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Amorphization of vortex matter and indication of a reentrant peak effect in $YBa_2Cu_3O_{7-\delta}$

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The peak effect (PE) has been observed in a twinned crystal of $YBa_2Cu_3O_{7-\delta}$ for $H\|c$ in the low-field range, close to the zero-field superconducting transition temperature $[T_c(0)]$. A sharp depinning transition succeeds the peak temperature T_p of the PE. The PE phenomenon broadens and its internal structure smoothens out as the field is increased or decreased beyond the interval between 250 and 1000 Oe. Moreover, the PE could not be observed above 10 kOe and below 20 Oe. The locus of the $T_p(H)$ values is indicative of the occurrence of a reentrant characteristic with a noselike feature located at $T_p(H)/T_c(0)\approx 0.99$ and $H\approx 100$ Oe (where the flux line lattice constant $a_0\approx$ penetration depth λ). The upper part of the PE curve ($0.5<H<10$ kOe) can be fitted to a melting scenario with the Lindemann number $c_L\approx 0.25$. The vortex phase diagram near $T_c(0)$ determined from the characteristic features of the PE in $YBa_2Cu_3O_{7-\delta}(H\|c)$ bears close resemblance to that in the 2H-$NbSe_2$ system, in which a reentrant PE had been distinctly observed earlier.

I. INTRODUCTION

The advent of high-T_c superconductors (HTSC's) provided a new impetus[1] to studies on phase transformations in the flux-line lattices (FLL's) of type-II superconductors in general and they remain a subject of considerable current interest. The competition among the elasticity of vortex medium, the pinning of vortex lines, and the fluctuation effects of the thermal energy is expected to yield an ordered vortex solid (presumably a dislocation free Bragg glass phase[2]), a plastically deformed vortex solid (presumably a vortex glass phase with proliferation of dislocations), and a pinned as well as an unpinned liquid phase in different parts of the field-temperature (H,T) phase space.[1–6] In the HTSC cuprate systems, thermal fluctuations are large and in the high-temperature part of the (H,T) space (i.e., for $t=T/T_c(0)\geqslant 0.9$, where $T_c(0)$ is the superconducting transition temperature in zero field), a first-order melting transition occurs between an ordered solid and a nearly pinning-free vortex liquid state.[7–9] This transition in the most investigated $YBa_2Cu_3O_{7-\delta}$ (YBCO) system is located[10–13] at the upper edge of the peak effect (PE) phenomenon in the critical current density J_c for fields of the order of a few T. At lower temperatures (i.e., $t<0.9$) and higher fields, where thermal fluctuations are weaker, a ''fishtail'' or ''second magnetization peak'' anomaly occurs[14] presumably across a *transformation* between a weakly pinned solid and a stronger pinned solid.[2,3]

The detailed characteristics of the evolution of the anomalous variation in J_c across the (H,T) region of the second magnetization peak and that of the conventional peak effect are far from being understood in the context of a variety of HTSC systems.[14–18] In contrast, in the conventional low-T_c superconductors (LTSC's) with considerably smaller (but often not negligible) thermal fluctuations, a PE near the normal-state boundary (H_{c2} line) is a common occurrence over the entire field-temperature regime.[19–24] Various attempts[25–28] to gain an understanding of the anomalous variations in J_c attribute this phenomenon to a softening of the (weakly pinned) ordered lattice and a consequent transformation into a more strongly pinned amorphous solid or a pinned liquid phase.[29,30] Disentangling the effects of the various possible sources of pinning and that of the thermal fluctuations has however remained difficult.[19,26–28] Despite this, there is a widespread acceptance (supported by evidence from microscopic μSR studies as well[31,32]) that the anomalous (sharp) variations in J_c signal a change in the state (i.e., in terms of spatial and temporal correlations) of the vortex matter. In the collective pinning framework due to Larkin and Ovchinnikov,[33] J_c relates inversely to the correlation volume V_c of the Larkin[34] domain as,

$$J_cH=\sqrt{\frac{n_p\langle f_p^2\rangle}{V_c}}, \qquad (1)$$

where n_p is the density of pinning centers and f_p is the elementary pinning interaction. Furthermore, in the context of LTSC systems, it is now known[35] that upon increasing the effective pinning either externally by enhancing the quenched random inhomogeneities in the atomic lattice or by

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changing the magnetic field in a given sample, the PE often develops internal structure. This has led to suggestions[22,24,35] of a richer and more complex transformation occurring in a stepwise manner between an ordered (quasilattice) phase and a fully amorphous one. Even more interestingly, the low-field part of the phase diagrams[37,38] in the weakly pinned samples of an archetypal LTSC system[19,36] $2H\text{-NbSe}_2$ show a variety of interesting features, including a reentrance into a disordered phase which is qualitatively similar to a reentrant glass/reentrant pinned liquid, postulated theoretically.[1,3,39]

In this paper, we report on the search and the identification of the anomalous variations in J_c via the ac magnetization measurements in a twinned crystal $[T_c(0)\approx 93.3\ \text{K}]$ of the YBCO system in the rarely reported low-field–high-temperature part of the vortex phase diagram. In the YBCO system, the presence of twin boundaries is considered[10,17,27] to facilitate the occurrence (and detection) of the PE phenomenon. The twinned crystal piece (dimensions $\sim 0.5 \times 0.5 \times 0.04\ \text{mm}^3$ and mass $\sim 700\ \mu\text{g}$) chosen for the measurements being reported here is obtained by flux growth technique, along with detwinned YBCO crystals[40] on which the first-order melting transition was observed via differential calorimetry.[9] In this twinned crystal, we are able to detect the PE phenomenon over a wide a field range (20 Oe–10 kOe), the lower limit being much lower than any previous study. The evolution in the characteristic of the PE is similar to that in the weakly pinned samples of a variety of LTSC systems,[22,24,37,38] but some significant differences exist as well.

II. EXPERIMENTAL DETAILS

The ac magnetization measurements were performed using a well shielded home built ac susceptometer.[41] The dc field (coaxial with ac field) was kept parallel to the c axis of the YBCO crystals. Both twinned and detwinned samples were investigated but PE was detected only in the former. Data were taken in both the field-cooled (FC) and the zero-field-cooled (ZFC) modes. Most of the data shown are in the former case, where the PE is more conspicuous.

III. RESULTS AND ANALYSIS

A. Location of the peak effect and elucidation of its characteristic features

Figures 1 and 2 present a collation of the temperature-dependent in-phase ac susceptibility data recorded with h_{ac} of 0.5 Oe (rms) and at the frequency 211 Hz in the field ranges where anomalous variations in J_c could be identified. In zero field, the normalized $4\pi\chi'$ has a value -1 (c.g.s. units) in the superconducting state and it crashes sharply towards the zero value [the transition width $(10\text{–}90\%), \Delta T_c(0)\approx 0.8\ \text{K}$ (Ref. 42)] in a featureless manner [see inset of Fig. 1(a)]. We now focus on the $\chi'(T)$ responses shown in the Figs. 1(a)–1(f) as H increases from 20 to 250 Oe. In $H=20\ \text{Oe}$ (where FLL $a_0\approx 1.1\times 10^4\ \text{Å}$), $\chi'(T)$ is still featureless, though the superconducting transition is broader. Figures 1(b) and 1(c) show that as H increases from 40 Oe $(a_0\approx 8\times 10^3\ \text{Å})$ to 170 Oe$(a_0\approx 4\times 10^3\ \text{Å})$, a characteristic feature reminiscent of the PE develops across the temperature region marked by a pair of arrows at T_{pl} and T_p in the respective panels. The shape of the $\chi'(T)$ curve at $H=250\ \text{Oe}$ $(a_0\approx 3.3\times 10^3\ \text{Å})$ in the inset of Fig. 1(f) identifies the PE phenomenon in an unambiguous manner. The temperature at which an anomalous variation sets in $\chi'(T)$ response at $H=250\ \text{Oe}$ in Fig. 1(f) can be distinctly marked as T_{pl}. Further, the peak temperature T_p at 250 Oe can also be precisely identified in the inset and main panels of Fig. 1(f) with the (deeper) minimum in $\chi'(T)$ curve. In Fig. 1(f), at $T=T_p, d\chi'/dT=0$, whereas in Figs. 1(b)–1(d), the T_p values have been identified with the (respective) temperature at which $d\chi'/dT$ is at a local minimum, and from which a sharp upturn in $d\chi'/dT$ commences [cf. insets in Figs. 1(b) and 1(c)].

