arXiv:cond-mat/0005272v1 [cond-mat.supr-con] 17 May 2000

Peak effect in CeRu$_2$: history dependence and supercooling

S. B. Roy, P. Chaddah and Sujeet Chaudhary

Low Temperature Physics Laboratory,

Centre for Advanced Technology,

Indore 452013, India

Abstract

We present experimental results on single crystal CeRu$_2$ showing that the extent of history dependence of peak-effect depends on the path followed in the space of field (H) and temperature (T). The (H,T) regime over which history effect is observed is larger if the vortex lattice is prepared by lowering T from above T$_C$ in constant H i.e. by field cooling. We compare this history effect with the very recently reported history dependence of peak-effect in detwinned single crystals of YBaCuO, highlighting the similarities and differences. We discuss the possibility of a first order vortex solid-solid transition in CeRu$_2$ within the realm of recent theoretical developments in the field of vortex matter.

Typeset using REVTEX

I. INTRODUCTION

Recent theoretical[1–4] and experimental[5–7] studies based on high T_C superconductors (HTSC) suggest the existence of at least two distinctly resolved solid phases of vortex matter which are distinguished from the high-temperature high-field vortex liquid. These two vortex solid phases are referred to as low-field quasi-ordered solid or Bragg-glass and high-field disordered solid or vortex-glass (see Ref.8). The important question now is, what is the the order of the thermodynamic phase transitions (if any) between the various vortex phases? The Bragg-glass has long range order and it is expected to melt to vortex liquid at high temperature through a first order transition. Experimentally, the indication of a first order transition usually comes via a hysteretic behaviour of various properties, not necessarily thermodynamic ones. In HTSC samples also initial suggestions of a first order melting transition came via distinct hysteresis observed in transport property measurements[9–11]. The confirmatory tests of first order transition ofcourse involve the detection of discontinuous change in thermodynamic observables and the estimation of latent heat, and this has subsequently been achieved for vortex melting in HTSC materials through magnetization[12,13] and calorimetric measurements[14]. There also exists a less rigorous class of experimental tests which involves the study of phase co-existence and supercooling across a first order transtion. This kind of experiment has also come out to be pretty informative for the first order melting transition of the Bragg-glass in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) (Ref.15).

With the establishment of the first order nature of the Bragg-glass to vortex liquid transition line, the focus in the recent years has shifted to the Bragg-glass to vortex-glass transition. In various HTSC materials peak-effect(PE) or fish-tail is used to track this field induced transition from Bragg-glass to vortex-glass, and this transition is obsereved to be a sharp transtion[5–7]. However, the exact nature of this transition –whether it is a continuous or a first order transition– is not established yet. Very recent magneto-optics studies on single crystal samples of BSCCO claim the presence of phase-coexistence[16,17] and supercooling[17] across the Bragg-glass-vortex-glass phase transition. These in turn suggest the possibility of a first order phase transition. Newer theoretical developments[18−21] have also taken place in the field of vortex-matter physics during last few years to understand the various field/disorder induced phenomena. This activity in vortex matter physics can even have deep correlations with a more general area namely disorder/pressure induced melting/amorphization in real solids[22,23].

Very recently interesting history dependence of PE has been reported for naturally untwinned and detwinned single crystal samples of $YBa_2Cu_3O_y$(YBCO) with $6.908 \leq y \leq 6.999$[24−26]. We have earlier observed very similar history dependence of PE in the low temperature ($T_C \approx 6.1$K) C15-Laves phase superconductor $CeRu_2$[27−29]. We believe that the "*minor hysteresis loop*" technique used in our early study of history dependence of PE in $CeRu_2$[27−29] and also in the similar recent studies on YBCO[24−26] belongs to that class of experiments which can investigate the phase coexistence and supercooling across a first order phase transition.

Interesting Fermi surface topology and enhanced pauli paramagnetism of $CeRu_2$ have given rise to various interesting possibilities, starting from an exotic non s-wave superconducting ground state[30] to a field induced change in the microscopic superconducting order parameter associated with the onset of a Fulde-Ferrel-Larkin-Ovchinnikov (FFLO) state[31−33]. Onset of FFLO state can cause softening of the vortex lattice and in turn enhanced pinning and PE[34]. It is quite clear that if a field induced first order transtion from a BCS state to FFLO state actually takes place in any system, a PE with definite history effects (typically associated with a first order transition) will be observed, and this has been motivating us, possibly as a red herring, in our study of vortex matter in $CeRu_2$. The question is can $CeRu_2$ actually sustain a FFLO state ? Our own macroscopic magnetization[27−29] and transport-property measurements[35] cannot provide any proof for (or against) the existance of FFLO state, and at this moment the global debate on this issue remain unsettled[31,32,36−38].

In the light of various recent developments described above regarding vortex matter, we believe that results obtained in $CeRu_2$ should be re-examined. In this paper we shall

1. present newer results on the history dependence of PE in a single crystal sample of $CeRu_2$. Recently we have extended the classical theory for supercooling across first order phase transitions to the case when both field and temperature are control variables and have shown how the observable region of metastability depends on the path followed in the space of these two variables[39]. We show that our present experimental results are in consonance with these theoretical predictions, and hence reinforce the idea of a first order transition from one kind of vortex solid to another.

2. compare our results on $CeRu_2$ with the recently reported history dependence of PE in single crystal samples of YBCO[24,26] and point out the similarity and difference between these two disparate class of materials. The relevance of the results on the phase coexistence and supercooling in BSCCO[16,17] will also be discussed.

3. discuss a possible origin of a first order transition between two kinds of vortex solid in $CeRu_2$ within the realm of the recent theoretical developments[18–21].

Preliminary results of the present work have been presented in the recently held LT-22 conference in Helsinki[40].

II. EXPERIMENTAL

In contrast to the polycrystalline samples of $CeRu_2$ used in our earlier studies[27–29] showing history effects associated with PE, in the present study we use a single crystal sample of $CeRu_2$ ($T_C \approx$6.1K). The details of the preparation and characterization of this sample can be found in Ref.41.

