MAGNETIC FIELD EFFECT ON THE TRANSPORT PROPERTIES OF THE ANOMALOUS HEAVY FERMION $PrFe_4P_{12}$*

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We report the effect of magnetic field on the transport properties in the exotic heavy fermion $PrFe_4P_{12}$. The temperature T_P of the resistivity maximum, ca. 13 K at zero field, shifts almost linearly with increasing field, correlated with the reduction of the effective mass determined from the de Haas–van Alphen (dHvA) measurement. The resistivity in 8 T shows a huge anisotropy with respect to the magnetic field direction.

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1. Introduction

The filled-skutterudite compounds ($RETr_4Pn_{12}$: RE= rare earth, Tr= Fe, Ru, Os, and Pn=pnictogen) have recently aroused renewed interest, since various exotic features such as metal insulator transition in $PrRu_4P_{12}$, anomalous heavy fermion (HF) behavior in $PrFe_4P_{12}$ and HF-superconductivity in $PrOs_4Sb_{12}$, have been observed [1–3]. The quadrupolar interaction is thought to be a key mechanism to explain such anomalous behavior. Especially for $PrFe_4P_{12}$, both the highly enhanced effective mass and the non-magnetic low field ordered state (LOS) below $T_A = 6.5$ K are inferred to have their origins in a quadrupolar interaction [4, 5]. In the high field HF states (HFS), both the mass enhancement in the dHvA and the specific heat coefficient γ were found to be suppressed with increasing magnetic field H. In this paper, the effect of magnetic field on the transport properties is reported.

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2. Results and discussion

Fig. 1 shows the temperature T dependence of electrical resistivity ρ below 50 K in selected fields H along $\langle 100\rangle$ axis measured on a single crystal grown by the ordinary tin-flux method having basically same quality as was used in the dHvA experiment [4]. $\rho(T)$ in zero field is basically the same

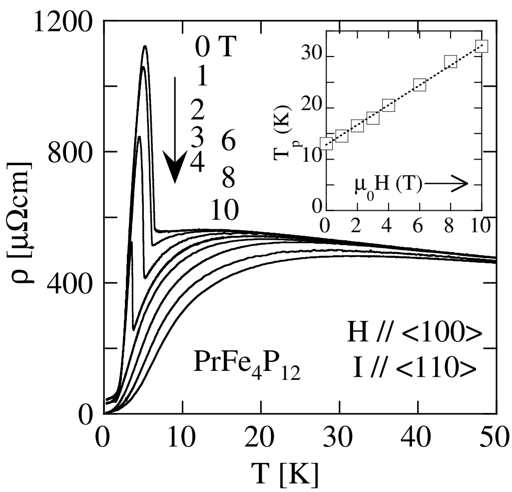

Fig. 1. Temperature dependence of of electrical resistivity ρ in $PrFe_4P_{12}$. Inset shows the field dependence of the peak temperature.

as reported previously [2]; it decreases up to 200 K almost logarithmically with increasing T after showing a faint maximum at $T_P \approx 13$ K. The sharp upturn at around $T_A = 6.5$ K reflects the reduction of carrier numbers resulting from the Fermi surface (FS) reconstruction. Below T_A, $\rho(T)$ does not follow the simple relation $\rho = \rho_0 + \mathrm{A}T^2$ expected for the Fermi liquid, but follows $\rho = \rho_0 + \mathrm{B}T^2\exp(-\mathrm{D}/k_\mathrm{B}T)$ reflecting a gap structure [2]. The HF-state in high fields above H_M has been confirmed both in the dHvA and the specific heat experiments [4, 5]. Also on the resistivity, we have found the T^2-dependence with a large coefficient A which approximately follows the Kadowaki–Woods relation [6].

