Anomalous peak effect in $CeRu_2$ and $2H$-$NbSe_2$: Fracturing of a flux line lattice

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$CeRu_2$ and $2H$-$NbSe_2$ display remarkable similarities in their magnetic response, reflecting the manner in which the weakly pinned flux line lattice (FLL) loses spatial order in the peak-effect (PE) regime. We present evidence for discontinuous changes in the screening response near the onset of the PE in these systems, and demonstrate history-dependent effects. We attribute these features to a disorder-induced fracturing and entanglement of the FLL, as an alternative to the appearance of a spatially modulated ground state for $CeRu_2$. [S0163-1829(98)05725-7]

The process by which a flux line lattice (FLL) loses spatial order in the presence of random pins is a subject of great current interest[1] in a variety of high-T_c and low-T_c superconducting systems. A physical phenomenon that relates to this process is the peak effect (PE), which is the occurrence of a peak in critical current density J_c of the system below its normal phase boundary.[2] Numerous recent studies[3–13] of the PE have been reported in several low-T_c systems and these include two very dissimilar compounds: the cubic Laves phase ($C15$) intermetallic $CeRu_2$ (Refs. 4–8) and the layered dichalcogenide $2H$-$NbSe_2$.[9–13] An abrupt transition between weak and strong magnetic irreversibility (i.e., the PE) in the vortex state of $CeRu_2$ has been attributed[6] to the appearance of a generalized Fulde-Ferrel-Larkin-Ovchinnikov (GFFLO) state, which is characterized by superconducting order parameter having nodes in real space along the flux lines,[6,14,15] and is believed to occur in systems with large normal state electronic susceptibility.[14] For the GFFLO state, vortex line(s) can become segmented into coupled pieces of lengths comparable to the wavelength of the modulation in the order parameter, and these segments could conform more easily to the inevitably present pinning centers, thereby enhancing pinning. The $2H$-$NbSe_2$ system is being widely pursued[9–13] due to its weak pinning property ($J_c/J_0 \sim 10^{-6}$ in its cleanest samples;[9] J_0 is the depairing current density). Moreover, the pronounced nature of PE in $2H$-$NbSe_2$ undergoes a rich evolution when the quenched disorder is varied.[12] Indeed, recent transport J_c measurements along different (H,T) paths in both $CeRu_2$ and $2H$-$NbSe_2$ display similar features.[7,10] Since the latter has a small normal state susceptibility,[9] it is not a candidate for the GFFLO state. This raises the question : *Is the PE in $CeRu_2$ of an origin different from that in $NbSe_2$, or do their magnetic responses elucidate the transformations generic to a weakly pinned FLL while approaching its normal phase boundary?*

In this paper, we present results of dc and ac magnetization studies in $CeRu_2$ and $2H$-$NbSe_2$, which show their remarkable similarity. In particular, both systems show *two* discontinuous transformations in the in-phase ac susceptibility (χ'), one at the onset of PE and the other at the peak of the PE. We propose that an explanation for the observed phenomenon is to be found in the process of *loss of order* of the FLL , namely, the occurrence of a fracturing and/or entanglement of the FLL, and does not, *a priori*, require the realization of a GFFLO state in $CeRu_2$.[6,14]

The experimental data are obtained from a standard Quantum Design Inc. superconducting quantum interference device magnetometer and an ac susceptometer.[16] The crystal of $CeRu_2$ ($2.75\times1.45\times0.9$ mm^3) with $T_c(0)\approx6.3$ K is the same as the one used for a de Haas–van Alphen study,[17] and

