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Physica C 341–348 (2000) 1085–1086

PHYSICA C

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Peak effect in $Ca_3Rh_4Sn_{13}$: Vortex Phase Diagram and Evidences for Stepwise Amorphization of Flux Line Lattice

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We elucidate the stepwise amorphization of the ordered flux line lattice and construct the vortex phase diagram in $Ca_3Rh_4Sn_{13}$ from the study of characteristics of the peak effect phenomenon in ac and dc magnetization measurements.

The ternary stannide $Ca_3Rh_4Sn_{13}$ is an isotropic superconductor (T_c of 8.2 K) in which, Tomy *et al* [1] recently reported the occurrence of peak effect (PE) phenomenon in its single crystal. However, their data did not reveal the possible existence of any characteristic, internal structure in the PE regime which has earlier been observed in clean single crystals of $NbSe_2$ and $CeRu_2$ by some of us [2] that could provide useful information on the details of the disordering process of the ordered flux line lattice (FLL). The studies on weak pinning systems are very instructive as the structural and dynamical behavior of the vortex array can be examined within the framework of Larkin–Ovchinnikov collective pinning theory [3]. We provide here a glimpse into extensive investigations of the PE through isofield ac and isothermal dc magnetization measurements on the same crystal of $Ca_3Rh_4Sn_{13}$ as used earlier by Tomy *et al* [1]. The PE regime indeed comprises rich structure, whose evolution and characteristics have been probed from a low threshold field of 3.5 kOe (corresponding to FLL $a_0 \sim 850$ A^0), where the occurrence of the PE could be first noticed (at $t = T/T_c(0) \approx 0.9$), upto the highest field of $H \sim 40$ kOe (i.e., down to $t \approx 0.25$).

Figure 1 displays typical in-phase ac susceptibility ($\chi'(T)$) data recorded under various conditions. Its panel (a) shows a comparison of $\chi'(T)$ response at a frequency (f) of 211 Hz and in an amplitude h_{ac} of 1 Oe (r.m.s.) for the vortex states created at 10 kOe ($a_0 \approx 500$ A^0) in zero field cooled (ZFC) and field cooled (FC) manner. The panel (b) depicts how the ZFC response changes (i) when h_{ac} is enhanced from 1 Oe (r.m.s.) to 3.5 Oe (r.m.s.) (keeping frequency fixed) and (ii) the frequency is decreased from 211 Hz to 21 Hz (keeping h_{ac} fixed at 1 Oe). Within the critical state model description, $\chi' \sim -1 + \alpha h_{ac}/ J_c$, where α is a geometry and sample size dependent factor [2]. Thus, in a χ' (T) response, the PE manifests as an anomalous dip before arrival of the normal state boundary. Note first the internal structure in $\chi'(T)$ curves across the PE region in Fig. 1. Two discontinuous, resolution limited (transition width < 5 mK) jumps occur near the onset (T_{pl}) and the peak (T_p) positions of the PE. The temperatures of these jumps are robust (they do not vary with the frequency or amplitude) and this attests to their claim as markers of the two phase boundaries. Thermal cyclings across both the transitions at T_{pl} and T_p produce a novel kind of irreversible behavior (somewhat different from the one seen in usual first order transitions), as has been noticed earlier also in $NbSe_2$ and $CeRu_2$ [2]. The difference between χ' response in ZFC and FC states (cf. Fig. 1(a)) at $T < T_{pl}$ implies that $J_c^{FC} > J_c^{ZFC}$. The observations that above T_p the $\chi'(T)$ response does not depend on magnetic history and frequency of h_{ac} indicates that metastability effects cease above T_p. Recalling the LO framework [3] where J_c relates inversely to the correlation volume V_c of the ordered FLL, the above observations imply that (i) FC state with smaller V_c is more disordered than the ZFC state and (ii) under

0921-4534/00/$ – see front matter
PII S0921-4534(00)00795-4

the influence of a given h_{ac}, V_c is minimum (and hence the FLL most disordered) near T_p and (iii) the pinned amorphous vortex state above T_p exemplifies the equilibrium condition of the vortex matter. The pinned amorphous state crosses over to the unpinned amorphous state above the irreversibility temperature T_{irr} ($<T_c(H)$). The FC procedure essentially attempts to supercool the amorphous state present at T_p. Likewise, if we attempt to cool down from the partially disordered situation between T_{pl} and T_p on the ZFC curve, we end up producing a completely disordered state while nearing T_{pl} [2].

