# Evidence for vortex staircases in the whole angular range due to competing correlated pinning mechanisms

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**Abstract**

We analyze the angular dependence of the irreversible magnetization of $YBa_2Cu_3O_7$ crystals with columnar defects inclined from the c-axis. At high fields a sharp maximum centered at the tracks' direction is observed. At low fields we identify a lock-in phase characterized by an angle-independent pinning strength and observe an angular shift of the peak towards the c-axis that originates in the material anisotropy. The interplay among columnar defects, twins and ab-planes generates a variety of staircase structures. We show that correlated pinning dominates for all field orientations.

A difficult aspect of the study of vortex dynamics in HTSC in the presence of correlated disorder is the determination of flux structures for applied fields tilted with respect to the pinning potential. As 3D vortex configurations cannot be directly observed, our knowledge is mostly based on the analysis of the angular dependence of magnetization, susceptibility or transport data[1, 2, 3, 4, 5, 6, 7, 8, 9, 10].

According to theoretical models[11, 12], when the angle between the applied field **H** and the defects is smaller than the lock-in angle $\varphi_L$ vortices remain locked into the defects thus producing a transverse Meissner effect. For tilt angles larger than $\varphi_L$ and smaller than a trapping angle $\varphi_T$, vortices form staircases with segments pinned into different defects and connected by unpinned or weakly pinned kinks. Beyond $\varphi_T$, vortices will be straight and take the direction of the applied field, thus being unaffected by the correlated nature of the pinning. In principle, this picture should apply with minor differences to twins, columnar defects and intrinsic pinning[12].

Many experiments have confirmed the directional pinning due to columnar defects, twins and Cu-O planes[1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. Evidence for a locked-in phase arises from the observation of the transverse Meissner effect[9], but a quantitative determination of $\varphi_L(H, T)$ for columnar defects had not been done until now. The introduction of columnar defects inclined with respect to the c-axis has been used[1, 6, 7, 9, 10] to discriminate their pinning effects from those due to twin boundaries, and from anisotropy effects. However, the combined effect of the various correlated structures on the vortex configurations remain largely unexplored.

In this work we report studies of the vortex pinning in $YBa_2Cu_3O_7$ crystals with inclined columnar defects, for the whole range of field orientations. This allows us to determine the misalignment between the applied and internal fields due to anisotropy, as well as to identify the angular range of influence of each correlated pinning structure. We present the first determination of the lock-in angle of tracks using irreversible magnetization.

The crystal used in this study was grown by the self flux method[13], and has dimensions $\sim 200 \times 600 \times 8.5 \mu m^3$. Columnar defects at an angle $\Theta_D \approx 32°$ from the c-axis and a density corresponding to a matching field $B_\Phi = 3T$ were introduced by irradiation with 315 $MeV$ $Au^{23+}$ ions at the Tandar accelerator (Buenos Aires, Argentina).

DC magnetization **M** was measured in a Quantum Design SQUID magnetometer with two sets of pick up coils, and both the longitudinal ($M_l$, parallel to **H**) and transverse ($M_t$, perpendicular to **H**) components were recorded. The sample could be rotated *in situ* around an axis perpendicular to **H** using a home-made device. The angle $\Theta$ between the normal to the crystal (that coincides with the c-axis) and **H** was determined with absolute accuracy $\sim 1°$, and relative variations between adjacent angles better than $0.2°$. The details of the procedure are described elsewhere[14].

Magnetization loops $M_l(H)$ and $M_t(H)$ were recorded at fixed $T$ and $\Theta$. Sample was then rotated, warmed up above $T_c$ and cooled down in zero field to start a new run. We use the hysteresis widths $\Delta M_l\,(H)$ and $\Delta M_t\,(H)$ to calculate the modulus $M_i = \frac{1}{2}\sqrt{\Delta M_l^2 + \Delta M_t^2}$ and direction of the irreversible magnetization vector $\mathbf{M}_i$. It is known that in thin samples $\mathbf{M}_i$ is normal to the surface due to geometrical constrains[14, 15], except above a critical angle (of $\sim 87°$ for our crystal). We confirmed that $\mathbf{M}_i \parallel c$ within $1°$, for all $\Theta < 85°$.

