Vortex Pinning by Competing Disorder: Bose-Glass to Vortex-Glass Crossover

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Magnetization measurements have been used to study the Bose-glass to vortex-glass crossover in $YBa_2Cu_3O_{7-x}$ crystals by varying the angle θ between the field and the twin planes. Two critical angles θ_L and θ_K are found: For $\theta < \theta_L$, vortices lock in to the twin planes; for $\theta_L < \theta < \theta_K$, a kinked vortex structure occurs; for $\theta > \theta_K$, hysteresis loops reproduce the magnetic response of the untwinned regions where pinning is produced by random point defects. The angles θ_K and θ_L depend only on the disorder in the untwinned regions and scale with $[\Delta M(\theta_K)]^{-0.5}$, where $\Delta M(\theta_K)$ is the hysteresis width for $\theta > \theta_K$.

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The mechanism of flux pinning in the superconducting $YBa_2Cu_3O_{7-x}$ (YBCO) crystals is still a matter of controversy and great interest [1–6]. The defect structures causing flux-line pinning in YBCO are a random distribution of point defects and randomly spaced twin boundaries which form a structure of planar defects. We have already reported that twin planes can very strongly affect the magnetic behavior [5]. In fact, we observed that twin planes, contrary to the usual belief, can reduce the effective pinning. We have demonstrated that in microtwinned crystals with one direction of twin planes (either 110 or $1\bar{1}0$), the magnetic hysteresis width is strongly reduced because of vortices channeling along twin planes.

Pinning by various defect structures has been the focus of extensive theoretical investigations [7–10]. Different defect structures may give rise to different vortex phases. For instance, in the presence of randomly distributed point defects a transition from a vortex fluid to a vortex glass is expected when decreasing the temperature [7]. In the case of extended defects, such as columnar defects or twin planes, the low temperature phase is expected to be a Bose-glass phase [8]. The experimental evidence for the existence of these two low temperature phases (the Bose-glass and the vortex-glass), which characterize the loss of the long range order of the vortex lattice, is still a matter of controversy. In the presence of strong point disorder, extended defects may become irrelevant and therefore the low temperature phase will be dominated by point defects [9] (vortex-glass phase). Since extended defects promote flux-line delocalization (for magnetic fields parallel to the extended defects), and point defects promote flux-line wandering, the dominant defect structure can be identified by changing the angle between the applied field and the extended defect [9]. In this Letter, we present a detailed magnetic study of microtwinned YBCO crystals with a simple twin structure at temperatures up to 70 K, magnetic fields up to 6 T, and at various angles between the twin planes and the applied field. The plane of rotation is defined by the c axis and the normal to the twin planes. We have observed for the first time clear experimental evidence of the existence of a critical angle θ_L below which vortices lock in to the twin planes and above which a kinked structure of vortices occurs at angles up to θ_K. So far, only the latter angle has been reported [11]. The field and temperature dependencies of θ_L and θ_K are found to be identical and are controlled by the disorder in the untwinned regions.

The crystals investigated were grown by a conventional self-flux method. The details of the growth, oxygenation, and detwinning process are described in Ref. [12]. All crystals investigated have a $T_c = 93.8$ K with $\Delta T_c <$ 0.3 K. The width of the transition, ΔT_c, is the temperature range over which the zero field cooled magnetization in a field of 0.1 mT varies from 10% to 90%. Using the data by LaGraff and Payne [13], we have assigned an oxygen content of $7 - x = 6.92$. Crystal A is microtwinned with one direction of twin planes (the twin planes go all the way through the crystal and their separation varies from about 0.5 to 5 μm), and crystal B was detwinned; after detwinning, polarized light microscopy revealed a surface fraction of misaligned phase of less than 1%. The sizes of the crystals are $0.78 \times 0.79 \times 0.02$ and $0.72 \times 0.7 \times 0.052$ mm^3, respectively. Magnetization measurements were carried out on a 6 T SQUID magnetometer (Cryogenics Ltd). Data were taken with an excursion length of the sample set to a minimum (1 cm) in order to avoid problems of field inhomogeneity.

Figure 1 represents a detailed angular analysis of the magnetization. The data are given for crystal A. The applied magnetic field $\mathbf{H}_a$ is rotated in the plane defined by the c axis and the normal to the twin planes as shown in the inset of Fig. 1. The angle θ between the c axis and $\mathbf{H}_a$ was varied from 0° to about 20°. The uncertainty in the angle was less than 0.5°.

