Microwave observation of the vortex locked-in state in $YBa_2Cu_3O_7$ thin films with columnar defects

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We report the angular dependence of microwave magnetoabsorption of both pristine and 270-MeV-Ag-ion-irradiated $YBa_2Cu_3O_{7-\delta}$ (YBCO) c-axis-oriented films. At these ion energies, columnar defects are introduced into YBCO, and Nelson and Vinokur [Phys. Rev. B. **68**, 2398 (1992)] have predicted a state in which vortices are locked to such columnar defects. This has been confirmed by Budhani *et al.* [Phys. Rev. Lett. **72**, 566 (1994)] using dc measurements. Such dc mesurements effectively measure the depth of the pinning potential. We show evidence of a similar effect in the microwave-frequency regime. Here the bottom rather than the edge of the pinning potential is being probed. A simple analysis suggests a distribution of accommodation angles.

The possibility of using columnar defects to improve the properties of cuprate superconductors for device applications has drawn a lot of attention recently. From the fundamental point of view there is the intriguing prediction by Nelson and Vinokur[1] of the formation of a flux-locked state when the magnetic field **B** is aligned parallel to the columns. The theory predicts a minimum in the linear dc resistivity for parallel alignment and a characteristic accommodation angle θ_α, measured from the column axis. For tilts larger than θ_α, the fluxons should follow the field as **B** is turned away from the columns provided that B is less than the matching field B_ϕ ($\sim\Phi_0\phi$) where ϕ is the fluence. For smaller tilt angles segments of the vortex line are "locked" to the column.

Angle-dependent dc resistivity[2] measurements have provided direct evidence for vortex localization. Other reports adduce the effects of localization by appeal to scaling laws.[3]. In this paper we present direct observation of vortex localization at microwave frequencies and discuss the differences and similarities to low-frequency measurements. These results are important from both fundamental and technological standpoints because (1) the microwave response involves small-amplitude oscillations of vortices and therefore probes only the bottom of the pinning-potential well. Speculations aside, there is no theory[4] available to calculate the role of columnar defects at high frequencies. (2) The observations, although qualitatively supportive of the idea[1] of vortex localization, contain novel features. A simple analysis requires a distribution of θ_α values. (3) One is able to access the ratio of the pinning constant along the column to that appropriate to tilted vortices. (4) For the fabrication of superconducting microwave devices such as circulators and Faraday isolators[5] where the films are subject to magnetic fields >0.1 T, it is essential to be able to control dissipation due to vortices. Even in these data, where optimization has not yet been performed, microwave losses in the best sample at 77 K and 0.5 T are reduced by a factor of more than 2 as compared to those of the pristine sample.

For the present measurements several $YBa_2Cu_3O_{7-\delta}$ (YBCO) c-axis-oriented films ≈ 1800 Å thick, passivated with a 300-Å PrBCO layer, were grown by pulsed-laser deposition onto $LaAlO_3$ substrates. Each film was broken into two pieces, one of which served as a control (pristine) sample (henceforth designated P), while the other was irradiated (henceforth designated I) with 270-MeV $^{109}Ag^{+17}$ ions from the 16-MV Tandem Pelletron accelerator at the Nuclear Science Center facility in New Delhi, India. The fluences varied between 0.5 and $8\times10^{15}/m^2$, and the columnar defects were aligned $5°\pm1°$ away from the c axis to avoid ion channeling.

The microwave technique used for this study has been amply described in previous reports from this laboratory.[6] In brief, the sample was placed in a rectangular copper cavity operating at ~ 10 GHz in the location where the rf magnetic field $\mathbf{b}_{rf}$ was a maximum. The microwave absorption was obtained by studying the temperature and field dependence ($0\le B\le 1.5$ T) of $P_c(B,T)$, the power reflected at the cavity frequency. For the field-induced absorption, the sample was zero-field cooled to the temperature of interest, and the field slowly ramped to ~ 1.5 T. It is important to note that in these high-quality films there is no low-field ($\sim 1-10$ mT) effect such as that observed in granular samples.[6] Rather, $\Delta P(B,T)=[P_c(B,T)-P_c(0,T)]$ increases roughly linearly with **B**, is nonzero only when T exceeds $\approx 0.85T_c$ and exhibits no hysteresis.[7] The angular dependence of $\Delta P(B,T,\theta)=[P_c(B,T,\theta)-P_c(B=0,T)]$, where θ is the field tilt with respect to the sample ab plane, was studied by rotating the **B** field from the ab plane to the c axis with $\mathbf{b}_{rf}\perp\mathbf{B}$ at all angles [inset of Fig. 2(a)]. It is to be noted that the absolute θ values are known to no better than 2° although the relative magnitudes have a much higher precision.

