

KONDO PROPERTIES IN  $(\text{Ce}_{1-x}\text{La}_x)\text{Cu}_5\text{In}^*$ 

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$(\text{Ce}_{1-x}\text{La}_x)\text{Cu}_5\text{In}$  alloys have been investigated by X-ray diffraction, specific heat, electrical transport and magnetic susceptibility measurements. Resistivity  $\rho(T)$  measurements enabled the extraction of the Kondo temperature  $T_K(x)$  for the different alloys. The monotonic decrease of  $T_K$  with increase in  $x$  has been interpreted in terms of the compressible Kondo model giving  $|JN(E_F)| = 0.063 \pm 0.005$  ( $J$  is the strength of the on-site Kondo interaction and  $N(E_F)$  the density of states at the Fermi level). Magnetoresistivity measurements interpreted within the single-ion Bethe ansatz description corroborate the magnitude of  $T_K$  found in the  $\rho(T)$  measurements.

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$\text{CeCu}_5\text{In}$  exhibits Kondo lattice properties with a specific heat  $\gamma$  coefficient of  $200 \text{ mJ mol}^{-1} \text{ K}^{-2}$ , and a resistivity  $\rho(T)$  showing a maximum at  $T_m = 35 \text{ K}$  with a Fermi-liquid-like  $AT^2$  dependence at low temperatures. No evidence of magnetic order was observed down to  $0.1 \text{ K}$ . The influence of substituting La for Ce in this compound is reported in the present paper.

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Samples were prepared by arc-melting on a water-cooled copper hearth in a high-purity argon atmosphere. X-ray diffraction spectra indicate that all alloys in the  $(\text{Ce}_{1-x}\text{La}_x)\text{Cu}_5\text{In}$  series ( $0 \leq x \leq 1$ ) retain the orthorhombic  $\text{CeCu}_6$ -type structure of the  $\text{CeCu}_5\text{In}$  parent compound. A Vegard's law-like linear increase of unit cell volume with  $x$  was observed amounting to 1.8% between  $\text{CeCu}_5\text{In}$  and  $\text{LaCu}_5\text{In}$ .

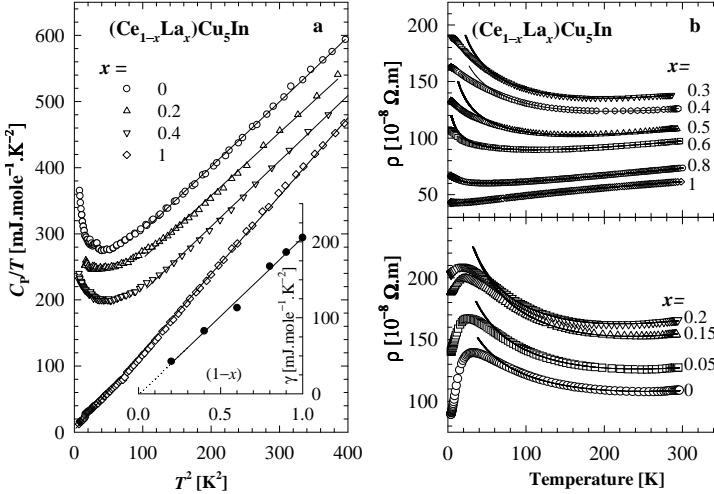


Fig. 1. (a) Specific heat of  $\text{Ce}_{1-x}\text{La}_x\text{Cu}_5\text{In}$ , and concentration dependence of the  $\gamma$ -coefficient (inset). (b) Electrical resistivity of  $\text{Ce}_{1-x}\text{La}_x\text{Cu}_5\text{In}$ . Solid lines indicate fits as described in the text.

Results of specific heat measurements are given in Fig. 1(a). These indicate the conventional  $C/T = \gamma + \beta T^2$  dependence for all alloys above 10 K, as well as a sharp upturn in  $C/T$  at the lowest temperatures signalling heavy-fermion behaviour.  $\gamma$ -values as derived from the linear portions of the  $C/T$  vs  $T^2$  plots are shown in the inset to Fig. 1(a) to scale accurately with Ce concentration  $(1-x)$ . For  $\text{CeCu}_5\text{In}$  a value of  $\gamma = 206 \text{ mJ mol}^{-1} \text{ K}^{-2}$  is obtained in agreement with earlier studies [1].

Measurements of  $\rho(T)$  for several alloys of the system  $(\text{Ce}_{1-x}\text{La}_x)\text{Cu}_5\text{In}$  are shown in Fig. 1(b). Alloys with  $0 \leq x \leq 0.2$  show coherent Kondo behaviour at low temperatures with the  $\rho(T)$  maximum ranging from  $T_m = 33 \text{ K}$  for  $\text{CeCu}_5\text{In}$  to  $T_m = 19 \text{ K}$  for the  $x = 0.2$  alloy. At higher temperatures for all alloys in the series,  $\rho(T) \sim -\ln T$  as is to be expected for incoherent Kondo scattering. The data in this region have been fitted to

$$\rho(T) = \rho_0 + \rho_{\text{ph}} - C_K \ln \left( \frac{T}{T_K} \right), \quad (1)$$

where the Bloch-Grüneisen (BG) formula was used for the electron-phonon

scattering term  $\rho_{\text{ph}} = 4\kappa\theta^{-6}T^5G(\theta/T)$  and the last term describes the incoherent Kondo scattering. In the BG formula a value of the Debye temperature  $\theta = 149$  K was used for all alloys in the series while the electron-phonon coupling constant  $\kappa$  was allowed along with  $\rho_0$ ,  $C_K$  and  $T_K$  to vary in a least-squares fit calculation of the experimental data *vs* Eq. (1). The Kondo temperatures thus derived decrease monotonically through the alloy series from  $T_K = 35$  K for  $\text{CeCu}_5\text{In}$  to 8.6 K for the  $x = 0.8$  alloy. This variation is described in terms of the compressible Kondo lattice model [2]