When the applied magnetic field $\mathbf{H}_a$ is tilted away from the c axis, the measured magnetization M arises mainly from the projection of the component along the c axis of the magnetization [3] $M_\perp$. Figure 1 shows

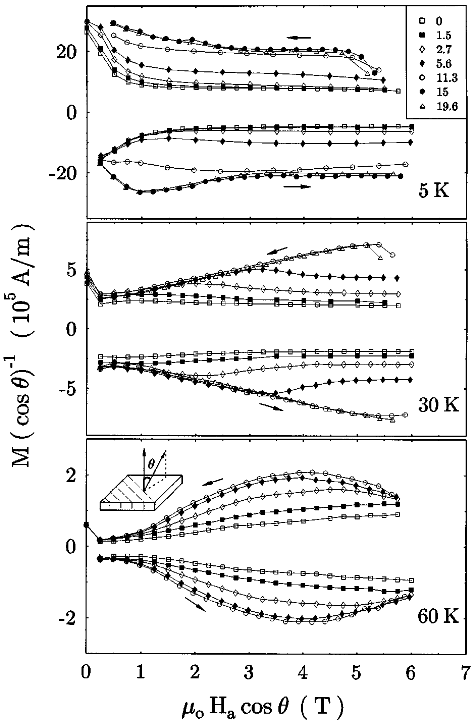

FIG. 1. Magnetic hysteresis at the indicated temperatures and angles for the microtwinned crystal A. The angle θ is between the applied magnetic field and the twin planes as sketched in the inset. The arrows indicate the field sweep direction.

$M_\perp = M/\cos\theta$ as a function of the component $\mathbf{H}_a$ along the c axis ($H_\perp = H_a \cos\theta$) at the indicated angles and temperatures. At a given temperature and in the field region where channeling of magnetic flux along twin planes occurs, the hysteresis width ΔM increases as $\mathbf{H}_a$ is tilted away from the twin planes, in agreement with our earlier report [5]. Two characteristic angles need to be defined: an angle θ_L above which ΔM starts to increase and an angle θ_K above which ΔM stops increasing. The angle θ_K increases as the difference between the inner hysteresis loop ($\theta = 0$) and the outer hysteresis loop ($\theta > \theta_K$) increases. This behavior is clearly seen at $T = 30$ K. It is worth noting that the magnetization is very weakly dependent on the magnetic field, whether vortices are fully or partly locked in the twin planes. This feature indicates that the twin planes behave as current limiters. The measured magnetization is the volume average of the magnetic moment produced by current loops flowing in the sample. The current density of the loops around the whole sample is limited by the critical current density along the twin planes. Once this limit is reached, these loops will split up into small ones to fill the untwinned regions. Since the magnetic moment is proportional to the area of the loops, the magnetization results mainly from the loops of the current flowing around the whole of the sample.

Figure 2 shows the hysteresis width ΔM at $\mu_0 H_\perp = 4$ T as a function of temperature, at the indicated angles. With increasing angle, the temperature dependence of $\Delta M(T)$ evolves gradually into the curve for $\theta = 19.6°$. Also shown, in the inset, is a comparison of $\Delta M(T)$ at $\theta = 19.6°$ for the microtwinned crystal A and $\Delta M(T)$ at $\theta = 0°$ for the detwinned crystal B. The data for the latter crystal have been normalized to the size of the former. This comparison indicates that for $\theta > \theta_K$, the magnetic behavior of the microtwinned crystal represents the magnetic response of the untwinned regions. It is worth noting that the value of θ_K increases when the pinning force $f_u \propto \Delta M(\theta_K)$ in the untwinned regions increases with decreasing temperature. A similar analysis can be made for the magnetic field dependence of θ_K. Since for $\theta < \theta_L$ the hysteresis width is almost field independent, the value of θ_K increases with f_u increasing. As we will see later, the temperature and magnetic field dependencies of θ_L and θ_K are closely related to those of f_u.

