"Phase Diagram" of the Vortex-Solid Phase in Y-Ba-Cu-O Crystals: A Crossover from Single-Vortex (1D) to Collective (3D) Pinning Regimes

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We construct a "phase diagram" of the vortex-solid phase of Y-Ba-Cu-O crystals by making a first overall connection of the shape of the magnetic hysteresis $M(H,T)$ with the single-vortex (1D) and collective (3D) pinning regimes. The crossovers between different regimes are visualized from contours of constant J_c in the H-T plane. We identify the transition from 1D to 3D pinning, and from the nonlocal into a local behavior of vortex bundles in the collective pinning regime. A direct correlation between $M(H)$ and the thermal relaxation rate is demonstrated. We also identify a signature of the thermal softening boundary at which thermal fluctuations on the scale of the coherence length ξ are relevant.

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It is well established now that in the mixed state of high-temperature superconductors, the conventional Abrikosov vortex lattice is replaced by a melted vortex liquid over large regions of the magnetic (H-T) phase diagram [1]. The behavior of vortices in the diminished solid phase below the melting transition is undoubtedly controlled by the numerous weak randomly distributed defects, such as oxygen vacancies [2], and it has been argued that the collective pinning theory [3], describing the critical current density J_c, should be relevant. Recently, Feigel'man and Vinokur [4] explored the vortex-solid phase in the framework of collective pinning by weak disorder. Considering thermal *harmonic* fluctuations of vortices, but neglecting thermally activated creep, they proposed a "phase diagram" of *nonequilibrium regimes* in the H-T plane and derived boundaries for the single-vortex and various collective pinning regimes. Specific regions of the vortex-solid phase, however, are complicated by creep effects (thermally activated jumps of vortices or bundles) [5] and the full picture has not yet been tested experimentally.

In this Letter, we construct the "phase diagram" of the vortex-solid regimes below the melting line for Y-Ba-Cu-O single crystals, by tracing the boundaries for the transitions from the single-vortex pinning (1D) to the collective pinning (3D) predicted in the theory of collective pinning [4]. We present a first *direct* association of the *shape* of dc magnetization $M(H,T)$ with various regimes in the H-T plane, which we show to be strongly influenced by the *field-dependent* thermal relaxation consistent with the collective creep [5] idea. The novel analysis technique allows us to confirm low-field anomalies which we have recently reported in the ac response [6] and associated with the *thermal softening transition* [4].

The dc magnetization $M(H)$ of single crystals of Y-Ba-Cu-O [7] was measured with a Quantum Design SQUID magnetometer up to 5.5-T fields at temperature intervals of 1 K. The magnetic hysteresis loops for a roughly millimeter size and 20-μm-thick crystal, with $T_c = 93$ K and $\Delta T_c \sim 300$ mK, at three temperatures shown in Fig. 1 are typical of all the crystals we measure [8]. The three temperatures represent three regimes, in which the shape of $M(H)$ is distinctly different. At low temperatures the width of the loop, $\Delta M(H)$, is essentially *field independent* at high fields up to the maximum field accessible in our SQUID. There is a central peak, which at 5 K is below $\simeq 1.5$ T and which shrinks to smaller fields with increasing temperature. As T increases ΔM is reduced, but above the central peak ΔM *remains field independent* up to our maximum field. At $T = 40$ K a new feature is observed, namely, a "dip" in ΔM above the central peak (now confined to fields below $\simeq 0.1$ T): ΔM *increases* with field up to $H \simeq 2$ T and is field independent above. At higher temperatures, the field dependence of

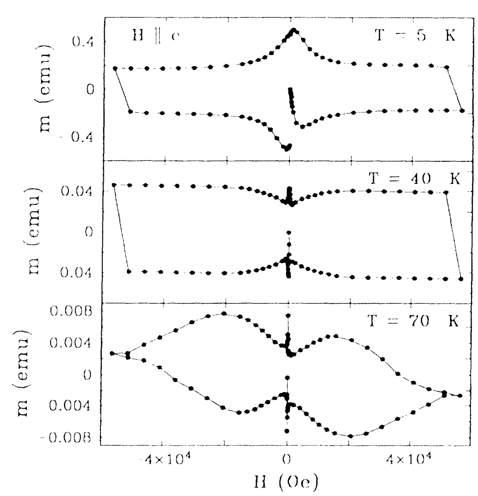

FIG. 1. Magnetic hysteresis loops of a Y-Ba-Cu-O crystal, displaying three characteristic shapes. The width Δm ($m = MV$, where V is the crystal volume) is field independent (outside of the region dominated by the self-field) at low (5–25 K) and intermediate (25–45 K) temperatures with a measurable "dip" at low fields above 25 K. A "bump" is always present above 45 K.

