High field magnetoresistance in heavy fermion superconductor $PrOs_4Sb_{12}$

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Abstract

We have measured the magnetoresistance (MR) in Pr-based heavy fermion superconductor $PrOs_4Sb_{12}$. We have found distinct anomalies in MR indicating the existence of field induced ordered phase above $\sim$ 4.5 T. The field dependences of transverse MR tend to saturate, indicating $PrOs_4Sb_{12}$ to be an uncompensated metal with the closed Fermi surface.

Key words: filled skutterudite; heavy fermion superconductor; $PrOs_4Sb_{12}$; magnetoresistance

Filled skutterudite compounds RT_4X_{12} (R=rare-earth; T=Fe, Ru and Os; X=P, As and Sb) have attracted much attention because of their interesting anomalous properties, such as metal-insulator transition in $PrRu_4P_{12}$[1] and unusual heavy fermion (HF) behavior in $PrFe_4P_{12}$ [2–4]. Recently, $PrOs_4Sb_{12}$ was reported to show superconductivity below $T_C =$ 1.85 K [5]. The large specific heat jump at T_C, $\Delta C/T_C \sim$ 500 mJ/K^2· mol, suggests a large mass enhancement in this compound, that is the first example of Pr-based HF-superconductor. Bauer *et al.* claims that the crystal electric field (CEF) ground state to be a Γ_3 non-magnetic doublet with quadrupolar moments based on the results of magnetic susceptibility χ, specific heat C, and inelastic neutron scattering measurements and the quadrupolar interaction plays an important role for the HF-behaviors and HF-superconductivity [5]. In order to understand the unusual properties in detail, we have measured the magnetoresistance (MR) in $PrOs_4Sb_{12}$ up to 14 T.

Single crystals of $PrOs_4Sb_{12}$ were grown by a Sb-self-flux method with the excess Sb (the ratio is R:Os:Sb=1:4:20) [5]. The high-purity materials, 4N (99.99% pure)-Pr, 3N-Os and 6N-Sb, were used for the crystal growing. The typical forms of single crystals were cubic or rectangular shape with a largest dimension of about 3 mm. The residual resistivity ρ_0 and the residual resistivity ratio (RRR) are $\rho_0 \sim 8\mu\Omega$·cm and RRR $\sim$ 55, respectively, indicating high quality of the sample, that is also ensured from the observation of de Haas-van Alphen (dHvA) effect [7]. The transverse MR was measured by the usual four-probe DC method in a top loading ^{3}He-refrigerator cooled down to 0.3 K with a 16 T superconducting magnet.

Figure 1 shows the temperature T dependence of electrical resistivity $\rho(T)$ under selected magnetic fields. Below 9 T, $\rho(T)$ shows qualitatively the same behavior as reported in ref. [6]. In zero field, $\rho(T)$ shows a typical metallic behavior with a negative curvature above $\sim$ 65 K (not shown) and a distinct decrease below $\sim$ 7 K followed by an abrupt drop to zero at T_C. Under 3 T above the superconducting upper critical field H_{C2}, $\rho(T)$ follows $\rho_0 + AT^2$ below $\sim$1.5 K with $A = 1.4$ $\mu\Omega$·cm/K^2. If we assume that the Sommerfeld coefficient γ in this compound is 500 mJ/K^2·mol, this

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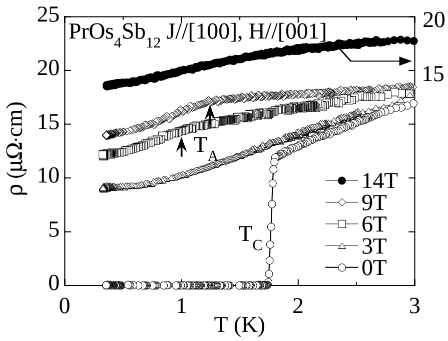

Fig. 1. Temperature dependence of the transverse MR at selected fields.

