Evidence for an angular dependent contribution from columnar defects to the equilibrium magnetization of YBa$_2$Cu$_3$O$_{7-\delta}$

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(March 24, 2022)

We have measured an angle–dependent contribution to the equilibrium magnetization of a YBa$_2$Cu$_3$O$_{7-\delta}$ single crystal with columnar defects created by irradiation with 5.8 GeV Pb ions. This contribution manifests itself as a jump in the equilibrium torque signal, when the magnetic field direction crosses that of the defects. The magnitude of the jump, which is observed in a narrow temperature interval of less than 2 K wide, for fields up to about twice the dose equivalent field $B_0$, is used to estimate the energy gained by vortex pinning on the defects. The vanishing of the effective pinning energy at a temperature below $T_c$ is attributed to its renormalization by thermal fluctuations.

I. INTRODUCTION

Since the discovery of increased pinning in heavy-ion irradiated samples, the interaction between flux-lines and columnar defects in high-$T_c$ superconductors has been the subject of intense experimental and theoretical investigations. An angle–dependent critical current enhancement has been put into evidence both in the moderately anisotropic material YBa$_2$Cu$_3$O$_{7-\delta}$ as in highly anisotropic materials such as Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$. The influence of correlated disorder on the equilibrium properties of the flux-line lattice has been the subject of fewer experimental investigations. Torque and magnetization experiments on Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ have revealed a pinning energy contribution to the equilibrium magnetization arising from the presence of the defects, but, in contrast to the irreversible magnetic moment, the equilibrium magnetization did not show any other angle–dependent contribution than the one arising from the layering of the material. Here, we investigate the less anisotropic compound YBa$_2$Cu$_3$O$_{7-\delta}$ and show that there exists a narrow domain in the (H-T) diagram where a reversible angular dependent contribution to the torque arises due to the interaction of flux-lines with the linear defects. This constitutes a direct demonstration that vortex lines in the liquid phase distort in order to accommodate to the linear irradiation defects.

II. EXPERIMENTAL DETAILS

The experiments were performed on a single crystal of dimensions $130 \times 37 \times 18 \, \mu$m$^3$; the shortest dimension was along the $c$-axis. The transition temperature after irradiation was $T_c = 90.3$ K. A single domain of parallel twin planes was observed, the planes running at 45° with respect to the crystal’s longest edge. The sample was irradiated with 5.8 GeV Pb ions to a dose $n = 10^{11}$ cm$^{-2}$, equivalent to a matching (dose equivalent) field $B_0 = \Phi_0 n = 20$ kG. The ion beam was directed perpendicular to the longer crystal edge, at an angle of 30 degrees with respect to the $c$-axis. The irradiation created continuous linear amorphous defects of radius $a = 35$ Å, oriented along the direction of the ion beam with density $n$. After the irradiation, the sample was characterized using the magneto-optic flux visualization technique at 65, 77 and 82 K; no evidence of any remaining influence of the twin planes on the flux penetration could be observed.

The torque was measured using a piezoresistive microlever from Park Scientific Instruments, as described in Ref. 7. The microlever formed part of a low temperature Wheatstone resistive bridge, in which a second lever with no sample was inserted in order to compensate for the background signal originating from the magnetoresistance of the levers. The measuring lever was fed with a current of 300 $\mu$A and thermalized to better than 0.01 K using He$^4$ exchange gas. The torque setup was calibrated from the Meissner slope of the reversible magnetization as a function of field at a fixed angle, as described elsewhere. In torque experiments with a single rotation axis, the plane in which the applied field $H$ is rotated is always at a misorientation angle $\alpha$ with respect to the plane enclosing the $c$-axis and the irradiation direction (Fig. 1). This angle is not known a priori: it results from the uncertainty in both the irradiation direction and the sample positioning. We estimate that it is less than a few degrees. The result of the misorientation is that the applied field is never strictly aligned with the irradiation
direction; \(\alpha\) is therefore the minimum angle between \(H\) and the ion tracks when the field direction is varied.