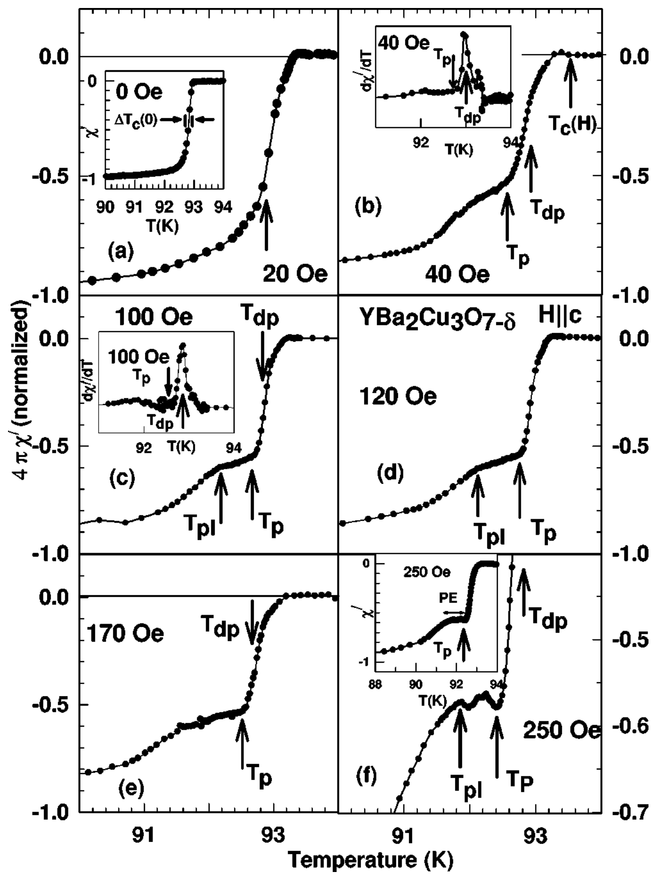

FIG. 1. Temperature dependence of the normalized values of the in-phase ac susceptibility $[4\pi\chi'(T)]$ in a twinned single crystal of $YBa_2Cu_3O_7$ measured with an amplitude (h_{ac}) of 0.5 Oe (rms) and at a frequency of 211 Hz in the dc fields $(\|c)$ as indicated in the different panels. The insets in (a) and (f) show the $\chi'(T)$ response in (nominal) zero field and 250 Oe, respectively. The onset (T_{pl}) and peak (T_p) temperatures of the PE have been marked in different panels. The inset panels in (b) and (c) show the plot of $d\chi'/dT$ vs T in $H=40$ and 100 Oe, respectively. The temperature of maximum in $d\chi'/dT$ marks the midpoint of the depinning transition (T_{dp}). An unlabeled arrow in (a) identifies the temperature across which a remanence of the PE phenomenon can be identified in the $\chi'(T)$ curve at $H=20\ \text{Oe}$ measured with a higher h_{ac} of 2 Oe (rms), as shown in the Fig. 3(b).

Within the Bean's critical state model prescription of the magnetization of irreversible superconductors,[43] the shielding response $\chi'(T)$ can be approximated as:[44]

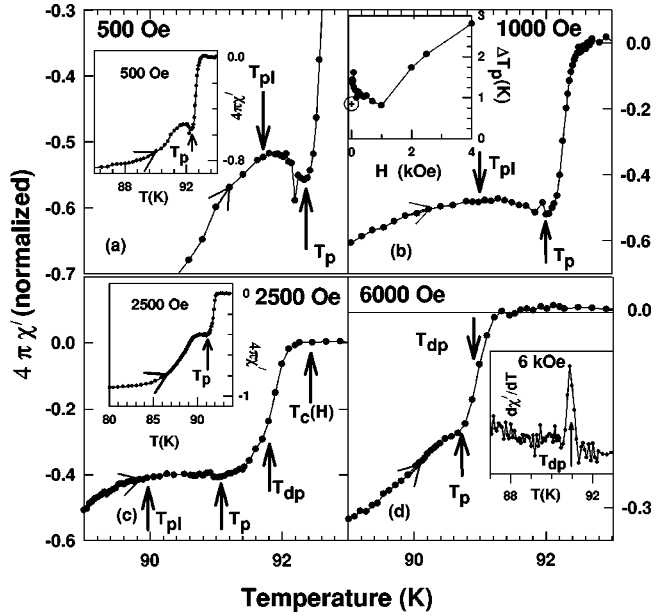

FIG. 2. Plots of $4\pi\chi'$ vs T in higher dc fields. The inset panels in (a) and (c) help to view the occurrence of the PE at $H=500$ and 2500 Oe, respectively. The inset in (d) shows the location of the T_{dp} via a plot of $d\chi'/dT$ versus T at $H=6000$ Oe. The inset in (b) shows a plot of the parameter ΔT_{dp} versus field (see text for details).

$$\chi'(T) \sim -1+\alpha\frac{h_{ac}}{J_c}\ ; \quad \text{for } h_{ac} \ll H^*, \tag{2}$$

$$\chi'(T) \sim -\beta\frac{J_c}{h_{ac}}\ ; \quad \text{for } h_{ac} > H^*, \tag{3}$$

where α and β are geometry and size dependent factors, H^* is the (threshold) parametric field at which the magnetic field penetrates the center of the sample. Equations (2) and (3) imply that the temperature variation in χ' is governed by the temperature variation of J_c in a given H. Thus the observed minimum in $\chi'(T)$ in the inset of Fig. 1(f) marks a peak in J_c, i.e., the PE, which is characterized by two temperatures, the onset T_{pl} and the peak at T_p. The vanishing of J_c above T_p, i.e., the depinning of the vortex state is characterized by the sharp increase in χ' to its normal-state value. A depinning temperature T_{dp} (notionally the mid point of collapse in J_c) is obtained from the peak in $d\chi'(T)/dT$, examples of which are shown in the insets of Figs. 1(b) and 2(d).

The other noteworthy features contained in Figs. 1 and 2 could be summarized as follows:

(i) The PE is sharpest around an intermediate field of $\sim$1000 Oe, it becomes a broad anomaly for both higher and lower fields, and cannot be detected above 10 kOe and below 40 Oe.

(ii) Characteristic structure (e.g., two well resolved minima instead of a single composite minimum in χ'), very similar to what has been seen in LTSC systems, appears in the intermediate field regime as evident in Figs. 1(f), 2(a), and 2(b). Such a structure has been reported in another study,[12] but in higher fields than is shown here.