First consider the data for $\theta=\pi/2$. As seen in Fig. 1, $\Delta P(B,T)$ in both the pristine and irradiated samples exhibits a rapid rise as T is increased, goes through a maximum and drops rapidly for $T>0.98T_c$. Following the

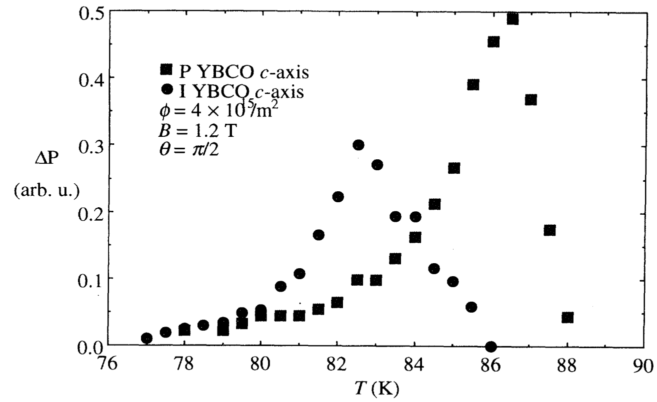

FIG. 1. Temperature dependence of the magnetoabsorption $\Delta P(B,T)$ with constant $B \| c$ axis for a pristine film and for an irradiated film with a fluence of 4×10^{15} m^2. Note the decrease in T_c with irradiation, as seen by other authors (Ref. 10).

method described in Ref. 5, the zero-temperature depinning frequency ω_{dp} is 60±20 GHz for all pristine samples, in reasonable accord with the magnitude of 50–100 GHz estimated by other authors.[8,9]

The introduction of columnar defects has several consequences: (1) T_c decreases with increasing ϕ (cf. Ref. 10); (2) the microwave transition broadens; (3) the peak in $\Delta P(\pi/2,B)$ vs T [$\Delta P(T_{pk})$] shifts to lower T and decreases in magnitude with increasing ϕ so that ΔP vs ϕ at fixed T does not have the same behavior in all T; (4) ΔP(1.2 T, 77 K, $\pi/2$) goes through a minimum at $\phi=2\times10^{15}/\text{m}^2$ [cf. Ref. 11].

The most telling result of the present investigation is the difference between the angular dependence of $\Delta P(B,T,\theta)$ seen in the pristine half [Fig. 2(a)] and its irradiated counterpart [Fig. 2(b)]. Whereas the former shows a simple $(c_1+c_2\sin\theta)$ variation as previously reported [full curve in Fig. 2(a)],[10] the latter has a marked dip around $\theta=\pi/2$, where **B** is aligned parallel to the columnar defects. Although a clear depression in $\Delta P(B,T,\theta)$ at $\theta=\pi/2$ is observed only at the highest dose, the effects of irradiation can be seen in the lower doses as well (Fig. 3). By measuring $\Delta P(B,\theta)$ at small θ, where the columns have little effect on the vortices and using $(c_1+c_2\sin\theta)$ for all θ (full lines, Fig. 3), one notices that the extrapolated curves can be placed one atop the other. This suggests that the ratio c_1/c_2 is universal in YBCO, irrespective of irradiation, but even more noteworthy is the fact that one can clearly see increased deviation from $(c_1+c_2\sin\theta)$ with increasing dosage. Further, it is to be noted that whereas the data for the pristine film exhibit such a $\sin\theta$ dependence for $\Delta P(B,\theta)$

