PHYSICAL REVIEW B, VOLUME 63, 144401

Magnetic, electrical transport, and thermal properties of a uranium intermetallic compound UCu_5In

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(Received 20 July 2000; revised manuscript received 27 October 2000; published 5 March 2001)

A ternary intermetallic compound UCu_5In has been studied by means of magnetization, electrical resistivity, magnetoresistivity, thermopower, thermal conductivity, heat-capacity, and thermal-expansion measurements. The experimental findings reveal UCu_5In to be antiferromagnetically ordered ($T_N = 25$ K) dense Kondo system ($T_K = 24$ K) with a considerable enhancement of the effective mass of conduction electrons at low temperatures, yielding the Sommerfeld coefficient $\gamma(0)$ of about 240 mJ/(mole K^2). Although the electrical resistivity and the thermopower of UCu_5In shows features characteristic of interplay of Kondo and crystal-field effects, the magnetoresistivity does not exhibit behavior expected for Kondo systems being large and positive even well above T_N. Consistent explanation of the latter results is attempted by considering the role of magnetic precursor effects and/or interfacelike effects due to the presence of nonmagnetic layers.

DOI: 10.1103/PhysRevB.63.144401 PACS number(s): 75.30.Mb, 75.20.Hr, 72.15.Qm, 61.66.Dk

I. INTRODUCTION

The compound UCu_5In is a representative of a family of ternary uranium intermetallics with the overall chemical composition UCu_5M, where $M = Al$, In, Sn.[1,2] While UCu_5Al crystallizes in a tetragonal structure of its own type,[3] and UCu_5Sn adopts a hexagonal unit cell of the $CeNi_5Sn$ type,[4] UCu_5In was shown in Ref. 5 to be isostructural with $CeCu_5Au$ (space group *Pnma*, Ref. 6), i.e., its crystal structure can be considered as an ordered version of the $CeCu_6$ type. Despite different crystal structures the three ternaries were found to exhibit rather similar physical properties. All of them order magnetically at low temperatures: UCu_5Al and UCu_5In are antiferromagnetic below $T_N = 18$ and 25 K, respectively[1,3,7,8], while UCu_5Sn shows complex magnetic behavior with the ferrimagnetic properties below $T_C = 54$ K.[1,9] The electrical properties of UCu_5Al and UCu_5Sn are dominated by a pronounced Kondo-like effect, and their specific-heat C/T term shows a notable enhancement at low temperatures. Due to those findings these two uranium intermetallics have been classified in Refs. 3 and 9 as magnetically ordered, medium-heavy-fermion systems.

In this paper we report on the physical behavior of the third compound from the 1:5:1 series, i.e., UCu_5In, which has been studied by means of magnetization, electrical resistivity, thermoelectric power, thermal conductivity, heat-capacity, and thermal-expansion measurements.

II. EXPERIMENT

Polycrystalline sample of UCu_5In was prepared by arc melting the constituent elements in a purified argon atmosphere. The button was subsequently wrapped in molybdenum foil and annealed in an evacuated quartz tube at 900°C for 2 weeks. After the heat treatment the sample was quenched by submerging the tubes in water. X-ray powder-diffraction examinations were performed on a STOE automatic diffractometer with Cu $K\alpha$ radiation. They revealed a single-phase character of the sample obtained, and yielded for it the orthorhombic lattice parameters as reported previously.[5]

Magnetic measurements were carried out in the temperature range 1.7–300 K and in magnetic fields up to 5 T employing a Quantum Design MPMS-5 superconducting quantum interference device magnetometer. The electrical resistivity was measured in the temperature interval 4.2–300 K and in applied magnetic fields up to 8 T using a conventional dc four-point technique. The polycrystalline specimens were parallelepipeds cut from larger pieces with a wire saw. The electrical leads were thin copper wires contacted to the samples by tin or indium soldering.

