Flux-flop in high temperature superconducting crystals with columnar defects

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Measurements of magnetization curves of Y-Ba-Cu-O crystals with columnar defects reveal pronounced peaks around $H=0$ for applied fields not parallel to the defect direction. The magnitude and direction of the remanent magnetization are independent of the direction of the applied field for a large range of angles. We show that the unidirectional character of the defects induces, in the low field limit, a flux-flop from a direction determined by the field to the defect direction. Implications to planar pinning are discussed.

I. INTRODUCTION

In a recent manuscript[1] we have reported on magnetic measurements in HTSC crystals irradiated with 5.3 GeV Pb ions which produce well-defined *continuous* cylindrical amorphous tracks along their paths, with a diameter of ~7 nm. As expected, these measurements have demonstrated that flux trapping is enhanced for fields along the defect direction. However, we have found a new feature: In the low field limit the enhancement of the flux trapping is independent of the field direction for a large range of angles due to reorientation of the flux lines along the direction of the defects. This reorientation is somewhat analogous to the well known phenomenon of spin flop in magnetic systems, hence we refer to it as "flux-flop."

In the present paper we briefly review the experimental results of Ref. 1 and add new data. We make an effort to interpret other experiments in terms of flux-flop and we elaborate on the energy considerations of this phenomenon.

II. SAMPLES AND MEASURING TECHNIQUES

We describe here measurements on a $0.6\times0.3\times0.02$ mm^3 crystal which was irradiated along the c direction and a $0.6\times0.6\times0.02$ mm^3 crystal irradiated in 45° relative to this direction. We refer to these crystals as IR0 and IR45, respectively. As a reference, we also describe measurements on an as-grown (AG) $1.4\times0.7\times0.03$ mm^3 sample from the same batch. Sample preparation is described in Ref. 2. The transition temperature $T_c=93.5$ K of the AG samples is reduced by 1–1.5 K after irradiation. Irradiation was done at the Grand Accelerateur National d'Ions Lourds (GANIL, Caen, France), with a beam of 5.3-GeV Pb ions, at room temperature. The total fluence was 10^{11} ions/cm^2.

All magnetic measurements were performed on an Oxford Vibrating Sample Magnetometer (VSM) which allows for a study of the angular dependence of the magnetization by rotating the sample relative to the magnetic field. The sensors of the VSM define a spatial direction $\bar{x}$, and only the component of the magnetization along $\bar{x}$ is measured.

III. EXPERIMENTAL RESULTS

A. Remanent magnetization and relaxation

The samples were cooled from above T_c in a field $H=1.6$ T forming an angle ϕ relative to the crystalline c axis. At the measurement temperature the field was turned off, the sample was rotated (the angle of rotation θ is measured relative to c and for $\theta=0$ $c\|\bar{x}$) and the component of M_{rem} along $\bar{x}$ was measured. In Fig. 1 we show for demonstration $M_{\text{rem}}(\theta)$ for IR45 ($\phi=\pm45°$) at 60 K. Our main observation is that the remanent magnetization for each sample is independent of ϕ in the range of our measurements ($-45°\leqslant\phi\leqslant45°$); i.e., in all the cases the remanent magnetization has the same magnitude and it is pointing along the c direction.

Measurements of the relaxation of M_{rem} for IR45 and IR0 at 60 K with $\phi=0$ and 45° yield for all these cases an effective barrier of $U_0\cong0.23$ eV as compared to 0.07 eV for

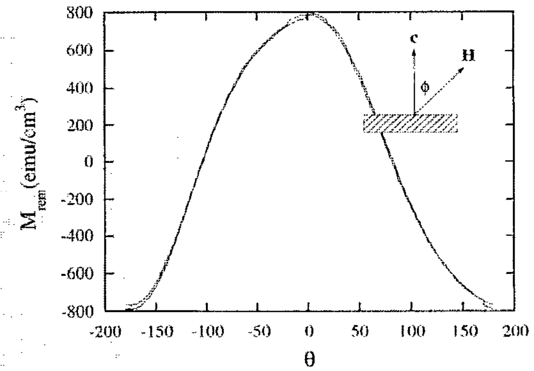

FIG. 1. The remanent magnetization of IR45 at $T=60$ K after cooling in a field of $H=1.6$ T (applied at $\phi=\pm45°$) vs the angle θ which is measured relative to the c direction. The two curves are almost indistinguishable.