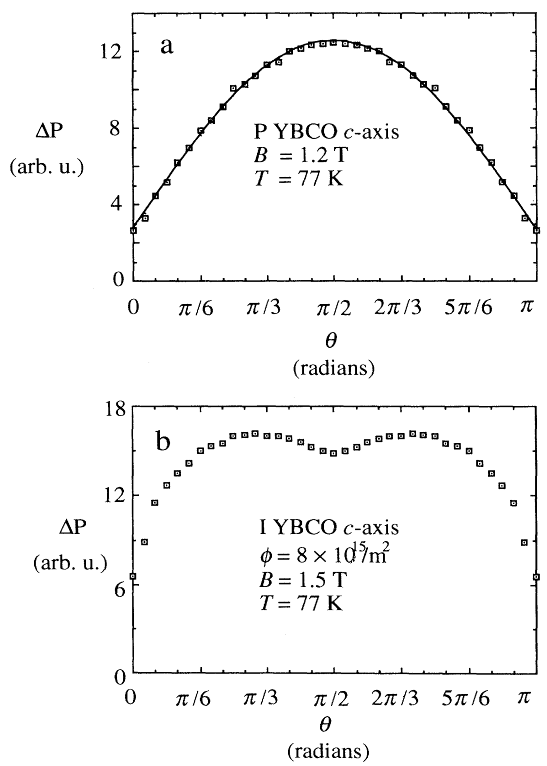

FIG. 2. (a) Angular dependence of $\Delta P(B=1.2$ T, $T=77$ K, $\theta)$ for an pristine film. Full line represents $(c_1+c_2\sin\theta)$. Inset shows experimental geometry used for the measurement of $\Delta P(B,T,\theta)$. (b) Angular dependence of $\Delta P(B=1.5$ T, $T=77$ K, $\theta)$ for an irradiated film.

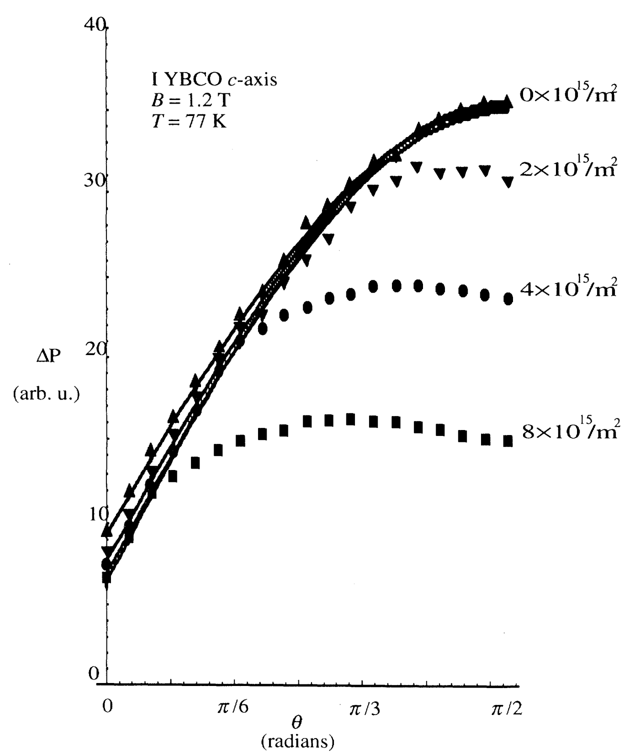

FIG. 3. Angular dependence of $\Delta P(B=1.2$ T, $T=77$ K, $\theta)$ for films with various fluences. Full lines represent $(c_1+c_2\sin\theta)$ fitted for small θ's (see text).

at all temperatures, the dip in $\Delta P(B,\theta)$ for the irradiated film becomes more marked as T is reduced (Fig. 4). Unfortunately, for the present range of fields, $\Delta P(B,\theta)$ becomes unobservably small at $T \leq 75$ K.

The observation of a sharp reduction in absorption, that is, enhanced pinning due to line locking when **B** is parallel to the columnar defects, is clearly in accord with the Nelson-Vinokur model although the prediction is only for the static case. The behavior at large tilt angles is also in qualitative agreement with their predictions. Detailed explanations for most of these features must await development of a theory of microwave surface impedance in the presence of columnar defects. Here we concentrate on the angular dependence as the first evidence that the presence of columnar defects localizes the vortices at high frequencies even though we are probing the pinning potential for extremely small (~ 1 Å) displacements of the vortex line.

To model the data we assume the "staircase" geometry shown in the inset of Fig. 5 where z and w, respectively, are measures of the "locked" and "free" lengths of one "step" of the "staircase," and d is the separation between the columns. Also, it is to be noted that θ measures the inclination of **B** with respect to the ab (film) plane while θ_α is measured from the column direction (c axis).

Here we display only kinks, but in reality there will be loops, superkinks, etc., as described by Nelson and Vinokur, and it is contended that these can be simulated by introducing a spread of θ_α values for a given film. One can then generalize the results of Ref. 12 and write for a single type of stair element

$$\Delta P(B,T,\theta) \propto \frac{B\Phi_0\eta(\theta)\omega^2\beta\sin^2\theta}{k^2+\eta^2(\theta)\omega^2} \times(\beta a \operatorname{cosech}^2\beta a+\coth\beta a)\ , \qquad (1)$$