$$T_K(x) = T_K(x=0) \exp \left[ -q \frac{(V - V_0)}{V_0} |JN(E_F)|_{x=0} \right], \quad (2)$$

where  $V$  and  $V_0$  are the volumes of the unit cell for the alloy and parent compound, respectively,  $J$  is the on-site Kondo interaction,  $N(E_F)$  is the density of states at the Fermi level and the constant  $q$  takes on values between 6 and 8. A plot of  $T_K$  as obtained from Fig. 1(b) *versus*  $(V - V_0)/V_0$  as obtained from our X-ray measurements, is given in Fig. 2(a). The solid line represents a least-squares fit of the data against Eq. (2). Using  $q = 6$  this yields  $|JN(E_F)| = 0.063 \pm 0.005$  for  $\text{CeCu}_5\text{In}$  which may be compared with 0.09 for  $\text{CeCu}_6$  [3].

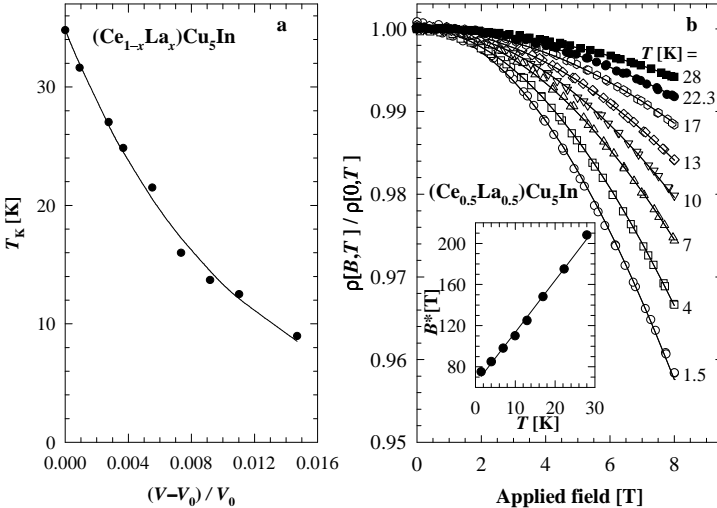


Fig. 2. (a) Volume dependence of the Kondo temperature  $T_K$  for  $\text{Ce}_{1-x}\text{La}_x\text{Cu}_5\text{In}$  observed experimentally (points) and fitted to the compressible Kondo model (line). (b) Magnetoresistivity of  $\text{Ce}_{0.5}\text{La}_{0.5}\text{Cu}_5\text{In}$ . The experimental data are fitted to the single-ion spin-1/2 Bethe ansatz description (see text).

In Fig. 2(a) magnetoresistivity measurements for  $(\text{Ce}_{0.5}\text{La}_{0.5})\text{Cu}_5\text{In}$  are presented for various fixed temperatures. The data have been fitted to the

single-ion, spin  $-\frac{1}{2}$  Bethe ansatz description [4]

$$\frac{\rho(B)}{\rho(B=0)} = \left[ \frac{1}{2j+1} \sin^2 \left( \frac{\pi n_f}{2j+1} \right) \sum_{\ell=0}^{2j} \sin^{-2}(\pi n_\ell) \right]^{-1} \quad (3)$$

for which an exact solution exists. This is considered appropriate notwithstanding that the  $\text{Ce}^{+3}$  ion has  $j = 5/2$ , because the crystal electric field for orthorhombic symmetry results in an effective  $j = \frac{1}{2}$  moment for the low-temperature ground state [5].  $\rho(B)/\rho(B=0)$  is determined by the characteristic field  $B^*$  which has the temperature dependence [6]

$$B^*(T) = B^*(0) + \left( \frac{k_B T}{g \mu_K} \right) = \frac{k_B (T_K + T)}{g \mu_K}. \quad (4)$$

Least-squares fits of the experimental data to Eq. (3) give values of  $B^*$  as plotted in the inset to Fig. 2(b). These are in accordance with the linear  $T$ -dependence given by Eq. (4). Values of  $T_K = 12.5(7)$  K and a much reduced moment  $\mu_K = 0.15(1) \mu_B$  for the Kondo ion compared to the free-ion moment ( $2.54 \mu_B$ ) are obtained. The value of  $T_K$  is in good agreement with that obtained from the  $\rho(T)$  data for this alloy. It is also noted that for the concentrated Ce alloys the position of the low-temperature peak in  $\rho(T)$  drops from  $T_m = 33$  K for  $\text{CeCu}_5\text{In}$  to  $T_m = 19$  K for the  $x = 0.2$  alloy. Thus the approximate relation  $T_m \approx T_K$  is obeyed for this material.

Finally, magnetic susceptibility measurements (not shown) have been performed for several compositions of  $(\text{Ce}_{1-x}\text{La}_x)\text{Cu}_5\text{In}$ . No evidence of magnetic order is observed for any of these down to 1.8 K. All the alloys follow the Curie-Weiss relation  $\chi(T) = C/(T - \theta_p)$  above 100 K with  $-\theta_p$  taking values in the range 40–70 K. The effective magnetic moment varies between 2.54 and  $2.67 \mu_B$  which is in agreement with the expected moment value of  $1.54 \mu_B$  for the  $\text{Ce}^{3+}$  ion.

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