From now on we analyze the modulus $M_i$ as a function of $T$, $H$ and $\Theta$. Figure 1 shows $M_i(\Theta)$ at 60 and $70K$ and several values of $H$. According to the Bean model, $M_i \propto J$, where the screening current density $J$ is lower than $J_c$ due to thermal relaxation. The geometrical factor $M_i/J$ depends on $\Theta$, but is almost constant for $\Theta$ below the critical angle.

The most obvious feature of Fig. 1 is the asymmetry with respect to the c-axis, which is due to the uniaxial pinning of the inclined tracks. At high fields ($H \geq 1T$) we observe a large peak in the direction of the tracks $\Theta_D \approx 32°$. For $H < 1T$ the peak becomes broader and *progressively shifts away from the tracks in the direction of the c-axis* as $H$ decreases. The shift decreases with increasing $T$ as shown in figure 2, where the angle $\Theta_{\max}$ of the maximum in $M_i$ is plotted as a function of $H$ for three temperatures. The inset of figure 2 shows a blow-up of the data of fig. 1 for $H = 0.4T$ and $T = 60K$. This curve exhibits the second main characteristic of the low field results, namely the existence of a *plateau* in $M_i\,(\Theta)$ (We define $\Theta_{\max}$ as the center of the plateau).

We first discuss the origin of the shift. Maximum pinning is expected to occur when the tracks are aligned with the direction that *the vortices would have in the absence of pinning.* For an anisotropic material, such direction *does not coincide* with $\mathbf{H}$. If $\Theta_B$ is the angle between the equilibrium induction field $\mathbf{B}$ (which represents the vortex direction) and the c-axis, minimization of the free energy for $H_{c1}^c \ll H \ll H_{c2}^c$ gives[12]

$$\sin(\Theta_B - \Theta) \approx \frac{H_{c1}^c(1-\varepsilon^2)}{2H\ln\kappa}\frac{\sin\Theta_B\cos\Theta_B}{\varepsilon\,(\Theta_B)}\ln\left(\frac{H_{c2}(\Theta_B)}{B}\right) \qquad (1)$$

where $H_{c2}(\Theta_B) = H_{c2}^c/\varepsilon(\Theta_B)$. Here $H_{c1}^c$ and $H_{c2}^c$ are the lower and upper c-axis critical fields, $\varepsilon$ is the anisotropy and $\varepsilon\,(\theta) = \left(\cos^2\theta + \varepsilon^2\sin^2\theta\right)^{1/2}$. For $\varepsilon < 1$ vortices tilt towards the *ab* plane. When $\Theta = \Theta_D$ we have $\Theta_B > \Theta_D$ and the optimum pinning situation is not satisfied. Instead, maximum $M_i$ occurs at the vortex-track alignment condition $\Theta_B = \Theta_D$. This corresponds to an applied field angle $\Theta_{\max} < \Theta_D$ that can be calculated from Eq. 1 by setting $\Theta_B = \Theta_D \approx 32°$. (In this picture the peak cannot occur at $\Theta < 0$, thus the negative values of $\Theta_{\max}$ given by Eq. 1 at low $H$ are unphysical, and $\Theta_{\max} \to 0$ as $H \to 0$).

The solid lines in fig. 2 are fits to Eq. 1 with *fixed* parameters[12] $\varepsilon = 1/7$ and $H^c_{c2}(T) = 1.6T/K \times (T_c - T)$ (the fits are not very sensitive to any of them). Using $H^c_{c1}(T)/2\ln\kappa = \Phi_0/8\pi\lambda^2_{ab}(T)$ and $\lambda^2_{ab}(T) \approx \lambda^2_{ab}(0)(1-T/T_c)^{-1}$, we obtain a good fit to the data as a function of field and temperature by setting only one free parameter, $\lambda_{ab}(0) \approx 500\mathring{A}$. Although this value is significantly smaller than the accepted value[12] ($\sim 1400\mathring{A}$), we nevertheless consider that this simple model captures the basic physics. We note that Zhukov et al. [9] have reported lock-in angles for twin boundaries in $YBa_2Cu_3O_7$ crystals that imply an $H^c_{c1}$ about 5 times larger than the usual values, a result suggestively similar to our case.

