above which it rises rapidly—at first linearly with $\theta - \theta_c$. Extrapolating this linear variation back to the θ axis, we find that $\theta_c = 17.8°$, 16.6°, and 14.8° (with an uncertainty of $\pm 0.5°$) for $H_e = 0.125$, 0.25, and 0.5 kOe, respectively. Note that the corresponding values of H_{ab}, the internal field in the ab plane (which closely equals $H_e \sin \theta_c$), are about 0.04, 0.07, and 0.13 kOe, whose large relative spread suggests that the near constancy of the θ_c values is the more significant factor. For $H_e = 0.75$ kOe, the variation of B_{ab} with θ clearly exhibits a small hysteresis, and the critical threshold behavior at low θ appears to have been removed. As Fig. 2(a) also shows, there is a drop in B_{ab} when θ exceeds 60°, and this peculiarity grows with increasing H_e. This anomalous effect indicates an increased vortex expulsion as $\mathbf{H}_e$ approaches the direction with the lowest demagnetization factor; a detailed discussion of this is beyond the scope of this paper.

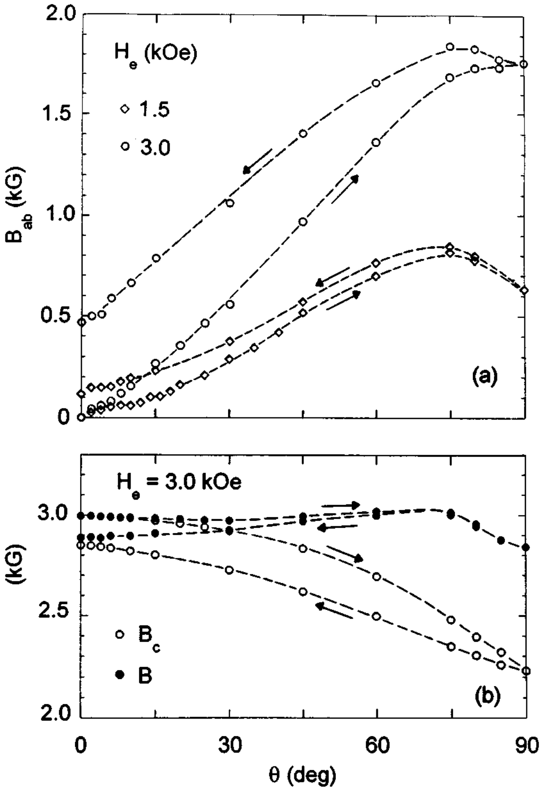

FIG. 3. (a) B_{ab} versus cycled tilt angle θ for higher values of H_e at 4.2 K. (b) B_c and total flux density B versus cycled θ for $H_e = 3$ kOe.

For a full view of the vortex flux in the crystal during the tilting experiment, we show in Fig. 2(b) a typical plot of B_c versus θ for the case of $H_e = 0.5$ kOe. At $\theta = 0$, B_c starts numerically very close to H_e, and it gradually diminishes to a value $\sim$14% lower at $\theta = 90°$. Also plotted here is the total flux density B, as obtained from a quadrature combination of B_c and B_{ab}. We see that B is nearly constant (within $\sim$2%) for θ out to 60°, above which it diminishes due to the anomalous drop in B_{ab}. Thus, at least for θ up to 60°, it appears that the total number of vortices in the crystal stays essentially unchanged, which allows us to conclude that the rise in B_{ab} when θ exceeds θ_c derives entirely from a bending of the vortices that were initially oriented along c. This vortex bending is displayed schematically in Fig. 1(b) where, consistent with relevant theory,[5,6] the zig-zag shape is taken to result from the very strong vortex pinning along the c axis and the much weaker pinning in the ab plane.

Our crystal-tilt experiments were also carried out at higher fields and, as displayed in Fig. 3(a) for $H_e = 1.5$ and 3 kOe, our results for B_{ab} show a continued increase of the hysteresis with cycled θ and the continued absence of a critical threshold behavior. Moreover, the anomalous drop in B_{ab} at large θ is now decreasing with increasing H_e; at still higher fields, it was seen to vanish altogether. The corresponding plots of B_c and B versus θ are shown in Fig. 3(b) for $H_e = 3$ kOe. Although B_c diminishes with increasing θ and its variation with cycled θ is highly hysteretic, as is that

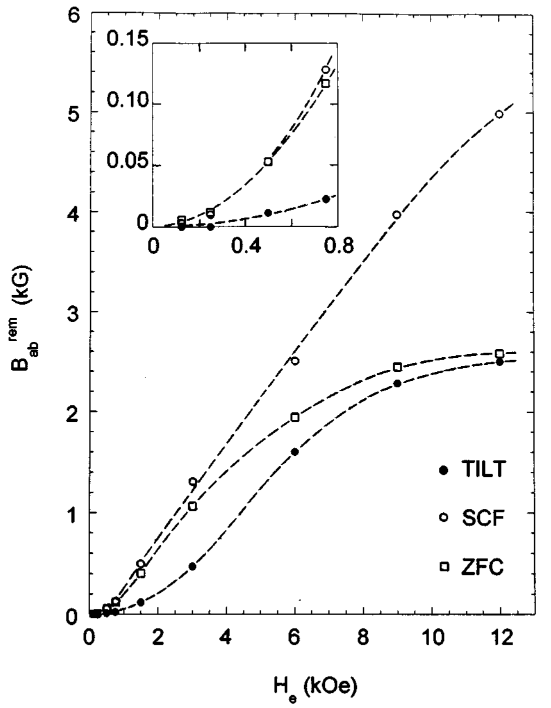

FIG. 4. Remanent B_{ab} versus H_e for TILT, SCF, and ZFC experiments at 4.2 K, as discussed in text. Inset shows expanded detail at low H_e.