In a separate experiment, the irreversibility line was measured using SQUID ac-susceptometry. It was located as the onset of the in-phase (reactive) component of the ac susceptibility measured in an oscillatory field of amplitude 0.1 Oe and frequency 13 Hz, oriented parallel to the dc field. These measurements were performed for two orientations of the static field, applied parallel to the direction of the tracks (i.e. at 30° with respect to the \(c\)-axis), and applied in the symmetric direction with respect to the \(c\)-axis. The irreversibility fields for both orientations were found to be linear with temperature; the line obtained with the field applied parallel to the tracks clearly lies above the one for the symmetric orientation (Fig. 2). In contrast to what is observed for \(\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}\), and more recently, in heavy-ion irradiated \(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}\) thick films, there is no change in the behavior at \(H > B_H\) up to our maximum measuring field of \(H = 50\) kOe, and the lines do not merge above the irradiation field.

### III. RESULTS AND DISCUSSION

Typical torque signals are displayed in Fig. 3. Below the irreversibility line determined by SQUID ac-susceptometry with the field along the tracks, the torque measurements reveal a hysteretic behavior when the field is aligned with the irradiation direction. Above the line, the system is in the so-called vortex liquid phase and the torque signal is reversible; however, in a narrow region typically 1 to 2 K wide, a kink is found, roughly symmetric with respect to the orientation of the columnar defects (Fig. 3). This behavior is similar to what is observed for conventional torque on a layered superconductor when the field is rotated across the plane of the layers, and indicates that the vortex lines deform in order to have their direction coincide with that of the linear defects. In other words, the free energy of the vortex liquid phase is lowered by flux-line pinning onto the columnar tracks.

At low temperatures, where thermal fluctuations are not important, theory predicts that when the external field is applied sufficiently close to the layer/track direction (i.e. the angle between applied field and the tracks \(\theta < \theta_1\) where \(\theta_1\) is the lock-in angle), the equilibrium configuration of a single flux-line is that in which the whole length of the line is aligned with the defect. At larger angles \(\theta_1 < \theta < \theta_c\), one expects a staircase configuration in which line segments aligned with the defects alternate with segments wandering between defects. For \(\theta\) larger than the accommodation angle \(\theta_c\), the vortices do not readjust to the columnar defects at all. In our experiment, it is unlikely that we achieve the locked configuration, as this would require the alignment of the external field with the track direction to within some angle \(\theta < \theta_1 < \alpha\). In the locked configuration, one should observe a linear variation of the torque signal with angle, with a slope \(B^2/4\pi\) erg cm\(^{-3}\) rad\(^{-1}\) (neglecting the anisotropy in the demagnetizing factors) i.e. \(\approx 5 \times 10^{-2}\) erg deg\(^{-1}\) in a 10 kOe field in our case. This is three orders of magnitude larger than the highest of the slopes in Fig. 3.

The predicted contribution \(\Gamma_{\text{v}}\) to the torque signal is shown in Fig. 4. As the field angle is increased from the irradiation direction, the torque first increases linearly, reaching a maximum at the lock-in angle, and then decreases linearly beyond this. For angles larger than \(\theta_1\), the torque contribution arising from the interaction between vortices and ion tracks should be zero. In practice, the lock-in angle is quite small, therefore the torque signal should be quasi-discontinuous when the field direction coincides. In the single vortex regime, the magnitude of the torque signal close to the irradiation direction may be obtained in terms of the lock-in angle:

\[
\Gamma_{\text{v}}(\theta) = \frac{B^2}{4\pi} \theta \left( \frac{\theta}{\theta_1} - 1 \right) \text{sign}(\theta)
\]

\[
\theta_1 = \frac{4\pi \sqrt{2}}{\Phi_0 H} \varepsilon_r^{1/2}
\]

