Instabilities in the Vortex Matter and the Peak Effect Phenomenon

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In single crystals of 2H-$NbSe_2$, we identify for the first time a crossover from a weak collective to a strong pinning regime in the vortex state which is not associated with the peak effect phenomenon. Instead, we find the crossover is associated with an anomalous history dependent magnetization response. In the dc magnetic field (B_{dc})-temperature (T) vortex matter phase diagram we demarcate this pinning crossover boundary. We also delineate another boundary which separates the strong pinning region from a thermal fluctuation dominated regime, and find that a peak effect appears on this boundary.

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The statics and dynamics of elastic media in a random pinning environment is common to a variety of systems like the vortex state in superconductors [1], Wigner crystals [2], charge density waves [3], magnetic domains [4], etc. The elastic vortex matter experiences a perennial tussle between elastic forces trying to order it and thermal fluctuations and pinning trying to disorder it, leading to a variety of phenomenon. Two widely observed phenomena are the thermally driven first order melting [1] of the vortex lattice in high T_c superconductors and the peak effect (PE) [5] in low T_c superconductors. While both phenomena are related to disordering of the vortex lattice, the PE phenomenon still lacks a comprehensive understanding. The ubiquitous PE phenomenon widely observed in a large variety of superconductors is an anomalously large enhancement in the critical current density (J_c) (or equivalently the pinning force density $= \vec{J}_c \times \vec{B}_{dc}$) close to the superconducting-normal boundary. While it is known that the vortex configuration changes across the PE, viz., the ordered vortex lattice disorders [6], one is yet to be certain about the mechanism which triggers the rise in pinning across the PE. To date no theory has been able to quantitatively explain the extent of rise in J_c across the PE. Many theories [7–10] have investigated the effects of pinning (both weak and strong) on the configuration of vortices in isotropic and anisotropic superconductors [11]. The vortex configuration in a sample with strong intrinsic pinning is more disordered [9] than a sample with weaker pinning [10]. However, in a sample with both weak and strong pins, how does the vortex matter behave? To understand the mechanism of PE, it maybe relevant to look at the different pinning regimes possible in the vortex matter. In literature two major pinning regimes for vortices have been identified. On the one hand the collective pinning theory (CP) [7,8] describes the collective action of *weak pins* and on the other the flux pinning theory by Labusch [12] describes the independent action of *strong pinning* centers on vortices. The effective pinning force in the CP theory is determined by calculating the extent of short range order present in the vortex matter created by weak pins trying to distort the rigid elastic medium of the vortex lattice. The Labusch theory, on the other hand, determines the pinning force from the competition of strong pins trying to distort an elastic vortex line. A recent theory [13] argues that the PE phenomenon occurs naturally due to an increase in pinning (and hence in J_c) associated with a crossover from the weak collective to a strong pinning regime. In this Letter based on magnetization measurements we identify the weak to strong pinning crossover regime and find that it is associated with only a small change in J_c, which is very much unlike PE. Rather than being associated with the crossover in pinning, we find that the PE phenomenon is situated in a special region of the phase diagram, which is on a boundary separating the strong pinning regime from a region dominated by thermal fluctuations, implying that the phenomenon is a complex superposition of both pinning and fluctuation effects.

Nature of Pinning in the static state of the vortex matter was investigated by measuring the ac susceptibility and dc magnetization response in two single crystals of 2H-$NbSe_2$ (No. 1 and No. 2), using a commercial Quantum Design SQUID magnetometer (Model No. MPMS-XL5)and an Oxford VSM (Model No. 3001). The two crystals have similar average dimensions of $1.5 \times 1.5 \times 0.1$ mm^3 and $T_c(0) \approx 7.2$ and 7.1 K respectively. To search for the weak to strong pinning crossover we selected single crystals with very weak pinning (i.e., $J_c \sim 500$ A/cm^2 at 5.0 K). To reduce the possibility of strong pinning generated by extended defects likely to be present along the c axis in layered 2H-$NbSe_2$ and, also, to avoid geometric and surface barrier effects which persist up to the PE in $B_{dc} \parallel c$ orientation [14], we have chosen the $B_{dc} \parallel ab$ direction for our measurements. Because of the layered nature of 2H-$NbSe_2$, conventional transport measurements are difficult in $B_{dc} \parallel ab$ orientation.