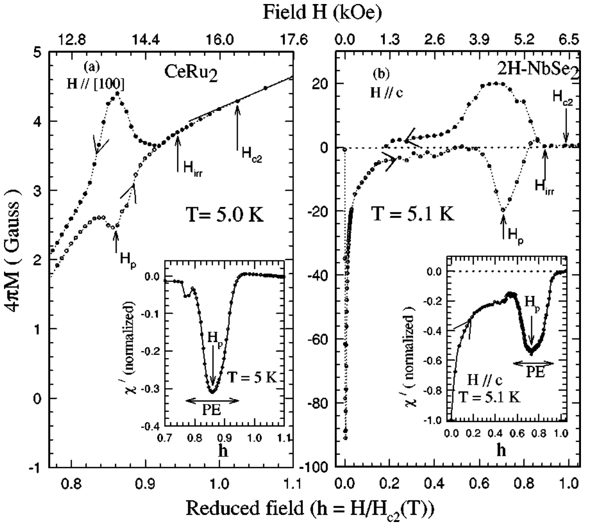

FIG. 1. Panels (a) and (b) show M-H curves in $CeRu_2$ and $2H$-$NbSe_2$, respectively, at the temperatures indicated. The insets in (a) and (b) show the in-phase ac $[f=211$ Hz, $h_{ac}=0.5$ Oe (rms)] susceptibility (χ') vs H. [The width of the hysteresis bubble in $CeRu_2$ in panel (a) is about ten times smaller than that in $2H$-$NbSe_2$ in panel (b), though the two samples have comparable physical dimensions. Transport J_c in $CeRu_2$ and $2H$-$NbSe_2$ are estimated to be $\sim 10^2$ and $\sim 10^3$ A/cm^2, respectively.]

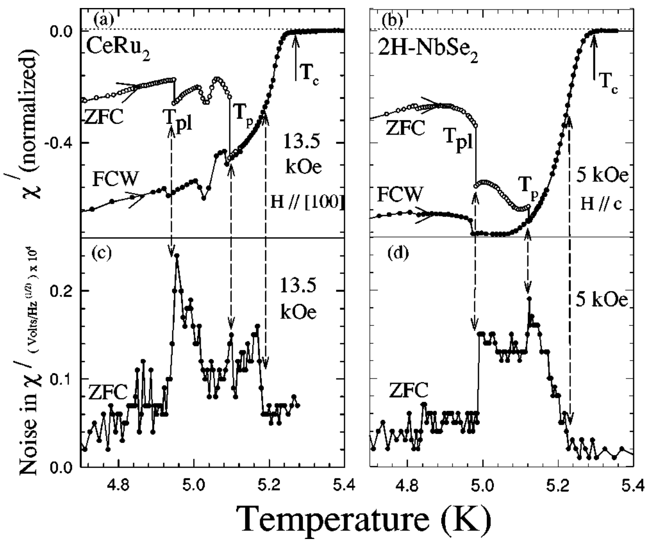

FIG. 2. $\chi'(T)$ in crystals of $CeRu_2$ and $2H$-$NbSe_2$ at dc fields as indicated. The upper panels (a) and (b) show χ' response recorded during warm-up (W) from the lowest temperature $(\sim 4$ K) for FLL prepared in ZFC and FC modes. The lower panels (c) and (d) show the noise signal in χ' for FLL prepared in ZFC mode. The noise signal shows jumps at T_{pl} and T_p, and returns to the background level between T_p and T_c. χ' data shown are obtained at the same values of frequency and ac amplitude $[f=211$ Hz, $h_{ac}=0.5$ Oe (rms)], though all features in focus are independent of frequency $(10-10^3$ Hz) and amplitude $(0.1-2$ Oe).

the crystal of $2H$-$NbSe_2$ $(2\times1.5\times0.3$ mm$^3)$ with $T_c(0)\approx 6$ K is from the same batch utilized by Henderson *et al.*[10] In the two crystals, the values of $R_{300\,K}/R_{7\,K}$ are 13 and 11, respectively and they appear to have similar levels of quenched disorder leading to comparable levels of (weak) pinning as obtained from dc magnetization hysteresis data in the PE region. Furthermore, they also have comparable values of the Ginzburg parameter (defined as the ratio of thermal energy to condensation energy[1]), Gi$\approx 5\times10^{-4}$ and $\approx 3\times10^{-4}$ in $CeRu_2$ and $2H$-$NbSe_2$, respectively. These values are considerably larger than those for typical low-T_c alloy systems (but smaller than those for the high-T_c cuprates[9]), thereby implying the possible importance of thermal fluctuation effects in the systems under study. $CeRu_2$ is almost isotropic $(\epsilon\approx1.05)$ and $2H$-$NbSe_2$ is anisotropic $(\epsilon \approx 3.3)$. However, PE in the latter system is observed in all orientations[9] in a way consistent with anisotropic Ginzburg-Landau theory.

The main panels of Fig. 1 show the dc magnetization hysteresis data in the PE region[18] in crystals of $CeRu_2$ and $2H$-$NbSe_2$ at ~ 5 K. The field where the magnetization hysteresis bubble is widest identifies the peak field H_p, and the collapse of hysteresis locates the irreversibility field H_{irr}, above which the differential magnetization $\Delta M/\Delta H$ is positive.[19] The inset panels in Figs. 1(a) and 1(b) show an H dependence of χ' at about 5 K. The PE is accompanied by a rapid enhancement in the diamagnetic χ' response, implying enhanced pinning.