For $\theta < \theta_K$, the temperature dependence of the hysteresis width, and hence J_c ($\Delta M \propto J_c$), is reduced. A weak temperature dependence of ΔM is observed when $\theta = 0°$. The twin planes are planar defects and therefore the pinning potential along the planes is less sensitive to thermal fluctuations. This is because the dimensionality of the thermal fluctuations is reduced. In this case, the critical current is expected to decrease with temperature according to the power law [10]. In the case of random point defects, the critical current is theoretically expected [10], and experimentally observed [14], to decrease exponentially with temperature. Hence the change of dimensionality of thermal fluctuations qualitatively explains

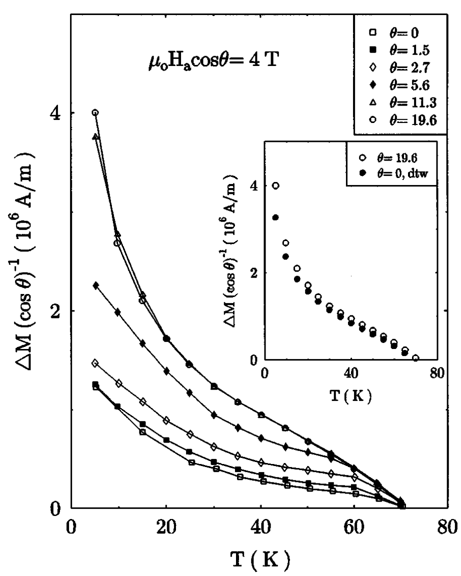

FIG. 2. Temperature dependence of the hysteresis width at the indicated angles and at the applied magnetic field $\mu_0 H_a \cos\theta = 4$ T. The inset shows a comparison between the microtwinned crystal A for $\theta > \theta_K(T)$ and the detwinned crystal B for $\theta = 0$.

why in the presence of a twin plane structure, the temperature dependence of ΔM is reduced.

Figure 3 represents the heart of this Letter. Figure 3(a) shows the angular dependence of the hysteresis width $\Delta M(\theta)$ at the indicated temperatures and magnetic field. The angles θ_L and θ_K are also shown. The data are normalized by the average value $\Delta M_{\max}$ of the hysteresis width obtained for $\theta > \theta_K$. Two important results need to be underlined in the depicted transitions. Firstly, the hysteresis width $\Delta M(\theta)$ varies linearly with θ for $\theta_L < \theta < \theta_K$ and secondly, the angle θ_K increases as the pinning force in the untwinned regions increases with decreasing temperature. Figure 3(b) represents the relative decrease δ_R, defined by

$$\delta_R = \frac{\Delta M(\theta) - \Delta M(\theta_K)}{\Delta M(\theta_K) - \Delta M(\theta_L)} \qquad (1)$$

as a function of $\theta/[\Delta M(\theta_K)]^{0.5}$ at the indicated temperatures. A similar analysis at $T = 30$ K for various applied magnetic fields leads to the same results. All the curves at all the temperatures and magnetic fields above $\mu_0 H > 2$ T collapse into one curve indicating that θ_L and θ_K are only governed by the disorder of the untwinned regions.

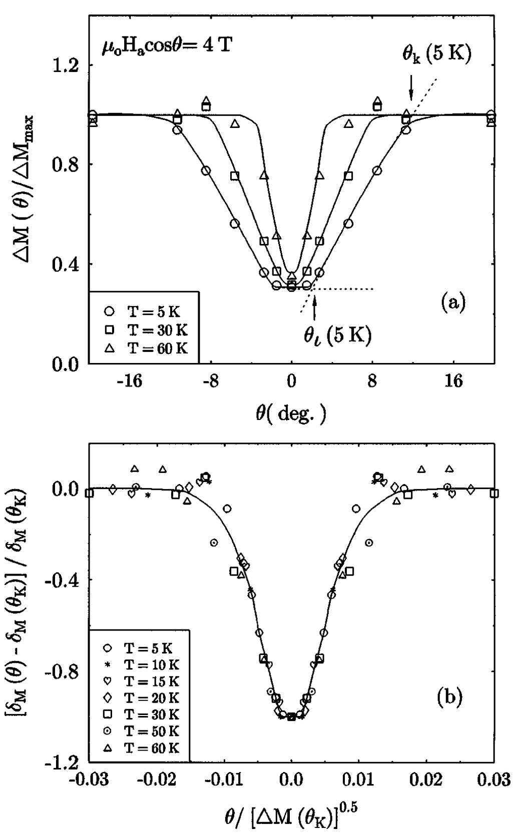

FIG. 3. (a) Angular dependence of the normalized hysteresis width to its maximum value, at the indicated temperatures and at the fixed applied magnetic field $\mu_0 H_a \cos\theta = 4$ T. Note the existence of two characteristic angles θ_L and θ_K. (b) Scaling of the curves represented in (a), δ_R is defined in the text; the lines are guides to the eye.