where k is the pinning constant per unit length, $\eta(\theta)$ is the viscosity per unit length $=\Phi_0 B_{c_2}(\theta)/\rho_n$ in the Bardeen-Stephen model[13] with $B_{c_2}(\theta) \sim \Phi_0/\xi_{ab}^2\sqrt{\sin^2\theta+\varepsilon^2\cos^2\theta}$, where ξ_{ab} is the coherence length in the ab plane and $\varepsilon^2=m_{ab}/m_c<1$ is the mass anisotropy ratio, ω is the angular frequency of the rf field, β is the reciprocal of the complex skin depth $(=\sqrt{1/\lambda^2+2i/\delta^2})$ with λ being the London penetration depth and $\delta(=2/\sqrt{\mu_0\omega\sigma_1})$ is the skin depth where σ_1 is the real part of the conductivity, m is the mass of the vortex per unit length, and a is the film thickness. For $T \leq 0.98T_c$ and the range of fields used here, β is effectively $1/\lambda$. Equation (1) can be simplified to

$$\Delta P(B,T,\theta) \propto \frac{B\eta(\theta)\sin^2\theta}{\lambda[k^2+\eta^2(\theta)\omega^2]} \times\left[\frac{a}{\lambda}\operatorname{cosech}^2\frac{a}{\lambda}+\coth\frac{a}{\lambda}\right] . \qquad (1a)$$

It is to be noted that in Eq. (1), the linear dependence on B arises from the areal density of the fluxons.

As demonstrated in Ref. 6, $k/\eta\omega>1$ for all temperatures discussed here. Because of this and the angular dependence of η, the angular dependence of Eq. (1) is effectively $\sin\theta$. Thus, at any given temperature of interest,

$$\Delta P(\theta) \propto \frac{\tan\theta-\cot\theta_\alpha}{\tan\theta}k^2+\frac{\cot^2\theta_\alpha\sin\theta_\alpha}{\tan\theta}k_c^2\ ; \quad \theta>\left[\frac{\pi}{2}-\theta_\alpha\right]\ ; \qquad (2a)$$

$$\Delta P(\theta) \propto k_c^2\sin\theta\ ; \quad \theta<\left[\frac{\pi}{2}-\theta_\alpha\right] \qquad (2b)$$

where k_c, k refer to the pinning-force constants for the localized and free segments, respectively. This also implicitly assumes that the viscosity is the same for both segments. It is important to point out that the required k_c is not a constant at a given temperature but is a function of the applied field (Table I) while at the same time, k appears to be independent of the field. As the fluence is increased, nonlinearity in $\Delta P(B)$ appears as a consequence of the fact that k_c is a function of B (Table I). To experimentally obtain the ratio of $k_c(B)/k$, one performs the fit $\Delta P(B,\theta)$ to $(c_1+c_2\sin\theta)$ for small θ as in Fig. 3. One can then set $k_c(B)/k=\sqrt{c_2/(\Delta P(B,\theta=\pi/2)-c_1}$, since c_2 would be the value of $\Delta P(B,\theta=\pi/2)$ if there were no

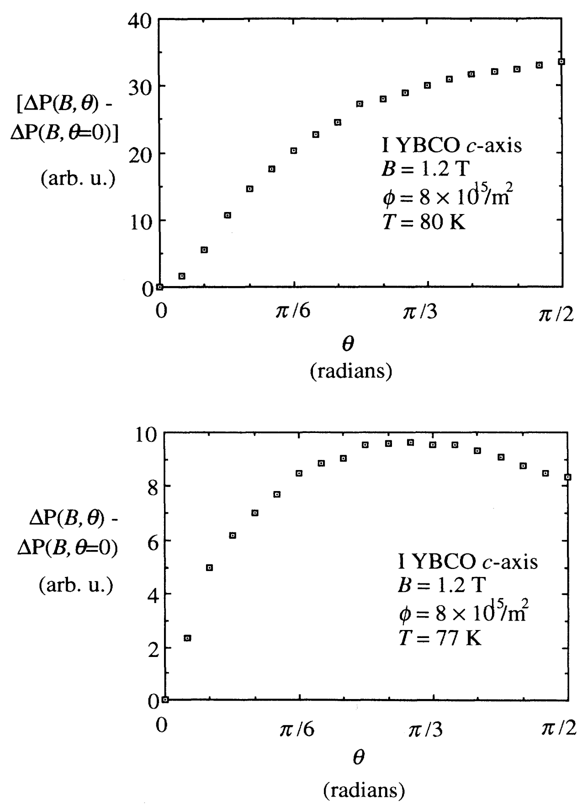

FIG. 4. Dependence on angle of $\Delta P(B=1.2\text{ T},\,\theta)$ for an irradiated film with a fluence of 8×10^{15} m^2 at two temperatures.

TABLE I. Ratio of the "locked" pinning k_c along the column to the "free" pinning k as a function of magnetic field B at 77 K for a sample irradiated at a fluence of 8×10^{15} m^2.