Magnetization measurements were performed using a commercial SQUID magnetometer (Quantum Design MPMS5). We have used a 2 cm scan length in the 'fixed-range' mode to minimize the sample movement in the inhomogeneous field of the superconducting magnet. In the 'auto-range' mode the sample goes through multiple movements while the system software searches for the most sensitive gain useful for the signal level detected. We carried out a separate preliminary run using the auto-range mode to identify the appropriate gain for the given experimental conditions and then performed a final run in the 'fixed-range' mode. In the case of 2cm scan-length, the field inhomogeneity in an applied field of 20 kOe is ≈2 Oe. We have concluded earlier[42] that in an isothermal field scan, as long as the field for full penetration at a particular field value is substantially larger than the field inhomogeneity during the sample measurement, the error in the results in the particular type of measurements reported here will be negligible. Inspite of all these cross-checks, in the light of general doubts[43,44] concerning the measurement procedure using commercial SQUID magnetometers, it has become important to reproduce the observed history effects using other techniques which minimize the sample movement. In a recent work[45] we have shown the existence of the history dependence of PE in the isothermal field variation of magnetization in polycrystalline samples of $CeRu_2$ using an axial-VSM (Oxford Instruments). In the present work we have used a transverse-VSM (Oxford Instruments) to get supporting results. In this transverse VSM the sample is placed in the centre of the pick-up coil and the superconducting magnet assembly, where the magnetic field inhomogeneity is ≈0.01% over 1 cm diameter spherical volume (DSV).

In contrast to the axial-VSM, the direction of sample vibration in the transverse-VSM is perpendicular to the applied field. No significant change is observed in the results by varying the sample vibration amplitude between 0.5 and 1.5mm; this rules out any distinct role of magnetic field inhomogeneity. In any case the field inhomogeneity encountered here is obviously much smaller than that encountered even in the 2cm-scan of SQUID magnetometer.

In magnetization hysteresis measurements, we draw an isothermal magnetization (M) versus field (H) curve by cycling H between $\pm H_{C2}$ at various temperatures (T) below T_C. These T of interest are reached by cooling through T_C in absence of any applied field H i.e. in zero-field- cooled (ZFC) mode. From various H-points on this isothermal M-H curve (or envelope curve), a *minor hysteresis loop* (MHL) can be be drawn either by decreasing H from the ascending field branch of the M-H curve (or lower envelope curve) or by increasing

H from the descending field branch (or upper envelope curve). We designate these MHLs as $(\mathrm{MHL})_{ZFC}$. One can also initiate MHLs from various H-points obtained by field cooling (FC) through T_C. In such a case the M-value at the starting H-point normally lies inbetween the upper and lower envelope curve (see Ref.27 and references cited therein). An MHL can be initiated from such FC H-points either by increasing or by decreasing H. We designate these MHLs as $(\mathrm{MHL})_{FC}$. Within the realm of a single-component Bean's crtical state model, all these MHLs (both ZFC and FC) are expected to saturate by reaching the enevelope curve[46]. Such a behaviour has actually been observed experimentally in various type-II superconductors . The same is also observed in all H-regimes, except a finite field regime encompassing at least a part of the PE regime, in various samples of $CeRu_2$[27] including the present single crystal sample. In this latter regime the MHLs do not behave in accordance with the critical state models, and we have used this anomalous behaviour of MHLs to study the interesting history dependence of PE in $CeRu_2$[27–29]. Very similar technique involving the $(\mathrm{MHL})_{ZFC}$ has very recently been used to study the history dependence of PE in single crystals of YBCO[24–26].

Apart from tracking the history dependence of PE the study of MHLs can provide with at least two more useful information in our present kind of study. First, it provides a way of estimating the field for full penetration at a particular H of interest[27,42]. The field inhomogeneity δH of the magnet causes the sample to effectively follow an MHL during measurements with a SQUID magnetometer[47]. Since δH rises with scan length, MHLs allow one to estimate the error δM in measurements made with various scan lengths. One can then choose a scan length such that δM is much smaller than the magnetization hysteresis, or, equivalently δH is much smaller than the field for full penetration. Second, a fair amount of information regarding the influence of surface barrier can be obtained from the nature of the approach (linear or non-linear) of these MHLs to the envelope curve[48]. These two information are useful even where the M-H curves are in accordance with the critical state models[46]. Thus the technique of MHLs has universal applicability in determining (i) the effect of field inhomogeneity of the magnet on a measurement (ii) the importance of surface barrier in the magnetization study.

While presenting newer results, the present study on a single crystal sample of $CeRu_2$ using both SQUID magnetometer and VSM, provides also a cross-check on our earlier results$^{27-29}$ obtained on polycrystalline samples mainly using a SQUID magnetometer. This will put the experimental situation regarding the PE in $CeRu_2$ on a more firm ground.

III. RESULTS AND DISCUSSION

Fig. 1 shows M-H plots of the $CeRu_2$ single crystal at T=4.5K, obtained using both SQUID magnetometer and VSM. These M-H curves are obtained by isothermally cycling H between ±25kOe. Since $H_{C2}(4.5K)$ ≈21.5kOe is less than 25 kOe, these provide the envelope hysteresis curve within which all the MHLs should be contained. This envelope M-H curve shows two distinct irreversible regimes separated by an almost reversible regime (see Fig. 1). While this intermediate regime appears quite reversible in the SQUID measurement (see inset of Fig. 1(a)), perceptible irreversibility is observed in the VSM measurement (see inset of Fig. 1(b)). This field-induced enhanced magnetization-irreversibility in the high field regime is the so called peak-effect (PE) and this is the subject of main interest in the present work. We note that in Fig.1 the onset field H_a^* of the PE in the ascending field cycle is distinctly different from the field H_d^* where the PE ceases to exist in the descending field cycle. Note that H_a^* and H_d^* obtained from the SQUID and VSM measurements are a bit different. We attribute this quantitative difference to (i)the difference in the magnetic field inhomogeneity encountered during SQUID and VSM measurements, (ii)possible minor difference in temperature in two different machines. Also the magnitude of measured M is smaller in the VSM measurement which we attribute to different sample orientation and the associated demagnetization factor. However, it should be noted that the actual measurement time involved in a VSM measurement, where the field is swept with a constant rate (100 Oe/s in the present case) is faster than in a SQUID measurement where the field is stabilized with a pause time (10 sec in the present case) before each measurement. In systems with finite magnetization relaxation, faster measurement with VSM would yield larger magnetization value. This is actually observed in the field regime just below the PE where magnetization hysteresis obtained with VSM measurements is perceptibly higher [see Fig.1(a) and Fig.1(b)].

We shall now present results obtained in the form of MHLs measured at closely spaced field intervals, after preparing the vortex lattice within the following experimental protocols :

1. Zero field cool (ZFC) the sample to the temperature of measurement, switch on a field less than -H_{C2}, and then increase the field isothermally to reach various points on the lower envelope curve. $(\mathrm{MHL})_{ZFC}$'s are drawn by reducing the field isothermally.

2. After the above step, increase the field to a value greater than H_{C2} and then reduce the field to reach the various points on the upper envelope curve, while maintaining the isothermal condition. $(\mathrm{MHL})_{ZFC}$'s are drawn by increasing the field isothermally.

3. Field cool (FC) the sample in various (positive) fields from a temperature substantially above T_C. After stabilizing the temperature of interest the $(\mathrm{MHL})_{FC}$'s can be drawn both by increasing and decreasing the field isothermally.