A value is in agreement with the Kadowaki-Woods relation [8]. The $\rho(T)$ shows a rapid decrease below $T_{\rm A} \sim 1$ K for 6 T and below $T_{\rm A} \sim 1.25$ K for 9 T, suggesting some type of phase transition occurs at T_A. Maple *et al.* observed such anomalies below 8 T [6], however, no detailed measurements have been done. Our recent specific heat measurements show λ-type anomalies at $T_{\rm A}$ above ~ 4.5 T [9], that is a clear thermodynamical evidence for the phase transition. The $T_{\rm A}$ determined from the present MR measurements is found to increase with increasing magnetic field up to 9 T, that is in agreement with the specific heat measurements below 8 T. The $T_{\rm A}$ presumably shows a rapid decrease with increasing field, since under 14 T, as shown in Fig. 1, no anomaly associated with the phase transition has been observed down to the lowest temperature of ~ 0.3 K, suggesting that the ordered phase exists between 4.5 T and 14 T.

Figure 2 shows the field H dependence of transverse MR $\rho(H)$ at selected temperatures. At 4.26 K, $\rho(H)$

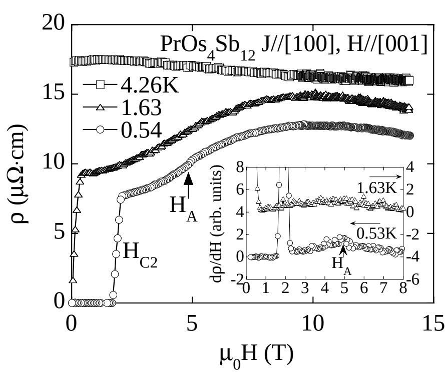

Fig. 2. Field dependence of the transverse MR at selected temperatures. Inset shows the H derivative of ρ $d\rho/dH$ versus H.

increases with increasing H up to ~ 1.5 T and decreases at higher H. At 1.63 K and 0.54 K, overall features in $\rho(H)$ are the same except the difference of $H_{\rm C2}$ and $\rho(0)$; $\rho(H)$ increases with increasing H following $\rho(H) \propto H^2$ up to ~ 4 T and shows a broad maximum around 10 T. It should be noted that $\rho(H)$ at 0.54 K shows a slight increase at $H_{\rm A} \sim 4.8$ T, which is more clear in the H dependence of $d\rho/dH$ as shown in the inset of this figure. The $H_{\rm A}$ agrees well with the phase boundary determined by the specific heat measurements [9]. The $\rho(H)$ in Fig. 2 could be understood as a combined effect of the ordinary positive MR saturated at ~ 10 T and the negative one which is due to the reduction of magnetic scattering. The positive transverse MR with saturating behavior claims that this compound is an uncompensated metal with the closed Fermi surface, that is consistent with the result of dHvA experiments [7]. On the other hand, for the negative MR, the origin is not clear at this stage. The CEF energy level scheme deduced from $\chi(T)$, $C(T)$ and inelastic neutron scattering measurements has a Γ_3 ground state with a low lying magnetic Γ_5 excited state (~ 10 K) [5,6,9]. The suppression of magnetic fluctuations under the magnetic field may be an origin for the negative MR. Also such a low lying CEF state may be related to the creation of field induced ordered phase.

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References

[1] C. Sekine, T. Uchiumi, I. Shirotani, T. Yagi, Phys. Rev. Lett. **79** (1997) 3218.

[2] H. Sato, Y. Abe, H. Okada, T. D. Matsuda, K. Abe, H. Sugawara, Y. Aoki, Phys. Rev. B **62** (2000) 15125.

[3] H Sugawara, T. D. Matsuda, K. Abe, Y. Aoki, H. Sato, S. Nojiri, Y. Inada, R. Settai, Y. Ōnuki, J. Magn. Magn. Mater. **48-50** (2001) 226.

[4] Y. Aoki, T. Namiki, T. D. Matsuda, K. Abe, H. Sugawara, H. Sato, Phys. Rev. B **65** (2002) 064446.

[5] E. D. Bauer, N. A. Frederick, P.-C. Ho, V. S. Zapf, M. B. Maple,Phys. Rev. B **65** (2002) 100506(R).

[6] M. B. Maple, P.-C. Ho, V. S. Zapf, N. A. Frederick, E. D. Bauer, W. M. Yuhasz, F. M. Woodward, J. W. Lynn, J. Phys. Soc. Jpn. **71** (2002) Suppl. 23.

[7] H. Sugawara *et al.*, in preparation.

[8] K. Kadowaki S. B. Woods, Solid State Commun. **58** (1986) 507.

[9] Y. Aoki, T. Namiki, S. Osaki, S. R. Saha, H. Sugawara, H. Sato, J. Phys. Soc. Jpn. **71** (2002), to be published.