KONDO PROPERTIES IN $(Ce_{1-x}La_x)Cu_5In$*

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$(Ce_{1-x}La_x)Cu_5In$ 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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$CeCu_5In$ exhibits Kondo lattice properties with a specific heat γ coefficient of 200 mJ mol^{-1} K^{-2}, and a resistivity $\rho(T)$ showing a maximum at $T_m = 35$ K with a Fermi-liquid-like AT^2 dependence at low temperatures. No evidence of magnetic order was observed down to 0.1 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 $(Ce_{1-x}La_x)Cu_5In$ series $(0 \leq x \leq 1)$ retain the orthorhombic $CeCu_6$-type structure of the $CeCu_5In$ parent compound. A Vegard's law-like linear increase of unit cell volume with x was observed amounting to 1.8% between $CeCu_5In$ and $LaCu_5In$.

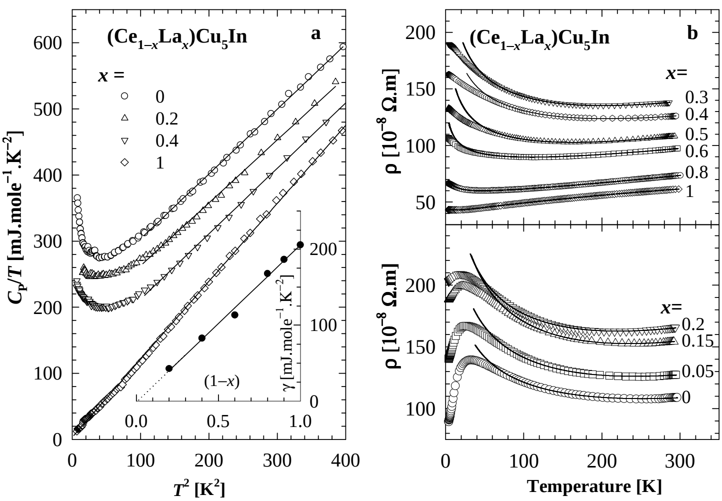

Fig. 1. (a) Specific heat of $Ce_{1-x}La_xCu_5In$, and concentration dependence of the $\gamma-$ coefficient (inset). (b) Electrical resistivity of $Ce_{1-x}La_xCu_5In$. Solid lines indicate fits as described in the text.

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. γ-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 $CeCu_5In$ a value of $\gamma = 206$ mJ mol^{-1} K^{-2} is obtained in agreement with earlier studies [1].

Measurements of $\rho(T)$ for several alloys of the system $(Ce_{1-x}La_x)Cu_5In$ 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 $T_{\rm m} = 33$ K for $CeCu_5In$ to $T_{\rm m} = 19$ 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

$$\rho(T) = \rho_0 + \rho_{\rm ph} - C_K \ln\left(\frac{T}{T_{\rm K}}\right), \tag{1}$$

where the Bloch–Grüneissen (BG) formula was used for the electron-phonon scattering term $\rho_{\rm ph} = 4\kappa\theta^{-6}T^5G(\theta/T)$ 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 κ was allowed along with ρ_0, $C_{\rm K}$ and $T_{\rm K}$ 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 $T_{\rm K} = 35$ K for $CeCu_5In$ to 8.6 K for the $x = 0.8$ alloy. This variation is described in terms of the compressible Kondo lattice model [2]

$$T_{\rm K}(x) = T_{\rm K}(x=0)\exp\left[-q\frac{(V-V_0)}{V_0}|JN(E_{\rm F})|_{x=0}\right], \qquad (2)$$

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, $N(E_{\rm F})$ is the density of states at the Fermi level and the constant q takes on values between 6 and 8. A plot of $T_{\rm K}$ 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 $|JN(E_{\rm F})| = 0.063 \pm 0.005$ for $CeCu_5In$ which may be compared with 0.09 for $CeCu_6$ [3].

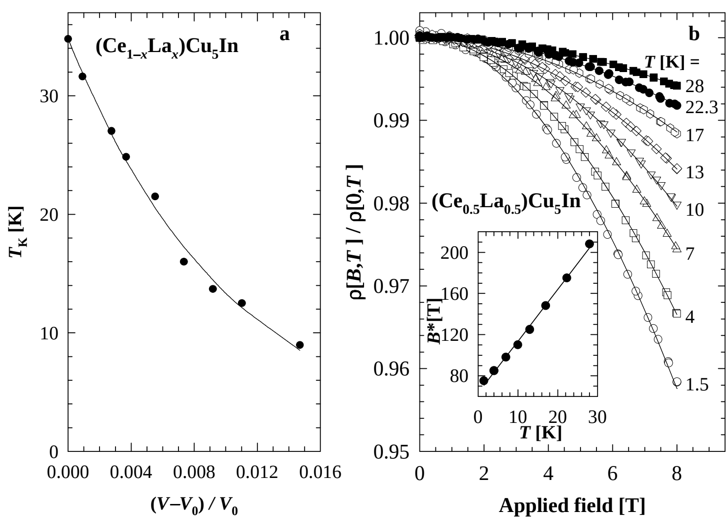

Fig. 2. (a) Volume dependence of the Kondo temperature $T_{\rm K}$ for $Ce_{1-x}La_xCu_5In$ observed experimentally (points) and fitted to the compressible Kondo model (line). (b) Magnetoresistivity of $Ce_{0.5}La_{0.5}Cu_5In$. The experimental data are fitted to the single-ion spin-1/2 Bethe ansatz description (see text).

In Fig. 2(a) magnetoresistivity measurements for $(Ce_{0.5}La_{0.5})Cu_5In$ are presented for various fixed temperatures. The data have been fitted to the single-ion, spin$-\frac{1}{2}$ Bethe ansatz description [4]

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

for which an exact solution exists. This is considered appropriate notwithstanding that the 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 $B^\star$ which has the temperature dependence [6]

$$B^\star(T) = B^\star(0) + \left(\frac{k_{\rm B}T}{g\mu_{\rm K}}\right) = \frac{k_{\rm B}(T_{\rm K}+T)}{g\mu_{\rm K}}\,. \tag{4}$$

Least-squares fits of the experimental data to Eq. (3) give values of $B^\star$ as plotted in the inset to Fig. 2(b). These are in accordance with the linear $T-$dependence given by Eq. (4). Values of $T_{\rm K} = 12.5(7)$ K and a much reduced moment $\mu_{\rm K} = 0.15(1)$ $\mu_{\rm B}$ for the Kondo ion compared to the free-ion moment (2.54 $\mu_{\rm B}$) are obtained. The value of $T_{\rm K}$ 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-temperate peak in $\rho(T)$ drops from $T_{\rm m} = 33$ K for $CeCu_5In$ to $T_{\rm m} = 19$ K for the $x = 0.2$ alloy. Thus the approximate relation $T_{\rm m} \approx T_{\rm K}$ is obeyed for this material.

Finally, magnetic susceptibility measurements (not shown) have been performed for several compositions of $(Ce_{1-x}La_x)Cu_5In$. No evidence of magnetic order is observed for any of these down to 1.8 K. All the alloys follow the Curie-Weiss relation $\chi(T) = C/(T-\theta_{\rm p})$ above 100 K with $-\theta_{\rm p}$ taking values in the range 40–70 K. The effective magnetic moment varies between 2.54 and 2.67 $\mu_{\rm B}$ which is in agreement with the expected moment value of 1.54 $\mu_{\rm B}$ for the Ce^{3+} ion.

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