Magnetic phase transitions in CePtSn under high pressure

A M Alsmadi1, M S Torikachvili2, M K Kothapalli3, F Nasreen1, and H. Nakotte1

1Physics Department, The Hashemite University, 13115 Zarqa, Jordan
2Physics Department, San Diego State University, San Diego, CA 92182, USA
3Physics Department, New Mexico State University, Las Cruces, NM 88003, USA

E-mail: alsmadi_abd@yahoo.com

Abstract. CePtSn crystallizes in the orthorhombic TiNiSi-type structure. The compound undergoes two antiferromagnetic transitions at \( T_N = 7.5 \) K and \( T_M = 5 \) K, and it exhibits large magnetic and transport anisotropy. We report on measurements of the electrical resistivity of single-crystalline CePtSn as a function of temperature and magnetic field (\( i \parallel c \) axis, \( H \parallel a \) axis) performed under hydrostatic pressure up to 20 kbar. At ambient pressure, the overall temperature dependence indicates Kondo-type behavior in the presence of the crystal field. The application of pressure causes a reduction of the magnetoresistance effect. We find that the maximum in \( \frac{\Delta \rho}{\rho_{B=0}} \) is only 0.05 at 20 kbar, while it is about 0.15 at ambient pressure. On the other hand, application of hydrostatic pressure in CePtSn has little effect on both \( T_N \) and \( T_M \). It initially increases both temperatures, but then reduces them again above 10 kbar. The results are discussed in terms of moment fluctuations and the variation due to increased 4f-ligand hybridization.

1. Introduction

CePtSn crystallizes in the orthorhombic TiNiSi-type structure, and it is known as an anisotropic dense Kondo compound. CePtSn orders antiferromagnetically (AF) below \( T_N = 7.5 \) K, and it undergoes an additional magnetic phase transition at \( T_M = 5 \) K [1]. Previously, several attempts to determine the magnetic structure of CePtSn were performed. Neutron-diffraction studies [2] were originally interpreted in terms of two sinusoidally modulated incommensurate antiferromagnetic structures characterized by the propagation vector \( q = (0, \delta, 0) \) with \( \delta = 0.466 \) at temperatures \( T < T_M \) and \( \delta = 0.418 \) for \( T_M < T < T_N \). However, this scenario was found to be inconsistent with the results of muon spin relaxation (\( \mu \)SR) experiments [3] that indicate locally commensurate ordering. A single-frequency \( \mu \)SR spectrum was seen for \( T_M < T < T_N \), while three discrete frequencies were found below \( T_M \). To reconcile the results of the two experiments, a spin-slip model had been proposed based on irreducible representation analysis [4]. In this picture the occurrence of periodic spin-slips of an essentially commensurate, \( q = (0, 1/2, 0) \) phase was proposed. Since \( \mu \)SR is sensitive to the local moment configuration and neutron diffraction is sensitive to the average long-range correlations, such arrangement of magnetic moments can satisfactorily explain both types of data.

Recent magnetoresistance measurements performed on CePtSn at 1.8 K in fields applied along the \( a \) or \( b \) axis revealed sharp magnetoresistive (MR) anomalies at 12.5 T for \( B \parallel a \), and 11 T for \( B \parallel b \) respectively. Furthermore, the \( b \) axis magnetoresistance at 1.8 K shows a sharp drop at 3.5 T, which

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1. To whom any correspondence should be addressed.
appears to be irreversible upon field removal [5]. With the anomalies from magnetization, magnetoresistance and specific heat, H-T magnetic phase diagrams of CePtSn for fields along the a and b axis had been proposed [5,6]. For B || a, the two-phase boundaries associated with T_N and T_M appear to merge around 8 T. In zero field, one can distinguish two antiferromagnetic phases AF_1 and AF_2, in addition to the paramagnetic phase above T_N. For fields applied along the a axis, a third field-induced antiferromagnetic phase appears. Also for B || b, two zero field antiferromagnetic phases can be distinguished, but now the AF_1 phase persists into high fields and two field-induced phases can be distinguished at low temperatures.

A spin-slip structure is consistent with the magnetoresistance data, for which irreversibility was observed upon application of a magnetic field (H). The intermediate field induced phase AF_1 is associated with the irreversible magnetoresistance transition. This phase is induced upon application of a magnetic field from a zero-field cooled state, but persists down to zero field upon field removal. Within the spin-slip model, this may be interpreted as a change in the periodicity of the spin-slip discommensurations by the applied field, or perhaps its suppression altogether. It is reasonable to expect that such a change would have a much large effect on the electrical resistivity (ρ) than on the magnetic susceptibility. In addition, irreversibility may be expected since the original spin slip configuration is unlikely to be recovered after the removal of the magnetic field.

Previous magnetic susceptibility measurements on CePtSn under hydrostatic pressures up to 8.2 kbar show very weak effect [7] leaving T_N and T_M nearly unaffected. This is rather unexpected because the volume contraction is possibly the main reason for the change from the antiferromagnetic Kondo metal behavior with T_N = 7.5 K in CePtSn to a non-magnetic Kondo semi-metal CeNiSn [8].

Here, we present the effect of hydrostatic pressure (P) on the electrical resistivity and magnetoresistance for fields applied along the a axis of single-crystalline CePtSn. The data supplement previously published data for fields applied along the other two directions [9,10].

2. Experimental
The CePtSn sample was cut from the same Czochralski grown crystal of Ref. 6. The ρ(T) measurements in pressures up to 20 kbar were performed in a 9 T superconducting magnet system at San Diego State University, using a Cu-Be pressure cell with a core of hardened NiCrAl alloy. The pressure-transmitting medium was a 50:50 mixture of Fluorinert FC72:FC84, and the pressure was determined from the superconducting transition of a lead manometer.

