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Angular variation of pinning near the irreversibility temperature in single crystal $YBa_2Cu_3O_{7-\delta}$ with splayed columnar defects

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Abstract

We have studied vortex pinning through ac susceptibility measurements in single crystals of YBCO with columnar defects (CDs). The CDs have 0°, 10° and 20° splay angle and average direction 10° off the *c*-axis. By studying the angular variation we can compensate for the anisotropy and effects of twins, etc. Using a simple expression we can obtain the angular spread when the field direction is outside the splay angle. An increase of pinning when the field direction is inside the angle defined by the CDs can be attributed to vortex entanglement due to the splay and the suppression of the sliding of double kinks. © 1998 Published by Elsevier Science B.V. All rights reserved.

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1. Introduction

The introduction of columnar defects (CDs) by heavy ion bombardment has proven to be an effective way of increasing the critical current in high T_c superconductors [1]. It has been suggested theoretically [2] that a further increase can be obtained when the columnar defects are produced in more than one orientation, i.e., a splay, with respect to the sample. Several experiments have tested this idea [3–8], in general with positive results, although some splay configurations produce a decrease in critical current [7]. This may be so, because the maximum pinning potential occurs when the magnetic field is parallel to the CDs. With non-parallel CDs, it is impossible to fulfil this condition and some pinning energy is lost. However, the loss may be counteracted by vortex entanglement and a suppression of the sliding of double kinks [2]. It is therefore important to study splay configurations which will optimize pinning.

The present paper studies single crystals of YBCO with parallel and splayed CDs. Based on previous results [7] we concentrate on ‘planar splay’, i.e., CDs in two directions. By having the average angle away from the *c*-axis, and by exploring the whole range of field orientations, we are able to subtract the effect of crystal anisotropy. We can thus quantitatively compare the angular dependence of the pinning produced by parallel and splayed CDs and we present a simple model to interpret the angular variation ob-

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served. We find that when the magnetic field direction is within the angle defined by the splay there is an enhancement in the pinning which is greater than the sum of the pinning produced by each set of tracks. For the case when the magnetic field is at an angle not lying between the splayed CDs a simple model is seen to account for the angular variation. The extra enhancement between the tracks is attributed to vortex entanglement and the suppression of vortex sliding by the splay.

2. Experimental details

The YBCO crystals were prepared by growth from the melt as described in Ref. [9], and were fully oxygenated before the irradiation. The crystals are naturally twinned and all come from the same batch, with $T_c \simeq 91.6$ K and typical dimensions $(1 \times 1 \times 0.01)$ mm^3. The irradiations, with 309 MeV Au^{26+} ions, were performed at room temperature in the Tandar heavy-ion accelerator (Buenos Aires) [10]. To introduce planar splay, the crystals were rotated by the desired angles around an axis contained in the *ab*-plane and perpendicular to the ion beam, and one or two irradiations were performed.

We present measurements on three samples: Sample SPL0 has one set of CDs at 10° with respect to the *c*-axis with a matching field $B_\phi = 3$ T and T_c is 90.25 K. Sample SPL10 has two sets of CDs; at 5° and 15°, with $B_\phi = 1.5$ T for each set of tracks. The T_c is 90.55 K. Sample SPL20 was irradiated at 0° and 20° with the same fluences as SPL10 and T_c is 90.15 K. Notice that the average angle is 10° off the *c*-axis in all samples. In this way, the uniaxial anisotropic pinning introduced by the tracks can be distinguished from the natural anisotropy of the material. Moreover, possible effects of twins, etc. perpendicular to the Cu–O planes should appear at a different angle than the effect of the tracks.

We have performed Monte Carlo TRIM calculations [11] to characterize the ion tracks. They show that the tracks deviate at most 5° from the incident direction, with 2° being typical. Near the entry point of the ion, the track deviates less and as the ion loses energy, the calculations show it deviates more, so that the angular spread is concentrated about 2 μm from the exit point of the ion. Because the samples were all irradiated in the same run, we expect that this natural splay is the same for all.

The dc magnetic field $H_{dc} \leq 1$ T, was produced by a normal magnet which rotates around a vertical axis. Because small misalignment resulted in smoothing and broadening of the peaks shown below, the sample was carefully mounted in a sapphire holder inside the coils, so that the axis of rotation of H_{dc} coincides with the axis of rotation during the irradiation. In this way, H_{dc} will be parallel to each set of tracks at the appropriate angle. In a typical experiment we perform a Field Cooling (FC) temperature sweep, measuring the ac susceptibility χ by means of miniature mutual inductances, for a fixed value of the angle and modulus of H_{dc}.