ΔM is manifested in the appearance of the "bump" which is clearly visible in the loop at $T=70$ K and which persists until the loop is immeasurable. This bump or "fishtail" has been seen by others [9,10] and attributed to oxygen inhomogeneities promoting a weak-link or granular behavior [9]. We have previously excluded the possible granularity in our crystals [8] and in what follows we show that the remarkable features of $M(H,T)$ are intimately related to the nonequilibrium crossovers in the vortex-solid phase. The measured ΔM is related to $J_c(H,T)$ within the phenomenology of the Bean critical-state model [11]. The field-independent ΔM implies a field-independent J_c, indicating that the vortices in the array are in the single-vortex pinning regime [4]. In a "static" picture (i.e., without creep), the relevant length in this regime is L_c, the longitudinal correlation length [4]. If L_c is less than the intervortex spacing $a_0 = (\Phi_0/B)^{1/2}$, the vortices are pinned independently and J_c is determined by pinning barriers for single vortices. We refer to this case as one-dimensional (1D) pinning. At high enough temperatures or fields the intervortex interaction becomes significant. The two relevant lengths are now L_c and $R_c > a_0$, the longitudinal and transverse size of the correlated region. In this regime J_c is controlled by collective pinning of vortex bundles confined by a correlation volume and thus is field dependent, as observed at $T=70$ K. We refer to this as three-dimensional (3D) pinning.

We make the connection with the phase diagram of Feigel'man and Vinokur [4] by translating the $M(H)$ data such as shown in Fig. 1 into a flow pattern of critical current density in the H-T plane. To do so, we calculate the width of the hysteresis loops $\Delta M(H)$ at all temperatures from 5 to 85 K. From this we extract $\Delta M(H,T)=$const for chosen values of ΔM. Visually, it means plotting $\Delta M(H)$ for all temperatures, making a cut at a fixed ΔM across the entire field range, and collecting the values of H and T for which the $\Delta M \propto J_c=$const line crosses the data points. J_c is calculated using the Bean model [11] with the "sandpile" approximation [12] appropriate for a rectangular crystal. The range of the critical current densities we obtain is ~ 2500 A/cm^2 at 80 K, $\sim 2\times10^5$ A/cm^2 at 40 K, and about 2×10^6 A/cm^2 at 5 K. This procedure yields contours of constant J_c which can be examined now in the H-T plane. The contours shown in Fig. 2 are at temperatures chosen for the visual clarity of the low-temperature regime (the high-temperature regime is shown later in Fig. 4).

We first explore the transition from the *single-vortex pinning* (1D) to a *collective pinning* (3D) regime. We argue that the essentially *vertical*, up to 5.5 T, boundary at $T_{sv} \simeq 45$ K indicates a crossover from the 1D regime *below* T_{sv} to the 3D regime *above*. Along this line, $L_c \simeq a_0$. The collective pinning theory [4] predicts that the 1D regime is bounded by $B_{sv}(T) \propto [\eta\gamma/\ln(\gamma a_0/\xi_{ab})]H_{c2}$, where $\eta = J_c/J_0$ is the ratio of the critical to the depairing current and $\gamma = \lambda_c/\lambda_{ab}$. The temperature bound T_{sv} of the 1D region at zero field is predicted for Y-Ba-Cu-O at ~ 30 K (Ref. [4]). At $T=0$ we evaluate $B_{sv} \sim 2$ T, although this is an order-of-magnitude estimate and can be as high as 10 T [13]. Experimentally, below T_{sv} we do not see the curvature in the J_c flow up to 5.5 T, and it had not been observed up to the 8-9-T fields [8,14].