3. Results and discussion
Electrical resistivity and magnetoresistance studies were performed in order to determine the pressure dependence of T_N and T_M. The behavior of ρ(T) under different pressures is shown in Fig. 1. The behavior of ρ(T) at P = 0 is reminiscent of other Kondo-type materials with crystal field splitting [11,12], with ρ(T) being characterized by a broad peak around 67 K followed by a minimum near 22 K and a sharp drop below 7 K. A CEF level scheme based on inelastic neutron scattering measurements was proposed for CePtSn (Ce^{3+} is a 2F_{5/2} ion), yielding a ground-state doublet and two excited doublets as $\Delta_1 = 273$ K and $\Delta_2 = 273$ K, respectively [12], all with $\Gamma_3$ symmetry.

The minimum in ρ(T) shifts to higher values with pressure while the Kondo temperature remains almost constant up to 20 kbar. Application of hydrostatic pressure on CePtSn increases the absolute value of the resistivity. The value of two antiferromagnetic transitions at $T_N = 7.5$ K and $T_M = 5$ K can be extracted from the derivative of the resistivity (the inset of Fig. 1 shows the derivative of the resistivity at ambient pressure). The effect of pressure on both T_N and T_M is minimal as shown in the inset of Fig. 2. Pressure increases both T_N and T_M initially but then reduces them again above 10 kbar. Even in an applied magnetic field, we observed similar pressure effect on the transition temperatures. A comparison of $dT_N/dT$ and $dT_M/dT$ with values for other Ce compounds [13], suggests that the 4f electrons the CePtSn seem to be fairly localized. For example, application of pressure causes a reduction of the ordering temperature in CePdAl at an approximate rate of -0.32 K/kbar and a rough estimate of the critical pressure to suppress the ordering in CePdAl is found to be around 10 kbar. In
addition, the magnetic susceptibility ($\chi$) in the CePtSn follows Curie–Weiss law very closely with an effective magnetic moment of 2.33 $\mu_B$ that is only slightly reduced from that of the Ce$^{3+}$ ion (2.45 $\mu_B$), indicating a well-localized character of the Ce 4$f$ electrons [14]. A deviation from the Curie–Weiss behavior was observed on going from CePtSn to CeRhAs, were the unit-cell volume decreases, suggesting an increase of the hybridization of 4$f$ electron states with the conduction band [14].

For Ce compounds, the key ingredient for the formation of 4$f$ magnetic moments and the long-range magnetic ordering is the degree of the 4$f$-ligand hybridization and the competition between the on-site Kondo interaction (with the quenching the 4$f$ localized magnetic moments) and the intersite RKKY interaction between these moments. Hydrostatic pressure usually shortens the interatomic distances and promotes hybridization. It seems that the 4$f$-ligand hybridization is not enhanced enough in 20 kbar to allow a change in balance between the Kondo and RKKY interactions.

![Figure 1. Temperature dependence of the normalized electrical resistivity of CePtSn at various pressures with $i \parallel c$ axis. The inset shows the temperature dependence of the derivative electrical resistivity at ambient pressure.](image1)

![Figure 2. Temperature dependence of the magnetoresistance of CePtSn under 20.3 kbar for various fields ($i \parallel c$ axis and $H \parallel a$ axis). The inset shows the pressure dependence of the critical temperatures in zero field.](image2)

Fig. 2 shows the $\rho(T)$ data for CePtSn for $P = 20$ kbar, for various fields parallel to the $a$ axis. Similar to the ambient pressure data, both magnetic phase transitions are accompanied by anomalies in $\rho(T)$. The transition associated with $T_N$ slowly moves to lower temperature with increasing fields, while the contrary is true for the transition associated with $T_M$, in good agreement with the previously published data [5,6].

In Fig. 3, the normalized magnetoresistance is plotted as a function of the magnetic field at $T = 2.1$ K, for $P = 0$ and 20 kbar. The application of pressure causes a reduction in magnetoresistance. We find that the maximum in $\Delta \rho / \rho_{P=0}$ is only 0.05 at 20 kbar, while it amounts to 0.15 at ambient pressure. Unfortunately, the superconducting magnet of this experiment was limited to 9 T, which is insufficient to probe the effect of pressure on the metamagnetic transition field (~12 T at 4.2 K for $H \parallel a$ axis). The anomalies in the $\rho(T)$ data permit delineating the magnetic phase diagram for field applied along the $a$-axis at ambient and under hydrostatic pressure of 20 kbar. The results are displayed in Fig. 4, which also includes the ambient pressure data taken from Ref. 5.

4. Conclusion

In conclusion, we studied the effect of hydrostatic pressure up to 20 kbar on the magnetic ordering temperatures of CePtSn by means of measurements of $\rho(T)$ in $H \cdot 9$ T and $P \cdot 20$ kbar, with up to 9 T. The field applied along the $a$-axis The application of hydrostatic pressure on CePtSn has little effect on both $T_N$ and $T_M$. Initially, pressure leads to small increase of both temperatures, $T_N$ and $T_M$, followed by a reduction after 10 kbar. The application of pressure causes a reduction in magnetoresistance. Measurements of $\rho(T, P, H)$ in higher fields to probe the stability of the spin-slip phase are in order.
**Figure 3.** Field dependence of the normalized electrical resistivity of CePtSn at 1.8 K at ambient pressure and under 20 kbar ($i \parallel c$ axis and $H \parallel a$ axis).

**Figure 4.** Magnetic H-T phase diagram of CePtSn for $H \parallel a$ axis. Solid squares are taken from the anomalies in $\rho(T)$ at ambient pressure while crosses are taken from Ref. 5. The solid circles are taken from the anomalies in $\rho(T)$ at 20 kbar.

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