The ac susceptibility response (χ' and χ'') of the sample was recorded as a function of T at fixed B_{dc} for different values of the ac magnetic field (h_{ac}) at a frequency of 211 Hz, on the SQUID magnetometer using the reciprocating sample option (RSO) for increased sensitivity and to reduce field inhomogeneity artifacts (Ref. http://www.qdusa.com/resources/pdf/mpmsappnotes/1014-820.pdf). Shown in Fig. 1(a) is the $\chi'(T)$ response for $B_{\rm dc} = 100$ G for different $h_{\rm ac}$. Anomalous enhancement in pinning associated with the PE causes the sample to shield the penetrating $h_{\rm ac}$ more efficiently from within its interior, thereby enhancing the diamagnetic (χ') response at the onset of PE, which begins at around 7.04 K in Fig. 1(a). For interpreting our results, it would be worthwhile to recall that χ'' is a measure of the dissipation [15] caused by the dragging of *normal* vortex cores which are oscillating under the influence of the periodically varying $h_{\rm ac}$. Insufficient penetration of $h_{\rm ac}$ into the sample or an enhancement in the pinning of vortices corresponds to a low χ'' response. From Fig. 1(b) it is clear that for $h_{\rm ac} < 1$ G and at low T, due to almost complete shielding of the probing $h_{\rm ac}$ from the bulk of the sample, the χ'' (T) response is nearly zero. Figure 1(b) shows that at fixed T (at say $T = 6.7$ K) as $h_{\rm ac}$ increases, the χ'' response also increases monotonically. Full penetration of $h_{\rm ac}$ up to the sample center causes a significant rise in dissipation in the sample, which in turn leads to a broad maximum in the χ'' response [16] [location marked as A in Fig. 1(b) for $h_{\rm ac} = 2$ G]. At the PE region due to enhancement in pinning we observe a drop in the dissipation (χ'') response [marked as T_p in Fig. 1(b)]. Beyond T_p, dissipation has a tendency to rise sharply before decreasing close to $T_c(B)$ (we discuss this feature in the next section).

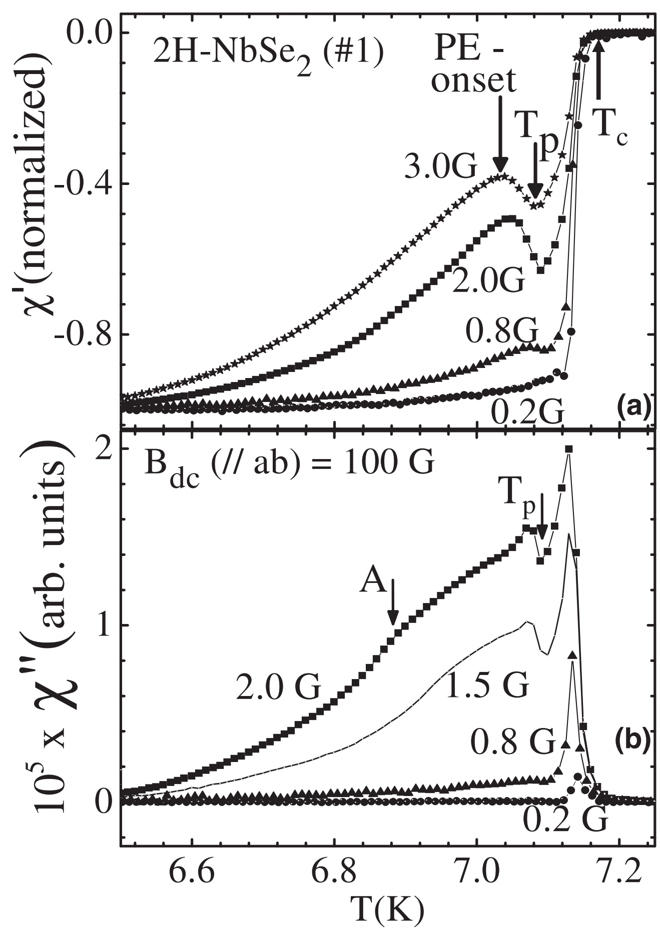

FIG. 1. The panels (a) and (b) show $\chi'(T)$ and $\chi''(T)$ response for $B_{\rm dc} = 100$ G($\parallel ab$) at different $h_{\rm ac}$, with $f = 211$ Hz.

