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# Peak effect studies in single crystals $CeRu_2$ and 2H-$NbS_2$

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**Abstract.** We have studied the peak effect (PE) phenomenon in single crystals of weakly pinned superconductors $CeRu_2$ and 2H-$NbS_2$. 2H-$NbS_2$ is iso-structural and iso-electronic to 2H-$NbSe_2$, whose similarity with $CeRu_2$ as regards the PE representing the order-to-disorder transformation of the flux line lattice was claimed some time ago. We report on the step change in equilibrium magnetization across the peak effect in $CeRu_2$. We also present the vortex phase diagram of 2H-$NbS_2$ obtained from the magnetization data, and compare the PE phenomenon in 2H-$NbS_2$ and 2H-$NbSe_2$.

**Keywords.** Peak effect; order–disorder transformation; charge density wave.

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## 1. Introduction

The macroscopic current density ($J_c$) sustained in the mixed phase of a type II superconductor usually decreases monotonically with increasing $H$ or $T$. However, in weakly pinned superconductors, the competition and interplay between the intervortex interaction and the flux pinning produces an anomalous peak in $J_c$, before it collapses to zero at (or just before) the superconductor–normal phase boundary ($H_{c2}/T_c(H)$ line). This phenomenon is known as the peak effect and it signals a transition from an ordered state to a disordered state in the flux line lattice (FLL), with proliferation of topological defects. In weakly pinned superconductors, the FLL can exist in different metastable vortex states. Recently, Ravikumar *et al* [1] have proposed a phenomenological model, which postulates a stable state of the vortex lattice with a critical current density, that is determined uniquely by the field and temperature, and is independent of the past magnetic history. This stable state is reached from any metastable vortex state by cycling the applied field by a small amplitude. Exploiting the notion of the stable state, we show here the determination of the step change in equilibrium magnetization across the PE in $CeRu_2$. We also sketch the vortex phase diagram in the system $NbS_2$, which is isoelectronic to $NbSe_2$, whose similarity with $CeRu_2$ was demonstrated earlier [2].

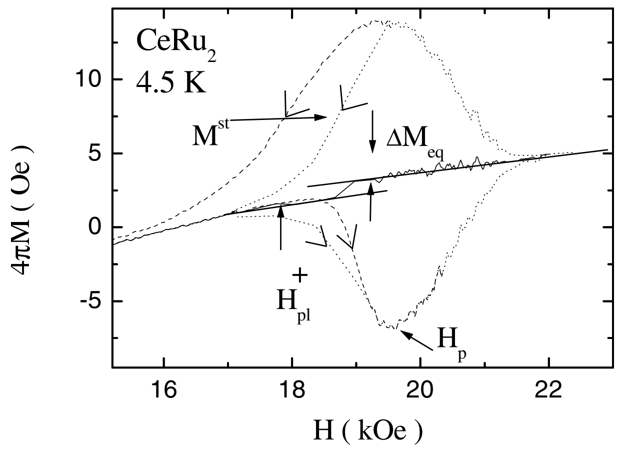


**Figure 1.** A portion of the $M$–$H$ loop showing the PE phenomenon at 4.5 K in a single crystal of $CeRu_2$. The dotted curve depicts the stable magnetization hysteresis loops by repeated cyclings of the field. The equilibrium magnetization ($M_{eq}$) values determined from the stable loop (see text) are also shown. $\Delta M_{eq}$ denotes the occurrence of a step change in $M_{eq}$ just above the onset field ($H_{pl}^{+}$) of the PE at 4.5 K.

## 2. Experimental

Isothermal dc magnetization measurements have been carried out using a commercial 12 T vibrating sample magnetometer (VSM) (Oxford Instruments, UK) on single crystal samples of $CeRu_2$ and 2H-$NbS_2$. All the measurements were carried out by cooling the sample in zero field (ZFC mode) and then by applying the magnetic field. The measurements were carried out with the magnetic field parallel to the cube edge for $CeRu_2$, whereas for $NbS_2$, the experiments were performed with applied field parallel to the *c*-axis as well as parallel to the *a*–*b* plane.