We now return to the plateau seen in the inset of figure 2. The constancy of $M_i(\Theta)$ indicates that the pinning energy remains constant and equal to the value at the alignment condition $\Theta_B = \Theta_D$. This behavior is a fingerprint of the lock-in phase[11]. The extension of the plateau in the $H - \Theta$ plane at $60K$ (determined with accuracy $\sim 1°$) is shown as bars in Fig. 2. Its width decreases approximately as $H^{-1}$, as expected[11] for $\varphi_L$, and for $H > 1T$ it becomes undetectable with our resolution. The decrease of $M_i$ at the edges of the plateau is sharp, a result consistent with the appearance of kinks, which not only reduce $J_c$ but also produce a faster relaxation.

When $|\Theta_B - \Theta_D| > \varphi_L$ vortices form staircases. Two questions arise here. First, which is the direction of the kinks that connect the pinned portions of the vortices? Second, do we observe evidence for a trapping angle $\varphi_T$?

For $\Theta > \Theta_{\max}$, there is a wide angular range in Fig. 1 in which $M_i(+\Theta) > M_i(-\Theta)$ for all $H$, i.e., pinning is stronger when $H$ is closer to the tracks than in the crystallographically equivalent configuration in the opposite side. This asymmetry demonstrates that at the angle $+\Theta$ vortices form staircases, with segments trapped in the tracks. For $\Theta < \Theta_{\max}$ we again observe asymmetry, $M_i(\Theta)$ crosses $\Theta = 0$ with positive slope, indicating that pinning decreases as $H$ is tilted away from the tracks. We can conclude that staircases extend at least beyond the c-axis into the $\Theta < 0$ region.

The angle $\theta_k$ between the kinks and the c-axis can be calculated by minimization of the free energy[12]. For simplicity, we consider the case $H \gg H^c_{c1}$, where $\Theta_B = \Theta$ and the problem reduces to calculate the energy of one vortex, as the other terms in the free energy are the same for all configurations[7, 10]. If $L_p$ is the length of a pinned segment, and $L_k$ the length of the kink (see sketch in figure 4), the energy is $E \propto L_p \epsilon_p (\Theta_D) + L_k \epsilon_f (\theta_k)$, where $\epsilon_f (\theta_k) \approx \varepsilon_0 \varepsilon (\theta_k) [\ln \kappa + 0.5]$ and $\epsilon_p (\Theta_D) \approx \varepsilon_0 \varepsilon (\Theta_D) [\ln \kappa + \alpha_t]$ are the line energy for free and pinned vortices respectively, $\varepsilon_0$ is the vortex energy scale and $\alpha_t < 0.5$ parametrizes the core pinning energy due to the tracks (smaller $\alpha_t$ implies stronger pinning). Minimizing $E$ with respect to $\theta_k$ we obtain two orientations, $\theta_k^-$ for $\Theta < \Theta_D$ and $\theta_k^+$ for $\Theta > \Theta_D$.