Figure 2 shows the behavior of $\chi''(T)$ response at different $B_{\rm dc}$ (>750 G). From $\chi'(T)$ we find PE disappears above 750 G in our crystals. For $B_{\rm dc} = 12500$ G, we have identified three distinct regimes of behavior in the $\chi''(T)$ response. In region 1, the high dissipation response emanates from full penetration of $h_{\rm ac}$ to the center of the sample [16], similar to the response at A in Fig. 1(b). One would have expected that in the absence of the PE phenomenon, if the pinning in the vortex state did not change then beyond region 1 the χ'' response should have smoothly joined the enhanced dissipation regime [similar to region beyond T_p in Fig. 1(b)] close to $T_c(B)$. Instead, in the cross shaded region 2 we see a new behavior in the dissipation (χ'') response; viz., in this region located between the two arrows there is a substantial decrease in the dissipation. Figure 2(a) shows the onset of the drop in dissipation (marked as $T_{\rm cr}$) determined from the derivative, $d\chi''/dT$. Subsequent to the drop in $\chi''(T)$ in region 2, the dissipation response attempts to show an abrupt increase at the onset of region 3 [marked as $T_{\rm fl}$ in Figs. 2 and 2(a)]. The abrupt increase in dissipation beyond $T_{\rm fl}$ is more pronounced at low B and high T. For $B_{\rm dc} < 750$ G, the $T_{\rm fl}$ location is the same as T_p [see Fig. 1(b) where dissipation enhances above $T_p = T_{\rm fl}$]. Figure 2(b) shows the absence of PE at $T_{\rm cr}$ in the $\chi'(T)$ response at 1000 G and 12 500 G, indicating that the anomalous drop in dissipation in region 2 is not associated with the PE phenomenon. An alternative way of investigating the nature of pinning above $T_{\rm cr}$ is by quenching the vortex state [field cooling (FC)]

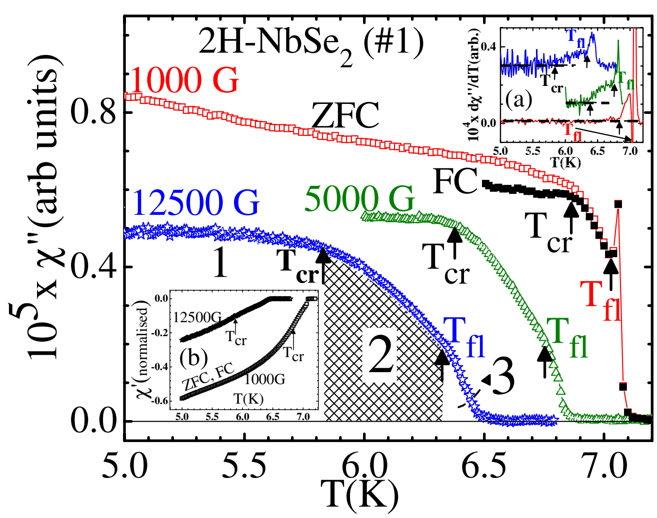

FIG. 2 (color online). Indicates the dissipation regimes in the $\chi''(T)$ response measured at $h_{\rm ac} = 2$ G and $f = 211$ Hz at 1000 G (red squares), 5000 G (green triangles) and 12 500 G (blue stars). Inset (a) shows $T_{\rm cr}$ and $T_{\rm fl}$ in $d\chi''/dT$ for different $B_{\rm dc}$ (cf. main panel). Inset (b) shows the absence of PE at $T_{\rm cr}$ in the $\chi'(T)$ response.

from $T > T_{cr}$. Our observation of a low dissipation (χ'') response in the FC state (cf. Fig. 2 at 1000 G) implies that the pinning enhances across T_{cr}. Above T_{cr} the high pinning regime exists till T_{fl}. The tendency of the dissipation to rapidly rise close to $T_{fl}(B)$ is a behavior which is expected across the irreversibility line (T_{irr}), where the bulk pinning in the superconductors vanishes. We have confirmed that $T_{fl}(B)$ coincides with $T_{irr}(B)$, by comparing dc magnetization with χ'' response measurements (cf. arrow marked as $T_{fl} = T_{irr}$ in Fig. 3).