Recently, we showed [3] how the minor hysteresis loops (MHLs) obtained by repeatedly cycling the field starting from different points in the PE region on the forward leg behaved in the $CeRu_2$ system. The MHLs initiated from the field values on the forward leg show progressive expansion with field cycling, and after a few field cycles, the MHLs retrace each other indicating that $J_c$ values do not change any further with more field cyclings, and vortex state so obtained corresponds to a stable configuration. On the reverse cycle, the MHLs starting within the PE region show progressive shrinkage obtained with field cyclings, and finally the MHLs retrace each other indicating the approach to the stable vortex state. Figure 1 shows the construction of the stable magnetization hysteresis loop obtained from the saturated values of the stable MHLs. Note that the determined stable loop is symmetric in contrast to the usual hysteresis loop which shows asymmetric behavior across the PE regime (the dashed line in figure 1). The equilibrium magnetization ($M_{eq}$) can be obtained from the stable state magnetization hysteresis loop using the relation, $M_{eq} = (M^{st}(H\uparrow) + M^{st}(H\downarrow)/2$ (see figure 1). It can be seen that $M_{eq}$ shows a sharp increase above the onset position of the PE region, implying the occurrence of a first-order phase transition from an ordered vortex phase to a disordered phase. The $\Delta M_{eq}$ value of 0.75 Oe

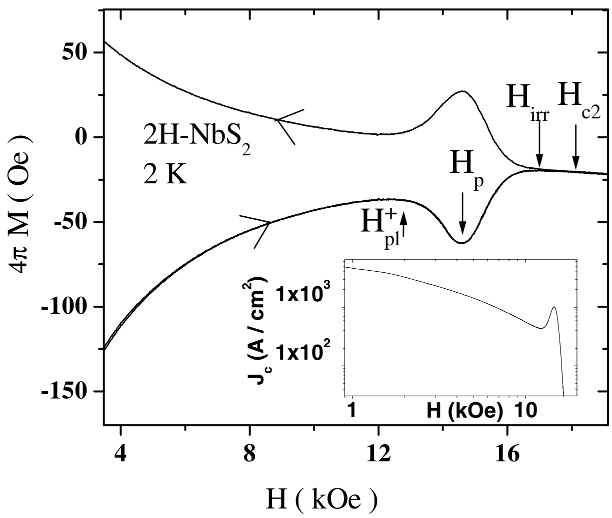


**Figure 2.** The main panel shows a portion of the $M$–$H$ loop for $H||c$ at 2 K in a single crystal of 2H-$NbS_2$. The onset field ($H^+_{\mathrm{pl}}$), the peak field ($H_{\mathrm{p}}$), the irreversibility field ($H_{\mathrm{irr}}$) and the upper critical field ($H_{\mathrm{c2}}$) have been marked. The inset shows the critical current density ($J_{\mathrm{c}}(H)$ vs. $H$) determined from the hysteresis data at 2 K.

obtained in the present case compares favorably with the values reported in the literature for the flux line lattice (FLL) melting transition in cuprate superconductors [4] and for the amorphization transition across the PE in a weakly pinned single crystal of 2H-$NbSe_2$ [5].

Figure 2 shows a portion of the $M$–$H$ hysteresis loop in a crystal of 2H-$NbS_2$ obtained at a fixed temperature of 2 K with the magnetic field parallel to the $c$-axis. The figure focuses on the portion of the ZFC hysteresis loop where the onset field for the PE ($H^+_{\mathrm{pl}}$), the peak field $H_{\mathrm{p}}$, and the irreversibility field $H_{\mathrm{irr}}$ have been marked. As per the prescription of the Bean's critical state model, the hysteresis in magnetization $\Delta M(H)=[M(H\uparrow)-M(H\downarrow)]$ provides a measure of the critical current density, $J_{\mathrm{c}}$ ($J_{\mathrm{c}} = \Delta M(H)/2gR$, where $R$ is the sample dimension transverse to the magnetic field and $g$ is a sample geometry dependent factor. The $J_{\mathrm{c}}(H)$ values obtained from the width of the hysteresis loop are plotted in the inset of figure 2. One can easily see the anomalous increase in $J_{\mathrm{c}}$, identifying the peak effect.