B (T)	k_c/k
0.3	1.10±0.05
0.6	1.55±0.10
0.9	1.75±0.10
1.2	1.75±0.10
1.5	1.75±0.10

columnar defects and $[\Delta P(B,\theta=\pi/2)-c_1]$ is the observed value when **B** is aligned with the columns. This can be seen from Eqs. (2a) and (2b).

In order to take account of a spread (supposed to take care of the variety of free segment geometries) in θ_α values one writes

$$\Delta P(B,\theta)\propto\int_0^{\pi/2}W_{\theta_\alpha}(\theta')\Delta P(B,\theta,\theta')d\theta' \ . \tag{3}$$

Figure 5 shows the results of a calculation using Eq. (2) when the effects of the spread in θ_α values is included by using a linear weighting function of the form

$$W_{\theta_\alpha}(\theta')=\frac{8}{\pi^2}\theta' \ . \tag{4}$$

$W_{\theta_\alpha}(\theta')$ is normalized such that $\int_0^{\pi/2}W_{\theta_\alpha}(\theta')d\theta'=1$. This distribution function implies that most of the accommodation angles are large. It is to be noted that for a single θ_α one gets a depressed loss for $\pi/2>\theta>(\pi/2-\theta_\alpha)$, but the curve has a kink that is not observed experimentally. The main advantage of using Eq. (3) is to produce results which are formally similar to the observations. Although the results are presented here only for the highest fluence, the analysis has been done for lower doses as well. Indeed it is found that as the fluence is decreased, the cutoff value of the weighting function $W_{\theta_\alpha}(\theta')$ is reduced from $\pi/2$ to $\theta_{\max}$ for smaller fluences; i.e.,

$$W_{\theta_\alpha}(\theta')=\frac{2}{\theta_{\max}^2}\theta' \ , \quad \theta'<\theta_{\max} \ ; \tag{5a}$$

$$W_{\theta_\alpha}(\theta')=0 \ , \quad \theta'>\theta_{\max} \tag{5b}$$

with $\theta_{\max}$ dropping with reducing ϕ. This also bodes well with the Nelson-Vinokur model.

In conclusion, we have presented direct evidence that even at high frequencies vortex localization due to columnar defects is directly observable. Although one could have speculated that the effect of localization should occur at high frequencies, the straightforward observation was unexpected because of the small amplitude of the vortex oscillation. As it happens the magnetoabsorption $\Delta P(B,\theta)$ actually shows a marked dip when **B** is aligned parallel to the columns. The width of this dip, which is related to the range of accommodation angles θ_α, is increased in samples with larger doses. Using a simple model based on viscously damped motion of weakly pinned vortices, the observations can be qualitatively understood as arising from a "staircase" vortex where part of the vortex is considered weakly pinned and part "locked" along the column as envisaged in Ref. 1. The effective pinning along the column k_c increases with increasing fluence and is a function of applied field.

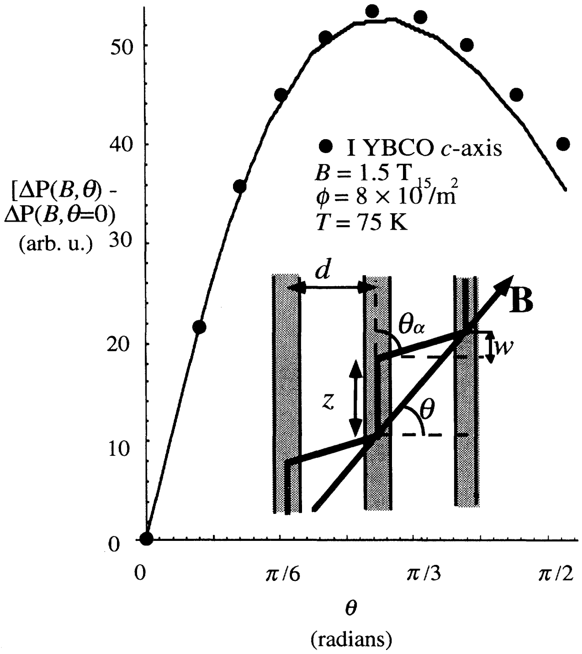

FIG. 5. Full line represents calculated angular dependence of the loss $[\Delta P(B,\theta)-\Delta P(B,\theta=0)]$ for a linear weighting function $W_{\theta_\alpha}=8/\pi^2\theta$ with $k_c/k=1.75$. Inset shows "staircase" geometry of the vortex which was used in computing ΔP when columnar defects are present (see text).

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