of B_{ab}, the total flux density B is relatively constant and exhibits much less hysteresis. Hence, even at these higher fields, the total number of vortices in the crystal appears to change very little with θ, which again indicates that the increase of B_{ab} with θ arises from a bending of the original vortices along c.

The hysteresis with cycled θ in the crystal-tilt experiment was studied at fields up to 12 kOe, but our results will be represented here simply by the remanent values of B_{ab} determined when θ was returned to zero from 90°. The experimental values of B_{ab}^{rem} are plotted versus the field of measurement H_e in Fig. 4 (closed circles for the TILT experiment), where they are shown together with the results of two additional experiments performed on the same crystal.

These two experiments were both carried out conventionally with the YBCO crystal held at $\theta = 90°$ while the field in the ab plane was raised to H_e and then reduced to zero—which mimics the variation of the field along ab during the TILT experiment at fixed $\mathbf{H}_e$. In one of these experiments, the crystal was initially prepared simply by zero-field cooling (ZFC) to 4.2 K. In the second experiment, the crystal was initially cooled to 4.2 K in the field $\mathbf{H}_e$ applied along c; the field was then removed and the crystal turned to $\theta = 90°$ for the subsequent field cycling up to H_e along ab. The latter, henceforth referred to as the standard cross-flux (SCF) experiment, was first performed in our laboratory[7–9] on grain-oriented and single-crystal YBCO, where it was discovered that the remanent vortex flux along c acts as a pinning agent for the vortices produced by the field applied along ab.

The remanent values of B_{ab} obtained from our ZFC and SCF experiments for various H_e are shown in Fig. 4, where they lie consistently higher than the B_{ab}^{rem} values from the TILT experiment. As shown in the figure inset, this comparison is particularly striking at low H_e, where the very small B_{ab}^{rem} values from the TILT experiment were barely measurable. This difference presumably derives from the fact that the vortices produced along ab in the ZFC and SCF experiments are held by pinning centers along the whole length of this plane in the crystal, whereas in the TILT experiment the vortex bending at low H_e involves vortex segments along ab that are short and thus encounter very few pinning centers. However, with increasing H_e, the vortex segments along ab produced by the vortex bending can be expected to lengthen and ultimately reach the linear size of the ab plane in the crystal. In fact, this is borne out in Fig. 4 by the rise in the TILT values of B_{ab}^{rem} and their eventual approach to the saturation ZFC value at high H_e.

Figure 4 also shows that the SCF values of B_{ab}^{rem} stay fairly close to the ZFC values up to $H_e \approx 3$ kOe, indicating that the cross flux is too small in concentration to produce any sizeable additional pinning. However, at higher H_e, the SCF values continue to rise rapidly and reach levels well above the saturation ZFC value, thus exhibiting the large cross-flux effect seen previously at high H_e.[9] From the vast difference in their relationships to the ZFC experiment, it is clear that the SCF and TILT experiments are probing very different vortex properties—even though they both involve an initial cooling in a field along c and a subsequent raising of a field component along ab. Indeed, from the fact that the TILT values of B_{ab}^{rem} approach the ZFC values rather than the much larger SCF values at high H_e, it would appear that in the TILT experiment the vortices are all bending in a similar fashion, such that there is no vortex crossing.

Very recently, Zhukov *et al.*[10] reported on a similar magnetization-vector study of a tilted YBCO crystal at 10 kOe and 60 K. Their results are cast differently but appear to show a broadened thresholdlike behavior resembling what we have seen at our higher fields at 4.2 K [Fig. 3(a)].

In summary, our crystal-tilt experiments on YBCO at 4.2 K are revealing that the vortex flux remains oriented along the c axis until the tilt angle θ reaches a critical threshold value (of about 15°), above which the vortex flux develops a component in the ab plane—which appears to derive solely from a bending of the vortices originally along c. This entire process, which occurs at low fields and is fairly consistent with recent theory,[5] is found to be essentially reversible with the cycling of θ. At higher fields, the threshold behavior vanishes with the appearance of hysteresis in the flux density along ab, which is initially very small but then grows rapidly and becomes comparable to the conventional hysteresis after zero-field cooling. The hysteresis seen in the crystal-tilt experiment with cycled θ is also compared with the conventional hysteresis of a cross-flux experiment. Although these two experiments are seemingly equivalent in many respects, they are found to be examining very different vortex properties.

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[*] Present address: Physics Department, Han-Yang University, Seong-Dong, Seoul, Korea.

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