

History dependence of peak effect in CeRu₂ and V₃Si: an analogy with the random field Ising systems

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Abstract

We present results of transport measurements showing distinct path dependence of the electrical resistance in the superconducting vortex state of single crystal samples of CeRu₂ and V₃Si. Resistance measured in the vortex state of both the systems prepared by field cooling (FC), indicates a relatively higher degree of disorder than when it is prepared by isothermal variation of field. Small oscillations of magnetic field modify the resistance in the FC state, highlighting the metastable nature of that state. An analogy is drawn with the FC state of the random-field Ising systems.

INTRODUCTION

Non-equilibrium properties associated with the peak-effect (PE) in the C15-Laves phase superconductor CeRu₂ have drawn some attention in recent years [1, 2, 3]. It is observed that in certain field (H) – temperature (T) regime (which includes part of the PE regime), the field-cooled (FC) vortex state in CeRu₂ is more disordered than the vortex state obtained by isothermal variation of H after zero field cooling (ZFC). This FC vortex state in CeRu₂ is quite metastable in nature and susceptible to external fluctuations [2]. The origin of PE and the associated non-equilibrium properties in CeRu₂ remain a matter of debate and various possibilities, starting from a underlying phase transition [1, 4, 5, 6, 7] to dynamical crossover in flux-pinning properties [8, 9], have been put forward.

In a recent communication [3] we have drawn analogy between the ZFC/FC response of the vortex state in and around the PE regime of CeRu₂ and the ZFC/FC response of a random field Ising systems (RFIM). Through dc magnetization study in polycrystalline samples of CeRu₂, we had shown that the magnetization hysteresis in the FC state is distinctly more than the ZFC state. This relatively large hysteresis in the FC state suggested that the FC state was more disordered. It should be recalled here that in the RFIM systems while there exists a long range order in the ZFC state, the same is absent in the FC state; instead the FC state is frozen into a disordered domain structure, which is quite metastable in nature [10, 11]. The analogous behaviour (if not the exact similarity) of these two disparate class of systems has motivated us to investigate more in this direction. In this communication we shall present results of transport properties measured on good quality single crystals of CeRu₂ and V₃Si. While the present results on CeRu₂ will enhance our earlier picture [3] obtained through dc magnetization study on polycrystalline samples, the additional results on the well known superconductor V₃Si will probably indicate more universality of the concerned features. We point out here that, although there exists report of PE in V₃Si [12], our results (described below) will show the existence of history effect and metastability associated with the PE of V₃Si.

EXPERIMENTAL

The single crystal samples of CeRu₂ and V₃Si used in this study are prepared by Dr. A. D. Huxley [13] and Dr. A. Menovsky [14] respectively, and the details of the sample preparation and characterization can be found in the references 13 and 14. The residual resistivity ratio for the CeRu₂ and V₃Si samples are 15 and 47 respectively [13, 14]. The electrical resistance measurements are performed using the standard linear four probe method. A superconducting magnet and cryostat system (Oxford Instruments, UK) is used to obtain the required temperature (T) and magnetic field (H) environment. In the configuration of our measurement the current (I_M) is passed along the $\langle 211 \rangle$ direction for the CeRu₂ sample and the $\langle 100 \rangle$ direction for the V₃Si sample. In all the measurements the direction of I_M is kept perpendicular to H. The T_C for the CeRu₂ and V₃Si samples (obtained from our zero field resistance measurements) are 6.1 and 16.5K respectively. The magnetic field dependence of the resistance (R(H)) is measured,

1. on zero field cooling (ZFC) the sample to various T ($<T_C$) followed by an isothermal variation of H.
2. on field cooling (FC) the sample across T_C in a fixed H to T ($<T_C$). This is done for various H at each T.