A new finding from Fig. 1 is the systematic shift of T_P with field as shown in the inset. Most naively, the peak is thought to reflect a transition into so-called coherent state below T_P, which is indirectly connected with the Kondo temperature. The increase of T_P with H in the inset is consistent with the decrease in both γ-value and the cyclotron effective mass with H. Another interesting result is the large angular dependence of ρ under magnetic field as shown in Fig. 2. The origin is not yet clear, however, it

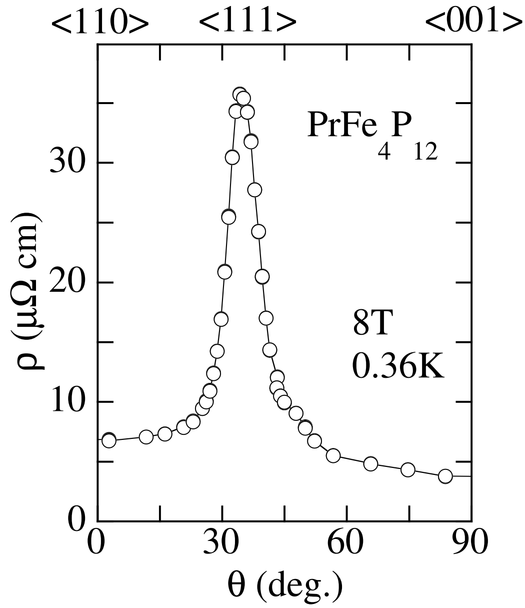

Fig. 2. Field dependence of ρ in $PrFe_4P_{12}$.

should be noted that the angular dependence reflects the anisotropy in a characteristic temperature below which the Fermi liquid behavior becomes apparent. No T^2-dependence in $\rho(T)$ has been observed down to the lowest temperature of 0.3K in the present experiment for $H \| \langle 111 \rangle$. Further studies are necessary to clarify the origin of this interesting anisotropy.

Fig. 3 shows the field dependence of Hall resistivity ρ_{H} at three temperatures above and below T_{A}. In low fields, ρ_{H} changes sign across T_{A} from negative above to positive below. The large change below T_{A} suggests the disappearance of an electron-like FS, if we assume the simplest two-spheres FS model. Both at 2.1 K and 4 K, ρ_{H} exhibits a sudden change at around H_{M}, indicating the recovery of the electron-like FS though the sign of ρ_{H} is positive in high fields. This discrepancy could be understood if we take into account the anomalous Hall effect contribution $\sim \chi \times \rho$ (the effective magnetic susceptibility times resistivity) in addition to the normal Hall coefficient R_{H0}. The negative sign of ρ_{H} above T_{A} in low fields is ascribed to the anomalous contribution [2]. The scenario is consistent with the change of sign in ρ_{H} for 7 K in high fields in Fig. 3. R_{H} (ca. $+5 \times 10^{-9}\mathrm{m}^3/\mathrm{C}$) estimated from ρ_{H} at 4 K and 2.1 K in high magnetic fields is slightly larger than R_{H} ($+1.5 \times 10^{-9}\mathrm{m}^3/\mathrm{C}$) at high temperatures ($\sim$290 K). The difference may become smaller in higher fields, since ρ_{H} shows a tendency to saturate at 10 T. Namely, R_{H0} is dominated by a hole-like FS both in HFS and in

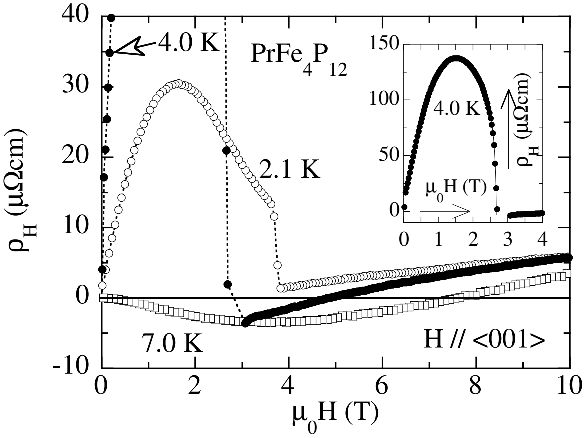

Fig. 3. Change of ρ_H as a function of the field direction in 8 T measured at 0.36 K.

high temperatures. No definitive information on the field dependence of effective mass has been obtained from the Hall effect at this stage.

Lastly, we discuss the anomalous part of ρ_H in LOS. Except near H_M where FS changes, R_{H0} ($+3 \times 10^{-7}$m^3/C determined from the initial slope of ρ_H *versus* H curve which is almost constant below 2 K) is independent of T. The enhancement of ρ_H with T below T_A indicates that the anomalous part of Hall effect is positive in LOS. Namely, the left–right asymmetry of conduction electron scattering changes sign between the two states. In order to clarify the origin, further studies including the anisotropy are necessary.

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