The interaction of the vortex system with extended defects (twin planes or columnar defects) has been theoretically investigated [8,9,15]. As the order parameter is depressed at the twin planes, there exists an energy barrier ε_{tp}, which impedes the motion transverse to the twin planes. It is because of this barrier [8,10] that vortices are expected to be locked in. It is also expected that when the magnetic field is tilted away from the twin planes by an angle θ smaller than a critical value θ_t, a kinked vortex structure occurs. The angle θ_t is predicted to vary as $[\varepsilon_{tp}]^{0.5}$ and to be only weakly dependent on temperature. In this work, the experimental value of the angle below which a kinked vortex structure is believed to occur is strongly temperature dependent, we chose to call it θ_K.

The locked-in situation and the kinked structure are revealed, in our case, through channeling of the trapped vortex segments in the twin planes, thereby leading to a depression of the magnetization. The "channel" produced by the twin planes will obviously be less effective when vortices are only partly trapped. For $\theta < \theta_L$ twin planes will trap the whole length of a vortex and exert on it a pinning force $f_{tp}(\theta \leq \theta_L) = f_{tp}(0)$. For $\theta > \theta_L$, a kinked structure will occur and the kinks will organize themselves into chains [9] so that the twin planes will still be fully occupied, but by vortex segments. These segments will feel an increased pinning force in the twin planes because they are part of vortices that are partly lying in the untwinned regions where the pinning force is stronger. The average force per unit length exerted on the vortices will increase with the number of kinks produced by the increase of the angle θ. This is because the size of the trapped segments in the twin planes will then decrease [10]. This force can be expressed in terms of the relative variation of the length of the trapped segments $\delta L/L$ as follows:

$$f_{tp}(\theta) = f_{tp}(\theta_L) \approx [f_u - f_{tp}(\theta_L)]\frac{\delta L}{L}, \qquad (2)$$

where the pinning force f_u in the untwinned regions is assumed to be angle independent, since in the magnetic field range of interest and for small angles only the component along the c axis is relevant for the magnetic response of the untwinned regions [3]. In the range of angles considered here [9], $\delta L/L \approx -(\theta - \theta_L)/(\theta_K - \theta_L)$, where we used the fact that $f_{tp}(\theta_K) = f_u$. It follows from Eq. (2) that

$$\delta_R \sim \frac{f_{tp}(\theta) - f_{tp}(\theta_L)}{f_u - f_{tp}(\theta_L)} - 1 \approx \frac{\theta - \theta_L}{\theta_K - \theta_L} - 1\,. \qquad (3)$$

This model is consistent with the linear behavior observed experimentally. We found from our experimental data that θ_K increases with increasing the pinning force f_u in the untwinned regions. The angles θ_L and θ_K have the same magnetic field and temperature dependence and both scale with $[\Delta M(\theta_K)]^{-0.5}$. Consequently, as f_u does not appear explicitly in Eq. (3), we must assume that the increase or decrease of f_u is followed by changes in the effective potential barrier produced by twin planes. At intermediate temperatures where the magnetization goes through a maximum at a magnetic field H_p, the field dependence of θ_K is symmetrical around H_p (see Fig. 1). This behavior suggests that only the current of density J, flowing in the untwinned regions, matters. Therefore, the Lorentz force exerted on the trapped vortices is a relevant parameter. This case is similar to the theoretical situation considered by Nelson and Vinokur [8] where they showed that in the presence of a Lorentz force perpendicular to a twin plane, segments of a vortex can be unpinned, forming half loops (see also Ref. [15]). The half loops extend for a distance $l_\perp$ and $l_\parallel$, respectively, in the directions perpendicular and parallel to the twin plane. We found a very good agreement with experimental data when we considered that the vortex is confined to the width $l_\perp$ instead of the width w of the potential barrier $\varepsilon_{\rm tp}$. Nelson and Vinokur [8] demonstrated that $l_\perp \propto 1/J$, where J is the current density producing the Lorentz force exerted on a trapped vortex. In our situation, the current density flowing in the untwinned regions is $J \propto \Delta M(\theta_K)$. The potential barrier $\varepsilon_{\rm tp}$ responsible for lock-in is then to be renormalized [8,10] by $w/l_\perp$ giving $\theta_K \equiv \theta_t \propto (\varepsilon_{\rm tp} w/l_\perp)^{0.5} \propto J^{0.5}$ where $l_\perp \propto [\Delta M(\theta_K)]^{-1} \propto J^{-1}$. This leads to $\theta_K \propto [\Delta M(\theta_K)]^{0.5}$.