Earlier studies[6] have shown that the onset of PE is discontinuous and hysteretic, characteristic of a first-order transition. The abrupt onset of PE in our measurements is seen clearly in $\chi'(T)$, in the upper panels of Fig. 2, where we show data for two magnetic histories. In one, the system is first cooled to the lowest T in zero-field (ZFC), and then the field is applied; in the other, it is cooled in a field (FC) to the same temperature. χ' data are recorded during warm-up (FCW). Note that the difference in χ' between ZFC and FCW curves occurs over a wide temperature range. This difference implies the importance of disorder in the FLL as it reaches different (metastable) states for the same H, T value.[10] (This is reminiscent of magnetic response in spin glasses[20]). The FC state produces a higher diamagnetic shielding response, implying that the FLL is more strongly pinned with a larger J_c than that in the ZFC state.[10] Within the Larkin-Ovchinnikov[21] description of collective pinning, the pinning force is given by $F_p=J_cB=(n_p\langle f_p^2\rangle/V_c)^{1/2}$, where f_p is the elementary pinning force, n_p is the density of pins, and V_c is the volume of Larkin domain within which the FLL is correlated.[21] The J_c values of different FLL states are reflected in the in-phase ac susceptibility (χ') data via a relation due to Bean's critical state model,[22] $\chi'\approx(-1+\alpha h_{ac}/J_c)$, where α is a size- and geometry-dependent constant, and h_{ac} is the ac field. Thus the difference in χ' between the two thermomagnetic histories (ZFC and FC) reflects a history dependence in V_c, since neither n_p nor f_p can be history dependent. *We infer that the FC branch represents much smaller regions of correlated lattice as compared to those in the ZFC branch, consistent*[23] *with neutron-scattering experiments*[5] *in* $CeRu_2$. Thus the ZFC state, being more ordered, shows more marked signatures of the disordering process with increasing T in the PE region, as compared to the FC state.

The onset of PE in the ZFC branch in both systems [cf. Figs. 2(a) and 2(b)] manifests itself as a reproducible resolution-limited jump of width <1 mK in χ' at $T=T_{pl}$. Above T_{pl}, χ' shows considerable structure, notably a smooth local minimum followed by yet another jump at T_p. Above T_p, most of the history dependence disappears. We propose that the transformation at T_{pl} is a disorder-induced[24] fracturing and/or entanglement transformation between a more ordered (nearly dislocation free) lattice to a highly defective lattice, likely analogous to an elastic-glass[25] to a plastic glass (vortex-glass) transformation.[26] T_p marks a further change into a wholly fractured amorphous state (though pinned, $J_c \neq 0$ at $T = T_p$). In what follows, we present results that support this conjecture.

Important clues to the differences in the states above and below the jumps at T_{pl} and T_p are obtained from the noise data in χ' for the ZFC state, shown in the lower panels of Fig. 2. Fluctuations in χ' are measured using a lock-in amplifier with a flatband filter. The noise signal increases abruptly at T_{pl} in our experiment, remains large in the PE region, and finally decreases above T_p with an associated vanishing of metastability and history dependence in χ'. The present experiment primarily probes the response of the pinned FLL; thus the fluctuating signal in χ' corresponds to transformations among the metastable (pinned) states of FLL accessible from the ZFC branch for a given h_{ac}. (Note that the ZFC branch itself is a metastable state with a deep minimum, and a large barrier separates it from, say, the FC state.) Flux flow noise studies[11,27] on moving FLL's have shown that, slightly above the depinning current, *the PE region in 2H-NbSe$_2$ is especially noisy due to spatially inhomogenous plastic flow channels that, however, persist in the pinned state.* Thus the abrupt increase in the noise signal at T_{pl} in our experiments would imply the sudden enhancement of transitions among metastable states associated with plastic creep and slow dynamics of the dislocations and grain boundaries in the fractured flux line lattice. The noise at $T < T_{\mathrm{pl}}$ is very small, due presumably to the absence of dislocations below the onset of fracturing of the FLL, while the collapse of the noise at higher T is consistent with a phase cancellation of a large number of incoherent fluctuators in the fully disordered (amorphous) state.