(iii) Depinning phenomenon across T_{dp} is a sharp anomaly. A simple fit of the form: $4\pi\chi' = a + T/\Delta T_{dp}$,

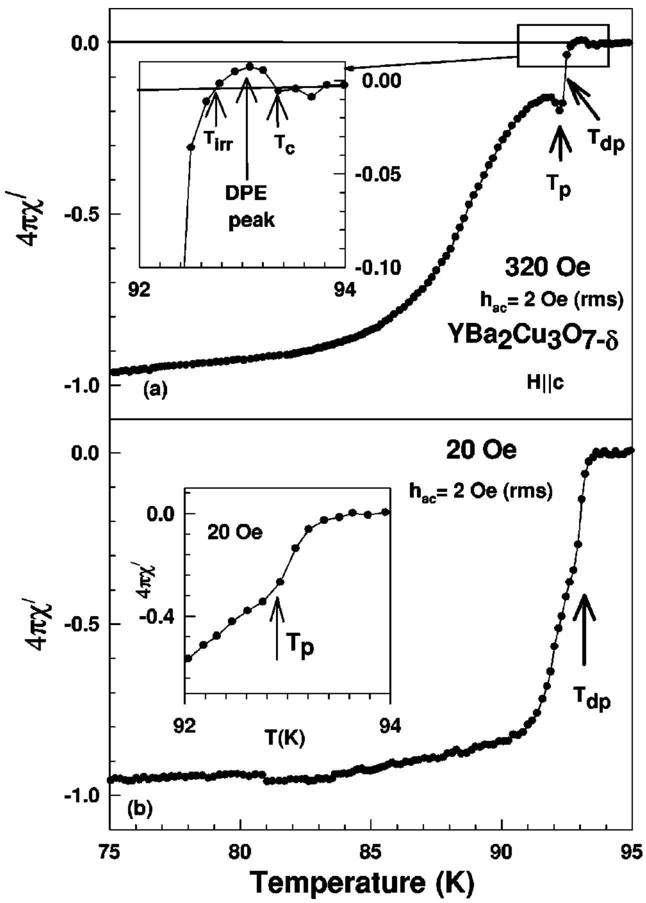

FIG. 3. The $\chi'(T)$ measured in a h_{ac} of 2 Oe (rms) and at a frequency of 211 Hz in (a) 320 Oe and (b) 20 Oe. An enlarged plot in the inset of panel (a) shows the presence of the differential paramagnetic effect (DPE), which follows the occurrence of the peak effect. The inset of panel (b) shows an inflection feature in the $\chi'(T)$ curve at $H=20$ Oe.

yields a characteristic width ΔT_{dp}, whose field dependence is shown in the inset of Fig. 2(b). Interestingly, $\Delta T_{dp}(H)$ is smallest for $H\approx 1000$ Oe and increases for both increasing and decreasing fields, as shown in the inset of Fig. 2(b). The $\Delta T_{dp}(H)$ at 1 kOe is smaller than its value even at zero field (see the encircled data point), the latter is very close to the $\Delta T_c(0)$, which is shown in the inset of Fig. 1(a).

B. Observation of the differential paramagnetic effect

Figures 3(a) and 3(b) show the $\chi'(T)$ values measured with a higher h_{ac} of 2 Oe (rms) at a frequency of 211 Hz for the vortex states obtained in 320 and 20 Oe, respectively. The PE in the main panel of Fig. 3(a) is pronounced.[45] A significant feature to note, however, is that χ' makes a sharp transition from diamagnetic values to *paramagnetic* values across the depinning temperature T_{dp}. The inset in Fig. 3(a) reveals a small paramagnetic peak above the temperature T_{irr} (only slightly greater than the so designated T_{dp}), the ubiquitous irreversibility temperature. The paramagnetic χ' response returns to the background level on crossing over to the normal state at $T_c(H)$. An identical paramagnetic peak located at the edge of the depinning transition has earlier been reported in LTSC systems, such as, $CeRu_2$ (Ref. 45) and 2H-$NbSe_2$ (Ref. 46) and identified with the *differential paramagnetic effect* (DPE).[47] Between $T_{irr}(H)$ and $T_c(H)$, the vortex state is reversible, for which dM/dH is positive, i.e., diamagnetic dc magnetization decreases as H increases, implying, a DPE. The paramagnetic peaks in the $\chi'(T)$ data in single crystals of YBCO and BSCCO had been reported in other studies as well.[48–50] Morozov *et al.*[48] had reported a sharp paramagnetic peak in a single crystal of $Bi_2Sr_2CaCu_2O_8$ (BSCCO) via local micro-Hall sensors at temperatures where a step change in equilibrium magnetization (M_{eq}) due to FLL melting is expected. However, no peak effect has been reported in these studies. The question as to whether the sharp onset of the DPE peak marks the step change in M_{eq} at the FLL melting transition[48] and/or it reflects the depinning transition located at the upper edge of the PE phenomenon, requires more detailed investigations. We note, however, that Ishida *et al.*[12] and Ravikumar *et al.*[51] have presented evidence of a step change in M_{eq} across the PE region in the low-field–high-temperature part of the (H,T) phase space in single crystals of YBCO and 2H-$NbSe_2$, respectively. Thus the sharp transition from the PE peak to a DPE peak in weakly pinned systems [as in Fig. 3(a)] may indeed mark the transition from a pinned to an unpinned state of the vortex matter.

Furthermore, Fig. 3(b) shows yet another effect of a larger ac amplitude: a residual PE now visible in contrast with the low amplitude data in Fig. 1(a). It is possible that a larger ac signal anneals[52] the dilute lattice thereby making the amorphization more easily detectable. The possible annealing effect of a larger ac field needs further investigations. Studies on samples of LTSC had earlier revealed[45] that specific details of the structure in the $\chi'(T)$ curve across the PE depend on the amplitude of the ac field.

C. History effects in $\chi'(T)$ behavior

The history effects pertain to the dependence of $\chi'(H,T)$ on the path followed in reaching a given H and T. A simple way to explore them is to examine the difference in $\chi'(T)$ between ZFC and FC modes. Figure 4 displays the $\chi'(T)$ data in h_{ac} of 2 Oe (rms) at $H = 500$ Oe $(\|c)$ (i.e., when the PE peak is well recognizable) for both ZFC and FC modes. The inset in Fig. 4 shows the data across the PE region on an expanded scale. Note first that above T_p, $\chi'(T)$ behavior is the same for both ZFC and FC modes. However, prior to the entry into the PE region (i.e., for $T < T_{pl}$), $|\chi'_{FC}| > |\chi'_{ZFC}|$. As per Eqs. (2) and (3), this inequality would translate as $J_c^{FC} \leqslant J_c^{ZFC}$ for $T < T_p$. In terms of Larkin-Ovchinnikov scenario [cf. Eq. (1)], this implies that the correlation volume V_c in the FC state is larger than that in the ZFC state. This inference agrees with the direct observation of better order for the vortex states (mostly at low fields) prepared in the FC manner as compared to those prepared in the ZFC manner in crystals of YBCO,[53] as well as in other high-T_c cuprates.[54] However, the above inequality is in complete contrast to the situation in weakly pinned samples of LTSC systems on which history dependent J_c data have been reported for long.[55–58,22,24]

In transport studies of single crystals of niobium, Steingart, Putz, and Kramer[55] had noted the inequality

