Ferromagnetic heavy fermion compound $SmFe_4P_{12}$

Naoya Takeda, [a,1] Masayasu Ishikawa [a],

[a] Institute for Solid State Physics, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8581, Japan

Abstract

We present the magnetic properties of a filled skutterudite compound $SmFe_4P_{12}$. The magnetic-susceptibility and specific-heat measurements reveal a ferromagnetic phase transition at 1.5 K. The temperature dependence of the electrical resistivity exhibits a Kondo effect and the electronic specific heat coefficient attains as large as 370 mJ/mole· K^2. This compound is thereby reported as the first Sm-based heavy fermion system with a ferromagnetic ground state.

Key words: filled skutterudite; $SmFe_4P_{12}$; ferromagnetism; heavy fermion

1. Introduction

Filled skutterudite compounds with a general formula RT_4X_{12} (R=alkaline earth, rare earth, Th and U, T=Fe, Ru and Os, X=P, As and Sb) crystalize in the body-centered cubic structure of a space group Im$\bar{3}$ (No. 204).[1] These compounds exhibit various interesting physical properties at low temperatures, such as superconductivity, magnetic order and semiconducting behavior.[2,3]

The magnetic susceptibility and electrical resistivity of $SmFe_4P_{12}$ were reported by Jeitschko et al.[4] They reported that $SmFe_4P_{12}$ is a Van Vleck paramagnet. It implies that the valency of Sm-ions is divalent and Hund's rule ground state is a non-magnetic singlet. On the other hand, the electrical resistivity implys a Kondo lattice rather than a simple paramagnetic metal. If this is so, Sm-ions are trivalent or mixed-valent and hence carry a local moment. The purpose of this work is to clarify this inconsisteny.

2. Experimantal

The samples were prepared by a molten-metal-flux growth method with a Sn flux. The X-ray diffraction examination does not show any impurity profiles. The lattice parameter determined by CuKα1 is 7.7990(1) Å which is very close to the reported value.[4]

The magnetic susceptibility above 2 K was measured by Quantum Design MPMS. The specific heat was measured by a semi-adiabatic heat-pulse method in a dilution refregerator. The elecrical resistivity was measured by a four-probe dc method in a ^{3}He-cryostat and a dilution refregerator.

3. Results and Discussion

The measured magnetic susceptibility is shown in Figure 1(a), where the theoretical curves for Sm^{3+} and Sm^{2+} are also included for comparison. As clearly seen, the experimental data fairly well follow the curve of Sm^{3+}, but the data below 3 K largely exceed the theoretical curve as shown Fig.1(b), implying the presence of a ferromagnetic transition.

The ferromagnetic transision is evidenced by the specific heat, ac magnetic susceptibility and magnetization measurements. We show the $C/T - T^2$ plot in

[1] Corresponding author. E-mail: ntakeda@issp.u-tokyo.ac.jp

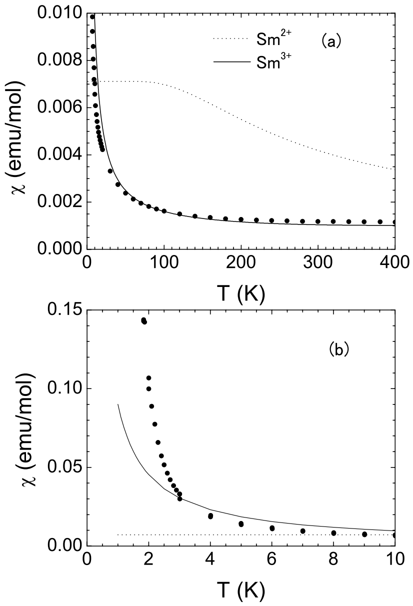

Fig. 1. (a) The temperature dependence of the magnetic susceptibility measured under magnetic field of 1 kOe. Solid and dotted lines are theoretical curves for Sm^{3+} and Sm^{2+}. (b) Low temperature part of the magnetic susceptibility.

Fig.2. The extraporated value of C/T to $T = 0$ K is 370 mJ/mol·K^2. This value is 6.5 times of $LaFe_4P_{12}$ in which a large cyclotron mass is observed by the de Haas-van Alphen effect.[5,6] The magnetic entropy evaluated by subtracting the specific heat of $LaFe_4P_{12}$ reaches about 1 J/mol·K at 1.5 K, which is about 60% of Rln2. It should be noted here that the specific heat below 0.8K is well described by a T^3-law, which is different from the theoretical prediction of ordinary ferromagnetic spin wave, $T^{3/2}$-law. Such a T-dependence is also reported for $NdFe_4P_{12}$ with the same crystal structure. [2]

Figure 3 shows the temperature dependence of the normalized electrical resistivity, which qualitatively agrees with the previous report.[4] $\rho(T)$ decreases linearly in T and deviates below 100K, followed by a sharp decrease. The characteristic feature of Kondo lattices can be seen in the shoulder below 100 K. The ferromagnetic transition apparently does not manifest itself in the resistivity for this system.

4. Summary

We have studied the magnetic properties of a filled skutterudite $SmFe_4P_{12}$. The magnetic measurements clearly showed that the compound is not a Van Vleck paramagnet but a ferromagnet below 1.5K. The elec-

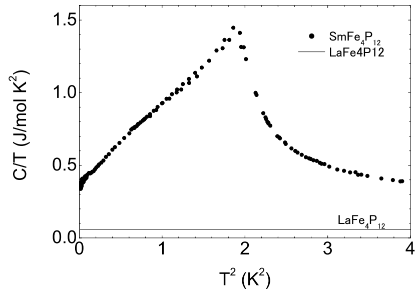

Fig. 2. The $C/T - T^2$ plot. Solid line is C/T of $LaFe_4P_{12}$. Note the T^3 dependence of C below 0.8 K.

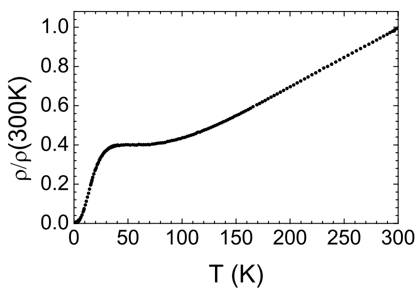

Fig. 3. The temperature dependence of the normalized electrical resistivity.

trical resistivity and the large γ-value strongly suggest that $SmFe_4P_{12}$ is a Kondo system.

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