As the tracks are inclined, $\left|\theta_k^-\right|$ and $\left|\theta_k^+\right|$ are different. However, those angles are independent of $\Theta$. As $|\Theta - \Theta_D|$ increases, $\theta_k^\pm$ remain constant while $L_p$ decreases and the number of kinks increases, consequently the pinning energy lowers. This accounts for an $M_i$ that decreases as we move away from the tracks. In particular, for $\Theta = \theta_k^\pm$ vortices become straight ($L_p = 0$), thus $\varphi_T^\pm = \left|\theta_k^\pm - \Theta_D\right|$ are the trapping angles in both directions. In general $\theta_k^\pm$ must be obtained numerically, but for $\varepsilon \tan \theta_k \ll 1$ and $\varepsilon \tan \Theta_D \ll 1$ we obtain

$$\tan \theta_k^\pm \approx \tan \Theta_D \pm \frac{1}{\varepsilon} \sqrt{\frac{1 - 2\alpha_t}{\ln \kappa + 0.5}} \tag{2}$$

Eq. 2 adequately describes the main features of the asymmetric region in Fig. 1, and for $\Theta_D = 0$ it coincides with the usual estimates[11, 12] of $\varphi_T$.

There is, however, an important missing ingredient in the standard description presented above, namely the existence of twins and Cu-O layers, which are additional sources of correlated pinning. This raises the possibility that vortices may simultaneously adjust to more than one of them, forming different types of staircases.

Pinning by twin boundaries is visible in figure 1 as an additional peak centered at the c-axis for $H = 2T$ and $T = 60K$. A blow-up of that peak is shown in the inset. We observe this maximum for $H \geq 1T$. The width of this peak, $\sim 5°$, is in the typical range of reported trapping angles for twins [3, 4, 5, 8, 9]. On the other hand, the fact that the peak is mounted over an inclined background implies that vortices are also trapped by the tracks. Thus, vortices in this angular range contain segments both in the tracks and in the twins. These two types of segments are enough to build up the staircases for $\Theta > 0$, but for $\Theta < 0$ a third group of inclined kinks with $\theta_k < 0$ must exist in order to have vortices parallel to $\mathbf{H}$.

Another fact to be considered is that there is an angle $\Theta_{sym}$ (which is only weakly dependent on $H$) beyond which $M_i(\Theta)$ recovers the symmetry with respect to the c-axis. This is illustrated in Fig. 3, where $M_i$ data for $-|\Theta|$ was reflected along the c-axis and superimposed to the results for $+|\Theta|$.

One possible interpretation is that for $\Theta > \Theta_{sym}$ staircases disappear, i.e., that $\Theta_{sym} = \theta_k^+$ and we are determining $\varphi_T^+ = \Theta_{sym} - \Theta_D$. However, this is inconsistent with our experimental results. Indeed, $\varphi_T^+$ should decrease with $T$, and this decrease should be particularly strong above the depinning temperature [16] $T_{dp} \sim 40K$ due to the reduction of the pinning energy by entropic effects [11]. This expectation is in sharp contrast with the observed increase of $\Theta_{sym}$ with $T$, which is shown in Figure 4 for $H = 2T$. Thus, the interpretation of $\Theta_{sym}$ as a measure of the trapping angle is ruled out. Moreover, if in a certain angular range vortices were not forming staircases, pinning could be described by a scalar disorder, then at high fields $M_i(\Theta)$ should follow the anisotropy scaling law[17] $M_i(H,\Theta) = M_i(\varepsilon(\Theta) H)$. Consistently, we do not observe such scaling in any angular range.

Our alternative interpretation is that, at large $\Theta$, the kinks become trapped by the $ab$-planes. This idea has been used by Hardy et al. [7] to explain that the $J_c$ at low $T$ in the very anisotropic Bi and Tl compounds with tracks at $\Theta_D = 45°$ was the same for either $\Theta = 45°$ or $\Theta = -45°$. Our situation is different, as we are comparing two kinked configurations.

We first note that, according to Eq. 2, $\theta_k^\pm$ cannot be exactly $90°$ for finite $\varepsilon$, thus the intrinsic pinning must be incorporated into the model by assigning a lower energy to kinks in the $ab$-planes. Vortices may now form structures consisting of segments trapped in the columns connected by segments trapped in the $ab$-planes, or alternatively an inclined kink may transform into a staircase of smaller kinks connecting segments in the planes (see sketches in figure 4). We should now compare the energy of the new configurations with that containing kinks at angles $\theta_k^\pm$. This is equivalent to figure out whether the kinks at $\theta_k^\pm$ lay within the trapping regime for the planes or not. The problem with this analysis is that, as $\theta_k^\pm$ are independent of $\Theta$, one of the two possibilities (either inclined or trapped kinks), will be the most favorable for all $\Theta$. Thus, this picture alone cannot explain the crossover from an asymmetric to a symmetric regime in $M_i(\Theta)$.