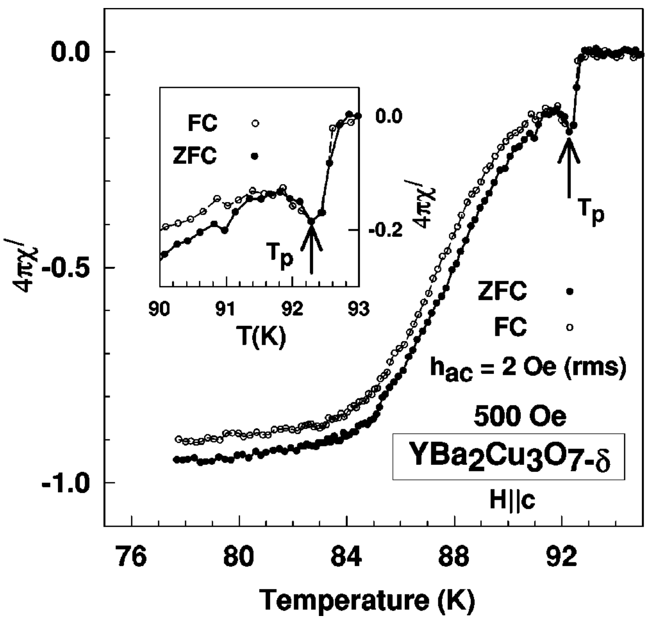

FIG. 4. Comparison of the $\chi'(T)$ behavior [$h_{ac} = 2$ Oe (rms) and $f = 211$ Hz] for the vortex states prepared at 500 Oe in the zero-field-cooled (ZFC) and the field-cooled (FC) modes. The inset shows an enlarged view of the data across T_p.

$$J_c^{FC}(H) > J_c^{rev}(H) > J_c^{ZFC}(H), \tag{4}$$

where $J_c^{rev}(H)$ is the current density while reversing the field from above H_{c2} to a given H in an isothermal scan. In recent years, the history effects and metastability (supercooling, etc.) has received new impetus.[57] The observations that (i) $J_c^{FC}(H) > J_c^{ZFC}(H)$ for $H < H_p$ and (ii) $J_c^{FC}(H) \approx J_c^{ZFC}(H)$ for $H > H_p$ in LTSC systems have led to the suggestion[22] that FC states attempt to freeze in (i.e., supercool) the amorphous correlations present at (and above) the peak position of the PE. A FC state is therefore more strongly pinned than the corresponding ZFC state. The ZFC phase, in contrast, is considered to be prepared by exposing the weakly pinned superconducting sample to an applied field which generates vortices that enter the sample at high velocities[59] and are able to overcome the effects of pinning centers to eventually explore the well ordered stable state of the system. It may be speculated here that while field cooling in the YBCO case, the temperature interval between the irreversibility temperature T_{irr} and the peak temperature T_p is so narrow [cf. Fig. 3(a)] that the sample fails to explore the (equilibrium) amorphous phase during a very fast cooldown. The vortex density in the sample is uniform in the FC state, whereas in the ZFC case, in particular at low fields, the strong pinning effects near the edges in the platelet-shaped samples of YBCO result in the vortex density being nonuniform across the cross section of the sample. Large thermal energy would help overcome the effects of pinning centers in both cases, however, the FC state being more (macroscopically) uniform eventually produces a better ordered FLL with a larger correlation volume V_c of the Larkin domain (than that in the ZFC case). We note that Kokkaliaris *et al.*[18] have recently reported that in an untwinned YBCO crystal, which displays the phenomenon of a broad second magnetization peak (to be designated as H_p^s) at high fields and lower temperatures, $J_c^{ZFC}(H) < J_c^{rev}(H)$ for

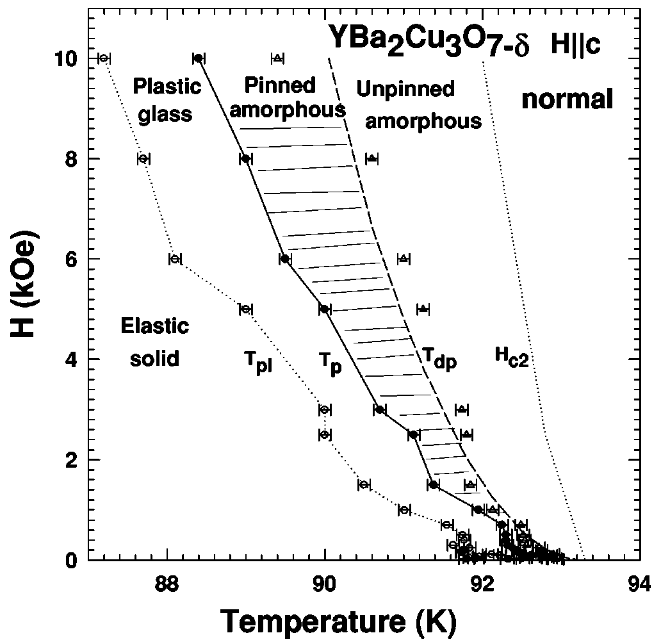

FIG. 5. The vortex phase diagram in the twinned $YBa_2Cu_3O_{7-\delta}$ crystal (for $H\|c$) constructed on the basis of the data on the onset (T_{pl}), the peak (T_p) and the end (i.e., the depinning temperature T_{dp}) of the peak effect phenomenon. The schematically drawn normal state boundary (i.e., the dotted H_{c2} line) corresponds to the (nominal) zero-field transition temperature of 93.3 K and the $T_c(H)$ values ascertained at high fields ($H>0.25$ kOe). The dashed line notionally marks the upper end of the pinned amorphous region and it corresponds to the relationship $H=7.9\times10^6[1-T/T_c(0)]^2$ Oe. For a justification of the nomenclature of the different vortex phases, see text.

$H<H_p^s$. Such an inequality is indeed consistent with the behavior in LTSC systems [cf. Eq. (4)]. The role that the width of the PE region could play in deciding the nature of the inequality between J_c^{FC} and J_c^{ZFC} in LTSC/HTSC systems remains to be further investigated. It is to be noted that regardless of the sign of the history dependence, in all cases reported so far, the T_p provides an upper limit of the history dependence. Thus, in analogy with disordered magnets such as spin glasses, T_p marks a characteristic ''transition'' temperature above which the system is disordered in ''equilibrium.''

D. Construction of the vortex phase diagram and its comparison with earlier reports

Figure 5 shows a collation of the data corresponding to the PE region marked by the onset (T_{pl}) and the peak (T_p) positions along with the depinning (T_{dp}) and the superconducting transition (T_c) temperatures over the (H,T) region, where the PE phenomenon could be identified. In view of the observation that the sharp depinning transition (i.e., the irreversibility temperature) immediately succeeds the peak of the PE, the $T_p(H)$ line in Fig. 5 runs parallel to the $T_{dp}(H)$ line. Several reports[10–13,17] in the twinned and untwinned crystals of YBCO provide evidence that the $T_p(H)$ values are located either in close proximity to the melting temperatures (as determined from the transport studies[10,11,17]) of the underlying pristine FLL or they coincide with the tempera-