The MHLs at the onset of the PE regime obtained within the above experimental protocols do not conform with the critical-state models;they do not show the expected merger with the envelope curve (see Fig.2). While the $(\mathrm{MHL})_{ZFC}$'s initiated from the lower envelope curve at H=18.25, 18.75 and 19 kOe saturate without touching the upper envelope curve (see Fig. 2(a)), the $(\mathrm{MHL})_{ZFC}$'s initiated from the upper envelope curve at H=18.4 kOe overshoots the lower envelope curve before reaching saturation (see Fig. 2(b)). The $(\mathrm{MHL})_{FC}$'s obtained following the FC path also overshoot the envelope curve (see Fig. 2(c)). For the sake of clarity and conciseness we show only few representative MHLs.

We have earlier reported[27,28] anomalous behaviour of $(\mathrm{MHL})_{ZFC}$'s obtained within the protocol no.1 in polycrystalline samples of $CeRu_2$. Tenya et al[49] have reported anomalous $(\mathrm{MHL})_{ZFC}$s under protocol no.2. Ravikumar et al (Ref.50) and ourselves (Ref.29(b)) reported anomalous $(\mathrm{MHL})_{FC}$'s under protocol no.3 in single crystal and polycrystalline samples of $\mathrm{CeRu_2}$ respectively. Actually the anomalous character of the $(\mathrm{MHL})_{ZFC}$ initiated from the upper envelope curve was visible in a relatively less prominent manner in our earlier studies of polycrystalline samples as well (see Fig.3 of Ref.29 (a)). However, from our standard cross-checks we were not sure whether the observed result was beyond error bar, hence did not emphasise much on that. (On the other hand we were aware of the metastable character of those $(\mathrm{MHL})_{ZFC}$'s drawn from the upper envelope curve, since they readily shattered on field cycling (see Fig. 3 of Ref. 29(a).) In the present work for the first time all the three different kinds of (MHL)s are shown on the same sample of $\mathrm{CeRu_2}$.

We shall now reproduce all these anomalous aspects of MHLs in the vicinity of PE using a transverse-VSM. Fig.3 shows the anomalous nature of the two $(\mathrm{MHL})_{ZFC}$'s drawn from the lower envelope curve at H=19.25 kOe and 20 kOe, and two $(\mathrm{MHL})_{FC}$'s drawn by reducing the field at H=17.25 and 19 kOe. In this transverse-VSM it is relatively difficult to stabilize the temperature for T <10K and actual temperature can vary by ±0.025K between different runs and some time even during a single complete run. This leads to a slight scatter in the data, but from multiple runs of the same experiment we ensure that the observed anomalous features are certainly well beyond the error bars. For the two kinds of MHLs described above we need to obtain the envelope M-H curve in a separate experimental cycle. However, the anomalous nature of the $(\mathrm{MHL})_{ZFC}$'s drawn from the upper envelope curve can be highlighted from a single experimental cycle. For this purpose we increase the field isothermally to field values well above H_{C2} (thus drawing the lower envelope curve) and then reach the various field points of interest on the upper envelope curve by isothermal reduction of the field. From such field points we draw $(\mathrm{MHL})_{ZFC}$'s by reversing the field sweep direction. In Fig.4 we show the MHLs initiated from the upper envelope curve at H=18.75 and 19.25 kOe and they distinctly overshoot the lower envelope curve before saturation. These representative MHLS provide support to the results obtained earlier with the SQUID magnetometer. Various envelope curves and MHLs presented in Fig.3 and 4 are obtained with field sweep rate 100 Oe/sec. We have also checked the qualitative aspects of our results by varying the field sweep rate between 20 and 200 Oe/sec.

Interesting history effects associated with the PE have been reported recently in detwinned and naturally untwinned single crystals of YBCO[24−26]. These history effects in YBCO are exactly in the same form of anomalous isothermal $(MHL)_{ZFC}$'s drawn from the upper and lower envelope M-H curve of $CeRu_2$ as shown in Fig. 2(a), 2(b), 3(a) and 4. In these reports, however, there is no mention of any measurement involving MHLs in a field cooled vortex state.

We have earlier associated these anomalous features in polycrystalline samples of $CeRu_2$ with a field induced first order transition to a superconducting mixed state with enhanced pinning properties[27−29]. While the multivaluedness in the saturation of the $(MHL)_{ZFC}$ in the ascending field cycle was attributed to the nucleation and growth of the high field phase, the overshooting of the envelope M-H curve by the $(MHL)_{ZFC}$'s in the descending field cycle and by the $(MHL)_{FC}$, was thought to be a result of supercooling of the high field phase across the proposed first order transition[27−29]. The present results on a good quality single crystal of $CeRu_2$ reinforce this picture.

We shall now provide newer evidence to support the conjecture of a first order phase transition in $CeRu_2$. Extending the classical theory for supercooling across first order phase transitions to the case when both field and temperature are control variables, we have shown theoretically that the observable region of metastability depends on the path followed in this space of two variables, with variation of field providing a source of fluctuations in the supercooled state[39]. We have predicted that a disordered phase can be supercooled upto the limit of metastability $T^*(H)$ only if T is lowered in constant H. If the $T_C(H)$ line is crossed by lowering H at constant T, then supercooling will terminate at $T_0(H)$ which lies above the $T^*(H)$ line[39]. If T_C falls with rising field, then $(T_0(H)-T^*(H))$ rises with rising field[39]. As narrated below both these predictions are experimentally found to be true in $CeRu_2$. We have found that the anomalous features in $(MHL)_{FC}$ in $CeRu_2$ continue to exist in a (H,T) regime which is well below the PE regime. In this regime the $(MHL)_{ZFC}$'s show normal behaviour as expected within the critical state models. This clearly suggests that the FC vortex state can be supercooled more than the isothermal ZFC state. Collating the H values where the various MHLs first show the anomalous behaviour at various T in our SQUID magnetometer measurements, in Fig.5 we present a (H,T) phase diagram. The distinct identity of the H_a^*(T) line (which indicates the onset of the PE regime in the isothermal ascending field cycle) and the H_d^*(T) line (at which the PE regime terminates in the isothermal descending field cycle) was infact earlier taken as an indication of a first order transition[31,32]. H_d^*(T) and H_{FC}^*(T) lines are akin to the T_0(H) and $T^*(H)$ lines respectively in our theoretical study[39]. Experimentally H_{FC}^* at a particular temperature is defined as the H value down to which the anomalous behaviour in the $(MHL)_{FC}$'s is observed. Similarly below H_d^*(T) (defined earlier) the $(MHL)_{ZFC}$'s drawn from the upper envelope curve show normal behaviour namely, they merge with the lower envelope curve without any overshooting. As shown in Fig.5 the H_{FC}^*(T) line is lying distinctly below the H_d^*(T) line and (H_d^*(T) - H_{FC}^*(T)) increases with the increase in H. Although anomalous behaviour of $(MHL)_{ZFC}$'s and $(MHL)_{FC}$'s in $CeRu_2$ has been highlighted by various groups during last three years[27–29,49,50], the path dependence of this anomalous behaviour in (H,T) space is definitely new and has not been reported so far. These new results, which are in accordance with our theoretical prediction[39], will provide further support for the existence of a first order transition in the vortex matter phase diagram of $CeRu_2$.

