Physica B 404 (2009) 2934–2937

Contents lists available at ScienceDirect

Physica B

journal homepage: www.elsevier.com/locate/physb

Pressure–temperature phase diagram of the ferromagnetic Kondo lattice compound CeRuPO

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A R T I C L E I N F O

PACS:
74.62.Fj
75.30.Mb
75.50.Cc

Keywords:
Pressure effect
Kondo lattice
Ferromagnetic materials

A B S T R A C T

The new example of a ferromagnetic Kondo lattice, CeRuPO, is a good candidate which offers the opportunity to investigate the physical properties near a ferromagnetic instability. Macroscopic experiments evidenced a Kondo temperature $T_K = 10\,K$ and Curie temperature of $T_C = 14\,K$. We have investigated the pressure–temperature phase diagram of CeRuPO by means of electrical resistivity measurements on high quality single crystals in the temperature interval from 1.8 to 300 K. The pressure dependence of the ordering temperature follows the anticipated behavior of a Ce-based Kondo lattice system, where pressure is expected to suppress the magnetic order. The critical pressure for the suppression of the transition temperature to zero is estimated to be $p_c \approx 3.2\,GPa$.

1. Introduction

Magnetically ordered heavy-fermion (HF) compounds attract a special interest due to unusual ground state properties that emerge where the magnetic ordering temperature is suppressed to zero temperature. For instance, the superconductivity dome near an antiferromagnetic instability (e.g. $CePd_2Si_2$ [1]), coexistence of superconductivity and ferromagnetic order (e.g. UGe_2 [2]). There are several examples of Ce-based compounds with antiferromagnetic ground states (e.g. $CePd_2Si_2$ [1], $CeRh_2Si_2$ [3]), while only few compounds which show ferromagnetic order are presently known (e.g. $CeAgSb_2$ [4], CePbSb [5]). Therefore, it is interesting to investigate systems that undergo a ferromagnetic transition. The ground state properties of this class of materials are determined mainly by the competition of two different mechanisms [6]. On rejected one hand, the Kondo effect leads to a non-magnetic ground state by screening the magnetic moments of the 4*f* electrons. On the other hand, the Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction favors magnetic order due to the indirect exchange between the local magnetic moments via the conduction electrons. Depending on the exchange coupling strength J between the localized 4*f* and the conduction electrons, the system has a magnetic ground state for small values of J while a non-magnetic ground state is expected for large J values. Pressure as tuning parameter allows to drive a Ce-based system from a magnetic to a non-magnetic ground state without introducing additional disorder.

CeRuPO is a rare example of a ferromagnetic Kondo lattice system and offers the opportunity to investigate the physical properties near a ferromagnetic instability. The ferromagnetic nature of the magnetic order is supported by magnetization and magnetic susceptibility measurements [7]. The transition to the ordered state was observed in specific heat and magnetic susceptibility measurements at about $T_C = 14\,K$. The anomaly observed in the temperature dependence of the resistivity $\rho(T)$ is in agreement with results obtained from $C(T)$. From thermopower and $C(T)$ measurements the Kondo temperature (T_K) could be estimated to be $T_K \approx 10\,K$ [8]. We report on the first pressure study on the ferromagnetic Kondo lattice CeRuPO by means of electrical resistivity.

2. Experimental details

CeRuPO crystallizes in the tetragonal ZrCuSiAs type of structure with alternating layers of RuP_4 and OCe_4. Single crystalline samples were grown from Sn flux as described elsewhere [7]. Electrical resistivity measurements using a conventional four-probe method with current applied within the crystallographic *ab*-plane were performed in a physical properties measurement system (Quantum Design) for temperatures $1.8\,K \leq T \leq 300\,K$. The experiments were carried out in a pressure range up to 3 GPa using a double-layer piston-cylinder type pressure cell with silicone liquid as pressure transmitting medium. A piece of Pb, placed near the sample, was used to determined the pressure inside the pressure cell. The narrow width of the superconducting transition of Pb confirmed good hydrostatic pressure conditions.