A detailed study of path dependence in χ' yields striking results, as shown in Fig. 3. [The dotted lines (with data points omitted) in Figs. 3(a) and 3(b) identify the χ' curves recorded while warming up from the lowest T in the ZFC state; these data are also contained in Figs. 2(a) and 2(b).] The FLL system, prepared in ZFC state at the lowest T, is warmed up to a preselected temperature T, such that (i) $T < T_{\mathrm{pl}}$, (ii) $T_{\mathrm{pl}} < T < T_p$, and (iii) $T_p < T < T_c$. The following features are noteworthy in Figs. 3(a) and 3(b).

(a) For $T < T_{\mathrm{pl}}$, the χ' data during the cooldown cycle retraces the response during the warm-up ZFC cycle.

(b) For $T_p < T < T_c$, during the cooldown cycle, χ' (see triangles) initially retraces (down to T_p) the ZFC χ' curve, but eventually, at $T < T_{\mathrm{pl}}$, the cooldown χ' curve resembles that recorded while warming up in the FC mode [compare FCC curves in Figs. 3(a) and 3(b) with FCW χ' curves in Figs. 2(a) and 2(b)]. In the intervening temperature region, $T_{\mathrm{pl}} < T < T_p$, χ' [in Figs. 3(a) and 3(b)] values are different from those lying on both the ZFC and FCW curves in the corresponding upper panels of Fig. 2. The observation that, down to T_p (see Fig. 3), the cooldown χ' retraces the common warm-up (dotted) curve, and that, after crossing T_p, the system proceeds to the FC-like state instead of following

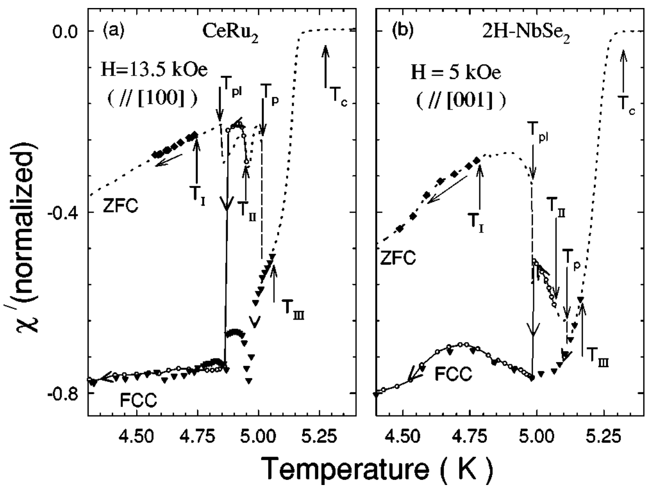

FIG. 3. $\chi'(T)$ curves following different T scans. T_{I}, T_{II}, and T_{III} identify the temperatures up to which a given sample was warmed up each time after preparing FLL in ZFC state at 4.2 K. The χ' data were recorded while cooling down (FCC) from T_{I}, T_{II}, and T_{III}. The dotted lines in (a) and (b) sketch (respectively) the ZFC curves of Figs. 2(a) and 2(b).

path(s) during warm up in the ZFC state is significant. *This is a clear indication of a transformation at T_p, above which the system is so disordered that its past history is immaterial, and such a disordered state can be preserved (''supercooled'') down to much lower temperatures ($T \ll T_p$).*

(c) For $T_{\mathrm{pl}} < T < T_p$, the system is cooled down from the partially disordered state. χ' starts to increase [see open circles in Figs. 3(a) and 3(b)] on lowering T (from T_{II}). It first overshoots the ZFC cycle in an attempt to recover the more ordered FLL as in the ZFC branch; however, at a temperature near, but, slightly above T_{pl}, it drops precipitously to a value close to the FCW branch instead [compare data in Figs. 3(a) and 3(b) with curves in Figs. 2(a) and 2(b)]. This

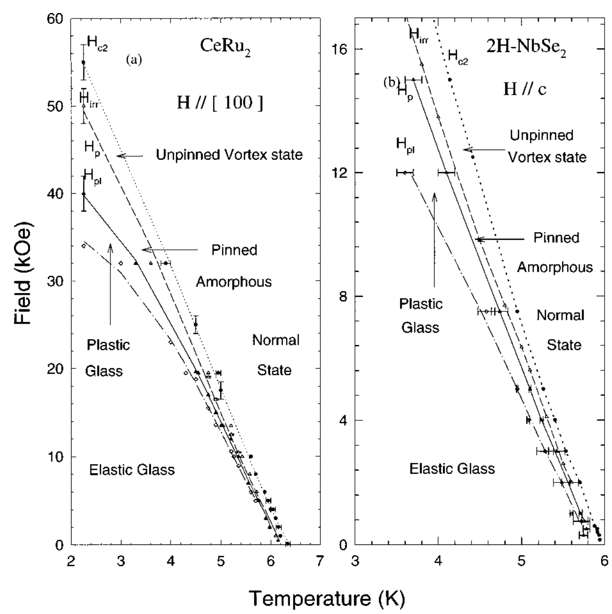

FIG. 4. Magnetic phase diagrams in (a) $CeRu_2$ and (b) 2H-$NbSe_2$, depicting H_{pl}, H_p, H_{irr}, and H_{c2} lines. For justification of nomenclature of different vortex states, see text.