with \(\varepsilon_r\) the pinning energy per unit length. The accommodation angle \(\theta_1 = \arctan(2\varepsilon_r/\varepsilon)\), where \(\varepsilon_1 = \gamma^{-2} \varepsilon_0 \ln(1/K)\) is the vortex line tension, the energy scale \(\varepsilon_0 = (\Phi_0/4\pi\lambda)^2\), and \(K\) is the typical wavevector of the vortex distortion induced by the columns. In optimally doped \(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}\), the penetration depth \(\lambda = 1400(1-T/T_c)^{-1/2}\) Å, the \(ab\)-plane coherence length \(\xi_{ab}(0) = 15\) Å, and the anisotropy parameter \(\gamma \approx 7.6\). From Eq. (1), one sees that one can directly obtain an estimate of the lock-in angle from the torque jump observed when the field is aligned with the columns and Eq. (2). A good estimate of the pinning energy \(\varepsilon_r\) is equally obtained from the torque jump:

\[
\varepsilon_r = \left( \frac{\Gamma(0) a_0}{2\varepsilon_1} \right)^2
\]

\((a_0 = (\Phi_0/B)^{1/2}\) is the mean separation between vortices). This method to obtain the pinning energy is more direct than estimates based on the angular dependence of the resistivity \(\rho\). Those rely on the identification of a shallow maximum of \(\rho\) at \(\theta_1\), or, alternatively, with a “depinning angle” determined by the rate at which vortices can liberate themselves from a track; the relation of the latter with the accommodation angle is not certain. Since the pinning energy is predicted to be proportional to \(\theta_1\), the method based on transport measurements can result in a large uncertainty in \(\varepsilon_r\).

The present approach has the advantage that there is only one assumption, which concerns the precise form of \(\varepsilon_1\). Taking the curve at \(H = 12\) kOe and \(T = 88.5\) K \((T/T_c = 0.98)\), i.e. at the onset of magnetic irreversibility, one has a typical value of the torque jump \(2\Gamma(0)\) \(\approx 400\) erg cm\(^{-3}\) (Fig. 3); consequently, \(\theta_1 \approx 10^{-5}\) deg. The parameter values \(a_0 = 400\) Å, \(\xi_{ab}(T) \approx 100\) Å, \(K_\parallel = 1/a_0\), and \(\gamma(T) \approx 7000\) Å, yield the pinning
energy per unit length $\varepsilon_r \approx 5 \times 10^{-9}$ erg cm$^{-1}$, and $\theta_e \approx 70^\circ$. The obtained value of the accomodation angle seems reasonable: the difference between the extrapolation of the torque from large positive and negative angles to $\theta = 0$, at which the field and the ion track are nearly aligned, is a good indication that $\theta_e$ lies beyond the angular range depicted in Fig. 3. Clearly, $\theta_e$ greatly exceeds the angular width of the irreversible regime just below the irreversibility line, which is about $8^\circ$ at 88.5 K and $H = 12$ kOe. The accomodation angle is comparable to the low–temperature limit of the “depinning angle” measured on an untwinned YBa$_2$Cu$_3$O$_{7-\delta}$ single crystal irradiated with 1.0 GeV U ions to the same nominal dose.\footnote{5}

Returning to the experimental data in Fig. 3 one observes that, in spite of the fact that a clear jump in the torque signal can be defined, the discontinuity at the irradiation angle is rather smooth. The smoothness of the curve is possibly due to the non-zero misalignment angle $\alpha$. The effect of misalignment can be quantitatively accounted for using simple trigonometric considerations. Projecting the torque as given in Ref.\footnote{13} on the experimental torque axis $\mathbf{u}$ (Fig. 3), one obtains the magnitude of the measured torque signal:

$$\Gamma = \frac{\sin(\tilde{\theta})}{\sin(\tilde{\theta})} |\Gamma_0(\tilde{\theta})|$$

(4)

where

$$\sin(\tilde{\theta}) = [\sin^2(\theta) + \sin^2(\alpha) \cos^2(\theta)]^{1/2}.$$  