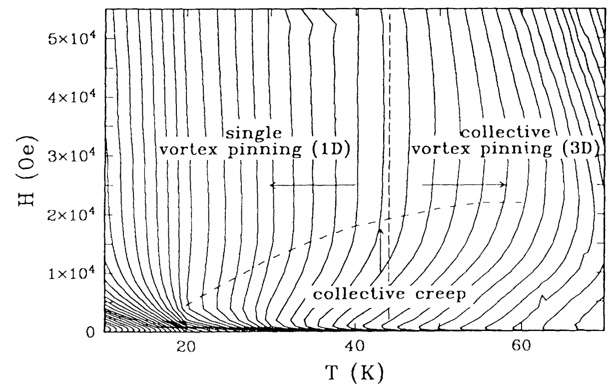

FIG. 2. Contours of constant J_c obtained from the data such as in Fig. 1. The contours are spaced as $J_c^{1/2}$ for easier visualization. The values of J_c at 10 and 70 K are $\sim 6.5\times10^5$ A/cm^2 and $\sim 2.65\times10^4$ A/cm^2, respectively. The boundary between the single-vortex and collective pinning regimes is indicated, with the "backflow" resulting from the transition to a collective creep.

Next we consider the low-field features of $M(H)$ in the single-vortex pinning regime. The central peak is essentially related to the curvature of the vortices at low applied fields due to self-field effects and has been discussed elsewhere [15]. Here we focus on the field range above the self-field-dominated region. It is clear from Fig. 2 that there is a noticeable "backflow" of the $J_c=$const lines starting at about 20-30 K, corresponding to the "dip" in $M(H)$, first at fields less than ~ 0.5 T and extending to higher fields at higher temperatures. We argue now the origin of this dip is a *collective (i.e., field-dependent) creep in the single-vortex pinning regime.* The dc magnetization gives, of course, only an estimate of J_c; it measures a *relaxed* value of $J(t) \le J_c$ at some time t_m (here $t_m \sim 10^2$ sec). Relaxation effects, due to vortices creeping out of the dense random pinning wells, affect $M(H)$ at all temperatures [16]. The theory of collective creep [5] gives an expression for the normalized relaxation rate $S = -d\ln M(t)/d\ln(t)$:

$$S = \frac{T}{U_c + \mu T \ln(t/\tau_0)}, \quad (1)$$

where U_c is the depth of the well, τ_0 is some attempt time, and μ is the exponent which governs the growth of the potential barriers with declining current, $U(J) \propto J^{-\mu}$. In the single-vortex pinning regime, the initial relaxation ($J \lesssim J_c$) is characterized [5] by $\mu = \frac{1}{7}$. As J decreases

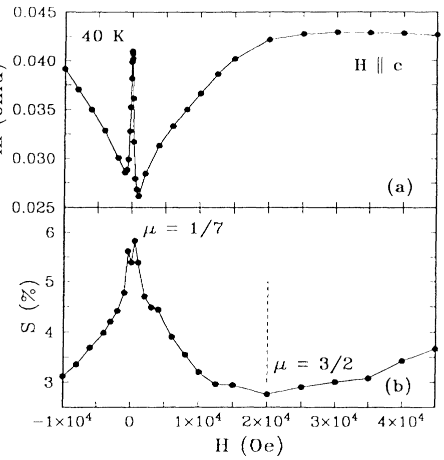

FIG. 3. Top portion of $M(H)$ at $T=40$ K and the corresponding normalized relaxation rate $S=-d\ln M(t)/d\ln t$. S is a mirror image of M, indicating that the dip is caused by a larger relaxation there. Theoretical predictions for the exponent μ in single-vortex creep regime ($\mu=\frac{1}{7}$), which is followed by a creep of vortex bundles ($\mu=\frac{3}{2}$), are indicated (see text for the discussion of μ).