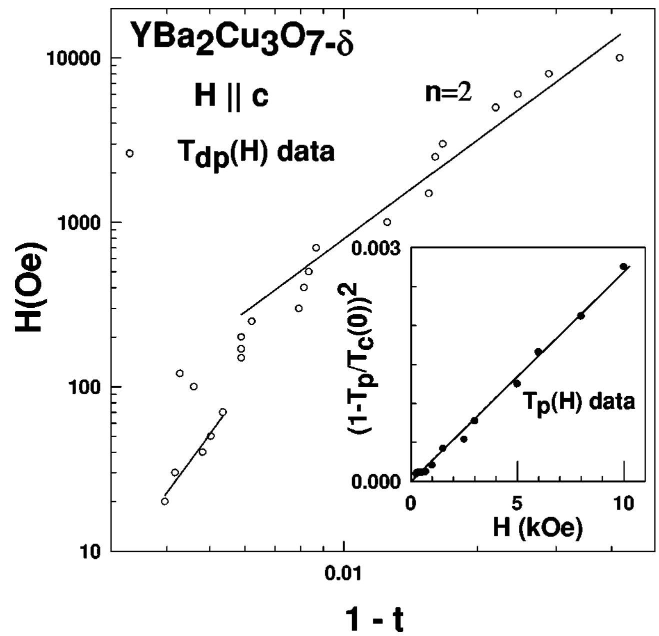

FIG. 6. Log-log plot of H vs $(1-t)$, where $t=T_{dp}/T_c(0)$. The solid lines correspond to the power law $[H\approx H_0(1-t)^n]$, above and below the field-temperature region of a collapse (or turn around) in the depinning line. The high-field ($H>0.3$ kOe) exponent is $n\approx2$ and the prefactor $H_0\approx7.9\times10^6$ Oe. The inset shows a plot of H vs $(1-t_p)^2$, where $t_p=T_p/T_c(0)$. $T_p(H)$ data yield prefactor $H_0\approx3.7\times10^6$ Oe.

tures of a step change in the equilibrium magnetization.[12,13,17] One could draw the loci of different features of the PE phenomenon seen in transport[11,17] and ac susceptibility measurements,[12,13,17] however, they all seem to indicate that H-T lines so drawn would conform to the power-law FLL melting relationship[1]

$$H_m=H_0\left(1-\frac{T}{T_c(0)}\right)^n, \tag{5}$$

where the prefactor $H_0\sim10^6$ Oe and $n\approx1$ to 2.[9,11,13,17,18] Most of the data on the PE curve or the melting line or the irreversibility line (in YBCO) in the literature, which have been found to conform to the power law relationship, are at fields larger than 1 kOe. A broken line satisfying the $T_{dp}(H)$ data points for $H>0.25$ kOe in Fig. 5 attests to the efficacy of the power-law behavior. We, however, find that in the low-field region (H<0.5 kOe), the deviations from the power-law relationship $[H\sim(1-t)^n]$ set in a significant manner for both the curves $T_{pl}(H)$ and $T_p(H)$.

We recall that a sudden collapse of the irreversibility line between 1 and 0.2 kOe in the twinned and the untwinned crystals of YBCO was reported by Krusin-Elbaum *et al.*[60] from high-frequency ac susceptibility measurements. However, in their data, there is no evidence of the occurrence of a PE. Below 200 Oe, the irreversibility line of Krusin-Elbaum *et al.*[60] can be seen to proceed towards the $T_c(0)$ value in a power-law manner once again, but with a different value of the exponent *n*. Following Ref. 60, we show in Fig. 6, the plot of log H versus log $(1-t)$ for the T_{dp} line in our sample of YBCO. Note that the data for $6000\leqslant H\leqslant250$ Oe and for $70\leqslant H\leqslant20$ Oe could be considered to conform to

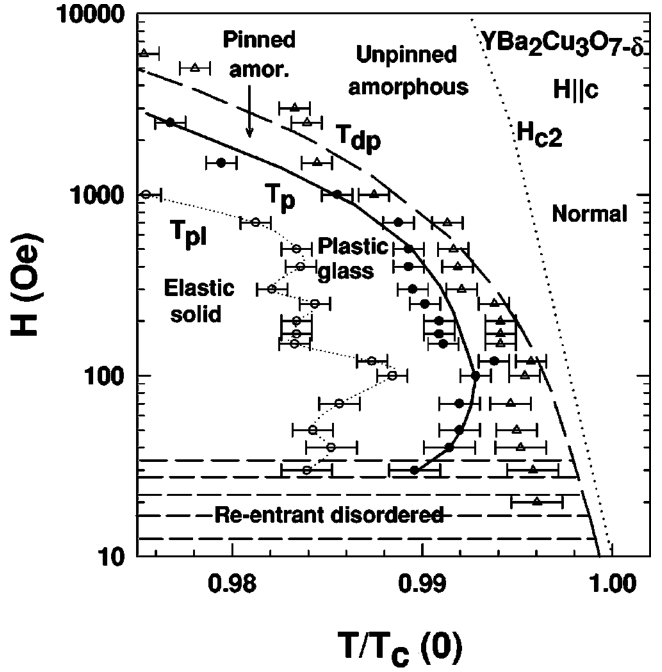

FIG. 7. The same data as in Fig. 5 on a semilog plot illustrating the shape of the $t_p(H)$ curve at low fields ($H<300$ Oe). As in Fig. 5, the dashed line conforms to the power-law relation with exponent $n\approx 2$. The solid line satisfying the $t_p(H)$ data points has been drawn in a freehand manner, it can be seen to run parallel to the dashed line for $H>300$ Oe. However, below 100 Oe, its departure from the the curvature of the dashed line and its tendency to turn-around strongly suggests the presence of noselike feature in the $T_p(H)$ curve. The dotted line joining the $t_{pl}(H)$ data points is just a guide to the eye.

the power-law relationship albeit with different values of the exponent n in the two intervals.[60] In the high-field region ($H>0.25$ kOe), both the exponent $n\approx 2$ and the prefactor $H_0\approx 7.9\times 10^6$ Oe are comparable to similar values ($n\approx 2$ and $H_0\approx 6\times 10^6$ Oe) found by Nishizaki *et al.*[17] in a high-quality twinned crystal of YBCO. In between the high-field and low-field regions, i.e., between 250 and 70 Oe, T_{dp} curve shows a noselike turnaround feature. Such a feature appears somewhat more accentuated in $T_p(H)$ and $T_{pl}(H)$ curves, as can be better elucidated via a replot of the vortex phase diagram in a semilog manner as shown in Fig. 7. In order to comprehend the genesis of the turnaround in $T_p(H)$ curve around 100 Oe, we refer to the $\chi'(T)$ curves displayed in Figs. 1(b)–(f). These figures show that the PE develops gradually, followed by a progressively rapid depinning immediately thereafter [cf. data in the inset of Fig. 2(b)]. A closer look at the $\chi'(T)$ curves in Figs. 1(b), 1(c), and 1(d) at $H=40$ Oe, 100 and 120 Oe shows how the sharpening of the PE features results in an apparent increase in $T_p(H)$ [and $T_{dp}(H)$] values with increasing H. Above about 150 Oe, $T_p(H)$ values start to show the usual decrease with increase in H. A comparison of the $Tp(H)$ values and the shapes of the $\chi'(T)$ curves at $H=250$ Oe, 120 and 40 Oe [vertically stacked in Figs. 1(f), 1(d), and 1(b), respectively] helps to illustrate the non-monotonicity in the characteristics of the PE between 40 and 250 Oe, whatever may be the criterion chosen to precisely mark the peak temperatures. The shape of the $T_p(H)$ curve in Fig. 7 is reminiscent of the reentrant characteristic in the PE curve noted by Ghosh *et al.*[37] in 2H-$NbSe_2$.