3. Results

Throughout this work, we have kept the ac field parallel to the *c*-axis at a value of $h_{ac} = 3.6$ Oe. An analysis of the shape of the susceptibility curves χ'' vs. χ' indicates that, at this h_{ac} level, we are detecting the Bean critical state at the susceptibility peak [12], as found in our previous studies in YBCO crystals with columnar defects [10] and in other materials [13]. The temperature corresponding to the maximum of χ'' will be referred to as T^* in the following. Within the Bean critical state model, such maximum in χ'' is seen when the ac field h_{ac} is related to the persistent current density $j(T^*)$ and a typical sample dimension d by $j(T^*) = ch_{ac}/2\pi d$. In our case, this gives a current density $j(T^*) \sim 3000$ A/cm^2. It is important to note that, due to thermal relaxation effects, j is significantly lower than the critical current density j_c, as discussed below. Thus, our T^* actually corresponds to a small but finite value of critical current density. We have checked that there is a small increase in T^* as the amplitude of the ac field decreases, which implies that the critical current drops abruptly in this temperature range, as seen also by Pasquini et al. [10]. We are therefore close to the transition from below, and T^* defined here corresponds to a point in the pinned vortex phase relatively near the irreversibility line.

We have observed a frequency dependence in the temperature of the peak in χ'', thus confirming that thermal activation is playing a role in our measurements. The shift in frequency is similar to that reported in the literature, i.e., T^* increases about 0.5 K/decade [14]. When j is affected by thermal activation, and one is measuring at a frequency ω, the temperature at which the peak is observed is related to the activation energy U as (see for example equation 10.57 in Blatter et al. [15])

$$U\left(j=\frac{ch_{ac}}{2\pi d}\right)=T\ln\frac{1}{\omega t_o}, \qquad (1)$$

where t_o is a macroscopic time scale as discussed in [15]. The temperature T^* of the peak in the χ'' signal as a function of angle, with an applied dc field of 0.7 T, is shown in Fig. 1. All measurements where performed at 100 kHz. We can see that there is an angular variation which corresponds to the anisotropy of the material, and relatively narrow peaks centered in the mean direction of irradiation, corresponding to the effect of the CDs.

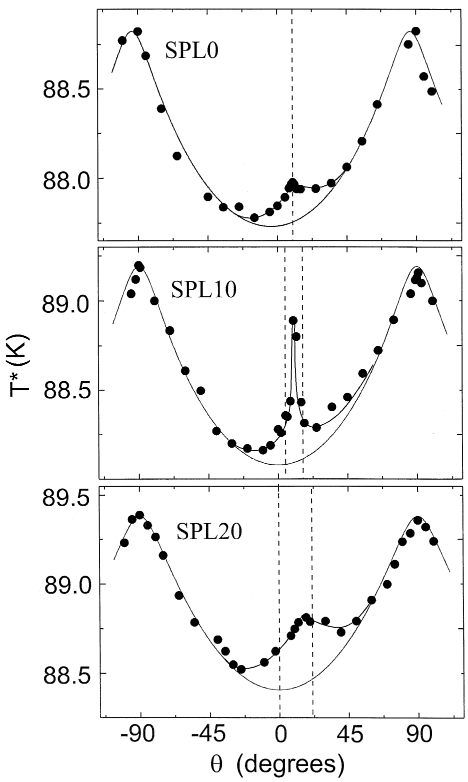

Fig. 1. Temperature of the peak in χ'' for a magnetic field of 0.7 T, as a function of angle for the three samples measured. The dotted lines show the position of the tracks (CDs). SPL0 has tracks 10° off the c-axis (no splay), SPL10 has tracks 5° and 15° off the c-axis (10° splay) and SPL20 has tracks 0° and 20° off the c-axis (20° splay). The lower full lines are fits which take into account the anisotropy of the crystal.

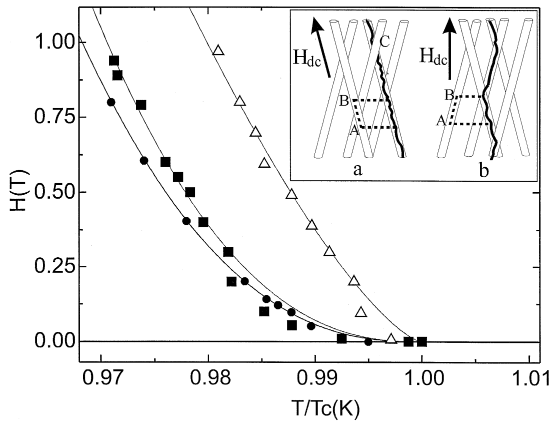

Fig. 2. Temperature of the peak in χ'', with the dc field H_{dc} parallel to the c-axis. Full lines are fits to the data by a function $f(T)=H_o(1-T/T_c)^{\alpha}$. Full circles: SPL0; Full squares: SPL10; Triangles: SPL20. Inset: Possible vortex configurations inside the CDs when H_{dc} is in different directions.