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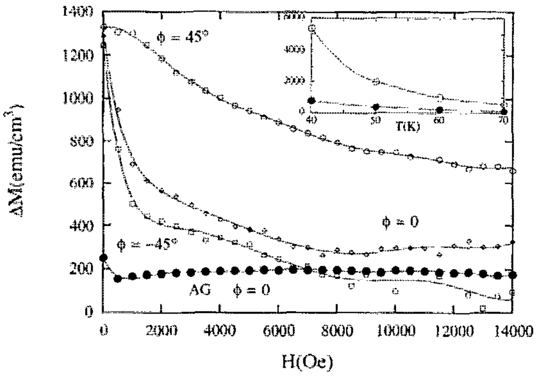

FIG. 2. Open symbols: The width of the magnetization curves at $T=60$ K of IR45 for $\phi=0$ and ±45°. Shaded symbols: Width for the AG sample for $\phi=0$. Inset: The width of the magnetization curves for $\phi=0$ of IR0 (open symbols) and AG (shaded symbols) at various temperatures.

the AG sample. The effective barrier U_0 was deduced from $U_0=k_B T/(\partial \ln M/\partial \ln t)$.

B. Magnetization curves

In Fig. 2 we compare the width of the magnetization curves for IR45 for three orientations of the applied field, namely, $\phi=0$ and $\pm 45°$ at $T=60$ K. For reference we also show the width of the AG sample for $\phi=0$. In these measurements the sample was cooled in zero field and the data were taken in steps of 500 Oe up to 1.6 T. In the inset of this figure we compare the width of the magnetization curves at $H=0$ for $\phi=0$ of IR0 and AG at various temperatures. Note that the exhibited data is divided by cos ϕ.[3] We observe that the width of the loop, which reflects the efficiency of flux trapping and the magnitude of the critical current,[4] is significantly increased after irradiation. It is apparent that at high fields the width depends on ϕ; it reaches its maximum value for $\phi=45°$, namely, for H parallel to the defects, and the width is much smaller for $\phi=0$ and $-45°$. This is expected due to the unidirectional anisotropy of the columnar defects. Our main observation is that the magnetization curves of IR45 for $\phi=0$ and $-45°$ and of IR0 for $\phi=45°$ exhibit a pronounced peak around $H=0$ where the magnitude of the magnetizations curves coincide with that of the $\phi=45°$ and $\phi=0$, respectively. In other words, the width of the magnetization curves in the low-field limit is independent of the orientation of the field relative to the direction of the defect.

IV. DISCUSSION

The remanent magnetization points preferably along the c direction and there are several explanations for this phenomenon which are based on the shape of the sample. There was an attempt to attribute this observation to the anisotropic demagnetization factors of a flat sample.[5] However, one should note that the remanent magnetization is measured after the field is decreased from its highest value. Therefore, the magnetization is positive due to flux trapping and the effect of the demagnetizing fields is a quicker *decrease* of the effective field in the c direction. Thus, using arguments of demagnetization factors alone is insufficient to explain the apparent anisotropy in flux trapping; its effect is more likely to decrease the remanent magnetization in the c direction. A different explanation,[6] which is based on the critical state in flat samples, seems to be adequate. This model also implies that when the magnetization points in the c direction, the vortices are not necessarily aligned along this direction.

The fact that the remanent magnetization has the same magnitude and the same relaxation rate for $\phi=0$ and 45° combined with the convergence of the magnetization curves at $H=0$ indicate that the magnetic "structure" at $H=0$ is independent of ϕ. The smooth behavior around $H=0$, of the magnetization curve of $\phi=45°$ in IR45 and of $\phi=0$ in IR0 indicate that in this structure the vortices are aligned along the defects. When the field does not point along the defect, then the vortices are aligned along a direction determined by the field only in the high field limit. When the field is reduced, the situation changes and the sharp upturn of the magnetization curves reflects a sudden increase of the pinning force due to flux-flop to the defect direction.

In order to understand such a flux-flop, we estimate now the energy gain in such a reorientation. According to a recent work by Nelson and Vinokur,[7] which considers the effect of columnar defects, there is a temperature range where the vortices form a "Bose-glass" state, i.e., each vortex is pinned by only one columnar defect. Taking into account the characteristics of the defects in our samples, we find that the Bose-glass persists up to, practically, T_c.[8] Thus, in our energy considerations, we assume that each vortex is pinned by only one columnar defect.

