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Magnetic - nonmagnetic transition of U_3P_4 at high pressures

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The transport properties of the itinerant ferromagnet U_3P_4 have been studied at high pressures up to 6.0 GPa using a diamond anvil cell. The Curie temperature T_C decreases with increasing pressure, but then T_C cannot be assigned above 4.0 GPa. The coefficient A, assuming the Fermi liquid behavior ($\rho(T) = \rho_0 + AT^2$) at low temperatures, shows a maximum at 5.3 GPa. The temperature dependence of the resistivity at 5.0 GPa follows $T^{5/3}$ which is expected in the SCR theory of a three dimensional ferromagnet. From these results, it is concluded that the ferromagnetic-nonmagnetic transition exists at around 5.0 GPa.

KEYWORDS: ***U_3P_4, high pressure, electrical resistivity, ferromagnetism, low temperature***

I. Introduction

Recently the coexistence of superconductivity and ferromagnetic ordering has been discovered successively in UGe_2[1-3], $ZrZn_2$[4] and URhGe[5]. The superconductivity was observed only in high-quality samples, which can be associated with a strong pair-breaking effect consistent with non-conventional superconducting. These discoveries raised the possibility that the superconductivity could occur more generally in ferromagnets, but the mechanisms responsible for the pairing remain unidentified. Thus, further research on other ferromagnets, particularly U-compounds is required. U_3P_4 is an itinerant ferromagnet where a high-quality single crystal could be grown successfully.[6]

U_3P_4 crystallizes in the body-centered-cubic (bcc) structure of Th_3P_4 type with a space group of $I\bar{4}3d$. The Curie temperature T_C is 138 K at ambient pressure.[6] The magnetic susceptibility follows the Curie-Weiss law with an effective moment μ_{eff} = 2.75 μ_B/U[7] while the saturated moment in the ordered state is obtained as 1.34 μ_B/U atom from neutron scattering experiments,[8] indicating the itinerant nature of the 5f electrons. The magnetic structure is a non-collinear, three sub lattice magnetic structure with a ferromagnetic component along the <111> direction.[8, 9] U_3P_4 is found to be a compensated metal by transverse magneto-resistance measurements where the magnetoresistance increases as a function of H^n (n ≃ 2) over a wide angular region.[6] De Haas-van Alphen measurements show a large cycrotron effective mass ranging from 7.8 to 33m_0.[6] The pressure effects on the electrical resistivity have been reported, where the application of pressure up to 8.2 kbar reduces T_C to 121.8K.[10]

In this study, we have measured the electrical resistivity in a wide temperature range from room temperature to 50 mK in a high-quality single crystal of U_3P_4 under high pressure up to 6.0 GPa. From these results, the pressure-temperature phase diagram and the critical behavior of the transport properties are discussed.

II. Experimental details

A single crystal of U_3P_4 was prepared by the chemical transport method[6]. More detail of the sample preparation was described in Ref. 6. The residual resistivity ratio ρ_{RT}/ρ_0 reaches about 1500 in a single crystal of U_3P_4 used in the present study indicating excellent quality.

Pressure was applied by utilizing a diamond-anvil cell (DAC) with a pair of 1/3 carat diamond-anvils with a top surface diameter of 1 mm. The Cu-Be alloy gasket was pre-indented to 0.15 mm in thickness using diamond-anvils. A mixture of c-BN powder and epoxy resin was placed on the pressure surface and pressed up to about 5 GPa, then a sample hole of 0.5 mm in diameter was made at the center of the gasket. Four electrodes were made of platinum foil and placed on the c-BN layer close to the sample hole. After preparation and cutting of the sample, gold wires of 10 μm