striking result suggests the following scenario. With increasing T toward the PE region, the FLL softens, the energy needed to create dislocations decreases, and the lattice spontaneously fractures at $T_{\rm pl}$. Upon lowering T from within the PE region, the lattice stiffens and stresses build up. The system fails to drive out the dislocations in order to heal back to the ZFC state. Instead, it fractures further in order to relieve stresses and reaches the other available metastable state, namely, the FC state. *This yields an open hysteresis curve in T (i.e., one cannot recover to the original ZFC-type state by cycling in T alone), which is highly unusual, and not seen in typical first-order transitions in the absence of disorder.*

Data such as in Figs. 1 and 2 were obtained at various values of H and T and the resulting loci of various anomalies at $(H_{\rm pl},T_{\rm pl})$, (H_p,T_p), and $(H_{\rm irr},T_{\rm irr})$ are plotted as magnetic phase diagrams in Figs. 4(a) and 4(b). In what follows, we propose a qualitative picture of the sequence by which the FLL loses order, based on the competition among three energy scales: the elastic energy $E_{\rm el}$, the pinning energy $E_{\rm pin}$, and the thermal energy $E_{\rm th}$.[28] At low T, $E_{\rm el}$ dominates and a phase akin to an elastic (Bragg) glass phase occurs.[25] With increasing T, $E_{\rm el}$ decreases faster than $E_{\rm pin}$, and above the $(H_{\rm pl},T_{\rm pl})$ line, $E_{\rm pin}$ dominates, leading to a proliferation of topological defects, likely similar to the vortex-glass–entangled-solid phase.[26,29,30] *This transformation would thus be explicitly disorder driven, and has no analog in the disorder-free case.* At even higher T, at the (H_p,T_p) line, $E_{\rm th}$ overcomes $E_{\rm el}$, and the residual order is lost due to thermal fluctuations. Indeed, fitting this line to a FLL meltinglike curve (for instance, Eq. 5.9 of Ref. 1), $B_m(T)=\beta_m(c_L^4/{\rm Gi})H_{c2}(0)(T_c/T)^2[1-(T/T_c)-(B_m/H_{c2}(0))]$, where $\beta_m=5.5$ (Ref. 1) and ${\rm Gi}\approx 5\times10^{-4}$ and 3×10^{-4} for $CeRu_2$ and $2H$-$NbSe_2$, respectively, we obtain a reasonable value of Lindemann's parameter $c_L\approx 0.13$ for both systems. However *the system above $T_p(H)$ has finite pinning although it has little or no history dependence in the macroscopic χ' response.* Thus the transition at the (H_p,T_p) line may be a disorder analog of melting, i.e., from the plastically deformed solid to a pinned amorphous phase. Above the $(H_{\rm irr},T_{\rm irr})$ line, $E_{\rm th}$ overcomes $E_{\rm pin}$, and the system crosses over to what appears to be a reversible vortex state.

The results presented here show the existence of not one, but two, sharp changes in the peak effect region in both $CeRu_2$ and $2H$-$NbSe_2$. Based on available data, we suggest that the first one at the $(H_{\rm pl},T_{\rm pl})$ line, attributed to the GFFLO state in the former system,[6] is a disorder-induced solid-to-solid transformation, analogous to fracturing and entanglement of a nearly defect-free lattice into a highly dislocated one. Furthermore, the entire sequence of disordering of the FLL from the defect-free lattice below the $(H_{\rm pl},T_{\rm pl})$ line to an unpinned vortex state above the $(H_{\rm irr},T_{\rm irr})$ line appears to be generically the same in both systems. More theoretical and experimental work is needed to understand the details of the intervening states and the transitions and crossovers among them.

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[19] See, for instance, Fig. 2 in (Ref. 8 and Fig. 1 in Ref. 12 for identification of $T_{\rm irr}$ in $CeRu_2$ and $NbSe_2$, respectively, as the onset of the differential paramagnetic effect in $\chi'(T)$.

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