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doi:10.1016/j.physb.2009.07.037

3. Results and discussion

The temperature dependence of the electrical resistivity plotted as ρ vs. T on a logarithmic temperature scale is shown in Fig. 1 for selected pressures. At ambient pressure, the electrical resistivity shows the typical behavior of a Kondo lattice system. A linear temperature dependence of the resistivity was observed between 300 and 100 K. With further decreasing temperature two principal features are appearing in the resistivity: a shoulder-like feature around $T_{max} \approx 70$ K suggesting the onset of coherent Kondo scattering and a second feature represented by a drop of the resistivity at $T_C \simeq 14$ K consistent with the onset of the ferromagnetic order [7]. Upon applying pressure, the shoulder is developing into a broad maximum in the resistivity that is shifting to lower temperatures and becomes more pronounced with increasing pressure. The single broad maximum observed in $\rho(T)$ for $p \leq 1.3$ GPa splits in a maximum and a shoulder at higher pressures. At $p = 1.62$ GPa the maximum, denoted as T_{max}^{high}, is observed at 40 K and a shoulder at 12 K, denoted as T_{max}^{low} can be resolved. With further increasing pressure, the shoulder evolves into a distinct maximum. The isothermal pressure dependence of the resistivity at $T = 1.8$ K, $\rho_{1.8\,K}(p)$ which is a good measure of the residual resistivity ρ_0, strongly increases with increasing pressure. At the same time the resistivity ratio $RR_{1.8\,K} = \rho_{300\,K}/\rho_{1.8\,K}$ is drastically reduced from $RR_{1.8\,K} = 20$ at ambient pressure to $RR_{1.8\,K} = 3.4$ at $p = 0.97$ GPa. With further increasing pressure, a weak monotonic decrease of the resistivity ratio is observed. The data are displayed in Fig. 2. In various heavy fermion systems (e.g. $CeCoIn_5$ [9]) the residual resistivity shows a strong pressure dependence. An increase of ρ_0 with increasing pressure can be associated to critical fluctuations in the proximity to a magnetic instability [10].

In Fig. 3 the pressure dependence of the resistivity maxima is depicted. Usually, pressure has a strong influence on the Kondo effect due to the pressure dependence of the exchange coupling constant J. In the case of Ce-based compounds in a first simple approach, $T_{max} \propto T_K$ is expected to increase with increasing pressure since $dJ/dp > 0$. Starting from $T_{max} \simeq 70$ K at ambient pressure, the resistivity maximum is decreasing for small values of applied pressure. The pressure dependence of the resistivity maximum cannot be understood if the Kondo temperature is the dominant energy scale of the system. Usually, the Kondo temperature scales with T_{max} when T_K is much smaller than the crystalline electric field splitting [11]. In the case of CeRuPO the effect of the crystalline electric field lifts the degeneracy of the ground state into two excited Kramer doublets above the ground state. According to Hanzawa et al. [12] the maximum in $\rho(T)$, denoted as T_K^h, is a combined effect coming from the incoherent Kondo scattering on the ground state and on the excited crystal electric field levels. The position of the maximum can be estimated as follows: $T_K^h = \sqrt[3]{T_K \Delta_1 \Delta_2}$, where $T_K^h = T_{max}$, Δ_1, Δ_2 are the excited crystal electric field levels and T_K is the Kondo temperature. The crystal electric field level scheme at atmospheric pressure was determined from the temperature