We further note that the broadening and eventual disappearance of the PE phenomenon at fields less than 30 Oe is also similar to the behavior in $NbSe_2$. If we assume that the PE curve(s) separates the ordered and disordered phases of vortex matter then the absence of the PE at low fields (<30 Oe, where $a_0>1$ μm) amounts to the absence of an ordered phase, when the dilute vortices are individually pinned by the quenched random disorder in the atomic lattice. In analogy with the results in $NbSe_2$ (Ref. 37) and other LTSC systems,[22,24] we have chosen to label the vortex phase between the higher field upper portion of the $T_p(H)$ curve and the T_{dp} line as the pinned amorphous (analogous to the pinned liquid) phase and the vortex phase above the T_{dp} line as unpinned amorphous phase (akin to unpinned liquid). The pinned and unpinned amorphous phases get distinguished by their (contrasting) diamagnetic and paramagnetic ac (differential) shielding responses. Also, the hysteretic dc magnetic response in the pinned region is subjected to relaxation effects on long time scales as compared to the absence of such effects in unpinned region. The (H,T) region below the reentrant leg of the $t_p(H)$ curve at low fields has been termed as the ''reentrant disordered'' (and filled with dotted lines) in the Fig. 7. The reentrant disordered and pinned amorphous regions would overlap near the turnaround in the $t_p(H)$ curve. At temperatures above the turnaround feature ($t>0.99$), the vortex state remains disordered at all fields. However, below this temperature (i.e., $t<0.98$) an ordered vortex phase (presumably akin to an elastic/Bragg glass) exists between the high field upper portion of $T_{pl}(H)$ curve and the ''reentrant disordered'' phase.[46] The vortex phase between $T_{pl}(H)$ and $T_p(H)$ curves is expected to be plastically deformed[11,19] and has therefore been termed as the plastic glass (akin to the vortex glass),[22,38,46] detailed theoretical understanding of which is still lacking. The pinned plastic glass can, however, be distinguished from the above-mentioned pinned amorphous phase by the absence of thermomagnetic history dependence in the ac shielding response in the latter case. The vortex phase diagram in YBCO (in Figs. 5 and 7) thus shows a close resemblance with the generic phase diagram for a weakly pinned superconductor drawn by Banerjee *et al.*[38,46] on the basis of characteristics of the peak effect in the 2H-$NbSe_2$ system.

It is instructive to dwell a little more on the similarities in the present YBCO crystal and the 2H-$NbSe_2$ sample studied by Ghosh *et al.*[37] We note that the nose feature in T_p $[=T_p(H)/T_c(0)]$ curve occurs at nearly the same (H,t) value of (~ 100 Oe,~ 0.99) and the PE also disappears in both the samples at $H<30$ Oe. Further, the FLL spacing a_0 near the nose feature in $NbSe_2$ was comparable to its in-plane penetration depth λ_{ab}.[46] We find the similar correspondence in YBCO; a_0 at 100 Oe is $\approx 5.0\times 10^3$ Å and the measured value of λ is $\approx 5.5\times 10^3$ Å (Ref. 61) at $t\approx 0.99$ in another crystal of YBCO grown by flux growth technique. The upper portion of the t_p curve in 2H-$NbSe_2$ was fitted (see inset in Fig. 2 of Ghosh *et al.*[37]) to the FLL melting relation with the exponent $n=2$ and the prefactor H_0 $=\beta_m(c_l^4/G_i)H_{c2}(0)$, where the various symbols have their usual meaning.[1] It yielded the Lindemann number c_L in $NbSe_2$ as 0.17. Following Ghosh *et al.*,[37] we plot H versus $(1-T_p)^2$ in YBCO in the inset of Fig. 6. A linear fit to the data above 500 Oe in this inset yields $c_L \approx 0.25$ [where $H_{c2}(0) \approx 150$ T, $\beta_m = 5.6, G_i = 10^{-21}$] The disappearance of the PE at low fields is rationalized[37] by invoking the notion that the pinning length L_c and the entanglement length L_E become comparable [cf. Eqn. (6.47) of Ref. 1] at $H \approx 30$ Oe. Recalling once again the same relation, the L_c/L_E is given as

$$\frac{L_c}{L_E} \simeq \frac{\pi\kappa^2 \ln\kappa}{\sqrt{2}} \left(\frac{a_0}{2\pi\lambda(0)}\right)^2 \left(\frac{j_c}{G_i j_0}\right)^{1/2} \frac{(1-t)^{4/3}}{t}, \qquad (6)$$

where the various symbols have their usual meaning.[1] Note, how the L_c/L_E scales with the crucial parameters, like the Ginzburg number $G_i[=(1/2)(k_B T_c/H_c^2 \xi^3 \epsilon)^2]$ and the ratio J_c/j_0, where J_c and j_0 represent the critical current density and the depairing current density, respectively. The G_i in YBCO ($\approx 10^{-2}$) is expected to be two to three orders larger than that in 2H-$NbSe_2$,[19,37] but it is compensated by the extreme smallness of J_c/j_0 value ($\sim 10^{-5}$–10^{-6}) in typically clean crystals of 2H-$NbSe_2$ as compared to that ($\sim 10^{-2}$–10^{-3}) in a clean YBCO sample.[19] At fields below 30 Oe, where $L_c/L_E < 1$, the dilute vortex array is expected to be so disordered that it does not display any anomalous variation in $J_c(T)$ corresponding to an order-disorder transformation in an isofield scan. This order of magnitude estimate for the field value of disorder-order transition in FLL correlations appears consistent with isothermal Bitter decoration data in samples of YBCO (Ref. 62) and BSSCO.[63]

IV. CONCLUSION

In summary, we have reported the occurrence of the peak effect phenomenon for sparse vortex arrays at very low fields as well as for the dense vortex arrays at moderately high fields in a twinned crystal of YBCO. The data delineate the order-disorder transformation regions at low fields, where the interaction is weaker and the disorder effects of the thermal fluctuations and/or small bundle (or individual) pinning dominate. These observations at low fields agree with an earlier report[60] of a collapse of the irreversibility line in the (H,T) region close to $T_c(0)$ in the context of the YBCO system. But, in addition, it shows a close connection with the ‘‘noselike’’ turnaround feature in the locus of the peak effect in a LTSC 2H-$NbSe_2$ system.[37] The notion of the thermal softening of the vortex cores[64] has been invoked[60] for YBCO, whereas a connection with the reentrant melting/reentrant disordered phase was proposed for 2H-$NbSe_2$. Both ideas imply a transformation/crossover from an interaction dominated collective pinning behavior to a different regime, where pinning/depinning of vortex lines have to be considered in isolation. The observation of the complexity in the PE regime (at intermediate fields), which comprises the onset of a sudden shrinkage in the correlation volume[22,24] and the internal structure, reinforces the notion of a stepwise loss of vortex correlations. Carruzzo and Yu[65] have recently theoretically proposed a two-step softening process of the FLL, in which a first-order transition initially transforms an ordered vortex solid to a (defective) soft vortex solid that has smaller, but, still finite shear modulus. The latter solid in turn could undergo another first order transition to the vortex liquid state. Our present results call for more detailed study on the PE in different systems to explore the loss in order of the FLL. The presence of twin boundaries in YBCO (Ref. 10) is usually considered to be detrimental to the observation of a first order melting transition. However, in our case, the presence of twin boundaries has facilitated the observation of the peak effect at low fields. Further, a recent study of the first-order FLL melting transition on the twinned crystals of $NdBa_2Cu_3O_7$ (Ref. 66) also shows the usefulness of the twinned crystals to explore basic issues in vortex state physics. As a final remark, we recall that Grier *et al.*[63] and Horiuchi *et al.*[67] have directly demonstrated how the disordered dilute vortex arrays undergo transformation to an ordered phase as the interaction effect increases due to an increase in the vortex density either by an increase in the applied field[63,67] or, more interestingly, by the collation of the vortices around a strong pinning center.[67] Such studies in samples of YBCO and $NbSe_2$, which show reentrant characteristic in the peak effect curve, are highly desirable.