RESULTS AND DISCUSSION

For a sample of type-II superconductor with pinning, the critical current (I_C) decreases with the increase in H and goes to zero at the irreversibility field ($H_{irrv} \leq H_{C2}$). However, for superconductors showing PE, $I_C(H)$ shows a peak or local maximum at an intermediate H value before finally going to zero at H_{irrv} . In an isothermal field variation, the consequence of PE will show up in $R(H)$ if the transport current (I_M) used in the measurement is larger than $I_C(H)$ for an intermediate H regime but smaller than $I_C(H)$ in the PE regime. In such a situation one would observe a flux flow resistivity at fields H where $I_M > I_C(H)$ but the resistance will once again fall back to zero in the PE regime where $I_M < I_C(H)$. Adjusting our measuring current I_M appropriately, we show in Fig. 1(a) and 1(b) the R vs H plots with distinct signatures of PE for $CeRu_2$ and V_3Si .

(Although we have results obtained with various other measuring currents at different temperatures, for the sake of clarity and conciseness we shall use these two representative figures for further discussions in the present work). The intermediate flux-flow regime ($0.8T \leq H \leq 1.24T$ for $CeRu_2$ and $1.9T \leq H \leq 3.47T$ for V_3Si) and the PE regime ($1.25T \leq H \leq 1.37T$ for $CeRu_2$ and $3.48T \leq H \leq 3.62T$ for V_3Si) are very clear in these figures. As H approaches H_{irrv} , the flux-flow resistivity starts appearing again which ultimately leads to the normal state behaviour at H_{C2} .

The PE regime for the $CeRu_2$ sample identified in our present transport measurements agrees well with that obtained earlier with the magnetic measurements [2, 3]. A comparison with the sole magnetic measurement (to our knowledge) on V_3Si [12] leads to a similar conclusion.

We shall now focus on the field-history dependence of the resistance in both $CeRu_2$ and V_3Si . The value of I_M was chosen for the two samples was such that the intermediate field flux-flow was observed in both the systems when the field is varied isothermally in the ZFC mode. The measured resistance is, however, found to be zero in the same field regime, when the measurement is performed following the FC protocol (see Fig.2). This clearly indicates that in this intermediate field regime $I_C(H)$ is greater than I_M in the FC mode while I_M is greater than $I_C(H)$ in the ZFC mode. Thus, $I_C(H)$ is higher in the FC mode than in the ZFC mode. A related history dependence of I_C in polycrystalline sample of $CeRu_2$ has earlier been reported by Dilley et al [9]. All these results of transport properties measurements, we believe, are correlated to the anomalous FC response observed in and around the PE regime of $CeRu_2$ in various magnetic measurements [2, 3, 15].

However, (to our knowledge) no such report of history effects exists for V_3Si either in magnetic properties or in transport properties. Similar field-history effects are well known in the RFIM systems[10, 11, 16]. Most experimental information in this regard has been obtained from various diluted antiferromagnets in an applied magnetic field. In ZFC mode, the diluted antiferromagnet is cooled (in zero field) through the zero-field Neel transition temperature. The resultant long range magnetic order is preserved when an external magnetic field is switched on at low temperatures. This long range order, however, gradually decreases on heating the sample to the high temperature paramagnetic phase. However, on cooling back now from the paramagnetic phase in the presence of the applied field (i.e. in the FC mode), the sample develops a short range ordered domain state [10, 11, 16]. The similarity with the vortex state in $CeRu_2$ and V_3Si is apparent here, namely the higher I_C in the FC vortex state of these systems clearly argues for a relatively more disordered FC vortex state.

To draw the analogy further, we shall now deal with the metastability of the FC state. It has been observed experimentally that the FC state in the RFIMs are unstable to field and temperature cycling below the phase boundary ; the FC state tend to get back the long range order through such cycling [16, 17]. To show the similar effects in the FC vortex state of $CeRu_2$ and V_3Si we subject the sample to field cycling after the initial field cooling experiment. We have found that the intermediate field zero resistance state is readily destroyed by a subsequent field cycling through a small value (of the order of few tens of mT) and the corresponding ZFC state flux-flow resistance is recovered (see Fig. 2). Such metastability is not observed in the low H regime ($H < 0.8T$ for $CeRu_2$ and $H < 1.9T$ for V_3Si) and inside the PE regime ($1.25T < H < 1.37T$ for $CeRu_2$ and $3.48T < H < 3.62T$ for V_3Si); the zero resistance state is quite stable to any field cycling in these H -regime.