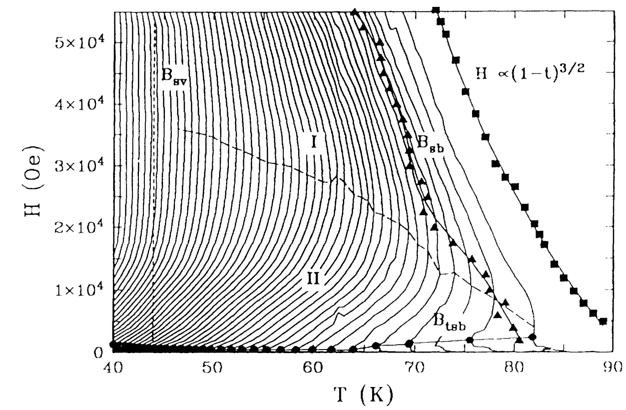

FIG. 4. Same as Fig. 2 expanded at higher temperatures with equal contour spacing. The collective pinning boundaries are indicated as follows: The vertical line B_{sv} is a transition from the single-vortex to a collective pinning regime. The solid triangles indicate a crossover from the nonlocal into a local regime $B_{sb}(T)$ (see text) and $B_{tsb}\propto T^2$ is a thermal softening boundary (also see Ref. [6]). The dc irreversibility line (solid squares) was determined with a current criterion of 100 A/cm^2 (Ref. [17]); it is fitted well by $H\propto(1-T/T_c)^{3/2}$. The dashed line is a guide to the eye through the bump; it separates region I [controlled by $J_c(H)$] and region II (controlled by relaxation).

with time, the size of the activated loop increases as $L=L_c(J_c/J)^{7/5}$. When L reaches a_0, the creep becomes collective and much slower with $\mu=\frac{3}{2}$. Below T_{sv} we are in the single-vortex pinning regime in the entire experimental field range; thus initially $\mu=\frac{1}{7}$ and J relaxes fast at all H. The condition $L(t)=a_0$ (the slowdown of the relaxation) occurs at a current J^* which grows with field as $J^*\propto a_0^{-5/7}\propto B^{5/14}$; i.e., at high fields the slowdown occurs sooner than at low fields. This implies that at lower fields J is smaller because it was relaxing fast (with respect to the field-independent J_c) during a longer time interval. If this interpretation is correct, the lower J at low fields should be linked to a faster relaxation rate S. This is confirmed by the data in Fig. 3, showing the top of the hysteresis loop $M(H)$ at 40 K and the corresponding normalized relaxation rate as a function of H. At each field, S was measured by increasing H up to 5.5 T, decreasing it to the target H, and recording $M(t)$ during approximately 1 h (in this short time window the time dependence of S is undetectable). Remarkably, the increase in the relaxation rate at low field is *a mirror image* of the dip in the magnetization. Hence, the dip in $M(H)$ in the intermediate temperatures is a result of a *transition to a collective creep in the single-vortex pinning regime.*

Now we turn to the flow pattern at temperatures above T_{sv} shown in Fig. 4, and throughout the remainder of this paper we will present the experimental evidence identifying various regimes of collective pinning [4]. The visualization of Fig. 4 is remarkable on several accounts. First we note that above T_{sv}, the curvature in the current flow pattern becomes more pronounced, reflecting the "fishtail" shape of $M(H)$. While, as we have discussed earlier, at low fields the observed J is dominated by the collective creep, at high fields (the large bundle regime) the pinning energy is large; hence the relaxation is small and the field dependence of J is essentially determined by $J_c(H)$. In the 3D collective pinning regime $J_c=(W/V_c)^{1/2}H^{-1}$, where $W\propto H$ is the mean square value of the random pinning force. The dimensions of the correlated region $V_c=L_cR_c^2$ are $L_c\simeq R_c(C_{44}/C_{66})^{1/2}$ and $R_c\simeq C_{44}^{1/2}C_{66}^{3/2}\xi^2/W$. At high fields $R_c>\lambda$, and thus the vortex system is in the *local* regime, where $C_{66}\propto H$ and $C_{44}\propto H^2$. The volume of the correlated region (bundle) in this regime expands as H^5 and J_c falls off as $1/H^3$. Figure 5 displays J_c versus field at $T=75$ K, clearly