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[1] G. Blatter, M.V. Feigel'man, V.B. Geshkenbein, A.I. Larkin, and V.M. Vinokur, Rev. Mod. Phys. **66**, 1125 (1994).
[2] T. Giamarchi and P. Le Doussal, Phys. Rev. Lett. **72**, 1530 (1994); Phys. Rev. B **52**, 1242 (1995).
[3] M.J.P. Gingras and D.A. Huse, Phys. Rev. B **53**, 15 193 (1996).
[4] D. Ertas and D.R. Nelson, Physica C **272**, 79 (1996).
[5] J. Kierfield, T. Natterman, and T. Hwa, Phys. Rev. B **55**, 626 (1997).
[6] T. Giamarchi and P. Le Doussal, Phys. Rev. B **55**, 6577 (1997).
[7] H. Safar, P. Gammel, D.A. Huse, D.J. Bishop, W.C. Lee, J. Giapintzakis, and D.M. Ginsberg, Phys. Rev. Lett. **69**, 824 (1992); **70**, 3800 (1993).
[8] E. Zeldov, D. Majer, M. Konczykowski, V.M. Vinokur, and H. Shtrikman, Nature (London) **375**, 373 (1995).
[9] A. Schilling, R.A. Fisher, N.E. Phillips, U. Welp, D. Dasgupta, W.K. Kwok, and G.W. Crabtree, Nature (London) **382**, 791 (1996).
[10] K. Kwok, J.A. Fendrich, C.J. van der Beek, and C.W. Crabtree, Phys. Rev. Lett. **73**, 2614 (1994).
[11] W. Jiang, N.C. Yeh, T.A. Tombrello, A.P. Rice, and F. Holtzberg, J. Phys.: Condens. Matter **9**, 8085 (1997).
[12] T. Ishida, K. Okuda, and H. Asaoka, Phys. Rev. B **56**, 5128 (1997).
[13] J. Shi, X.S. Ling, D.A. Bonn, and W.M. Hardy, Phys. Rev. B **60**, R12 593 (1999).
[14] M. Daeumling, J.M. Seuntjens, and D.C. Larbalestier, Nature (London) **336**, 332 (1990); K. Deligiannis, P.A.J. de Groot, M. Oussena, S. Pifold, R.H. Langan, R. Gagnon, and L. Taillefer,

Phys. Rev. Lett. **79**, 2121 (1997).

[15] B. Khaykovich, E. Zeldov, D. Majer, T.W. Li, P.H. Kes, and M. Konczykowski, Phys. Rev. Lett. **76**, 2555 (1996).

[16] H. Küpfer, Th. Wolf, C. Lessing, A.A. Zhukov, X. Lanon, R. Meier-Hirmer, W. Schauer, and H. Wühl, Phys. Rev. B **58**, 2886 (1998), and references cited therein.

[17] T. Nishizaki, T. Naito, and N. Kobayashi, Phys. Rev. B **58**, 11 169 (1998); *ibid.* **53**, 82 (1996); J. Low. Temp. Phys. **105**, 1183 (1996).

[18] R.M. Langan, S.N. Gordeev, P.A.J. de Groot, A.G.M. Jansen, R. Gagnon, and L. Taillefer, Phys. Rev. B **58**, 14 548 (1998); S. Kokkaliaris, D.A.J. de Groot, S.N. Gordeev, A.A. Zhukov, R. Gagnon, and L. Taillefer, Phys. Rev. Lett. **82**, 5116 (1999).

[19] M.J. Higgins and S. Bhattacharya, Physica C **257**, 232 (1996), and references cited therein.

[20] K. Gloos, R. Modler, H. Schimanski, C.D. Bredl, C. Geibel, F. Steglich, A.I. Buzdin, N. Sato, and T. Komatsubara, Phys. Rev. Lett. **70**, 501 (1993); A. Ishiguro, A. Sawada, Y. Inada, J. Kimura, M. Suzuki, N. Sato, and T. Komatsubara, J. Phys. Soc. Jpn. **64**, 378 (1995).

[21] R. Wordenweber and P.H. Kes, Phys. Rev. B **34**, 494 (1986).

[22] S.S. Banerjee, N.G. Patil, S. Saha, S. Ramakrishnan, A.K. Grover, S. Bhattacharya, G. Ravikumar, P.K. Mishra, T.V. Chandrasekhar Rao, V.C. Sahni, M.J. Higgins, E. Yamamoto, Y. Haga, M. Hedo, Y. Inada, and Y. Onuki, Phys. Rev. B **58**, 995 (1998).

[23] K. Tenya, S. Yasunami, T. Tayama, H. Amitsuka, T. Sakakibara, M. Hedo, Y. Inada, E. Yamanoto, Y. Haga, and Y. Onuki, J. Phys. Soc. Jpn. **68**, 224 (1999), and references cited therein.

[24] S. Sarkar, D. Pal, S.S. Banerjee, S. Ramakrishnan, A.K. Grover, C.V. Tomy, G. Ravikumar, P.K. Mishra, V.C. Sahni, G. Balakrishnan, D.Mck. Paul, and S. Bhattacharya, Phys. Rev. B **61**, 12 394 (2000).

[25] A.B. Pippard, Philos. Mag. **19**, 217 (1969); A.M. Campbell and J.E. Evetts, Adv. Phys. **21**, 327 (1972), and references therein.

[26] A.I. Larkin and Yu.N. Ovchinnikov, J. Low Temp. Phys. **34**, 409 (1979).

[27] A.I. Larkin, M.C. Marchetti, and V.M. Vinokur, Phys. Rev. Lett. **75**, 2992 (1995); A. Gurevich and V.M. Vinokur, *ibid.* **83**, 3037 (1999).

[28] M.C. Cha and H.A. Fertig, Phys. Rev. Lett. **80**, 3851 (1998); C. Reichhardt, K. Moon, R. Scalettar, and G. Zimanyi, *ibid.* **83**, 2282 (1999).

[29] P.L. Gammel, U. Yaron, A.P. Ramirez, D.J. Bishop, A.M. Chang, R. Ruel, L.N. Pfeiffer, and E. Bucher, Phys. Rev. Lett. **80**, 833 (1998).

[30] I. Joumard, J. Marcus, T. Klein, and R. Cubitt, Phys. Rev. Lett. **82**, 4930 (1999).

[31] C. Bernhard, C. Wenger, Ch. Niedermayer, D.M. Pooke, J.L. Tallon, Y. Kotaka, J. Shimoyama, K. Kishio, D.R. Noakes, C.E. Stronach, T. Sembiring, and E.J. Ansaldo, Phys. Rev. B **52**, R7050 (1995); C.M. Aegerter, S.L. Lee, H. Keller, E.M. Forgan, and S.H. Lloyd, *ibid.* **54**, R15 661 (1996).

[32] T.V.C. Rao, V.C. Sahni, P.K. Mishra, G. Ravikumar, C.V. Tomy, G. Balakrishnan, D. Mck. Paul, C.A. Scott, S.S. Banerjee, N.G. Patil, S. Saha, S. Ramakrishnan, A.K. Grover, and S. Bhattacharya, Physica C **299**, 267 (1998).