Figure 3 shows the magnetization hysteresis in the two crystals of 2H-$NbSe_2$ measured on a SQUID and VSM. Figure 3(a) shows the hysteresis loop recorded at 6 K. A striking feature of the M-H loop is the asymmetry in the forward (M_{for}) and reverse (M_{rev}) legs of the magnetization hysteresis response. A feature which can easily be missed on the scale of the full hysteresis loop is the small change in curvature [marked with an arrow in Fig. 3(a)] on the M_{rev} leg. In the main panel of Fig. 3, we have plotted only the M_{rev} recorded at different T. At the locations marked with arrows in Fig. 3 there is a substantial change in slopes of the M_{rev} curves. The characteristic bump-like feature (marked with the arrow) is observed at different T and only on the M_{rev} curve but not on the M_{for} leg. This strong history dependence is in a region of the B-T phase diagram, which is far from the PE region. We have confirmed all the above new features in ac and dc magnetization measurements in sample No. 2 with similar weak pinning in the $B_{dc} \parallel ab$ orientation.

Figure 4 shows the B_{dc}-T, vortex matter phase diagram wherein we show the location of the $T_c(B)$ line which is determined by the onset of diamagnetism in $\chi'(T)$, the $T_p(B)$ line which denotes the location of the PE phenomenon, the $T_{cr}(B)$ line across which the $\chi''(T)$ response (shaded region 2 in Fig. 2) shows a substantial decrease in the dissipation and the T_{fl} line beyond which dissipation attempts to increase. The PE ceases to be a distinct noticeable feature beyond 750 G and the T_p line continues as the T_{fl} line. Unlike the behavior [17] of the $T_p(B)$ line, which usually runs parallel to $T_c(B)$, the $T_{cr}(B)$ line has a distinct curvature that extrapolates to zero close to $T_c(0) \sim 7.2$ K.

We consider the $T_{cr}(B)$ line as a crossover in the pinning strength experienced by vortices, which occurs well prior to the PE. A criterion [1,13] for weak to strong pinning crossover is that the change in the pinning force far exceeds the change in the elastic energy of the vortex lattice, due to pinning induced distortions of the vortex line. This can be expressed as [13] the pinning force (f_p) ~ Labusch force (f_{Lab}) = ($\epsilon_0 \xi / a_0$), where $\epsilon_0 = (\phi_0 / 4\pi\lambda)^2$ is the energy scale for the vortex line tension, ξ is the coherence length, ϕ_0 is the flux quantum associated with a vortex, λ is the penetration depth, and a_0 is the inter vortex spacing ($a_0 \propto B^{-0.5}$). A softening of the vortex lattice satisfies the criterion for the crossover in pinning. At the crossover in pinning we have a relationship, $a_0 \approx \epsilon_0 \xi f_p^{-1}$. At $B = B_{cr}$ and far away from T_c, if we use a monotonically decreasing temperature dependent function for $f_p \sim f_{po}(1 - t)^{\beta}$, where $t = T/T_c(0)$ and $\beta > 0$, then we obtain the relation $B_{cr}(T) \propto (1 - t)^{2\beta}$. We have used the form derived for $B_{cr}(T)$ to obtain a good fit [bottom dotted line (red online) in Fig. 4] for $T_{cr}(B)$ data, giving $2\beta \sim 1.66 \pm 0.03$. Inset of Fig. 4 is a log-log plot of the width of the magnetization loop (ΔM) versus B_{dc}. Upon reducing the B_{dc} from B_{c2}, $\Delta M \propto J_c$ (or equivalently pinning) increases up to B_{cr}. ΔM subsequently decreases at $B < B_{cr}$ and smoothly crosses over to a weak collective pinning regime. The weak collective pinning regime [18] is characterized by the region shown in the inset, viz., the range of B_{dc} values wherein the measured $\Delta M(B)$ open circles (red online) coincides with

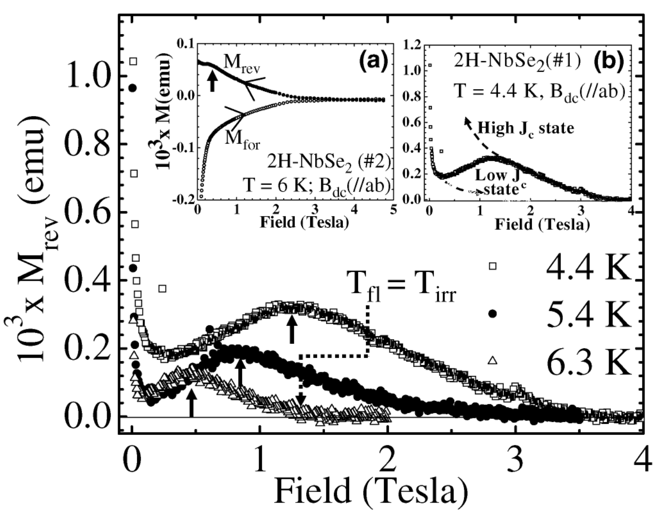

FIG. 3. $M_{rev}(B)$ at different T measured for sample No. 1. Inset (a) shows the full magnetization hysteresis loop. The arrow in inset (b) shows the "bump" in $M_{rev}(B)$. Also schematically illustrated are the two branches of magnetization response which correspond to vortex states with high and low J_c (or pinning).