The key additional concept in this scenario is the dispersion in the pinning energy. The angles $\theta_k^\pm$ depend on the pinning strength of the adjacent tracks ($\alpha_t$ in Eq. 2), thus dispersion in $\alpha_t$ implies dispersion in $\theta_k^\pm$. As $\Theta$ increases, it becomes larger than the smaller $\theta_k^\pm$'s (that connect the weaker defects) and the corresponding kinks disappear. The vortices involved, however, do not become straight, but remain trapped by stronger pins connected by longer kinks with larger $\theta_k^{\pm}$. This process goes on as $\Theta$ grows: the weaker tracks progressively become unnefective as the "local" $\theta_k$ is exceeded, and the distribution of $\theta_k^{\pm}$ shifts towards the *ab*-planes. When a particular kink falls within the trapping angle of the planes, a switch to the pinned-kink structure occurs. In this picture, the gradual crossover to the symmetric regime takes place when most of the remaining kinks are pinned by the planes.

If kinks become locked, the total length of a vortex that is trapped inside columnar defects is the total length of a track, independent of $\Theta$, and the total length of the kinks is $\propto \tan(|\Theta \pm \Theta_D|)$ for field orientations $\pm\Theta$ respectively. As $|\Theta|$ grows, the relative difference between the line energy in both orientations decreases, an effect that is reinforced by the small line energy of the kinks in the *ab*-planes. If kinks are not locked but rather form staircases, taking into account that the trapping angle for the ab-planes is small[4] ($\sim 5°$), the same argument still applies to a good approximation. The temperature dependence of $\Theta_{sym}$ is now easily explained by a faster decrease of the pinning of the *ab*-planes with $T$ as compared to the columnar defects. Additional evidence in support of our description comes from recent transport measurements in *twinned* $YBa_2Cu_3O_7$ crystals, which show that in the liquid phase vortices remain correlated along the c-axis *for all field orientations*[18], suggesting that they are composed solely of segments in the twins and in the *ab*-planes.

In summary, we have shown that the combined effect of the three sources of correlated pinning must be taken into account to describe the vortex structure in samples with inclined columnar defects. We demonstrate that the lock-in phase exhibits an angle independent pinning strength, and show the decrease of the lock-in angle with field. Our results show that a variety of complex staircases are formed depending on the field orientation and strongly suggest that, at high temperatures, correlated structures dominate vortex pinning over random disorder in the whole angular range.

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Figure 1:Irreversible magnetization $M_i$ as a function of the applied field angle $\Theta$ for several fields $H$, at temperatures (a) $70K$ and (b) $60K$. Inset: blow

up of the $H = 2T$ data near the c-axis for $T = 60K$ (the units are the same of those in the main figure.

Figure 2:Angle $\Theta_{max}$ of the maximum in $M_i(\Theta)$ as a function of H for three temperatures. The solid lines are fits to Eq.(1) (see text). Bars mark the width of the plateau. Inset: $M_i(\Theta)$ in the region of the plateau.

Figure 3:Irreversible magnetization $M_i$ versus field angle $\Theta$ for three fields (curves are vertically displaced for clarity). Open symbols: data for $\Theta > 0$. Solid symbols: data for $\Theta < 0$, reflected with respect to the c-axis. Arrows indicate the angle $\Theta_{sym}$ beyond which the behavior is symmetric. The procedure of reflection is sketched in the inset.

Figure 4:Temperature dependence of $\Theta_{sym}$ (see fig.3). The solid line is a guide to the eye. The sketches show possible vortex staircases for $\Theta > \Theta_D$.

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