The observed history effects in YBCO are interpreted in terms of a transition from a low field elastic vortex lattice to a high field plastic vortex lattice[24–26]. We have previously discussed this mechanism in the context of PE in polycrystalline samples of $CeRu_2$, and argued that a first order transition probably has an edge over this mechanism in explaining the history dependent phenomena associated with PE (see Ref.29(b)). Since then our view point is reinforced by the transport study of the PE on a single crystal sample of $CeRu_2$[35]. We have shown that the FC state at the vicinity of the PE regime is metastable in nature and it can be shattered easily with a small field cycling (see Ref. 29(b) and 35). This observation can be relatively easily explained in terms of the metastable nature of a supercooled state and its sensitivity to any environmental fluctuation[39]. In a very recent study of magnetization in untwinned single crystal of YBCO using micro Hall probe, history effects in FC measurements have now been reported[51]. Relatively complicated (H,T) phase diagram of YBCO[52] needs a contrived path to ensure proper FC measurements[51] and this probably may be the reason why FC measurements were not reported in earlier studies[24–26]. In contrast to the suggestion that the observed history effects are properties of the high field plastic vortex lattice[24–26], it is asserted that both the low field and the high field vortex lattice are robust in nature, and the history effects and metastability are associated with the transition regime from the low field to high field phase[51]. This recent observation makes the possibility of a first order transition in YBCO much stronger, and hence the similarity with $CeRu_2$.

Contrary to our earlier suggestion based on bulk magnetization study[29], a very recent magneto optical study in good single crystals of BSCCO has claimed that the solid-solid transition in the vortex matter is indeed a first order transtion accompanied by supercooling[17]. If this claim turns out to be true, it is possible that the supercooled (H,T) regime in BSCCO is quite narrow and/or fragile. So in our magnetization measurement we have either missed the supercooled regime and/or the fluctuation induced during the measurement procedure might have shattered the supercooled phase.

At this juncture we must point out some important difference in the history effects associated with PE in $CeRu_2$ and YBCO. While the history effects associated with PE were observed only in naturally untwinned and detwinned single crystals of YBCO and vanish quite readily with the change in oxygen stoichiometry[26], the same effects are quite robust in $CeRu_2$ and are observed with all the characteristic features in good quality single crystal, polycrystal, off-stoichiometric polycrystal and Nd-doped polycrystal samples of $CeRu_2$[27–29,37,52]. These results suggest that, in contrast with $CeRu_2$ the characteristic features associated with the vortex solid-solid transition in YBCO are quite sensitive to the defect. Also the negative dynamic creep at the onset of PE regime of YBCO (as reported recently (Ref.25)), is not observed with identical measurements on $CeRu_2$[54]. On the other hand, while the PE ceases to exist above a temperature $T^* \approx 0.92\ T_C$[31,32] in all kinds of samples of $CeRu_2$, there is no report (to our knowledge) so far of a vortex-solid to vortex-liquid melting transition in $CeRu_2$.

We shall now discuss some recent developments in the field of vortex matter physics[18−21] since they appear relevant to our experimental results in $CeRu_2$. At low tempeartures and at high fields disorder dominates in vortex matter and topological defects proliferate, resulting in highly disordered solid . We shall now explore the possibility of a disorder induced first order transition in the vortex matter which can lead to a softening of the vortex lattice. PE will be used as an observable effect of such lattice softening. (This is in contrast with the field induced FFLO state where the lattice softening is due to a micorscopic change in the superconducting order parameter[34].) The point defects in the underlying crystalline lattice can cause transverse wandering of the vortex lines and this frozen-in wanderings can destroy the long-range order of the vortex lattice (Ref.4). This is analogous to the action of the thermal noise and can generate topological defects in the vortex lattice. The role of topological defects in the superconducting mixed state of type-II superconductors has been a subject of interest over the years[55,56] and has come under closer scrutiny recently in the context of vortex-solid[18−21]. Frey, Nelson and Fisher[18] suggested that in the low temperature-high field regime of vortex matter, topological defects in the form of vacancies and interstitials can start proliferating leading to an intermediate supersolid state. The vortex supersolid is characterized by the coexistence of crystalline order and a finite equilibrium density of vacancy and interstitial defects[18,20]. The vortex supersolid then can transform continuously into a vortex liquid state[20,57]. Vortex liquid state is characterized by unbound dislocation loops as well as finite density of vacancy and interstitials[20]. The exact nature of the transition from defect free vortex-solid to supersolid transition is not quite clear and possibility exist for both a continuous and a first order transition[18]. Caruzzo and Yu[19] have also considered the possibility of a first order transition to a supersoftened solid induced by interstitial and vacancy line defects in vortex lattice. Although Caruzzo and Yu[19] mainly discuss the cases of phase transitions as a function of temperature, their theoretical approach actually is based on earlier works on disorder induced softening and first order transition in real solids[58]. A supersoftened solid can be quite relevant in our present discussion on the field/disorder induced transitions in vortex soilds of various superconductors.

It will not be totally out of place to mention here that defect induced melting and solid state amorphization is a distinct possibility in real solids and has remained a subject of continued interest[22,23]. A first order transition in such cases can be characterized by a discontinuous increase in point defects.

IV. CONCLUSION

Based on our results concerning history dependence of PE, we suggest the existence of a first order phase transition from one kind of vortex solid to another in the vortex matter phase diagram of $CeRu_2$. The high-field phase can be supercooled by reducing either of the two control variables viz H and T. The extent of supercooling observed depends on the path followed in this space of two variables. In the light of very recent observation of history dependence of PE in detwinned sample of YBCO both in the ZFC[24−26,51] and FC measurements[51], it will be now of interest to check experimentally for a similar (T,H) path dependence and possibility of a first order solid-solid phase transition in the vortex phase diagram of YBCO.

V. ACKNOWLEDGEMENT

We acknowledge Mohammed, S. Hebert, G. Perkins, L. F. Cohen and A. D. Caplin for various help in the experiments involving the transverse-VSM and many useful discussion. We also acknowledge Y. Radzyner, D. Giller, A. Shaulov and Y. Yeshurun for useful discussion. We thank Dr. A. D. Huxley for providing us with the single crystal sample of $CeRu_2$ used in the present study.