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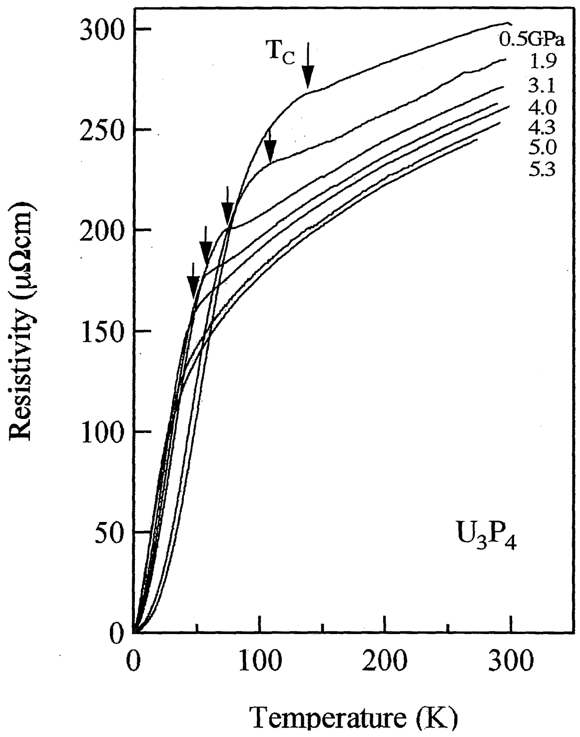

Fig.1 Temperature dependence of the electrical resistvity in U_3P_4 at selected pressures. The Curie temperatures are marked with the arrows.

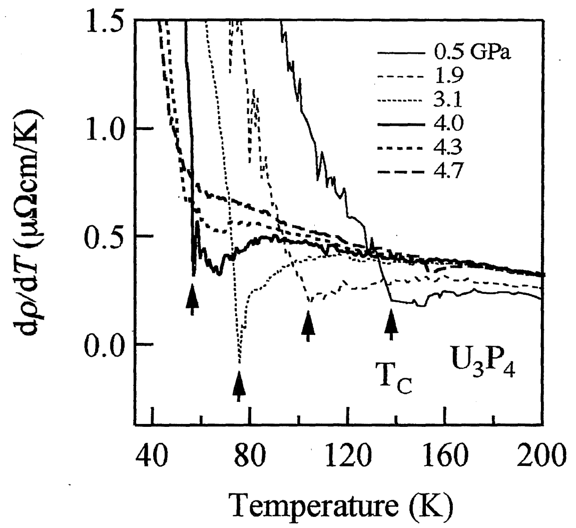

Fig. 2 Temperature dependence of the temperature derivative dρ/dT at high pressures. The Curie temperatures are defined as a minimum of dρ/dT. The minimum of dρ/dT disappears above 4.3 GPa

in diameter were bonded to the small sample (200 x 100 x 50 μm^3) using a micro-manipulating electric-discharge technique[11, 12]. The sample and some small ruby tips were clamped with Daphne 7373 oil as a pressure medium.

The preparation for the experiment is difficult because the single crystal of U_3P_4 was very brittle. Though the preparation was made many times, the experiment was carried out successfully only two times. The pressure determination was carried out by a pressure shift in the sharp R-line fluorescence spectrum of ruby.

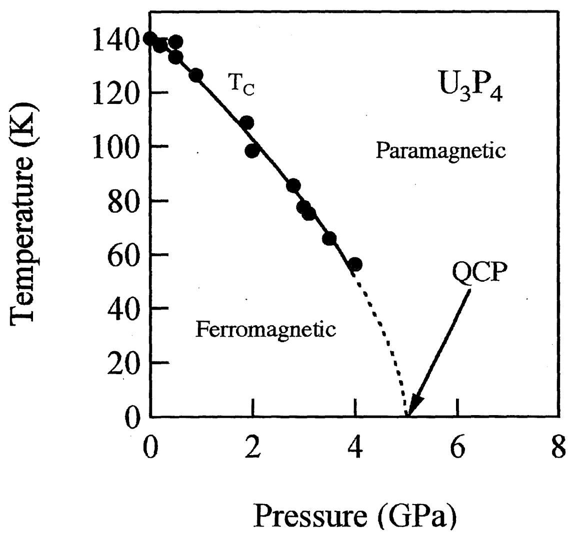

Fig. 3 Pressure-temperature phase diagram of U_3P_4. QCP is estimated by the consideration of the pressure variation of the coefficient A and power law dependence in the resistivity.