[33] A.I. Larkin and Yu.N. Ovchinnikov, Zh. Éksp. Teor. Fiz. **65**, 1704 (1973) [Sov. Phys. JETP **38**, 854 (1974)].

[34] A.I. Larkin, J. Low Temp. Phys. **34**, 409 (1970).

[35] S.S. Banerjee, N.G. Patil, S. Ramakrishnan, A.K. Grover, S. Bhattacharya, G. Ravikumar, P.K. Mishra, T.V. Chandrasekhar Rao, V.C. Sahni, M.J. Higgins, C.V. Tomy, G. Balakrishnan, and D.Mck. Paul, Phys. Rev. B **59**, 6043 (1999).

[36] P.H. Kes, Nature (London) **376**, 729 (1995); L.A. Angurel, F. Amin, M. Polichetti, J. Aarts, and P.H. Kes, Phys. Rev. B **56**, 3425 (1997).

[37] K. Ghosh, S. Ramakrishnan, A.K. Grover, Gautam I. Menon, Girish Chandra, T.V. Chandrasekhar Rao, G. Ravikumar, P.K. Mishra, V.C. Sahni, C.V. Tomy, G. Balakrishnan, D.Mck. Paul, and S. Bhattacharya, Phys. Rev. Lett. **76**, 4600 (1996).

[38] S. S. Banerjee, S. Ramakrishnan, D. Pal, S. Sarkar, A. K. Grover, G. Ravikumar, P. K. Mishra, T. V. Chandrasekhar Rao, V. C. Sahni, C. V. Tomy, M. J. Higgins, and S. Bhattacharya, *Workshop on Frontiers in Magnetism, Kyoto, 1999* [J. Phys. Soc. Jpn. (Suppl.) **69**, 262 (2000)].

[39] D.R. Nelson, Phys. Rev. Lett. **60**, 1973 (1988).

[40] The crystals selected for elucidating the melting transition in calorimetric data typically have very low levels of quenched impurities.

[41] S. Ramakrishnan, S. Sundaram, R.S. Pandit, and G. Chandra, J. Phys. E **18**, 650 (1985).

[42] The untwinned crystal in which a giant PE was reported at high fields in Ref. 13 had 10–90 % width of 0.85 K.

[43] C.P. Bean, Rev. Mod. Phys. **38**, 36 (1964).

[44] X. S. Ling and J. I. Budnick, in *Magnetic Susceptibility of Superconductors and other Spin Systems*, edited by R. A. Hein, T. L. Francavilla, and D. H. Leibenberg (Plenum Press, New York, 1991), p. 377.

[45] N. G. Patil *et al.*, in *Advances in Superconductivity: New Materials, Critical Currents and Devices*, edited by R. P. Pinto *et al.* (New Age International Ltd. Publishers, New Delhi, India, 1997), p. 335.

[46] S.S. Banerjee, S. Saha, N.G. Patil, S. Ramakrishnan, A.K. Grover, S. Bhattacharya, G. Ravikumar, P.K. Mishra, T.V.C. Rao, V.C. Sahni, C.V. Tomy, G. Balakrishnan, D.Mck. Paul, and M.J. Higgins, Physica C **308**, 25 (1998).

[47] R.A. Hein and R.A. Falge, Jr., Phys. Rev. **123**, 407 (1961).

[48] N. Morozov, E. Zeldov, D. Majer, and M. Konczykowski, Phys. Rev. B **54**, R3784 (1996).

[49] A.F. Khoder, M. Couach, and J.L. Jorda, Phys. Rev. B **42**, 8714 (1990).

[50] A.K. Grover *et al.*, Physica C **220**, 353 (1994); Pramana, J. Phys. **42**, 193 (1994); and Y. Yamaguchi *et al.*, in *Advances in Superconductivity VII*, edited by K. Yamafuji and T. Morishita (Springer-Verlag, Tokyo, Japan, 1995), p. 205.

[51] G. Ravikumar, P.K. Mishra, V.C. Sahni, S.S. Banerjee, S. Ramakrishnan, A.K. Grover, P.L. Gammel, D.J. Bishop, E. Bucher, M.J. Higgins, and S. Bhattacharya, Physica C **322**, 145 (1999).

[52] S.S. Banerjee, N.G. Patil, S. Ramakrishnan, A.K. Grover, S. Bhattacharya, G. Ravikumar, P.K. Mishra, T.V. Chandrasekhar Rao, V.C. Sahni, and M.J. Higgins, Appl. Phys. Lett. **74**, 126 (1999).

[53] P.L. Gammel, D.J. Bishop, G.J. Dolan, J.R. Kwo, C.A. Murray, L.F. Scneemeyer, and J.V. Waszczozak, Phys. Rev. Lett. **59**, 2592 (1987).

[54] M. V. Marchvesky, Ph.D. thesis, University of Leiden, The Netherlands, 1997.

[55] M. Steingart, A.G. Pute, and E.J. Kramer, J. Appl. Phys. **44**, 5580 (1973).

[56] R. Wordenweber, P.H. Kes, and C.C. Tsuei, Phys. Rev. B **33**, 3172 (1986).
[57] W. Henderson, E.Y. Andrei, M.J. Higgins, and S. Bhattacharya, Phys. Rev. Lett. **77**, 2077 (1996).
[58] G. Ravikumar, V.C. Sahni, P.K. Mishra, T.V.C. Rao, S.S. Banerjee, A.K. Grover, S. Ramakrishnan, S. Bhattacharya, M.J. Higgins, E. Yamamoto, Y. Haga, M. Hedo, Y. Inada, and Y. Onuki, Phys. Rev. B **57**, R11069 (1998).
[59] S.S. Banerjee, S. Ramakrishnan, A.K. Grover, G. Ravikumar, P.K. Mishra, V.C. Sahni, C.V. Tomy, G. Balakrishnan, D.Mck. Paul, M.J. Higgins, S. Bhattacharya, Proceedings of the First European Conference on the Vortex State, Crete, Greece, 1999 [Physica C **332**, 135 (2000)].
[60] L. Krusin-Elbaum, L. Civale, F. Holtzberg, A.P. Malozemoff, and C. Field, Phys. Rev. Lett. **67**, 3156 (1991).
[61] S. Kamal, D.A. Bonn, N. Goldenfeld, P.J. Hirschfeld, R. Liang, and W.N. Hardy, Phys. Rev. Lett. **73**, 1845 (1994).
[62] G.J. Dolan, G.V. Chandrasekhar, T.R. Dinger, C. Feild, and F. Holtzberg, Phys. Rev. Lett. **62**, 827 (1989).
[63] C.A. Murray, P.L. Gammel, D.J. Bishop, D.B. Mitzi, and A. Kapitulnik, Phys. Rev. Lett. **64**, 2312 (1990); D.G. Grier, C.A. Murray, C.A. Bolle, P.L. Gammel, D.J. Bishop, D.B. Mitzi, and A. Kapitulnik, *ibid.* **66**, 2270 (1992).
[64] M.V. Feigel'man and V.M. Vinokur, Phys. Rev. B **41**, 8986 (1990).
[65] H.M. Carruzzo and C.C. Yu, Philos. Mag. B **77**, 1001 (1998).
[66] A.K. Pradhan, S. Shibata, K. Nakao, and N. Koshizuka, Europhys. Lett. **46**, 787 (1999).
[67] S. Horiuchi, M. Catoni, M. Uchida, T. Tsurta, and Y. Matsi, Appl. Phys. Lett. **73**, 1293 (1998); Bull. Mater. Sci. **22**, 227 (1999).