(5)

$\tilde{\theta}$ is the field rotation angle in the laboratory frame, and $\theta$, as before, is the real angle between the direction of the magnetic field and that of the ion tracks. The curves plotted in Fig. 3 shows that the effect of the misalignment is both to widen the angular interval between the torque maxima (now $\approx 2\alpha$ from one another) and to decrease the torque value at the maximum. Using $\theta_l \ll \theta_e$, $\theta_l \approx 30^\circ$, and $\alpha = 5^\circ$ we find that the maximum torque is only about 0.6 $\Gamma_0(0^-)$ so that the pinning potential estimated from the apparent torque jump is in this case only about 40% of the actual value, which, at $H = 12$ kOe and $T = 88.5$ K, would amount to $\varepsilon_r = 1.3 \times 10^{-8}$ erg cm$^{-1}$.

The absolute value of the pinning energy per unit length is in reasonable agreement with the estimate for core pinning of individual vortices\footnote{14}

$$\varepsilon_r = \varepsilon_0 \left( \frac{\varepsilon_0}{2\xi_{ab}} \right)^2 \times (1 - T/T_c)^2$$

(6)

(with $\varepsilon_0(0) = 5 \times 10^{-8}$ erg cm$^{-1}$) In the temperature regime of interest, this mechanism is more relevant than electromagnetic pinning\footnote{14} because $\xi_{ab}(T)$ greatly exceeds the track radius. Using the same parameter values as above, the model yields the theoretical value $\varepsilon_r \approx 1 \times 10^{-9}$ erg cm$^{-1}$ (at $T/T_c = 0.98$). Recent measurements on heavy–ion irradiated Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$\footnote{15} showed that in that material, the dependence of pinning energy on track diameter and temperature is in agreement with the core pinning model, although the magnitude of the pinning energy exceeded the theoretical expectation\footnote{16} by a factor 5. In the present case, the strong temperature and field dependence of the experimentally obtained pinning energy, displayed in Fig. 3 show that a simple “zero temperature” single vortex pinning approach is inadequate. The reasons for this are that (i) the fields under consideration are not small with respect to $B_{\phi}$, so that only a fraction of vortices can be expected to be actually trapped on a columnar track, and (ii) the proximity to $T_c$ possibly necessitates the inclusion of the effect of strong thermal fluctuations\footnote{14}.

A theoretical description of the effect of a field rotation, or even of the total pinning energy, in the case where the vortex density is comparable to the density of a system of strong linear pins has, to our knowledge, not been developed at present. Although the decrease of the pinning energy per unit volume as field is increased, and the eventual disappearance of the torque jump at $H \gg B_{\phi}$, is the straightforward consequence of the averaging of the pinning energy gain obtained from the restricted number of vortices trapped on an ion track and the ever increasing number of those that are not, there are few predictions about the resulting field dependence of the equilibrium magnetization. Extensive numerical calculations of the vortex energy distribution in the presence of columnar pins were carried out by Wengel and Täuber\footnote{14} however, they did not make any specific predictions as to the precise temperature or field dependence of the magnetization.

The effect of thermal fluctuations must also be considered. In resistivity measurements, such fluctuations are usually accounted for by stating that, at the angle at which depinning occurs, i.e. at which the probability to find a pinned vortex segment becomes exponentially small, the thermal energy and the pinning energy of a single trapped vortex segment are equal\footnote{14}. As a consequence, the “depinning angle” measured by the angular dependence of the resistivity is smaller than the accomodation angle and is given by\footnote{14}

$$\varepsilon_r \approx \varepsilon_0 \left( \frac{2k_B T \tan \theta_{depin}}{\varepsilon_0 a_0} \right)^{2/3}.$$  

(7)