III. Results and discussions

Figure 1 shows the temperature dependence of the electrical resistivity under high pressures. The ferromagnetic transition at T_C = 138 K at ambient pressure is observed as a tiny kink and the resistivity shows a large upward curvature below T_C. The Curie temperature under high pressure is defined as a minimum of its temperature derivative as shown in Fig. 2. Though the reduction of T_C can be observed up to 4.0 GPa, T_C cannot be determined above 4.3 GPa because of the absence of the minimum in dρ/dT as can be seen in Fig. 2. From these results, the pressure-temperature phase diagram of U_3P_4 is obtained as shown in Fig. 3. The magnetization measurements under pressure up to 3.6 GPa reproduce the pressure dependence of T_C in Fig. 3. Therefore the definition of T_C in the present study is reliable. The result of the magnetization measurement will be published elsewhere. The critical pressure (P_C) is

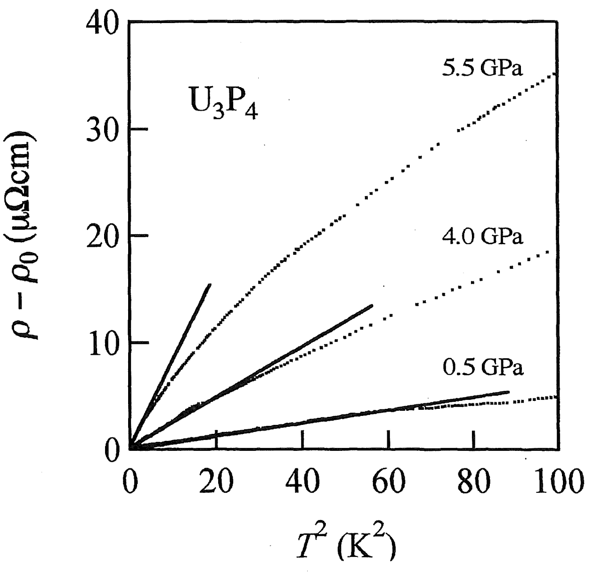

Fig. 4 The temperature dependence of ρ-ρ_0 as a function of T^2 at high pressures.

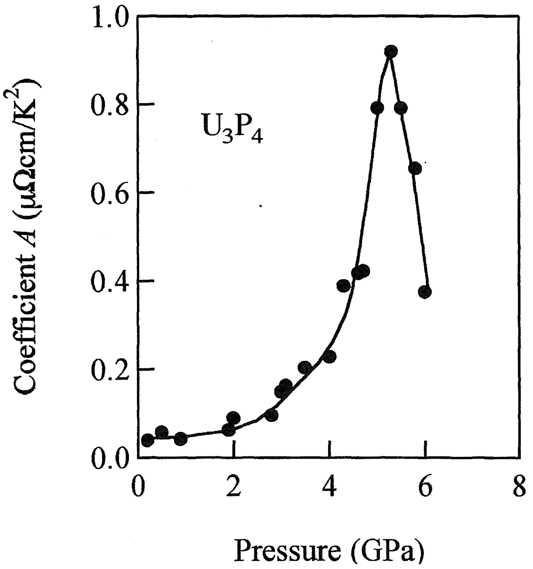

Fig. 5 Pressure dependence of the coefficient A obtained from ρ - ρ_0 vs T 2 plot (Fig. 4). The A value reveals a maximum at 5.3 GPa.

estimated as 5.0 GPa as discussed later.

In the Fermi-liquid system the electrical resistivity at low temperatures follow a quadratic dependence: $\rho = \rho_0 + AT^2$, where ρ_0 is the residual resistivity. The temperature dependence of the resistivity is plotted against T^2 in Fig. 4. At 0.5 GPa the resistivity follows a T^2-dependence below 8K. The temperature range where the resistivity follows a T^2-dependence decreases with increasing pressure. The pressure dependence of the coefficient A obtained from Fig.