We first emphasize that the (electromagnetic) energy ϵ of a fluxon in an insulating columnar defect with a diameter d ($\lambda \gg d > \xi$) is of order

$$\epsilon_P=(\Phi_0/4\pi\lambda)^2 \ln(\lambda/d) < \epsilon_0=(\Phi_0/4\pi\lambda)^2 \ln(\lambda/\xi),$$

where ϵ_0 is the energy of an Abrikosov vortex.[9] Substituting reasonable values for d (70 Å), ξ (13 Å), and λ (1400 Å) we find

$$u_P=(\epsilon_0-\epsilon_P)/\epsilon_0=0.4.$$

Thus, the relative energy gain for a fluxon along the columnar defect is of order ϵ_0, much larger than the usual gain in the core condensation energy $\epsilon_c=H_c^2\xi^2/8\pi$ for point defects which is only a few percent of ϵ_0 when $\lambda \gg \xi$.

The actual direction of the vortex is determined by minimization of the Gibbs free energy, where three factors are competing: (a) Alignment along the direction of the field decreases the Gibbs energy by a factor which is proportional to the intensity of the field. (b) The total vortex energy is proportional to its length; in a platelet sample this length is minimized by alignment perpendicular to the flat surface. (c) The gain in the pinning energy by alignment along the columnar defect. Due to the competition between (a) and (b) the vortices are not oriented along the field direction ϕ, but rather along an intermediate angle ϕ', where $\phi > \phi' > 0$ are measured relative to c. In the high-field limit ϕ' coincides with ϕ. As the field is reduced, ϕ' *gradually* decreases.

In a contrast to the gradual change in ϕ', an abrupt change is expected in the presence of unidirectional pinning. Columnar defects are effective in trapping only when the fluxon is along the defect and therefore there is no energy gain in a gradual change of the orientation of the fluxon toward the direction of the defect. We thus expect that when there is a gain in the Gibbs energy by alignment of a vortex along the defect, a flux-flop occurs.[10] An estimation of the field for flux-flop for IR45, treating the sample as an infinite superconducting layer, yields

$$H_{\mathrm{fl}} \approx 0.3 H_{c1}, \qquad \text{for} \quad \phi = 0$$

and

$$H_{\mathrm{fl}} \approx 0.15 H_{c1}, \qquad \text{for} \quad \phi = -45°.$$

Taking into account finite-size effects we conclude that qualitatively, the onset of flux-flop in our experiment agrees with this prediction.

Another interesting prediction is that the flop is limited to cases where the defects form an angle $\alpha < \alpha_{\mathrm{cr}}$ relative to c, where

$$\cos \alpha_{\mathrm{cr}} = 1 - u_p .$$

In our case $u_p \approx 0.4$ and $\alpha_{\mathrm{cr}} \approx 53°$. For larger α the energy gain in the defect $(1 - u_p)$ is smaller than the energy loss due to the increase (by a factor $1/\cos \alpha$) in the length of the fluxon.

One should note that our estimation of the critical angle assumes continuous columnar defects which is indeed the case for Pb irradiation. Other heavy ions irradiation such as Sn or I produce discontinuous tracks and therefore the critical angle may be much smaller. In these cases it is more plausible to observe an *inverse flux-flop*, namely, when the field is applied along the defect, the flop is from the direction of the defect toward the c direction. Such an inverse flux-flop should yield a dip in the low field limit. We suggest that this may be the origin for the unexplained dips in the magnetization curves of Y–Ba–Cu–O crystals irradiated with 580-MeV Sn ions in 30° relative to the c direction.[11]

The flux-flop phenomenon resembles features related to the predicted lock-in transition toward the layer planes[12] and to the measured decrease of the resistivity due to twin boundaries in Y–Ba–Cu–O crystals.[13] In these cases however, the vortices are confined in planes rather than along lines. Nevertheless, the main features which lead to flux-flop still remain. Therefore, the lock-in transition toward the layer planes and the pinning at the twin boundaries should also be observed in magnetization curves. A reminiscence of this expectation may be found in the angular dependence of the irreversible contribution to torque, in Y–Ba–Cu–O crystals, which exhibit pronounced peaks around $\phi = 0$, and $\pi/2$, i.e., for $H \| c$ and $H \| ab$.[14] Similar peaks were observed in the angular variation of the remanent magnetic moment of an Y–Ba–Cu–O crystal.[15]

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