REFERENCES

[1] T. Giamarchi and P Le Doussal, Phys. Rev. **B52** 1242 (1995); Phys. Rev. **B55** 6577 (1997).

[2] D. Ertas and D. R. Nelson, Physica **C272** 79 (1996).

[3] M. P. J. Gingras and D. A. Huse Phys. Rev. **B53** 15193 (1996).

[4] V. M. Vinokur, B. Khaykovich, E. Zeldov, M. Konczykowski and R. A. Doyle, Physica **C295** 209 (1998).

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

[6] K. Deligiannis, P. A. J. de Groot, M. Oussena, S. Pinfold, R. Langan, R. Gagnon and L. Taillefer, Phys. Rev. Lett. **79** 2121 (1997).

[7] D. Giller, A. Shaulov, R. Prozorov, Y. Abulafia, Y. Wolfus, L. Burlachkov, Y. Yeshurun, E. Zeldov, V. M. Vinokur, J. L. Peng and R. L. Greene, Phys. Rev. Lett. **79** 2542 (1997).

[8] G. Blatter, Physica **C282-287** 19 (1997)

[9] H. Safar, P. L. Gammel, D. A. Huse, D. J. Bishop, J. P. Rice and D. M. Ginsberg, Phys. Rev. Lett. **69** 824 (1992).

[10] H. Safar, P. L. Gammel, D. A. Huse, D. J. Bishop, W. C. Lee, J. Giapintzakis and D. M. Ginsberg, Phys. Rev. Lett. **70** 3800 (1993).

[11] W. K. Kwok, J. A. Fendrich, S. Fleshler, U. Welp, J. Downey and G. W. Crabtree, Phys. Rev. Lett. **72** 1092 (1994).

[12] E. Zeldov, D. Majer, M. Konczykowski, V. B. Geshkenbein, V. M. Vinokur and H. Shtrikman, Nature **375** 373 (1995).

[13] U. Welp, J. A. Fendrich, W. K. Kwok, G. W. Crabtree and B. W. Veal, Phys. Rev. Lett.

76 4809 (1996).

[14] A. Schilling, R. A. Fisher, N. E. Phillips, U. Welp, D. Dasgupta, W. K. Kwok and G. W. Crabtree, Nature **382** 791 (1996).

[15] A. Soibel, Proc. of LT-22 Conf. Helsinki 1999, Physica B (in press).

[16] D. Giller, A. Shaulov and Y. Yeshurun, Proc. of LT-22, Helsinki 1999, Physica B (in press);D. Giller, A. Shaulov, T. Tamegai and Y. Yeshurun, Phys. Rev. Lett. **84** 3698 (2000).

[17] C. J. van der Beek, S. Colson, M. V. Indenbohm and M. Konczykowski, Phys. Rev. Lett. **84** 4196 (2000)

[18] E. Frey, D. R. Nelson and D. S. Fisher Phys. Rev.**B49**, 9723 (1994).

[19] H. M. Caruzzo and C. Yu, LANL Archive preprint, cond-mat/9705092 (1997).

[20] M. C. Marchetti and L. Radzihovsky, Phys. Rev. **B59** 12001 (1999).

[21] J. Kierfeld and V. Vinokur LANL Archive preprint cond-mat/9909190 (1999)

[22] D. Kuhlmann-Wilsdorf, Phys. Rev. **140** A1599 (1965).

[23] P. R. Okamoto, N. Q. Lam and L. E. Rehn Solid State Physics **V52** Ed. H. Ehrenreich and F. Spaepen (Academic Press, 1999) p 2.

[24] S. Kokkaliaris, P. A. J. de Groot, S. N. Gordeev, A. A. Zhukov, R. Gagnon, L. Taillefer, Phys. Rev. Lett. **82** 5116 (1999).

[25] A. A. Zhukov, S. Kokkaliaris, P. A. J. de Groot, M. J. Higgins, S. Bhattacharya, R. Gagnon and L. Taillefer, Phys. Rev. **B61**, R887 (2000).

[26] S. Kokaliaris, A. A. Zhukov, P. A. J. de Groot, R. Gagnon, L. Taillefer and T. Wolf, Phys. Rev. **B61** 3656 (2000).

[27] S. B. Roy and P. Chaddah, Physica **C279** 70 (1997)

[28] S. B. Roy and P. Chaddah, J. Phys.: Condens. Matter **9** L625 (1997).

[29] S. B. Roy, P. Chaddah and S. Chaudhary, (a) J. Phys.: Condens. Matter **10** 4885 (1998), (b) ibid. **10** 8327 (1998).

[30] D. F. Agterberg, V. Barzykin and L. P. Gor'kov, Euro. Phys. Lett. **48** 449 (1999).

[31] R. Modler, P. Gegenwart, M. Lang, M. Deppe, M. Weiden, T. Luhmann, C. Geibel, F. Steglich, C. Paulsen, J. L. Tholence, N. Sato, T. Komatsubara, Y. Onuki, M. Tachiki, and S. Takahashi, Phys. Rev. Lett. **76** 1292 (1996).

[32] F. Steglich, R. Modler, P. Gegenwart, M. deppe, M. Weiden, M. Lang, C. Geibel, T. Luhmann, C. Paulsen, J. L. Tholence, Y. Onuki, M. Tachiki and S. Takahashi, Physica **C263** 498 (1996).

[33] A. Yamashita, K. Ishii, T. Yokoo, J. Akimitsu, M. Hedo, Y. Inada, Y. Onuki, E. Yamamoto, Y. Haga and R. Kadono, Phys. Rev. Lett. **79** 3771 (1997).

[34] M. Tachiki, S. Takahashi, P. Gegenwart, M. Weiden, C. Geibel, F. Steglich, R. Modler, C. Paulsen and Y. Onuki, Z. Phys. **B100** 369 (1996).

[35] S. Chaudhary, A. K. Rajarajan, K. J. Singh, S. B. Roy and P. Chaddah, Solid St. Commun. **114** 5 (2000).

[36] K. Kadowaki, H. Takeya and K. Hirata Phys. Rev. **B54** 462 (1996).

[37] N. R. Dilley and M. B. Maple Physica **C278** 207 (1997).

[38] R. Modler, Czech. J. Phys. **46** 3123 (1996).

[39] P. Chaddah and S. B. Roy Phys. Rev. **B60** 11926 (1999).

[40] S. Chaudhary, S. B. Roy and P. Chaddah, Physica **B280** 229 (2000).