In order to isolate the effect of the CDs we need to know the angular variation of T^* due to the crystallographic anisotropy of the material. This is well known for high-T_c materials with moderate anisotropy γ, where the irreversibility field H_{irr} has been found (see, e.g., Ref. [16]) to depend on temperature and angle in the form

$$H_{irr}(T,\theta)=f(T)\frac{1}{\sqrt{\cos^2(\theta)+\gamma^{-2}\sin^2(\theta)}}, \qquad (2)$$

which is also consistent with the scaling approach of Blatter et al. [17].

In this expression $f(T)$ is the temperature dependence of the irreversibility field H_{irr} at $\theta=0$. To determine $f(T)$ we have measured T^* for different magnetic fields in the c-axis direction. The resulting H–T diagram is shown in Fig. 2. For fields above 0.1 T the curves can be fitted by a function $f(T)=H_o(1-T/T_c)^{\alpha}$, with $\alpha\sim 2$ in agreement with previous results when $H<0.5\ B_{\phi}$ [18] although there is some variation from sample to sample. The exponent α changes for fields below 0.1 T and is closer to 4. A similar behavior has been reported by Ishida et al. [19]. Blatter et al. [15] have also proposed an exponent of 4 for low fields. However, we have not explored this region fully, and a more systematic investigation will be the subject of further work.

The lower full lines in Fig. 1 have been obtained by using Eq. (2) and the $f(T)$ values obtained from fitting the data in Fig. 2 with no further adjustable parameters.

4. Discussion

In Fig. 3 we show the effect produced by the tracks, with the anisotropy of the material subtracted, i.e., we have plotted the difference between the full lines and the experimental points of Fig. 1. We can see that T^* is increased above the ‘background’ over an angular range of around 35°. According to Nelson and Vinokur [20] there are two regimes when the field is tilted with respect to the CDs. For angles smaller than a given value θ_L, the vortices are locked to the tracks. When the angle is greater than θ_L but smaller than θ_A, the accommodation angle, the vortex is partially pinned to the tracks forming a staircase pattern [20,21]. Evaluating their expressions in our experimental situation we estimate $\theta_L \sim 0.002°$ while $\theta_A \sim 30°$. Thus, the configuration where the vortices are locked is almost impossible to observe, while the accommodation angle agrees with the angular range where we observe an enhancement of T^*.

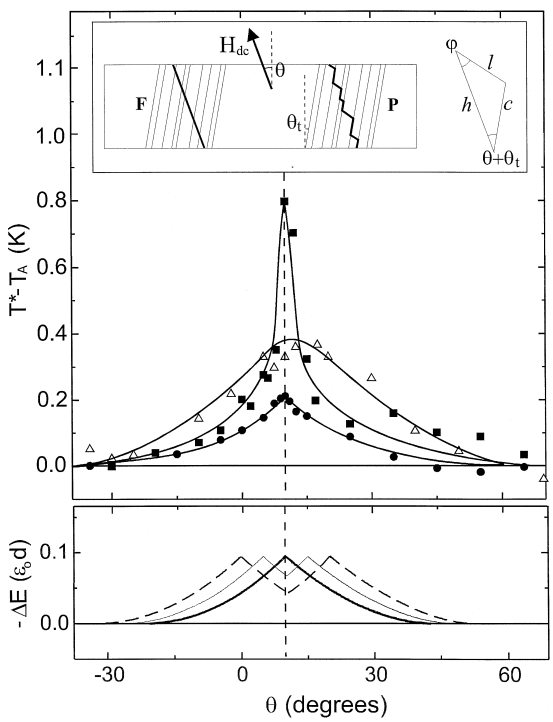

Fig. 3. Upper part: The irreversibility temperatures with the effect of the anisotropy substracted. Full circles: SPL0; Full squares: SPL10; Triangles: SPL20. Lower part: Difference in energy when a vortex is inside a CD or outside. Inset: Configuration F shows a vortex outside the tracks with length h, while in position P it is inside the tracks in a length c and outside in a length l. The average direction is along H_{dc}.

