Pressure effect of transport properties of hexagonal Yb$_2$Ni$_{12}$P$_7$

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Abstract. We prepared single crystals of Yb$_2$Ni$_{12}$P$_7$ using a Sn-flux method and measured their resistivity under hydrostatic pressure up to 8 GPa. At ambient pressure, the magnetic part of resistivity $\rho_{\text{mag}}(T)$ shows a peak around $T_{\text{max}} \sim 100$ K and $T^2$ dependence below the characteristic temperature of the Fermi liquid, $T_{FL} = 3$ K. When pressure increases up to 2.06 GPa, the value of $\rho_{\text{mag}}(T)$ above $T_{\text{max}}$ decreases slightly but $\rho_{\text{mag}}$ below $T_{\text{max}}$ increases slightly. $T_{FL}$ decreases with increasing pressure, and is expected to become zero at 2.5 GPa. Around this pressure, the coefficient of $T^2$ in $\rho_{\text{mag}}$ significantly increases, suggesting the existence of a quantum critical point. Above 2.5 GPa, overall $\rho_{\text{mag}}$ gradually decreases with increasing pressure up to 6 GPa, but it below 15.5 K increases above 6 GPa.

1. Introduction

In Yb-based intermetallic compounds, it is well known that magnetic/valence instability is induced by hybridization between 4f- and conduction-electrons. Hybridization is controlled by pressure, and nonmagnetic-magnetic and/or valence quantum phase transitions are expected. Yb$_2$Ni$_{12}$P$_7$ is one of the candidates in which a nonmagnetic-magnetic quantum critical point (QCP) is expected by applying pressure.

The crystal structure of Yb$_2$Ni$_{12}$P$_7$ is a hexagonal Zr$_2$Fe$_{12}$P$_7$-type structure (Space group P$\overline{6}$)[1]. There are 1c and 1f crystallographic sites with hexagonal point symmetry for each Yb ion which occupies voids of the Cr$_{12}$P$_7$-type structure. Recently, rare earth intermetallic compounds which crystallize in a cage structure (such as Yb$_2$Ni$_{12}$P$_7$) have attracted much attention because of their various properties, such as magnetism, superconductivity, heavy fermion, multipole order, and rattling. The susceptibility of Yb$_2$Ni$_{12}$P$_7$ follows Curie-Weiss law down to 50 K from room temperature with an effective Bohr magneton 4.5 $\mu_B$, indicating the trivalent state of Yb-ions[2]. This compound shows no magnetic transition down to 50 mK and heavy fermion like behaviour with the electric specific heat coefficient $\gamma = 200$ mJ/K$^2$mol-Yb[2, 3]. In order to explore the QCP, we prepared high quality single crystals of Yb$_2$Ni$_{12}$P$_7$ using a Sn-flux method, and measured their electrical resistivity under hydrostatic pressure.

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2. Experimental detail

The single-crystal samples of Yb$_2$Ni$_{12}$P$_7$ were prepared by a molten-metal flux method using Sn as the flux. Detail of sample synthesis is described in [4]. Hexagonal prism crystals with a typical length of 0.5 mm were obtained after eliminating the flux using hydrochloric acid. The X-ray powder diffraction patterns confirmed the Zr$_2$Fe$_{12}$P$_7$-type structure. The electrical resistivity $\rho$ was measured using a DC four-probe method with excitation current parallel to the cylindrical axis of the hexagonal prism crystal in a $^3$He cryostat down to 280 mK. Hydrostatic pressure was generated using a NiCrAl-CuBe hybrid-piston-cylinder cell up to 2.06 GPa[5] and a cubic-type anvil cell up to 8 GPa. Daphne oil 7373 and mixture of Flourinert FC 70 & 77 were used as pressure transmitting media for the piston cylinder cell and the cubic anvil cell, respectively.

3. Results and discussion

![Figure 1](image1.png)  
**Figure 1.** Magnetic part of resistivity $\rho_{\text{mag}}$ of Yb$_2$Ni$_{12}$P$_7$ as a function of temperature under hydrostatic pressure up to 2.06 GPa. Inset: resistivity $\rho$ of Yb$_2$Ni$_{12}$P$_7$ at ambient pressure.

![Figure 2](image2.png)  
**Figure 2** $\rho_{\text{mag}} - \rho_0$ of Yb$_2$Ni$_{12}$P$_7$ under selected pressures as a function of $T^2$.