[41] A. D. Huxley, C. Paulsen, O. Laborde, J. L. Tholence, D. Sanchez, A. Junod and R. Calemczuk, J. Phys.:Condens. Matter **5** 7709 (1993).

[42] S. B. Roy and P. Chaddah, Physica **C273** 120 (1996).

[43] G. Ravikumar, T. V. C. Rao, P. K. Mishra, V. C. Sahni, S. Saha, S. S. Banerjee, N. G. Patil, A. K. Grover, S. Ramakrishnan, S. Bhattacharya, E. Yamamoto, Y. Haga, M. Hedo, Y. Inada and Y. Onuki, Physica **C276** 9 (1997).

[44] G. Ravikumar, T. V. C. Rao, P. K. Mishra, V. C. Sahni, S. S. Banerjee, A. K. Grover, S. Ramamkrishnan, S. Bhattacharya, M. J. Higgins, E. Yamamoto, Y. Haga, M. Hedo, Y. Inada and Y. Onuki, Physica **C298** 122 (1998).

[45] S. B. Roy, S. Chaudhary, P. Chaddah and L. F. Cohen, Physica **C322** 115 (1999).

[46] P. Chaddah, S. B. Roy, S. Kumar and K. V. Bhagwat, Phys. Rev. **B46** 11737 (1992).

[47] Quantum Design Technical Advisory Note No.1, 1989.

[48] H. Ullmaier, Irreversible Properties of Type-II Superconductors, Springer Verlag, p124 (1975). (See fig. 58).

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

[50] 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. **B57** R11069 (1998).

[51] Y. Radzyner, S. B. Roy, D. Giller, Y. Wolfus, A. Shaulov, P. Chaddah and Y. Yeshurun, Phys. Rev. **B** (to appear in June 1, 2000 issue).

[52] D. Giller, A. Shaulov, Y. Yeshurun, J. Giapintzakis, Phys. Rev. **B60** 106 (1999).

[53] S. B. Roy and P. Chaddah, Physica **B262** 20 (1999).

[54] S. B. Roy, S. Chaudhary, P. Chaddah, G. Perkins and L. F. Cohen (unpublished).

[55] J. Lowell, Cryogenics 440 (1972).

[56] R. Wordenweber, P. H. Kes and C. C. Tsuei, Phys. Rev. **33** 3172 (1986).

[57] L. Balents and L. Radzihovsky, Phys. Rev. Lett. **76** 3416 (1996).

[58] A. V. Granato, Phys. Rev. Lett. **68** 974 (1992).

FIGURES

FIG. 1. Magnetization (M) vs field (H) plot for $CeRu_2$ at 4.5K obtained with (a) SQUID magnetometer (b) vibrating sample magnetometer. See text for details. The insets highlight the peak-effect regime.

FIG. 2. Forward legs of various minor hysteresis loops (MHL) at 4.5K obtained with SQUID magnetometer. (a) Open triangles denote $(MHL)_{ZFC}$ initiated from the lower envelope curve at H= 18.25, 18.75 and 19kOe; they saturate without touching the upper envelope curve. $(MHL)_{ZFC}$ initated from 19.6 kOe saturates on touching the upper envelope curve. (b)Open triangles denote $(MHL)_{ZFC}$ initiated from the upper envelope curve at H=18.4 and 18.75 kOe. The $(MHL)_{ZFC}$ initiated at H=18.4 kOe overshoots the lower envelope curve. (c)Open triangles denote $(MHL)_{FC}$ initiated on decreasing field form H = 17.5, 18.4 and 19.6 kOe after field cooling. The starting points of these MHLS are marked with X. While the first two MHLs overshoot the upper envelope curve, the one initiated at H=19.6 kOe behaves normally, namely it saturates on touching the upper envelope curve. We also show one $(MHL)_{FC}$ (represnted by open squares) initiated from H= 18.4 kOe by increasing H. See text for details. Filled triangles represent the envelope curve.

FIG. 3. Forward legs of various minor hysteresis loops (MHL) at 4.5K obtained with vibrating sample magnetometer. (a)$(MHL)_{ZFC}$ initiated from the lower envelope curve at H=19.25 (open circle) and 20 kOe (open triangle); as in the case of SQUID magnetometer measurements the MHLs saturate clearly below the upper envelope curve and meet the envelope curve after crossing the peak-effect regime. (b)$(MHL)_{FC}$ initiated on decreasing field form H =17.25 (open circle) and 19 kOe (open triangle) after field cooling; they overshoot the envelope curve. X marks the starting points of the $(MHL)_{FC}$'s. Filled triangles represent the envelope curve.

FIG. 4. Minor hysteresis loops $(\mathrm{MHL})_{ZFC}$ drawn at 4.5K (obtained with VSM) after increasing H isothermally from 0 to well above H_{C2} (thus drawing the lower envelope curve) and then reaching the various field points of interest on the upper envelope curve by isothermal reduction of H. The MHLs are drawn be reversing the field sweep direction at (a) H=18.75 kOe. and (b) H=19.25kOe. The envelope curve is represented by open triangle and the $(\mathrm{MHL})_{ZFC}$ by filled triangle. The MHLs distinctly overshoot the lower envelope curve.

FIG. 5. Experimentally obtained H-T phase diagram of $CeRu_2$, highlighting the history dpendence in the peak-effect regime. See text for details.