Figures 3a and b show the vortex phase diagrams of $NbS_2$ for $H||c$ and $H||ab$ respectively, obtained from the magnetization data. The various phases of the flux line lattice have been marked in figure 3. The ($H_{\mathrm{pl}}$, $T_{\mathrm{pl}}$) line denotes the onset of the peak effect and the ($H_{\mathrm{p}}$, $T_{\mathrm{p}}$) line denotes the peak position of the peak effect and the $(H, T)$ region bounded by these two curves show plastic motion in the flux flow behavior.

It had been suggested in the earlier studies [6] that the non-observation of the PE in 2H-$NbS_2$, in contrast to its presence in $NbSe_2$, may be due to the absence of the charge density wave (CDW) in the former and its presence in the latter. The fact that a high quality single crystal sample of 2H-$NbS_2$ used in our present work displays the PE phenomenon implies that the existence of CDW is not related to the PE.

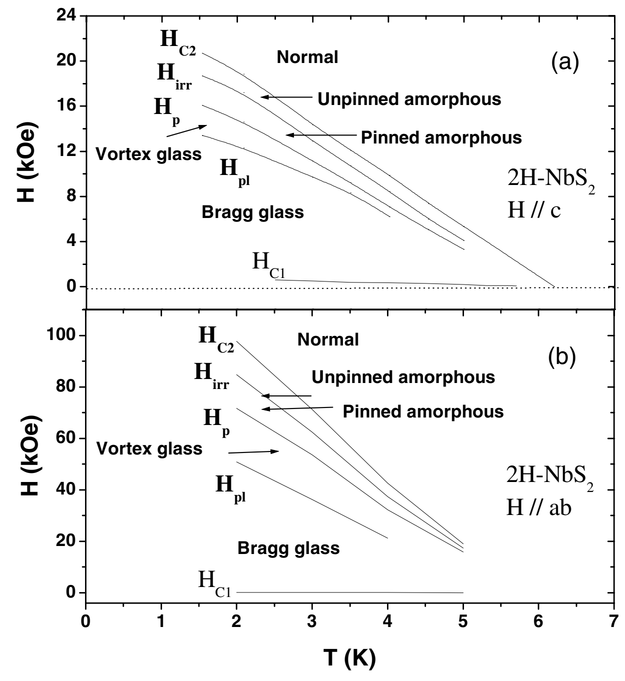


**Figure 3.** The panels (**a**) and (**b**) show the vortex phase diagrams determined from the $M$–$H$ data in the given crystal of 2H-$NbS_2$ for $H||c$ and $H||a$, respectively.

## 3. Conclusion

We have shown that the PE could correspond to a first-order phase transition from an ordered phase to a disordered phase by elucidating the step change in the equilibrium magnetization of $CeRu_2$. We have also shown that the existence of CDW in 2H-$NbSe_2$ is not related to the PE phenomenon by studying the PE in the isoelectronic system 2H-$NbS_2$.

## References


[1] G Ravikumar *et al*, *Phys. Rev.* **B61**, R6479 (2000)
[2] S S Banerjee *et al*, *Phys. Rev.* **B58**, 995 (1998)
[3] A A Tulapurkar *et al*, *Physica* **C355**, 59 (2001)
[4] Matthew J W Dodgson *et al*, *Phys. Rev. Lett.* **80**, 837 (1998)
[5] G Ravikumar *et al*, *Phys. Rev.* **B63**, 024505 (2001)
[6] M Chung *et al*, *Phys. Rev.* **B50**, 1329 (1994)