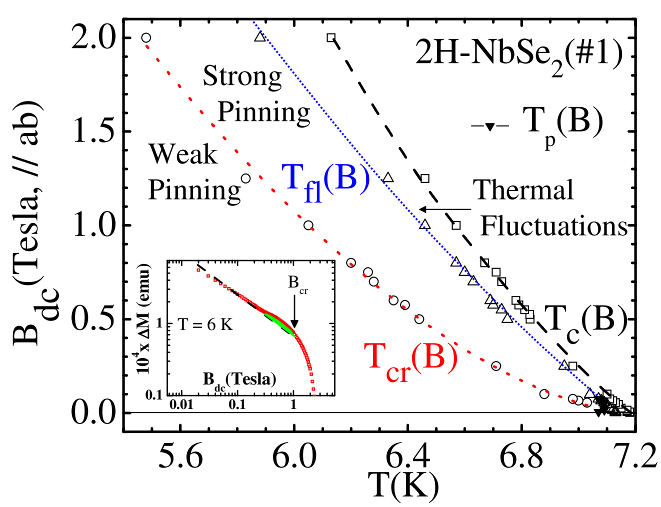

FIG. 4 (color online). Phase diagram showing the $T_{cr}(B)$, $T_p(B)$, $T_{fl}(B)$, and $T_c(B)$ boundaries. The inset is a log-log plot of ΔM versus B_{dc}. Refer to discussion in text.

the black dashed line, viz., $\Delta M \propto J_c \propto 1/B_{\rm dc}^p$ with p a positive integer. The shaded region (in green online) in the $\Delta M(B)$ plot shows the excess pinning that develops due to the pinning crossover across $B_{\rm cr}$. The distinctness of the $T_{\rm cr}$ and T_p lines in Fig. 4 shows that the excess pinning associated with the pinning crossover does not produce any PE. Based on the above discussion we surmise that the $T_{\rm cr}(B)$ line marks the onset of an instability in the static vortex lattice due to which there is a crossover from weak (region 1 in Fig. 2) to a strong pinning regime (region 2 in Fig. 2). The crossover in pinning produces interesting history dependent response in the superconductor, as seen in the $M_{\rm rev}$ measurements of Fig. 3 and in the $\chi''(T)$ response for the zero field cooled response (ZFC) and FC vortex states, in Fig. 2. In Fig. 3(b) we have schematically identified the pinning crossover by distinguishing two different branches in the $M_{\rm rev}(B)$ curve, which correspond to magnetization response of vortex states with high and low J_c. The reasons for the instability across $T_{\rm cr}(B)$ could be a softening of the elastic modulii of the lattice due to the proliferation of topological defects in the static vortex lattice [10]. It is interesting to note that a similar behavior has been observed in the driven vortex state, as deduced from transport measurements [19]. We reiterate that the onset of instability in the vortex lattice sets in well prior to PE phenomenon without producing the anomalous PE.

As the strong pinning regime commences upon crossing $B_{\rm cr}$, how then does pinning dramatically enhance across PE? The $T_{\rm fl}(B)$ line in Fig. 4 marks the end of the strong pinning regime of the vortex state. Above the $T_{\rm fl}(B)$ line and close to $T_c(B)$, the tendency of the dissipation response to increase rapidly (Figs. 1 and 2) especially at low B and high T, implies that thermal fluctuation effects dominate over pinning. We find that our values ($B_{\rm fl}$, $T_{\rm fl}$) in Fig. 4, satisfies the equation governing the melting of the vortex state [1], viz., $B_{\rm fl} = \beta_m(\frac{c_L^4}{G_i})H_{c2}(0)(\frac{T_c}{T_{\rm fl}})^2[1 - \frac{T_{\rm fl}}{T_c} - \frac{B_{\rm fl}}{H_{c2}(0)}]^2$, where, $\beta_m = 5.6$ (Ref. [1]), Lindemann No. $c_L \sim 0.25$ (Ref. [6], Troyanovski *et al.*), $H_{c2}^{\|ab}(0) = 14.5$ T, if a parameter, G_i is in the range of 1.5×10^{-3} to 10^{-4}. The Ginzburg number, G_i, in the above equation controls the size of the $B_{\rm dc}$-T region in which thermal fluctuations dominate. A value of $O(10^{-4})$ is expected for 2H-$NbSe_2$ (Ref. [17], Higgins *et al.*). The above discussion implies a thermal fluctuations dominated regime exists beyond $T_{\rm fl}(B)$. By noting that $T_p(B)$ appears very close to $T_{\rm fl}(B)$ it seems that PE appears on the boundary separating strong pinning and thermal fluctuation dominated regimes.

