THERMODYNAMIC AND TRANSPORT PROPERTIES OF THE HEAVY-FERMION FERRIMAGNET UCu_5Sn*

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We have studied the specific heat $C_p(T)$, thermal expansion $\alpha(T)$, thermal conductivity κ, thermoelectric power S and magnetoresistance $\Delta\rho/\rho$ of the heavy-fermion ferrimagnet UCu_5Sn. The anomalies observed in the $C_p(T)$-, $\alpha(T)$- and $\Delta\rho/\rho(T)$-dependencies confirm the existence of long-range magnetic order. $\Delta\rho/\rho$ is negative in the investigated temperature and magnetic field ranges. The fitting of the magnetic specific heat in the temperature range 10–40 K gives $\gamma_{\rm ord} = 78$ mJ/moleK^2, $\beta = 0.5$ mJ/moleK^4 and $\Delta/k_{\rm B} = 21$ K. The effective Grüneisen parameter reaches a value of 4.7 at low temperatures, supporting the strongly correlated electron nature of this material. The thermoelectric power shows a maximum around 24 K, which might be related to either the Kondo effect or the phonon drag process. Below 100 K, the phonon contribution $\kappa_{\rm ph}$ dominates the thermal conductivity. The reduced Lorenz number $\kappa\rho/L_0T$ shows a broad peak at ~10 K. This behavior might be explained by a dominant phonon scattering process off the U magnetic moments.

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UCu_5Sn crystallizes in the hexagonal $CeCu_5Sn$-type crystal structure [1, 2]. We have shown previously that this compound although being ferrimagnetic below 53 K [2], exhibits an enhanced coefficient electronic specific heat, $\gamma(0)$, of 330 mJ/mole K^2 [3]. Thus, UCu_5Sn is an interesting $5f$-system for studying the heavy-fermion properties with competing magnetic interactions. Furthermore, the Th substitution up to about 90% increases the

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$\gamma(0)$-value up to 600 mJ/mole-U K^2, exhibiting unusual logarithmic dependences of C_p/T [4]. In this contribution, we will report on the specific heat C_p, measured with a relaxation method (T = 2–300 K, $\mu_0 H$ =0–6 T), the thermal expansion α, measured using a capacitance dilatometer (4–80 K), the thermal conductivity κ, as well as the thermoelectric power S, measured with a steady-state method (4–300 K) and the magnetoresistance $\Delta\varrho/\varrho$, measured with the standard four-probe method (2–100 K, 0–14 T). The measurements were made on polycrystalline samples of UCu_5Sn which were prepared by arc-melting and were characterized according to a procedure previously described [3].

In Fig.1 we show the temperature dependence of the specific heat divided by temperature for UCu_5Sn and $ThCu_5Sn$. C_p of UCu_5Sn is dominated by a sharp anomaly at T_C = 53 K, which clearly corroborates the ferrimagnetic transition reported previously [3].

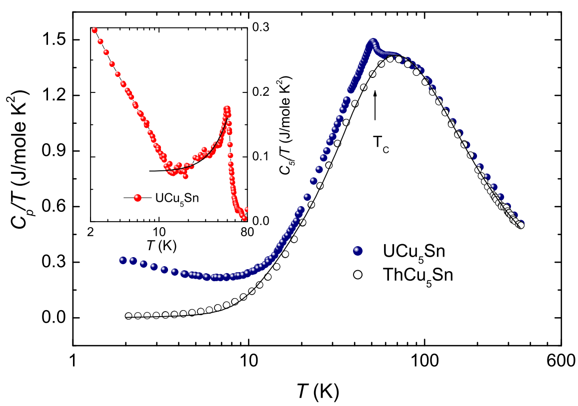

Fig. 1. C_p/T *vs* T (on a logarithmic scale) for UCu_5Sn and $ThCu_5Sn$. The inset shows C_{5f}/T of Cu_5Sn as a function of T (on a logarithmic scale). The solid line is a fit (see the text). Inset shows the magnetic entropy as a function of T.

$C_p(T)$ of $ThCu_5Sn$ may represent the behaviour typical of the lattice specific heat. We have fitted the experimental data of $ThCu_5Sn$ to the formula $C_p(T) = C_{\mathrm{el}} + C_{\mathrm{ph}}$, where $C_{\mathrm{el}} = \gamma(0)T$ and $C_{\mathrm{ph}} = 9R(T/\Theta_D)^3 \int_0^{\Theta_D/T}$ $[(x^4 e^x dx)/(e^x - 1)^2]$. We got the following values Θ_D = 250 K and γ = 9.2 mJ/mole-Th K^2. Fig. 1 (b) shows the magnetic contribution to the specific heat of UCu_5Sn, obtained by subtracting the lattice contribution based on C_p of $ThCu_5Sn$. As seen, below 10 K C_{5f}/T also manifests a clear linear upturn in log T, at least down to 1.5 K as found previously [4]. We observe that the coefficient $\gamma(0) = C_{5f}/T$, reaches 300 mJ/mole-U K^2 at 2 K and, moreover, this value is not affected by the application of magnetic fields up to 6 T. For the temperature range between 10 and 40 K, C_{5f} follows the equation: $C_{5f} = \gamma_{\rm ord}T + \beta T^3 \exp(-\Delta/k_{\rm B}T)$, with $\gamma_{\rm ord} = 78$ mJ/moleK^2, $\beta = 0.5$ mJ/moleK^4 and $\Delta/k_{\rm B} = 21$ K. The coefficients $\gamma_{\rm ord}$ and β denote the contribution of the electronic specific heat in the ordered state and the magnon contribution to the specific heat, respectively. Δ is the energy gap in the magnon excitation spectrum. The magnetic entropy S_m, which exhibits a knee at $T_{\rm C}$, at which temperature the entropy release amounts to about 0.8Rln2.