A continuous phase transition from an elastic vortex solid (or Bragg-glass) to a plastic vortex solid (or Vortex-glass) has been put forward as an explanation of the PE in various HTSC materials [18]. However, any ZFC/FC history effect has not been associated with the PE in these materials so far. Although it is widely accepted that the PE in $CeRu_2$ indicates a transition from a relatively ordered vortex solid to a disordered vortex solid[1, 2, 4, 5, 6, 7, 8, 9] the exact nature of this transition remains a matter of debate. We have earlier suggested that the existence of a first order thermodynamic phase transition and the associated supercooling can explain various interesting features associated with PE in $CeRu_2$ including the history effects [1, 6, 7]. Here the history effect is associated with the supercooling of the high field high temperature disordered vortex state (with enhanced pinning) across the transition line. This picture gains further weight by our recent theoretical argument that the range of supercooling will be more

while varying the temperature than while varying the field [19]. The experimental support in this regard already existed in magnetic studies of CeRu₂, and further support is obtained through our present transport measurements. There is a finite hysteresis in the field variation of the resistance in CeRu₂ between the ascending and the descending field cycle (see inset of Fig. 1(a)). Such a hysteresis in the isothermal field variation of R(H), however, is not very distinct for V₃Si. As shown in Fig.2, the path dependence of R(H) is very clear for both CeRu₂ and V₃Si when the vortex state prepared through the FC protocol. In spite of all these arguments, we must point out here that a definite microscopic experimental evidence in support of (or against) a first order phase transition in CeRu₂ is yet to appear. The analogy with the RFIM systems continues here, since the question regarding the underlying phase transition is yet to be settled in the RFIM systems also [11, 20].

CONCLUSION

We have presented results of transport measurements in CeRu₂ which, in conjunction with our earlier magnetic measurements [3], show clear analogy between the vortex state of CeRu₂ around the PE regime and the RFIM systems. Our study shows that like in RFIM systems, the FC vortex state in CeRu₂ is relatively more disordered and metastable in character. In addition, we have shown here the existence of the same features in the well known superconductor V₃Si.

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Figure Captions

Fig. 1 (a) Resistance (R) vs field (H) plot for CeRu₂ obtained in the ZFC mode at 5K with $I_M = 100$ mA. Open squares (open triangles) denote the data points in the ascending (descending) H cycle. The inset shows the hysteresis in R(H) between the ascending and the descending H cycle, at the onset of the PE regime. (b) Resistance (R) vs Field (H) plot for V₃Si at 14.5K with $I_M = 85$ mA.

Fig. 2 (a) Metastable behaviour of R(H) of CeRu₂ obtained in the FC mode at 5K with $I_M = 100$ mA. Solid circles denote R(H) values obtained after field cooling in various H values. Filled triangles denote R(H) values obtained after a field cycling of maximum 25 mT subsequent to the first FC measurement at the corresponding H. Solid and dashed lines denote the R(H) obtained in the isothermal ZFC mode in the ascending and descending H respectively (same as in Fig. 1(a)). (b) Metastable behaviour of R(H) of V₃Si obtained in the FC mode at 14.5K with $I_M = 85$ mA. Solid circles denote R(H) values obtained after field cooling in various H values. Filled triangles denote R(H) values obtained after a field cycling of maximum 50 mT subsequent to the first FC measurement at the corresponding H. Solid and dashed lines denote the R(H) obtained in the isothermal ZFC mode in the ascending and descending H respectively (same as in Fig. 1(b)).







