Unusual pressure response of electronic transport properties of a Kondo insulator CeRu₄Sn₆

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Abstract. We report the effect of hydrostatic pressure (up to 20.6 kbar) on the electrical resistivity (1.8 K to 300 K) of a Kondo insulator CeRu₄Sn₆, crystallizing in a tetragonal structure with space group I-4 2m. The absolute value of resistivity is found to increase monotonically with pressure in the entire temperature range. The hybridization gap, contrary to common observation on other Ce systems, is also found to increase up to 15.1 kbar. Magnetoresistance under pressure appears interesting. For instance, at 1.8 K and at 15.1 kbar, MR is negative till about 100 kOe, showing a minimum around 60 kOe, subsequently showing a sign change; magnetoresistance becomes positive at and above 10 K and at same pressure. These results indicate subtle changes induced by magnetic field on the hybridization gap.

1. Introduction
Kondo insulators (KI) have recently attracted much attention because of their unusual physical properties [1]. The electronic structure of KI is thought to derive from the coherent hybridization of 4f orbital in a periodic lattice of Kondo ions. In such systems, a small gap/pseudo-gap develops at low temperature in the density of states at the Fermi level.

CeRu₄Sn₆ in this regard occupies a special place in this class of system. The Kondo insulating behaviour was first reported by Das and Sampathkumaran [2]. Recent NMR and heat capacity measurements at low temperatures reveal that this system is different from other known KI [3]. Measurements on single crystals showed pronounced magnetic anisotropy and a nodal/line gap has been proposed for this material [4]. It is important to note that while most of KIs form in cubic structure and a few in orthorhombic structure, only CeRu₄Sn₆ and CeCuAs₂ [5] are reported to form in a tetragonal structure. We considered it worthwhile to investigate how external pressure modifies the electronic transport properties of this compound.

2. Experimental details
The sample was prepared by arc melting and followed the same procedure as described in one of earlier works [2]. The electrical resistivity (ρ) measurements, using standard four-probe method, as a function of temperature (T) and magnetic-field (H) were performed employing a commercial clamp type piston-cylinder cell (easyLab Technologies Ltd, UK) with the help of physical property

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measurements system (PPMS, Quantum Design). The measurements have been taken in a hydrostatic pressure medium using a 1:1 mixture of n-pentane and isopentane.

3. Results and discussions

Resistivity of CeRu$_4$Sn$_6$ at ambient pressure has already been reported in the earlier work [2]. While LaRu$_4$Sn$_6$ shows normal metallic properties, CeRu$_4$Sn$_6$ is nonmagnetic and behaves as an insulator from room temperature down to 50 mK [4]. Figure 1 shows resistivity at different applied pressures - 3.2, 6.6, 10.4, 15.1 and 20.6 kbar. It is to be noted that the absolute values are found to increase continuously with increasing pressure in the entire temperature range (see inset of figure 1). For instance, at 20.6 kbar, the $\rho(T)$ at 1.8 and 300 K is enhanced nearly by an order of magnitude compared to that at ambient pressure, and the magnitude of increase is relatively larger at 1.8 K. We attribute it to enhancement of hybridization gap with increasing pressure in this system.

Figure 1. Normalized resistivity of CeRu$_4$Sn$_6$ at different pressures. The arrows in the figure indicate the shoulder. Inset shows variation of resistivity at 1.8 K and 300 K with applied pressure. The continuous lines through data points are guide to eyes.

Figure 2 is derived from figure 1. Figure 2a shows the relative change of $\rho(1.8K)$ with respect to $\rho(300K)$. The ratio increases up to 15.1 kbar, produces a maximum and subsequently starts to decrease. The maximum is marked by an arrow in figure 2a. An increase in the resistivity ratio suggests that the gap increases with pressure up to around the maximum at 15.1 kbar. An initial increase in gap with pressure was also reported for a few Kondo insulators, e.g., CeRhSb [6], but this finding is contrary to that observed in other tetragonal KI CeCuAs$_2$ [7]. The decrease in $\rho(1.8K)/\rho(300K)$ above 15 kbar probably signifies that the gap tends to decrease at higher pressures.

Another novel feature is that $\rho(T)$ develops a shoulder (marked by an arrow in the figure 1) which moves towards a higher temperature with increasing pressure. In figure 2b, the temperature $T_{max}$ where the shoulder of $\rho(T)$ appears in figure 1 is plotted versus pressure. Though the exact origin of this is not clear, we believe that the shoulder arises from the Kondo coherence effect with the characteristic temperature moving up with pressure, as this kind of pressure dependence of Kondo coherence
temperature is well-known for the Kondo lattices [6] and the low temperature upturn may be dominated by gap effect. It may be noted that the single-ion Kondo temperature ($T_K$) estimated from the paramagnetic Curie temperature, $\theta_p$, in this system ($T_K \approx |\theta_p|/4$ [8]) at ambient pressure is near 40 K and it is expected to increase with pressure. It is therefore reasonable to assume that the Kondo coherence temperature also increases with pressure.

Magnetoresistance (MR) at an intermediate pressure, 15.1 kbar, is shown in figure 3. The MR is defined as $[\rho(H) - \rho(H = 0)]/\rho(H = 0)$. MR at 10 K and 50 K are positive. At 50 K, it varies quadratically with field over a wide range of field (e.g., till 100 kOe), whereas quadratic variation is restricted to lower field range (till 20 kOe) at 10 K. Dashed lines through data shows $H^2$ fit. Positive MR behaviour is consistent with the Kondo coherence effects, while the deviation from the quadratic behaviour as the temperature is lowered well below 50 K implies interference from some other effects, namely, gap effect. There could be contributions to positive MR from Lorentz force on the conduction electrons. At 1.8 K, a puzzling non-monotonic variation of MR is observed. That is, MR is negative between 0 to around 100 kOe with a minimum around 60 kOe. MR changes sign above 100 kOe. This complicated behaviour at 1.8 K could possibly be related to modification of the hybridization gap and/or interference from Kondo coherence at high magnetic fields and the non-monotonic variation is quite unusual compared to the behaviour of other KIs reported so far [9] at ambient pressure. It is worth noting that MR of CeRu$_4$Sn$_6$ was also reported [10] to show unusual behaviour at ambient pressure. At 20.6 kbar, the qualitative behaviour of MR measured at 10 K and 50 K remains almost similar to that at 15.1 kbar (not shown here).
4. Summary

We have presented the results of transport and magneto-transport properties of a Kondo insulator CeRu$_4$Sn$_6$ under hydrostatic pressure. There is an enhancement of electrical resistivity with the application of pressure with the degree of enhancement being larger with decreasing temperature. Features attributable to interplay between the Kondo coherence effect and the gap effect could be seen in the high pressure data. While application of pressure causes a continuous suppression of gap in some compounds, e.g., CeNiSn [11], SmB$_6$ [12] or CeCuAs$_2$ [7] or an increase in gap in some others, e.g., Ce$_3$Bi$_4$Pt$_3$ [13]- the behaviour in the present system appears to resemble that in CeRhSb [6], a nonmonotonic response with pressure. It is of interest to study this system at further high pressures to see whether there is any insulator-metal transition in this system.

5. References

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