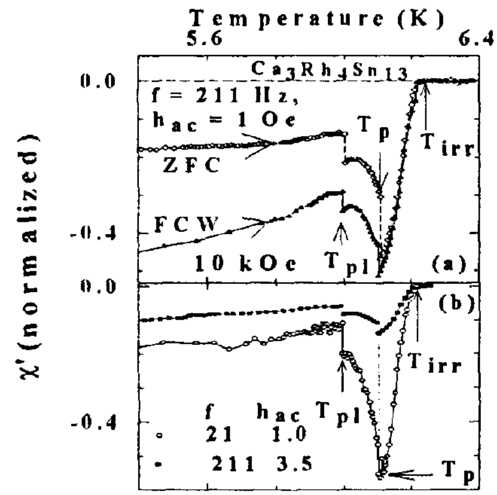

Figure 1: $\chi'(T)$ in $Ca_3Rh_4Sn_{13}$ showing characteristic behavior across PE at 10 kOe (see text for details).

It is useful to confirm the existence of irreversible behavior across onset and peak positions of peak effect (PE) via a thermodynamic measurement. Figure 2 displays a portion of the M-H loop at a fixed temperature of 4.5 K across the PE regime (15-19 kOe). It also shows some of the minor curves. Noteworthy observations in Fig. 2 are: (i) The onset field of PE on the forward leg (H_{pl}^f) is smaller than that (H_{pl}^r) on the reverse leg; (ii) The minor curves initiated from fields above H_p merge into the reverse envelope curve, which is the usual behavior understandable in terms of path independence in $J_c(H)$; (iii) The minor curves initiated from FC magnetization values (M_{FC}) cut across the envelope loop thereby confirming that $J_c^{FC}(H)>J_c^{ZFC}(H)$ for $H<H_p$; (iv) Inability of the minor curves initiated from $M_{ZFC}(H)$ for ($H_{pl}^f<H<H_p$) to reach upto the

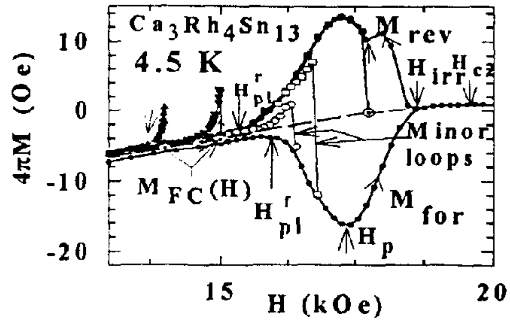

Figure 2: M-H loop, minor loops and loops initiated from FC state shown across the PE region at 4.5 K.

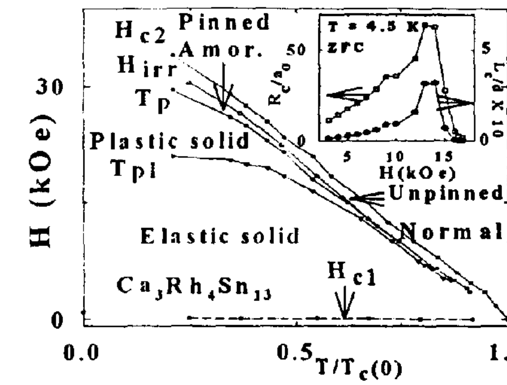

Figure 3: Vortex phase diagram in $Ca_3Rh_4Sn_{13}$

reverse envelope loop implies that $J_c^{ZFC}(H)<J_c^{rev}(H)$, where J_c^{rev} is the current density on the reverse leg.

All these features confirm the presence of metastability effects and attest to the manifestation of the irreversible behavior across H_{pl}^f and H_p. Figure 3 summarizes the data on the onset, the peak and the end of the PE alongwith T_c/H_{c2} in the form of a vortex phase diagram. It comprises the phases - Bragg glass ($H<H_{pl}^f$), vortex glass ($H_{pl}^f<H<H_p$), pinned amorphous ($H_p<H<H_{irr}$) and unpinned amorphous ($H>H_{irr}$). The inset of Fig. 3 shows computed values of R_c/a_0 and L_c/d, where R_c and L_c are the radial and longitudinal correlation lengths respectively at 4.5 K. These values support the nomenclature adopted in Fig. 3.

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