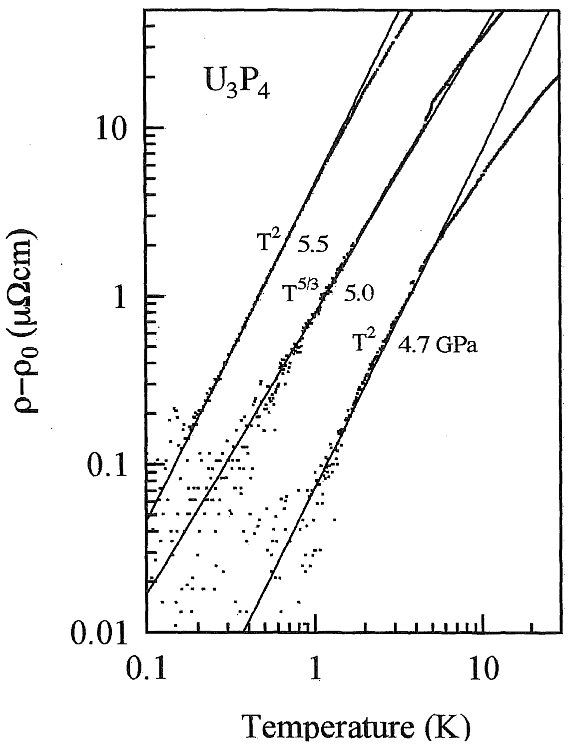

Fig. 6 The temperature dependence of ρ-ρ_0 at high pressures. The resistivity data at 4.7 and 5.5 GPa are multiplied by 1/10 and 10, respectively. At 5.0 GPa the temperature dependence of resistivity os close to $T^{5/3}$.

4 is shown in Fig. 5. Though at 5.0 GPa a T^2-dependence is not observed even at the lowest temperatures as discussed later, the A value is estimated approximately from a ρ - ρ_0 vs T^2 plot in the temperature range below 0.7 K. The A value increases rapidly above 3 GPa and shows a maximum at around 5.3 GPa. At higher pressures the A value decreases rapidly.

In order to discuss the power law dependence of $\rho \sim T^n$ at low temperatures, the temperature dependence of ρ-ρ_0 is shown in a log-log plot in Fig. 6. Below 4.7 GPa the resistivity obeys a T^2-dependence at low temperatures. At 5.0 GPa the temperature dependence of the resistivity is closer to $T^{5/3}$ than T^2 below 5 K. At higher pressures the power law dependence recovers to T^2 at low temperatures below 1 K.

In the itinerant ferromagnets MnSi and $ZrZn_2$, the critical behavior in the vicinity of the ferromagnetic quantum critical point (QCP) was investigated in detail.[13, 14)] In the case of MnSi, there was a rapid increase of the coefficient A below P_C. Non Fermi liquid behavior $\rho \sim T^{1.6}$, $T^{1.7}$ near P_C were reported by Cambridge and Grenoble groups, respectively. Similar non Fermi liquid behavior of $\rho \sim T^{1.6}$ near P_C was observed in $ZrZn_2$. These non-Fermi-liquid behaviors are close to $T^{5/3}$, as predicted by the SCR theory [13, 14] in the case of a three dimensional ferromagnet. In the present results of U_3P_4, the coefficient A reveals a maximum at 5.3 GPa and the non Fermi liquid behavior $\rho \sim T^{5/3}$ is observed at 5.0 GPa. Therefore it can be concluded that the QCP exists at around 5.0 GPa in U_3P_4 as shown in Fig .3.

Through the present study no trace of superconductivity was observed in the pressure range up to 5.8 GPa for a the temperature range down to 50 mK in spite of the excellent quality (RRR ~ 1500). Its Th_3P_4 type crystal structure without an inversion symmetry may cause the absence of the superconductivity. G. G. Lonzarich pointed out that the inversion symmetry is required to guarantee that equal-spin states of opposite momentum are degenerate and hence effectively coupled by magnetic interactions.[1)]

IV. Conclusion

The electrical resistivity of U_3P_4 has been studied under hydrostatic pressure up to 6 GPa. The Curie temperature decreases with increasing pressure. T_C is assigned up to 4GPa by resistivity measurements. The coefficient A ($\rho(T) = \rho_0 + AT^2$) shows a maximum at around 5.3 GPa. The temperature dependence of resistivity at 5.0 GPa follows $T^{5/3}$ predicted by the SCR theory. Therefore it can be concluded that the quantum critical point exists at around 5.0 GPa in U_3P_4.

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