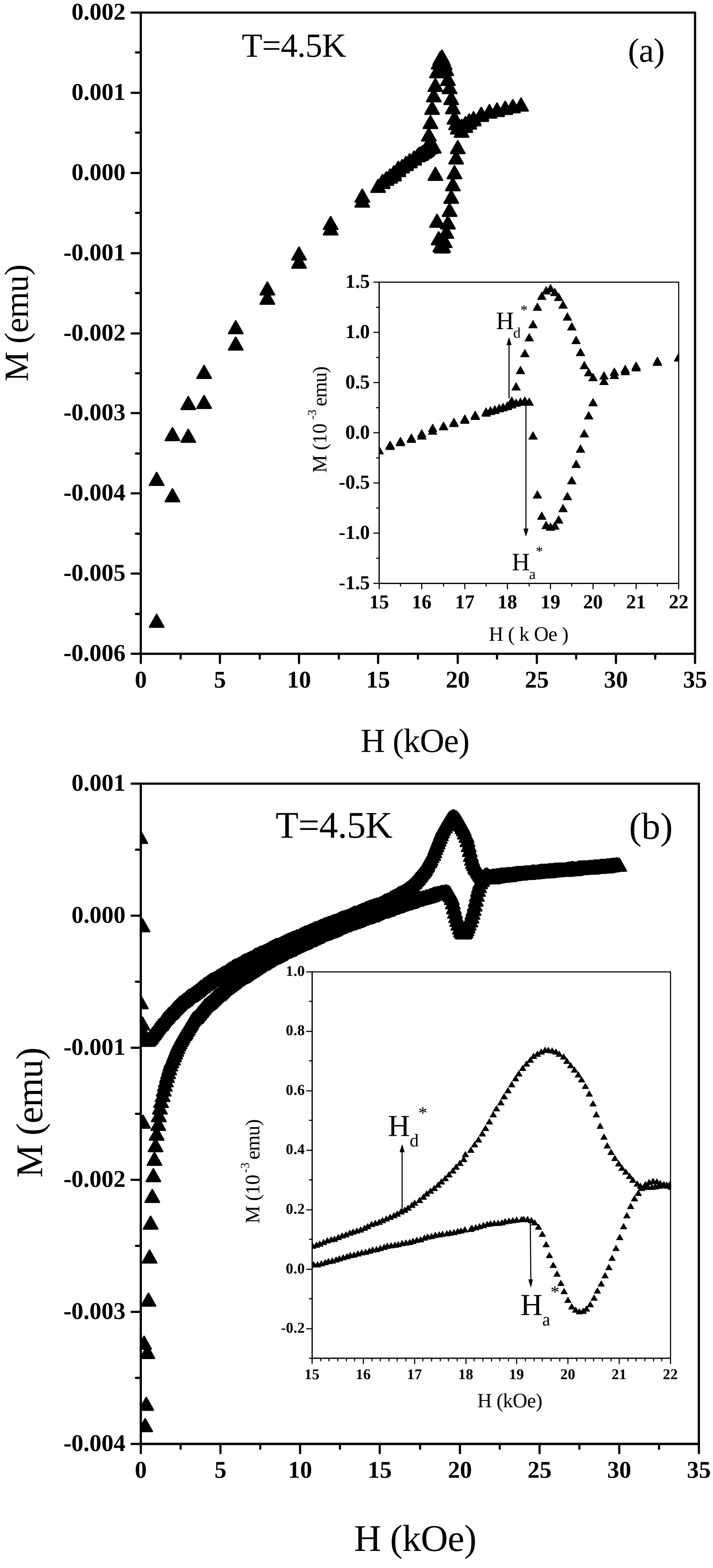
T=4.5K
(a)
M (emu)
0.002
0.001
0.000
-0.001
-0.002
-0.003
-0.004
-0.005
-0.006
0
5
10
15
20
25
30
35
H (kOe)
H_d^*
H_a^*
M (10^{-3} emu)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
15
16
17
18
19
20
21
22
H (k Oe)
T=4.5K
(b)
M (emu)
0.001
0.000
-0.001
-0.002
-0.003
-0.004
0
5
10
15
20
25
30
35
H (kOe)
H_d^*
H_a^*
M (10^{-3} emu)
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
15
16
17
18
19
20
21
22
H (kOe)

Fig. 1 of 5

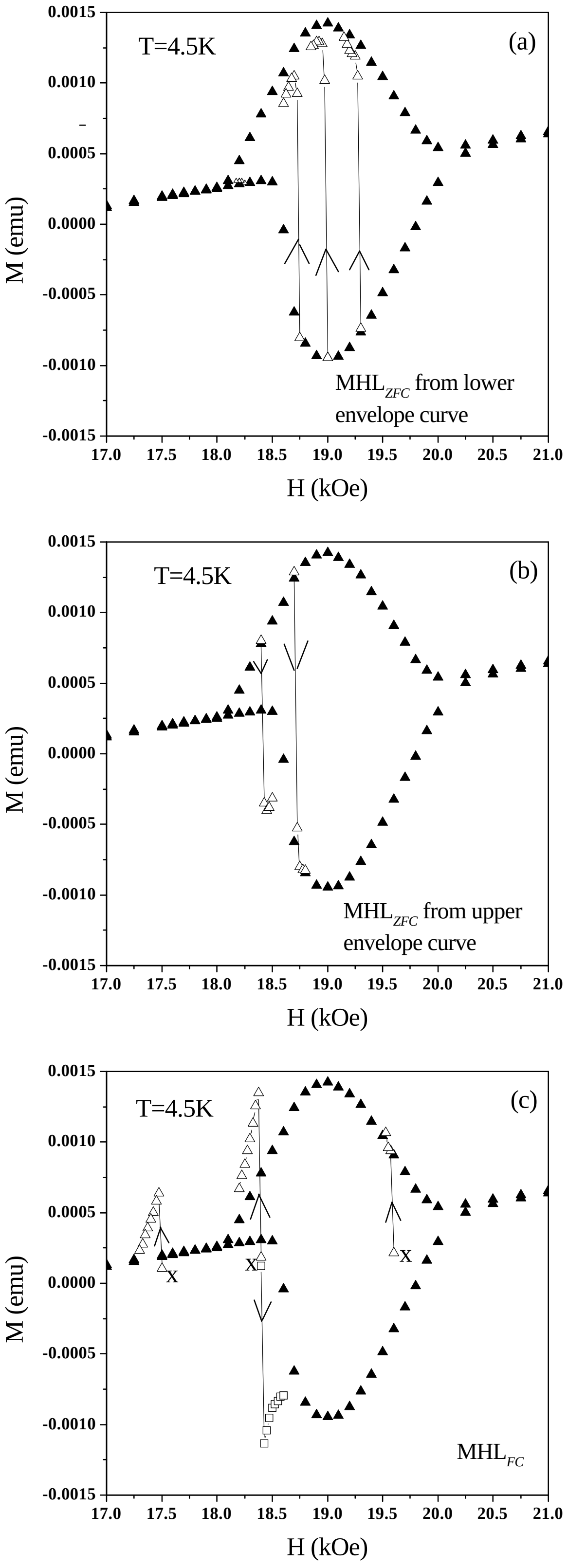
T=4.5K
(a)
MHL$_{ZFC}$ from lower envelope curve
(b)
MHL$_{ZFC}$ from upper envelope curve
(c)
MHL$_{FC}$
x
x
x
M (emu)
H (kOe)
0.0015
0.0010
0.0005
0.0000
-0.0005
-0.0010
-0.0015
17.0
17.5
18.0
18.5
19.0
19.5
20.0
20.5
21.0