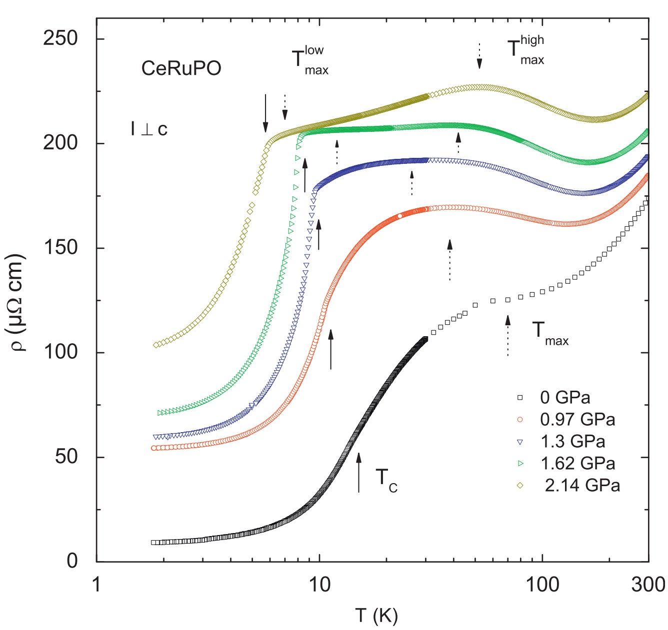

Fig. 1. (Color online) Temperature dependence of the electrical resistivity $\rho(T)$ of CeRuPO for different pressures in the temperature range $1.8\,K \leq T \leq 300$ K. The solid arrows indicate the transition temperature. The dashed arrows correspond to the resistivity maxima.

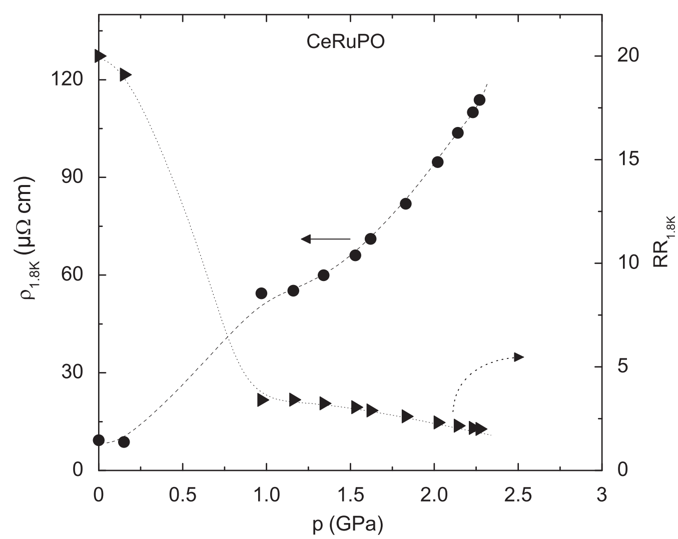

Fig. 2. Isothermal pressure dependence of the resistivity at $T = 1.8$ K, $\rho_{1.8\,K}$ and resistivity ratio $RR_{1.8\,K}$ as a function of pressure of CeRuPO. The dashed line is a guide to the eye.

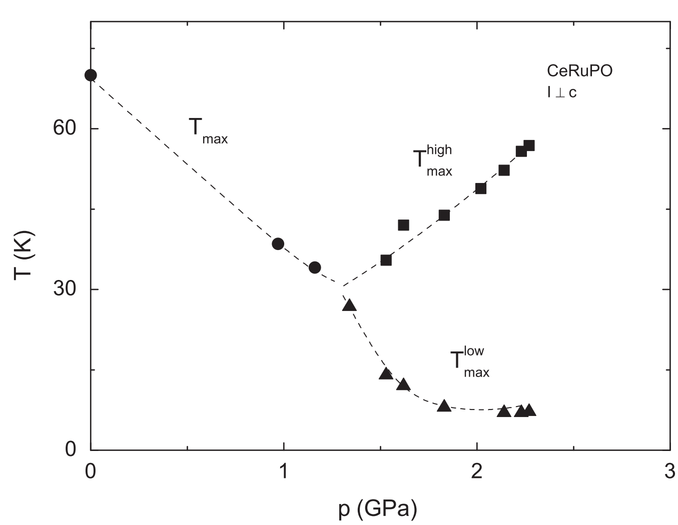

Fig. 3. Pressure dependence of the different maxima observed in the resistivity data of CeRuPO. The dashed lines are guides to the eye.