

Specific heat study on the *anomalous* normal state of heavy-fermion superconductor $\text{PrOs}_4\text{Sb}_{12}$

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Abstract

The normal state of the Pr-based heavy-fermion superconductor $\text{PrOs}_4\text{Sb}_{12}$ has been studied by low-temperature specific heat (C) measurements in magnetic fields applied along the $\langle 100 \rangle$ direction using a high-quality single crystal. A pronounced Schottky-like anomaly appearing at ~ 2 K in C/T vs T shifts to lower temperatures in applied magnetic fields although the gap-like behavior still remains even at the boundary (~ 4.5 T) of the field-induced ordered phase (FIOP). Isothermal field scans for $T \leq 0.5$ K reveal that the electronic specific heat increases progressively with increasing field and has largely enhanced values in the FIOP.

Key words: heavy fermion superconductor; filled skutterudites; specific heat; $\text{PrOs}_4\text{Sb}_{12}$

Formation of rare $4f^2$ -based heavy-fermion (HF) states has been established recently in Pr-based filled skutterudites $\text{PrFe}_4\text{P}_{12}$ [1–3] and $\text{PrOs}_4\text{Sb}_{12}$ [4]. In the latter compound, a pronounced specific heat jump $\Delta C/T = 0.5$ J/K² mol at a superconducting (SC) transition temperature $T_c = 1.85$ K provides compelling evidence that the SC state involves quasiparticles with heavily-renormalized effective mass. The existence of a field-induced ordered phase (FIOP), recently revealed in a specific heat study [5], reflects anomalous nature of the normal state in $\text{PrOs}_4\text{Sb}_{12}$. In this paper, we report further detailed thermal property measurements putting emphasis on isothermal field scans, which have revealed the field variation of the thermal excitation in the electron system at low temperatures. For all measurements, we used the same single crystal (grown by Sb-flux method) investigated previously in Ref. [5].

Figure 1 shows the C/T -vs- T data for applied magnetic fields along the $\langle 100 \rangle$ direction. In zero field, a jump of $\Delta C/T = 0.52$ J/K² mol associated with the

SC transition at $T_c = 1.81$ K is superimposed on a Schottky-like anomaly with a broad maximum at ~ 2.1 K. This structure in the normal state could be attributed to, in two extremal cases, either a crystalline-electric-field (CEF) excitation (localized f -electron) or a strongly energy-dependent quasiparticle excitation with a gap-like structure (itinerant f -electron). In applied fields, the maximum shifts to lower temperatures down to 0.64 K in 5 T, while in a C -vs- T plot (see Ref. [5]) the Schottky-like anomaly appears to be suppressed monotonically. With further increasing field in $\mu_0 H \geq 5$ T, the anomaly starts to develop changing its shape into a λ -type peak, evidencing the phase transition into the FIOP. The temperature of the maximum in C/T , T_{max} , is plotted in a H -vs- T phase diagram of Fig. 2. The field variation of T_{max} suggests that the gap-like feature in the thermal excitation is suppressed by applied magnetic fields although it does not completely vanish even at the boundary of the FIOP.

Figure 3(a) shows several C/T -vs- H isothermal curves. We define the phase boundary of the FIOP as a maximum of $d(C/T)/dH$, which is plotted in Fig. 2. Thus determined phase boundary, which agrees well with the one obtained from the C -vs- T data [5], appears to approach $H \simeq 4.4$ T for $T \rightarrow 0$. In Fig.3(a),

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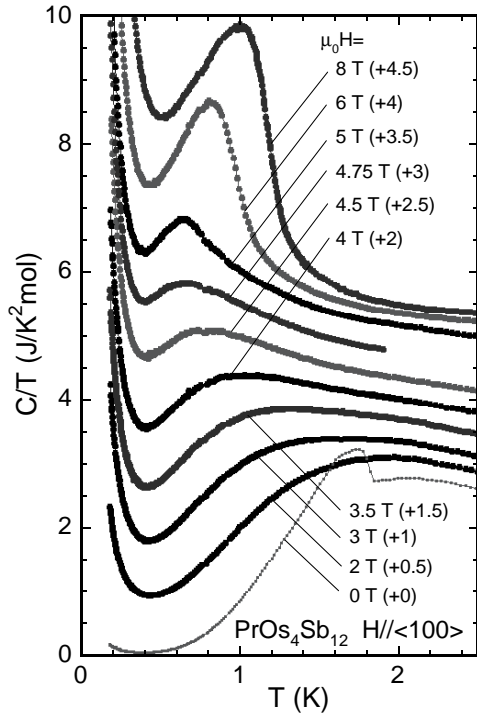


