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ANGULAR DEPENDENCE OF THE FIELD-COOLED, ZERO-FIELD COOLED AND REMANENT MAGNETIZATION IN $YBa_2Cu_3O_7$ AND $Bi_2Sr_2CaCu_2O_8$ SINGLE CRYSTALS

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We have studied the angular dependence of the zero-field-cooled (M_{ZFC}), field-cooled (M_{FC}) and remanent magnetization (M_{rem}) of $YBa_2Cu_3O_7$ and $Bi_2Sr_2CaCu_2O_8$ single crystals, by rotating the crystal relative to the applied field direction. Two compatible mechanisms, namely shape anisotropy and intrinsic anisotropy are used to describe the angular dependence of these quantities. At sufficiently low temperatures, the pinning forces are strong and the relation $M_{FC}=M_{ZFC}+M_{rem}$ holds for all orientations. The angular dependence of M_{ZFC} is due only to variation of the demagnetization factor by rotation; whereas the angular dependence of the remanent magnetization can be interpreted by using the two mechanisms. For larger fields or higher temperature the pinning forces are weaker and $|M_{FC}|<|M_{ZFC}+M_{rem}|$.

In an earlier experiment[1] we demonstrated the existence of uniaxial anisotropy in $YBa_2Cu_3O_7$ (YBCO) and Bi-Sr-Ca-Cu-O (BSCCO) single crystals by measuring the angular dependence of the remanent magnetization. In the present paper we discuss M_{ZFC} and M_{FC} results, as well. We show that in the low field limit when the pinning of vortices is sufficiently strong the relation $M_{FC}=M_{ZFC}+M_{rem}$ is valid in all orientations of the crystal relative to H. This relation is independent of the orientation of the crystal during the cooling process. The results obtained for YBCO and BSCCO are compared. We will briefly discuss the origin of the observed anisotropy.

The 920x410x60 μm^3 (axbxc) YBCO crystal used in the present study was grown by the technique of Kaiser et al[2]. The BSCCO crystal is the one measured in ref.(1). Magnetic measurements were performed on a Vibrating Sample Magnetometer (VSM), which enables a rotation of the sample relative to the external field. The experimental procedures are as follows. The sample was cooled to 4.2 K either in a field (FC) or in a nominal zero field (less than 3 Oe) (ZFC). The "cooling angle" is the angle between H and the c axis during the cooling process. In the ZFC measurements a field (1 kOe) was applied at 4.2 K and M_{ZFC} was measured as a function of the angle θ between H and c. The axis of rotation was parallel to the a-b plane. In the FC process the sample was rotated in the cooling field (1 kOe), and M_{FC} was obtained as a function of θ. Similar rotation of a field-cooled sample in the absence of external field yield $M_{rem}(\theta)$.

Fig.1 and 2 exhibit the angular dependence of M_{rem}, M_{ZFC} and M_{FC} as a function of the rotation angle θ for φ=0 of YBCO and BSCCO, respectively. The dotted line through the ZFC results is a fit to

$$M_{ZFC}=-\frac{H}{4\pi}\left(\frac{\cos^2\theta}{1-N_c}+\frac{\sin^2\theta}{1-N_b}\right) \quad (1)$$

where H is the external field and $N_{b,c}$ are the demagnetization correction factors of the θ=90 and θ=0 directions, respectively. $N_{b,c}$ were extracted from M vs. H measurements in the $H<H_{c1}$ regime. These values are in excellent agreement with values calculated by approximating the crystal as an ellipsoid of rotation and using conventional tables[3]. The independency of M_{ZFC} on φ suggested by eq(1) was confirmed. The results imply that this measurement probes the

angular dependence of the demagnetization factor.