The magnetoresistance measurements were performed in fields up to 14 T (not shown here). At this field, $\Delta\varrho/\varrho$ reaches a maximum value of -10% at the lowest temperature measured (2 K) as is expected for a Kondo-like system. The Curie temperature $T_{\rm C}$ inferred from the $\Delta\rho/\rho(T,H)$-curves increases with increasing strength of the magnetic field. For instance, $T_{\rm C}$ reaches 66 K in a field of 14 T.

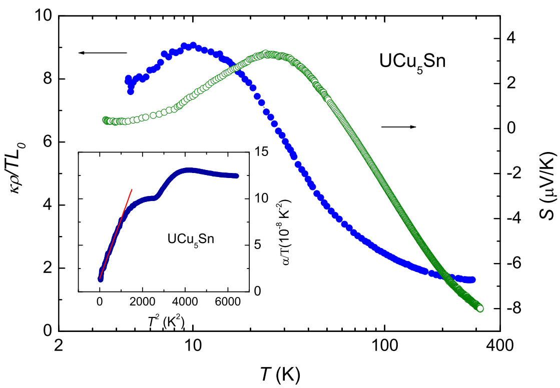

Fig. 2. Temperature dependence of thermoelectric power S and the reduced Lorenz number for UCu_5Sn. Inset shows α/T *vs* T^2.

The thermoelectric power for UCu_5Sn is displayed in Fig. 2 as a function of temperature. S is negative at room temperature (-8μV/K). With decreasing temperature its absolute value decreases and changes the sign at about 65 K. No anomaly is observed around the ferrimagnetic transition at 53 K, reflecting that the spin-dependent scattering does not influence the *S(T)*. At 24 K, a pronounced maximum of 3 $\mu V/K$ occurs. One can consider this maximum as being due to the phonon-drag effect, because this effect often leads to a maximum in *S(T)* at temperatures between (0.1–0.3)Θ_D. For UCu_5Sn, Θ_D is estimated to be 250 K from the $C_p(T)$ measurements, consistent with the thermoelectric power data. However, one can not exclude that this maximum is caused by crystal-field splitting or the Kondo effect. Especially, in a number of heavy-fermion compounds the latter effect often manifests itself by a maximum in *S(T)*-curves in the vicinity of the Kondo temperature.

In Fig. 2 we show also the reduced Lorenz number $L/L_0 = \kappa\rho/L_0T$ as a function of temperature for UCu_5Sn, where $L_0 = 2.45 \times 10^{-8}$ WΩK^{-2} is the Lorenz constant and ρ is the electrical resistivity. L/L_0 strongly suggests that below 100 K the carriers of thermal energy are phonons. Interestingly, below about 10 K $\kappa\rho/L_0T$ slightly decreases down to 4.2 K. Since the phonon thermal conductivity κ_{ph} is related to the lattice heat capacity C_{ph}, sound velocity ν and relaxation time τ_{ph} by the relation: $\kappa_{\mathrm{ph}} = C_{\mathrm{ph}}\nu^2\tau_{\mathrm{ph}}/3$, the decrease in $\kappa\rho/L_0T$ below 10 K may be ascribed to the sudden decrease in the relaxation time of phonons, *e.g.*, due to an increasing phonon-impurity scattering.

The result of the thermal expansion measurements for UCu_5Sn is shown in Fig. 2. $\alpha(T)$ reflects a pronounced magnetic contribution around T_{C}. Below 30 K, the thermal expansion follows the equation $\alpha(T) = aT + bT^3$ with $a = 1.464 \times 10^{-8}\mathrm{K}^{-2}$ and $b = 6.22 \times 10^{-11}\mathrm{K}^{-4}$. The electronic parts of the thermal expansion, α_{el}, and the specific heat, C_{el}, are related to each other by an effective Grüneissen parameter: $\mathit{\Gamma}_{\mathrm{eff}} = \frac{3V\alpha_{\mathrm{el}}(T)}{\mathrm{K}C_{\mathrm{el}}(T)}$, where V is the molar volume (6.6×10^{-5} m^3/mole) and K is the isothermal compressibility. The value K$= 0.794$ Mbar^{-1} is estimated from the pure elements [5]. Taking $\gamma_{\mathrm{ord}} = 78$ mJ/mole K^2 we find $\mathit{\Gamma}_{\mathrm{eff}} = 4.7$, which is of the same order of magnitude as that of heavy-fermion antiferromagnet UPd_2Al_3 ($\mathit{\Gamma}_{\mathrm{eff}} = 5.5$ at T_{N}) [6].

In conclusion, we have shown that the experimental data obtained from numerous thermal and transport measurements provide new support for the heavy-fermion nature of the ferrimagnet UCu_5Sn.

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