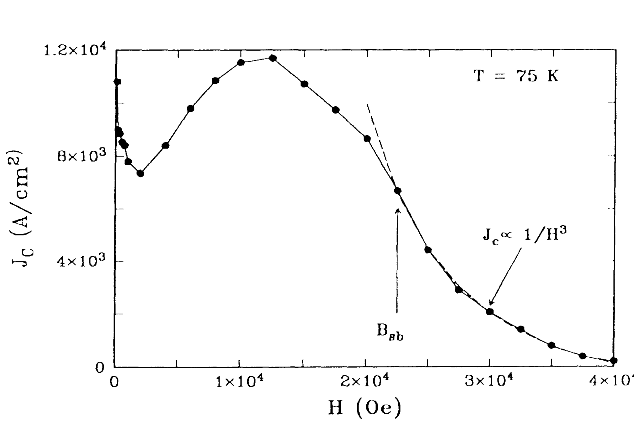

FIG. 5. Critical current density J_c vs field displays a bump at high temperatures. The fit by the $1/H^3$ falloff of J_c in the local regime is shown as the dashed line.

showing the "bump." We indeed find that the dependence $J_c \propto 1/H^3$ fits remarkably well at high fields. The calculated $J_c = \gamma^2(J_0/\kappa^2)\eta^3[H_{c2}/B]^3$ value [4] at $H=3$ T is $\sim 7\times 10^3$ A/cm^2 as compared with the measured value of $\sim 2\times 10^3$ A/cm^2, consistent with the relatively slow relaxation in this regime.

With decreasing field R_c shrinks until $R_c \leq \lambda$, and the *local* description fails. This crossover is predicted to occur at a field $B_{sb}(T) \propto B_{sv} \ln^{2/3}(B_{sv}/H_{c1})$ and is about $3B_{sv}$ at $T=0$. The transition from the nonlocal into a local regime, taken as the onset of the $1/H^3$ falloff of J_c, is plotted as $B_{sb}(T)$ in Fig. 4. The low-temperature turnover of B_{sb} is not accessible in the field range of our experiment. The bump in the *nonlocal* regime may be understood as follows. On the low-field side of the bump, similarly to what we have discussed earlier, J is controlled by collective creep. At higher fields near the top of the bump, the relaxation slows down and $J(t)$ is controlled by $J_c(H)$, which decays as $J_c(H) \propto e^{-\beta H^{3/2}}$. Here β contains the temperature dependence of H_{c2}, the pinning strength η, and the temperature of thermal softening [4,6].

So far we have considered the temperature regime where the harmonic fluctuations of vortices $\langle u^2\rangle^{1/2}$ are smaller than the coherence length ξ (Ref. [4]). A *thermal softening of the core pinning* will occur when $\langle u^2\rangle^{1/2}$ becomes comparable to ξ and thus the pinning landscape is smeared out on the same length scale [4]. The thermal softening boundary (TSB) is the *only* known crossover in the phase diagram which *increases* with temperature [4]; i.e., $B_{tsb} \propto T^2$. Note that the constant-J_c contours turn back and then *reenter* at low fields. The point of reentry, corresponding to a *minimum* in ΔM at low fields, also increases as T^2 as shown in Fig. 4, and is suggestive of TSB. The T^2 behavior is clearly seen above 60 K; it is obscured at lower temperatures by the growing prominence of the self-field peak. The value of B_{tsb} is ~ 0.2 T at 85 K, *above* the lower critical field H_{c1} (Ref. [6]). We have reported recently the *same flow pattern* in ac response [6,17] much closer to T_c. There we have proposed that the thermal softening boundary crosses the irreversibility line H_{irr}, shifting it to lower fields [6]. The remnant of the H_{irr} *collapse* in the H-T plane is seen below H_{irr} in both ac and dc response. However, the nature of the backflow and the reentrant regime at high temperatures and low fields still remains to be established. The theory is yet to provide a more complete description of the regime close to H_{c1} where the elastic energy becomes negligible.

In summary, we have constructed the nonequilibrium "phase diagram" of the vortex-solid phase in Y-Ba-Cu-O crystals. A single-vortex pinning regime is observed at temperatures below T_{sv} in the entire experimental field range. Within this regime, collective creep effects are apparent in the "mirror-image" correlation between $M(H)$ and the thermal relaxation rate at low fields and intermediate temperatures. Above T_{sv}, the pinning becomes collective. There, the crossover from the nonlocal to local behavior of vortex bundles is marked by the onset of $1/H^3$ decay of J_c. The T^2 feature in the J_c flow pattern in the H-T plane is associated with thermal softening.

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