To summarize, we have found evidence in dissipation (χ'') measurements for a weak to strong pinning crossover in very weakly pinned crystals of 2H-$NbSe_2$. We have found that the pinning crossover is located far from the PE region, and is also associated with interesting history dependent magnetization response. Our observations imply that instabilities developing within the elastic vortex lattice (perhaps softening) leads to the crossover in pinning which occurs well before the PE. In fact, PE seems to sit on a boundary which separates a strong pinning dominated regime from a thermal fluctuation dominated regime. Our assertion has significant ramifications pertaining to the origin of PE which was originally attributed to a softening of the elastic modulii of the vortex lattice [5]. Even though thermal fluctuations try to reduce pinning, we believe our results show that through PE the two combine in a nontrivial way to enhance the pinning dramatically. The close proximity of PE to the thermal fluctuation dominated regime implies that, perhaps, one also needs to investigate the nature of the superconducting order parameter in the PE region. We speculate that PE maybe be influenced by effects related to a weakening of the superconducting order parameter close to $T_c(B)$, making the superconductor more susceptible to local perturbations close to this region. We hope our results would pave the way for a fresh approach towards understanding the origins of the puzzling phenomenon of PE.

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[1] G. Blatter *et al.*, Rev. Mod. Phys. **66**, 1125 (1994).
[2] R. Chitra, T. Giamarchi, and P. Le Doussal, Phys. Rev. B **65**, 035312 (2001) and references therein.
[3] G. Gruner, Rev. Mod. Phys. **60**, 1129 (1988) and references therein.
[4] S. Lemerle *et al.*, Phys. Rev. Lett. **80**, 849 (1998); V. Repain *et al.*, Europhys. Lett. **68**, 460 (2004).
[5] A. B. Pippard, Philos. Mag. **19**, 217 (1969).
[6] X. S. Ling *et al.*, Phys. Rev. Lett. **86**, 712 (2001); A. M. Troyanovski *et al.*, Phys. Rev. Lett. **89**, 147006 (2002).
[7] A. I. Larkin, Sov. Phys. JETP **31**, 784 (1970).
[8] A. I. Larkin and Y. N. Ovchinnikov, J. Low Temp. Phys. **34**, 409 (1979).
[9] D. S. Fisher, M. P. A. Fisher, and D. A. Huse, Phys. Rev. B **43**, 130 (1991).
[10] T. Giamarchi and P. Le Doussal, Phys. Rev. B **52**, 1242 (1995) and reference therein.
[11] J. P. Rodriguez, Phys. Rev. B **73**, 214520 (2006).
[12] R. Labusch, Cryst. Lattice Defects **1**, 1 (1969).
[13] G. Blatter, V. B. Geshkenbein, and J. A. G. Koopmann, Phys. Rev. Lett. **92**, 067009 (2004).
[14] Y. Paltiel *et al.*, Phys. Rev. B **58**, R14763 (1998).
[15] X. S. Ling and J. Budnick, *Magnetic Susceptibility of Superconductors and Other Spin Systems*, edited by R. A. Hein, T. L. Francavilla, and D. H. Leibenberg (Plenium Press, New York, 1991), p. 377.
[16] L. A. Angurel *et al.*, Phys. Rev. B **56**, 3425 (1997).
[17] S. S. Banerjee *et al.*, Phys. Rev. B **62**, 11 838 (2000) and reference therein; M. J. Higgins and S. Bhattacharya, Physica (Amsterdam) **257C**, 232 (1996).
[18] A. Duarte *et al.*, Phys. Rev. B **53**, 11 336 (1996).
[19] G. Li *et al.*, Phys. Rev. Lett. **96**, 017009 (2006).