For glassy vortex phases, it has been proposed that the activation energy U is given by [15,20,22]:

$$U(j,T) = U^{o}(T)\left[(J_c/j)^{\mu} - 1\right], \tag{3}$$

were U^o is the characteristic pinning energy.

In our experiment, we see an increase over the ‘background’ in T^* caused by the columnar defects. The pinning potential $U^o(T)$ consists of a background term which will follow the characteristic anisotropy of the material plus a second anisotropic term ΔE due to pinning by the CDs, with a different angular variation, stronger in the direction of the tracks. From Eqs. (1) and (3), it can be seen that ΔT^* the increase in T^* over the background term will be proportional to first order on the CDs pinning energy term ΔE. We wish to estimate the angular variation of ΔE, using a simple model, to check it a posteriori, whether ΔT^* follows ΔE.

In the temperature and field region explored here, we expect to be in the collective pinning regime [15]. The vortices in this case move in bundles, and in general it is not easy to model this behavior. We shall assume that the vortices form a staircase pattern, and that the length of any possible half loops, or double kinks will be greater than the mean kink separation, so that the pinning energy to be considered is an effective average over the kinked vortices.

We now estimate the angular variation of the pinning energy ΔE. When the external magnetic field is not parallel to the tracks, the vortices adopt the arrangement shown in the inset of Fig. 3. In this configuration they are partially pinned to the CDs with pieces inside and outside the tracks so that the mean direction is along H_{dc}. In the field range of our study, $H_{dc} \gg H_{c1}$ the internal field B (mean direction of the vortices) is expected to be parallel to H_{dc} [5,15]. Because the applied field is smaller than the matching field, $H_{dc} < \eta B\phi$ ($\eta \sim 0.5$), when H_{dc} is in the direction of the CDs most of the vortices are expected to be totally pinned to the tracks.

We consider the difference $\Delta E = E_p - E_f$ between the vortex line energy E_p of a vortex in the configuration P (see inset of Fig. 3) and the energy E_f of a vortex in the state F characterized by straight vortex lines aligned in the direction of H_{dc}. To evaluate E_p and E_f we consider the vortex line energy of the segments inside and outside the CDs and their respective total lengths. We use the work by Hardy et al. [5] as a starting point so that the same general approximations and free energy considerations apply.

The line energy per unit length for a vortex outside the CDs is [5]:

$$\varepsilon_l(\theta) = \varepsilon_0 \varepsilon(\theta)\left\{\ln\left[\kappa/\sqrt{\varepsilon(\theta)}\right] + \alpha_c\right\}, \tag{4}$$

where θ is the angle between the local vortex direction and the c axis, κ the Ginzburg–Landau parameter, $\alpha_c \approx 0.5$, $\varepsilon_0 = [\phi_0/4\pi\lambda_{ab}(T)]^2$, λ_{ab} is the in-plane penetration depth and

$$\varepsilon(\theta) = \sqrt{\cos^2\theta + \gamma^{-2}\sin^2\theta},$$

where γ is the electronic anisotropy (λ_c/λ_{ab}) and we neglect the pinning at the points where the vortex crosses the tracks.

In the work of Hardy et al. [5], they consider $R > \xi$ that for a vortex segment inside a columnar defect, the contribution of the condensation energy to form the normal core α_c, is zero. This term is replaced by $\alpha_p = \ln[\xi_{ab}/R]$ because the currents are within distances $r > R$ instead of $r > \xi_{ab}$, with R the radius of a CD and ξ_{ab} the in-plane coherence length. In our range of temperatures, however, the temperature dependent coherence length is greater than the defect radius R. In this case the vortex currents are not affected, and the energy to form the core is greater than zero but less than if the CD were not present. We have evaluated this energy by using the approach found in Blatter et al. [15]. The line energy per unit length for a segment of vortex inside a CD is:

$$\varepsilon_p(\theta) = \varepsilon_0 \varepsilon(\theta) \times \left\{\ln\left[\frac{\kappa}{\sqrt{\varepsilon(\theta)}}\right] + \frac{1}{2} - \frac{1}{2}\ln\left[1 + \frac{R^2}{2\xi^2}\right]\right\}. \tag{5}$$

To calculate ΔE we need to evaluate the actual lengths of the vortices in configurations P and F. The segments corresponding to P can be straightened out mentally to construct the triangle shown in the inset of Fig. 3 (sides c and l) while for configuration F side h is obtained. From these lengths and their pinning energies (Eqs. (4) and (5)) we obtain:

$$E_p^l(\theta,\varphi) = \frac{d\left[\varepsilon_p(\theta_t)\sin(\varphi) + \varepsilon_l(\theta+\varphi)\sin(\theta+\theta_t)\right]}{\sin(180-\varphi-\theta-\theta_t)\cos(\theta)} \tag{6}$$

when the field direction is to the left of the CDs ($\theta < \theta_t$).

$$E_p^r(\theta,\varphi) = \frac{d\left[\varepsilon_p(\theta_t)\sin(\varphi) + \varepsilon_l(\theta+\varphi)\sin(\theta-\theta_t)\right]}{\sin(180-\varphi-\theta+\theta_t)\cos(\theta)} \tag{7}$$

when it is to the right of the CDs ($\theta > \theta_t$).