Fig. 1. Temperature dependences of specific heat divided by temperature C/T in different magnetic fields for $\mu_0 H \parallel \langle 100 \rangle$; the data are partly from Ref. [5]. Each curve is vertically shifted by an amount given in parentheses (in the unit of $\text{J/K}^2\text{mol}$).

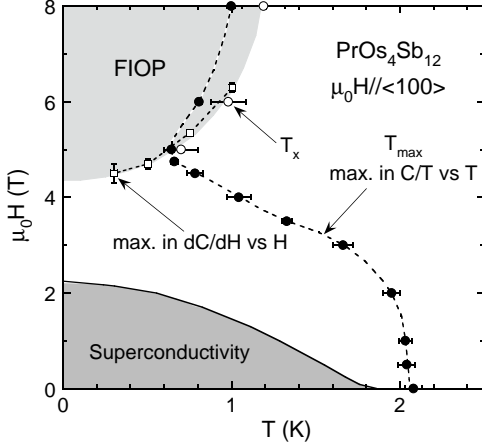


Fig. 2. Magnetic-field-vs-temperature phase diagram; the transition temperatures (T_x) are from Ref. [5].

C/T gradually increases with increasing field for $T \leq 0.5$ K while it decreases at 5 K, consistent with the shift of T_{max} to lower temperatures. The isothermal curves for $T \leq 0.5$ K are contaminated by the nuclear contribution ($C_n \simeq A_n/T^2$), which appears as an up-turn below 0.5 K in Fig.1. To obtain the electronic contribution C_e/T , two types of C_n/T data estimated

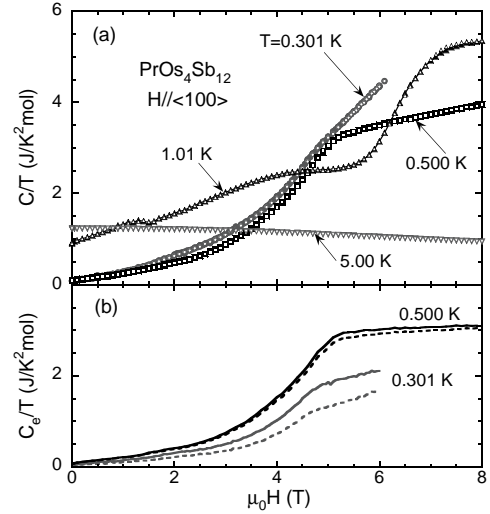


Fig. 3. (a) Magnetic field dependences of specific heat divided by temperature C/T . The data of closed (open) symbol were obtained with increasing (decreasing) H ; no hysteretic behavior is visible. For $T = 1.01$ K, an anomaly appears at the upper critical field of ~ 1.5 T. (b) Estimated electronic part C_e/T as a function of H . See text for definition of the solid and dashed curves.

in Ref. [5] are subtracted from the measured C/T data. Thus obtained C_e/T -vs- H curves are shown in Fig. 3(b). For the solid curve, A_n was estimated by a low- T fit of $C(T) = A_n/T^2 + \gamma T + \alpha T^n$ to the data. The dashed curve provides a lower bound for C_e/T since an upper bound for C_n , which was obtained by $A_n \equiv CT^2$ at 0.2 K, is used. Although an accurate estimation of $\gamma \equiv C_e/T|_{T \rightarrow 0}$ is difficult because of the substantial C_n contribution, these C_e/T -vs- H curves suggest that γ increases monotonically with increasing field and has largely enhanced values in the FIOP. This interpretation is supported by the similar field dependence of a T^2 coefficient in recent electrical resistivity measurements [6,7] as expected from the Kadowaki-Woods relation.

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