In summary, we studied the crossover from the Bose-glass to the vortex-glass phase by investigating the angular dependence of the hysteresis loops of a microtwinned YBCO crystal with only one direction of twin planes. We found for the first time clear experimental evidence of the existence of an angle θ_L, below which vortices lock in to the twin planes and the pinning behavior is dominated by the extended defects. For $\theta > \theta_L$, a kinked vortex structure occurs at angles up to θ_K. At higher angles, the hysteresis loops reproduce the magnetic response of the twin-free regions. Both angles θ_L and θ_K are proved to be similarly controlled by the disorder in the untwinned regions. The experimental data are consistently explained when the potential well produced by a twin plane is properly normalized by considering that the vortices are localized in a plane of width $l_\perp \propto J^{-1}$, where J is the current density flowing in the untwinned regions.

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[1] V. K. Vlasko-Vlasov, L. A. Dorosinskii, A. A. Polyanskii, V. I. Nikitenko, U. Welp, B. W. Veal, and G. W. Crabtree, Phys. Rev. Lett. **72**, 3246 (1994); see also Comment of C. A. Duran *et al., ibid.* **74**, 3712 (1995).
[2] L. Krusin-Elbaum, L. Civale, V. M. Vinokur, and F. Holtzberg, Phys. Rev. Lett. **69**, 2280 (1992).
[3] L. Klein, E. R. Yacoby, Y. Yeshurun, A. Erb, G. Muller-Vogt, V. Breit, and H. Wuhl, Phys. Rev. B **49**, 4403 (1994).
[4] A. A. Zhukov, H. Kupfer, G. Perkins, L. F. Cohen, A. D. Caplin, S. A. Klestov, H. Claus, V. I. Voronkova, T. Wolf, and H. Wuhl, Phys. Rev. B **51**, 12 704 (1995).
[5] M. Oussena, P. A. J. de Groot, S. Porter, R. Gagnon, and L. Taillefer, Phys. Rev. B **51**, 1389 (1995).
[6] G. Perkins, L. F. Cohen, A. A. Zhukov, and A. D. Caplin, Phys. Rev. B **51**, 8513 (1995).
[7] D. S. Fisher, M. P. A. Fisher, and D. A. Huse, Phys. Rev. B **43**, 130 (1991).
[8] D. R. Nelson and V. M. Vinokur, Phys. Rev. B **48**, 13 060 (1993).
[9] T. Hwa, D. R. Nelson, and V. M. Vinokur, Phys. Rev. B **48**, 1167 (1993).
[10] G. Blatter, M. V. Feigel'man, V. B. Geshkenbein, A. I. Larkin, and V. M. Vinokur, Rev. Mod. Phys. **66**, 1125 (1994).
[11] W. K. Kwok, U. Welp, G. W. Crabtree, K. G. Vandervoort, R. Hulscher, and J. Z. Liu, Phys. Rev. Lett. **64**, 966 (1990).
[12] R. Gagnon, C. Lupien, and L. Taillefer, Phys. Rev. B **50**, 3458 (1994); R. Gagnon, M. Oussena, and M. Aubin, J. Cryst. Growth **121**, 559 (1992).
[13] J. R. LaGraff and D. A. Payne, Physica (Amsterdam) **212C**, 478 (1993).
[14] S. Senoussi, M. Oussena, G. Collin, and I. A. Campbell, Phys. Rev. B **37**, 9792 (1988).
[15] E. H. Brandt, Phys. Rev. Lett. **69**, 1105 (1992).