For configuration F:

$$E_f(\theta) = \varepsilon_l(\theta)\frac{d}{\cos(\theta)}, \tag{8}$$

where d is the thickness of the sample, θ_t is the angle of the CDs, θ is the direction of H_{dc},and φ is the angle between the segment out of the CD and H_{dc} (see inset of Fig. 3).

Observe that for a given direction of H_{dc}, E_p depends on an additional degree of freedom: the direction of the vortex segments between the CDs determined by φ. To get $\Delta E(\theta)$ we take a value of φ such that it minimizes E_p. We find that this corresponds to vortex segments which do not lie in the a–b planes. Taking typical parameters for YBCO: $\gamma = 5$, $\kappa = 100$, $\xi_0 = 12$ Å and $R = 50$ Å we find the curves shown in Fig. 3, using a reduced temperature $t = 0.975$. For $\theta_t = 10°$, ΔE is negative for $-20° < \theta < 42°$ so in this angular range the vortices will arrange in a configuration such as P, and in a configuration such as F otherwise. The angular spread is comparable to those found for temperature enhancements in the literature, in splayed [8] or unsplayed [23] CDs, considering that the actual values are dependent on the diameter of the tracks.

The curve drawn in thick lines is the result for $\theta_t = 10°$, it shows that in the case of parallel CDs, in sample SPL0, the shapes of T^* and ΔE agree. In Eq. (3) this could come about through a change in $U°$, proportional to ΔE implying a corresponding change in T^* through Eq. (1). The model we are considering is just a very rough approximation, but in this case it appears to give good agreement with the measurements.

Although we have considered CDs only in one direction we can use Eqs. (6) and (7) when CDs in two different angles are present by assuming that because there are many more CDs than vortices, the vortices will be pinned individually to the track lying lower in energy for that particular angle of H_{dc}. The results are plotted in Fig. 3, where the thin lines correspond to tracks at 5° and 15° (sample SPL10) and the dotted lines to 0° and 20° (SPL20). In this case ΔE and T^* do not agree. The maximum enhancement in T^* is almost four times as large for the sample with 10° splay (SPL10), and more than twice as large for the 20° (SPL20) sample than the reference sample with zero splay (SPL0).

These results can be understood within the model of vortex entanglement. As proposed by Hwa et al. [2], the vortices are harder to move because the splay of the CDs inhibits vortex sliding and also produces an entangled state which favors pinning [24]. This more than compensates for the loss of pinning energy seen in the calculation for ΔE, and is quite sharp in angle. When the vortices are at an angle not lying between the splayed tracks, the agreement between T^* and ΔE is better. This can be understood because in this case most of the vortices will be aligned with the tracks of lower energy (see inset of Fig. 2). The entanglement is smaller in this configuration. For vortices between the tracks, there will be many configurations with equivalent energy were the vortex may switch between tracks of different orientation. This is a complex situation to evaluate, but because it implies a change from a Bose to a polymer like entangled glass [2] it may conceivably change the exponent in Eq. (3) or produce some other non-linear change in the activation energy U.

The higher values of T^* correspond to the sample with 10° splay which seems to optimize the trade-off between ground state energy and suppression of vortex sliding. The data of Krusin-Elbaum et al. [7] also show maximum increase of pinning for the same splay angle and Hardy et al. [6] also observe an increase in pinning for samples of YBCO with splay around 10° at high temperatures, though in their case a splay of 45° seems to be better at low temperatures. The random 'natural' splay due to the bending of the ion trajectories seen in the TRIM calculations may enhance the entanglement, however, it seems not to be strong enough to wash out the effect of the introduced splay, because the observed difference between the samples is significant.

Our simple model, assuming that vortices are aligned in a staircase pattern, and are mainly pinned to the subset of tracks lying closer in angle to the field direction seems to capture the main contribution for the pinning of the CDs when the field direction lies outside the splay. We also show that the splayed CDs are effective for pinning at temperatures close to the irreversibility line, a region not covered by previous published work, which is beginning to be explored at present [25,26].

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