The temperature dependence of $\rho$ at ambient pressure is metallic, and shows a shoulder around 100 K as shown in the inset of Fig. 1[2]. The magnetic part of $\rho$, $\rho_{\text{mag}}$, was evaluated by subtracting phonon contribution using the $\rho-\rho_0$ of non-magnetic Lu$_2$Ni$_{12}$P$_7$, where $\rho_0$ is a temperature independent residual resistivity. Figure 1 shows $\rho_{\text{mag}}(T)$ under selected pressures. $\rho_{\text{mag}}(T)$ roughly shows -log $T$ dependence from room temperature down to 150 K, and shows a broad maximum around $T_{\text{max}} \sim 100$ K. These behaviours are characteristic of the Kondo effect. $\rho_{\text{mag}}(T)$ smoothly decreases below $T_{\text{max}}$ and shows $T^2$ dependence below $T_{\text{FL}} = 3$ K as shown in Fig 2, indicating that the electronic state of Yb$_2$Ni$_{12}$P$_7$ at ambient pressure is the Fermi liquid state. Here, $T_{\text{FL}}$ is defined as the upper limit of $T^2$ dependence in $\rho_{\text{mag}}(T)$.

The overall $\rho_{\text{mag}}(T)$ does not change drastically by applying pressure, as shown in Fig. 1. With increasing pressure, the value of $\rho_{\text{mag}}(T)$ above $T_{\text{max}}$ decreases slightly, but it below $T_{\text{max}}$ increases slightly. In contrast with the overall $\rho_{\text{mag}}(T)$, $T_{\text{FL}}$ clearly decreases with increasing pressure with initial slope of -0.55 K/GPa as shown in Fig. 3(a). $T_{\text{FL}}$ abruptly decreases above 1.5 GPa, and hence the disappearance of $T_{\text{FL}}$ and the existence of QCP are expected around 2.5 GPa. The temperature
dependence of $\rho_{\text{mag}}$ for Fermi liquid in the low-temperature region is described by the well-known formula,

$$\rho_{\text{mag}} = \rho_0 + AT^2$$ (1),

where, the first term is the residual resistivity from scattering by impurities. The second term is the resistivity from scattering between conduction electrons. $\rho_0$ and $A$ are displayed in Fig. 3(b) and (c), respectively. $\rho_0$ and $A$ increase with increasing pressure up to 2.06 GPa. These behaviors of $\rho_0$ and $A$ are observed around QCP with superconducting phase as CeCu$_2$Ge$_2$[6].

Figure 3. (a) $T_{\text{FL}}$, (b) $\rho_0$ and (c) $A$ of Yb$_2$Ni$_{12}$P$_7$ as a function of pressure

In order to explore the QCP, we measured resistivity under high pressures from 1.5 to 8 GPa using a cubic-type anvil cell and the results are shown in Fig. 4(a). The overall $\rho_{\text{mag}}$ gradually decreases above 2.5 GPa, however, the value of $\rho_{\text{mag}}$ below 15.5 K at 8 GPa becomes larger than that at 6 GPa as shown in Fig. 4(b). This behavior would be consistent with that an ordered phase is induced by applying pressure as observed in the Yb-based compound YbCo$_2$Zn$_{20}$ [7].
4. Summary

We have measured $\rho$ of $\text{Yb}_2\text{Ni}_{12}P_7$ single crystals under hydrostatic pressure up to 8 GPa. At ambient pressure, $\rho_{\text{mag}}(T)$ shows a peak around $T_{\text{max}} \sim 100$ K and Fermi liquid like $T^2$ dependence below $T_{\text{FL}} = 3$ K. With increasing pressure, overall $\rho_{\text{mag}}(T)$ does not show drastic change but $T_{\text{FL}}$ decreases with divergence of $\lambda$ and the significant increase of $\rho_0$. It is expected that $T_{\text{FL}}$ becomes zero and QCP exists at 2.5 GPa. Above 2.5 GPa, $\rho_{\text{mag}}$ gradually decreases up to 6 GPa but the value of $\rho_{\text{mag}}$ below 15.5 K increases with increasing pressure. This behavior would be consistent with an ordered phase induced by applying pressure, as observed in some Yb-based compounds.

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