The dotted line through the M_{rem} results is a fit to[1]

$$(2)\quad M_{rem}(\theta,\phi) = M^{c}_{rem}\cos\theta\cos\phi + M^{ab}_{rem}\sin\theta\sin\phi$$

where M^{c}_{rem} and M^{ab}_{rem} are the remanent values measured for ϕ=0 at θ=0 (H||c) and for ϕ=90 at θ=90 (H⊥c). Trapping of flux is extremely anisotropic. For the present crystal we obtain $M^{c}_{rem}/M^{ab}_{rem} \approx 5$. In a previous paper[1] we argued that this anisotropy demonstrates the tendency of the vortices to be pinned in the c direction as predicted by models for anisotropic superconductors[4].

Following the comment of Kolesnik et al[5], we have performed similar measurements on flat and disc shaped polycrysytalline YBCO samples. These samples were characterized by x-ray diffraction and were found to be granular with no preferred orientation. The qualitative similarity between $M_{rem}(\theta)$ measured on policrystalline samples and the single crystal may suggest that its angular dependence does not reflect intrinsic anisotropy of flux trapping

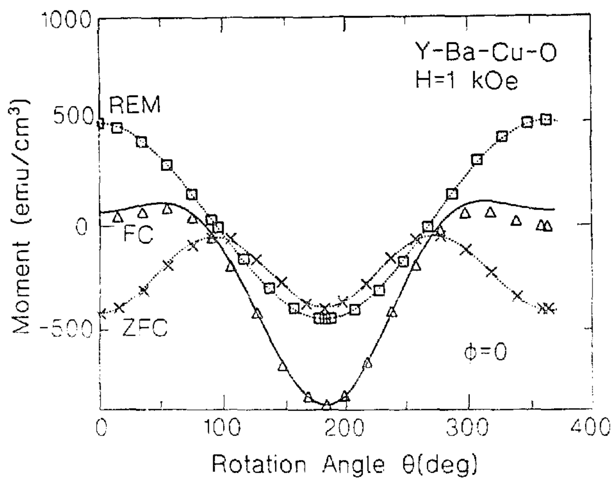

FIGURE 1
Angular dependence of M_{rem}, M_{FC} and M_{ZFC} of YBCO. The solid line is the sum of $M_{ZFC}+M_{rem}$.

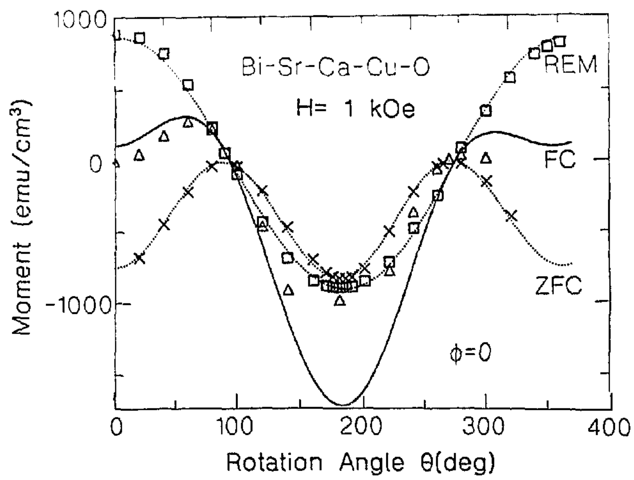

FIGURE 2
Angular dependence of M_{rem}, M_{FC} and M_{ZFC} of BSCCO. The solid line is the sum of $M_{ZFC}+M_{rem}$.

but rather reflects the strong angular dependence of the demagnetization factor.

The solid line is the sum of the M_{ZFC} and M_{rem} curves. The M_{FC} results are marked by triangles. For YBCO (Fig.1), the fit is quite good (better fits are obtained at lower fields) proving that M_{FC} could be described by the sum of eq(1) and eq(2). This relation between M_{FC}, M_{ZFC} and M_{rem} holds for all ϕ. On the contrary, in the BSCCO case (fig.2), M_{FC} collapses and coincides with M_{ZFC} in most of the angular regime. The solid line represent $M_{ZFC}+M_{rem}$ and the huge differences between this curve and M_{FC} are evident. This result is a direct outcome of the weakness of the pinning forces in BSCCO.

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