With the parameters values as used above, we obtain $\theta_{depin} \approx 15^\circ$, which is comparable to the angular width of the irreversible regime in Fig. 3. The same type of argument leads one to conclude that at the same temperature, thermal fluctuations are much less efficient when the field is aligned with the track direction, because the length and the trapping energy of the pinned line segments are large. Nevertheless, the fact that the magnetization is reversible and that the resistivity measured under similar conditions is linear\footnote{15} implies that although it may be small,
the thermal depinning rate is non–zero. Since the measured pinning energy is proportional to the average vortex length trapped on a columnar defect at any one moment, the rapid decrease of $\varepsilon_r$ with temperature, which is in agreement with estimates obtained from resistivity data, does not seem to be an artefact of the method used to analyze torque or resistivity data, but reflects the increasing efficiency of thermal fluctuations in liberating vortices from the tracks. Strong vortex wandering above a “depinning temperature” $T^* = (c_0/\pi) \sqrt{\varepsilon_r}$, such as proposed in Refs. 11, 15, and 18 would lead to a torque jump that follows an exponential temperature dependence. Such a dependence was observed in Ref. 21, where the rapid decrease of the accommodation angle measured in heavy-ion irradiated Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ was attributed to the effect of thermal fluctuations. Although the reduced range of temperatures over which $\varepsilon_r$ could be determined in the present experiments makes a direct comparison very difficult, thermal wandering of flux lines could be responsible for the disappearance of the pinning energy and the torque jump at temperatures below $T_{c2}(H)$ (see Fig. 3).

IV. CONCLUSION

We have, from thermodynamic torque measurements, obtained the first evidence for an angle–dependent contribution of amorphous columnar defects to the equilibrium magnetization in YBa$_2$Cu$_3$O$_{7-\delta}$. The analysis of the torque signal allowed us to directly determine the lock-in angle and the pinning energy of the linear defects. The magnitude of the pinning energy is in qualitative agreement with the core pinning mechanism by columnar defects; however, the observed strong field dependence means that the interactions between flux lines are not negligible in the range of magnetic fields investigated here. The strong temperature dependence of the torque jump, and the disappearance of the pinning energy below $H_{c2}(T)$ are the consequence of thermal fluctuations in the vortex liquid state, which are increasingly efficient in liberating vortex segments from the tracks as temperature increases.

V. ACKNOWLEDGEMENTS

The work of STJ is funded by the EC, TMR grant Nr. ERBFMBICT961728. We thank F. Holtzberg (emeritus, I.B.M. Thomas J. Watson Research Center, Yorktown Heights) for providing the YBa$_2$Cu$_3$O$_{7-\delta}$ single crystal.
FIG. 1. Scheme depicting the torque microlever and the orientation of the applied field, the crystalline \( c \)-axis, and the direction of the columnar defects.

FIG. 2. The irreversibility lines, circles and stars, obtained from the onset of the screening component of the \( ac \)-susceptibility with field oriented at \( \theta = -30^\circ \) and \( \theta = +30^\circ \) with respect to the \( c \)-axis. The squares represent the conditions of temperature and magnetic field under which the signature of the tracks could be observed in the reversible torque signal. Full and dotted lines are the melting line and \( H_{c2}(T) \) obtained in Refs. 8 and 9, rescaled by a factor \((\cos^2(\theta) + \gamma^{-2}\sin^2(\theta))^{-1/2}\) with \( \theta = 30^\circ \).

FIG. 3. Torque signal in the vicinity of the irradiation direction (\( \theta = 30^\circ \)). A smooth background has been subtracted from the raw signal.

FIG. 4. The theoretical torque signals arising from the interaction of the vortices with the amorphous columnar defects for two values of the misfit angle \( \alpha \): solid line \( \alpha = 5^\circ \), dotted line \( \alpha = 0 \) The other parameters were \( \theta_l = 3^\circ \) and \( \theta_t = 30^\circ \).
FIG. 5. The pinning energy, as given by the torque jump using Eq. 3 and the parameters given in the text. Drawn lines are guides to the eye.