Fig. 2 of 5

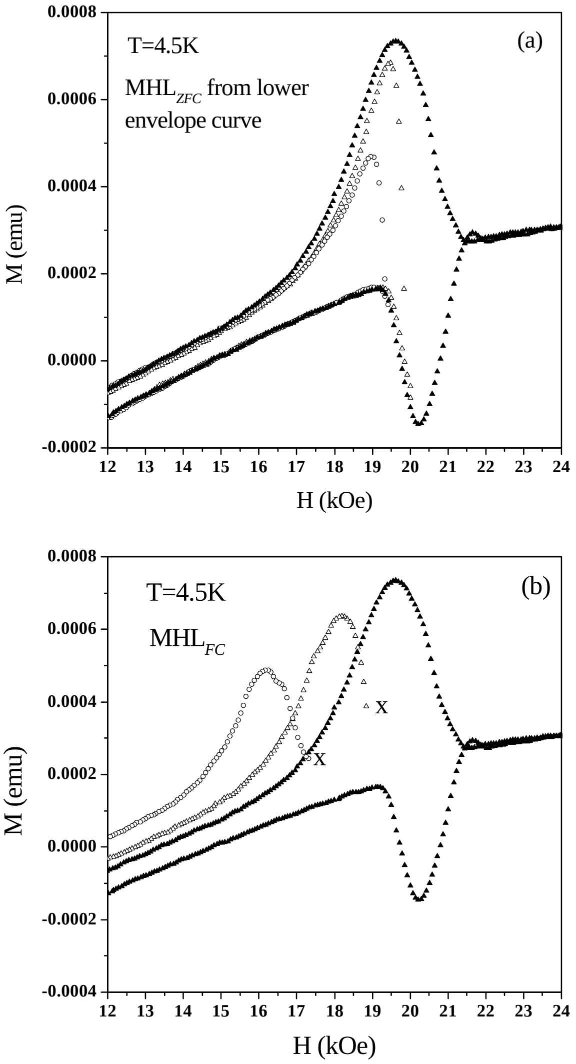
(a)
T=4.5K
MHL_ZFC from lower envelope curve
M (emu)
H (kOe)
0.0008
0.0006
0.0004
0.0002
0.0000
-0.0002
12
13
14
15
16
17
18
19
20
21
22
23
24
(b)
T=4.5K
MHL_FC
x
x
M (emu)
H (kOe)
0.0008
0.0006
0.0004
0.0002
0.0000
-0.0002
-0.0004
12
13
14
15
16
17
18
19
20
21
22
23
24

Fig. 3 of 5

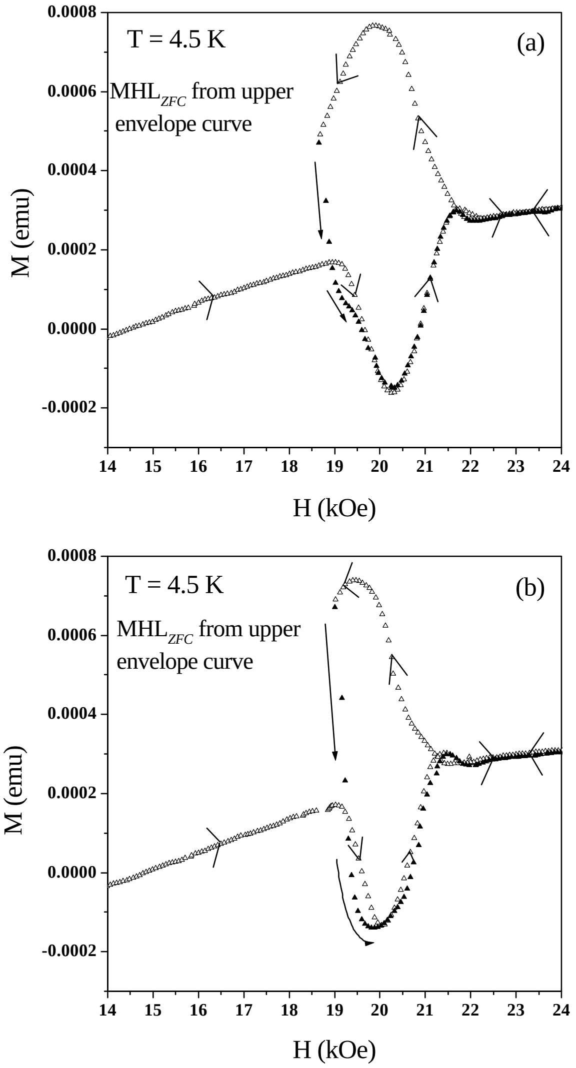
T = 4.5 K
(a)
MHL$_{ZFC}$ from upper envelope curve
M (emu)
H (kOe)
0.0008
0.0006
0.0004
0.0002
0.0000
-0.0002
14
15
16
17
18
19
20
21
22
23
24
T = 4.5 K
(b)
MHL$_{ZFC}$ from upper envelope curve
M (emu)
H (kOe)
0.0008
0.0006
0.0004
0.0002
0.0000
-0.0002
14
15
16
17
18
19
20
21
22
23
24

Fig. 4 of 5

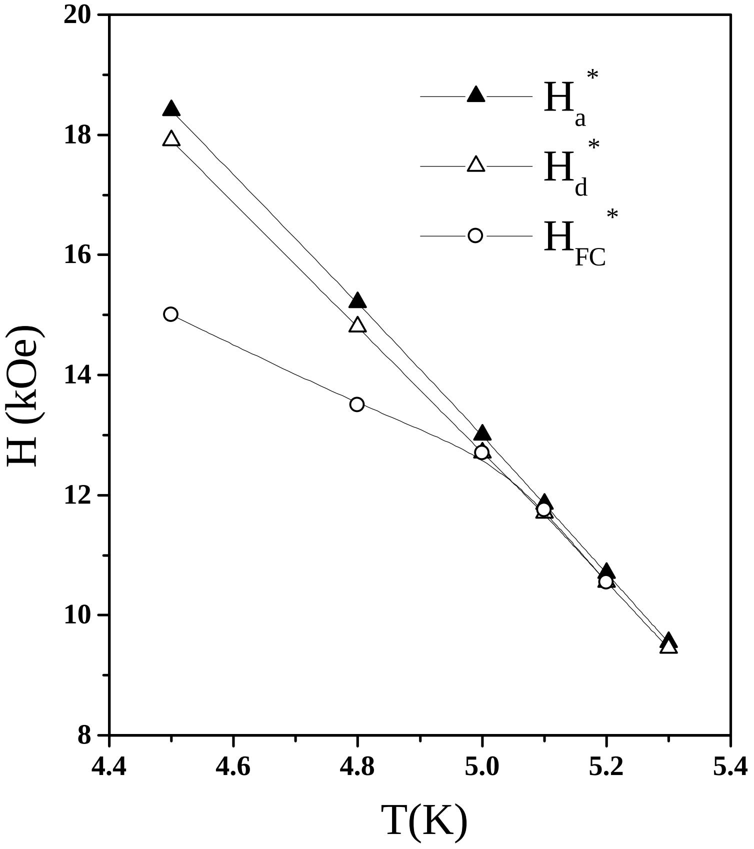

Fig. 5 of 5