Thermoelectric power (TEP) measurements were done on a rectangular sample with the dimensions $2\times2\times10$ mm^3 in the temperature range 5–300 K by a standard differential method.[10] Small temperature gradients ΔT were measured with a AuFe-chromel thermocouple and voltages induced across the sample ΔV were measured with a Solatron 7071 voltmeter using a AgAu reference wire. The absolute value of TEP was calculated as $S(T) = S_{AgAu}(T) - \Delta V/\Delta T$, where $S_{AgAu}(T)$ was determined using YBCO superconductor and Cu reference below and above 90 K, respectively.

The thermal conductivity was studied within the range 5–300 K by an axial stationary heat-flow method. Absolute temperature as well as temperature gradient along the sample were determined with a manganin-constantan thermocouple. An average error in the measured thermal conductivity coefficient was about ±1.5%.

The heat capacity was measured in the temperature range 2–70 K by a relaxation method. The thermal-expansion measurements were carried out within the range 5–80 K by a capacitance dylatometry. The very same specimen was measured as used in TEP studies. The capacitance was measured with a frequency of 1 kHz using an ultraprecise Andeen-Hagerling 2500A capacitance bridge (sensitivity of 10^{-7} pF). The relative change of length (the measurement precision of about 10^{-8}) was determined with respect to a length change of copper (spectrally pure, annealed in an argon atmosphere at 750°C for 4 h). The calibration data for copper were taken from Ref. 11.

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III. RESULTS AND DISCUSSION

A. Magnetic properties

The temperature variation of the inverse molar magnetic susceptibility of UCu$_5$In is shown in Fig. 1(a). As previously reported,[1,2,8] the compound orders antiferromagnetically at $T_N = 25$ K, which manifests itself by a characteristic minimum in $\chi^{-1}(T)$. In the paramagnetic region (above 27 K) the susceptibility follows a modified Curie-Weiss law with the effective magnetic moment μ_{eff} of 2.43μ_B, with a rather large paramagnetic Curie temperature θ_p of -63 K, and the temperature independent term $\chi_0 = 6.2\times10^{-4}$ emu/mole. A convex curvature of $\chi^{-1}(T)$ indicates a strongly anisotropic character of the compound, caused by crystal electric-field (CEF) effect, even in the paramagnetic state. Thus the reduction in μ_{eff} in respect to a free U^{3+} (or U^{4+}) ion value is probably due to an interplay of CEF and Kondo-like screening effects, as discussed below. The inset to Fig. 1(a) presents the field dependence of the magnetization $\sigma(B)$ in UCu$_5$In measured at 1.7 K. Apparently, this quantity is a linear function of the magnetic-field strength without hysteretic behavior, thus corroborating an antiferromagnetic nature of the ordered state at low temperatures. Another unambiguous proof for antiferomagnetism in UCu$_5$In has recently been got from neutron powder-diffraction studies.[12]

B. Electrical transport properties

The electrical resistivity of UCu$_5$In, shown in Fig. 1(b), is only slightly temperature dependent. In the paramagnetic region $\rho(T)$ forms a broad shallow maximum centered at about 170 K, whereas just below T_N the resistivity exhibits a pronounced hump with a maximum at $T_{\max} = 15$ K. The Néel temperature manifests itself as a sharp dip in the $\rho(T)$ curve.

The broad anomaly at elevated temperatures is reminiscent of the effect of interplay of phonon, CEF, and Kondo-like scattering processes. In order to check this presumption, the electrical resistivity of a nonmagnetic isostructural compound ThCu$_5$In was measured, and then used as an approximation of the phonon contribution to the total electrical resistivity of UCu$_5$In. As also shown in Fig. 1(b), the resistivity of ThCu$_5$In has a metallic character throughout the whole temperature range studied, with an almost linear dependence on T at ambient temperatures and a clear saturation below about 20 K. The experimental $\rho(T)$ curve can easily be fitted to the so-called modified Bloch-Grüneisen expression

$$\begin{aligned}\rho(T) &= \rho_0 + \rho_{ph}(T)\\ &= \rho_0 + 4RT\left(\frac{T}{\Theta_D}\right)^4 \int_0^{\Theta_D/T} \frac{x^5 dx}{(e^x-1)(1-e^{-x})}\\ &\quad - KT^3, \end{aligned} \tag{1}$$

where ρ_0 stands for the residual resistivity, Θ_D is the Debye temperature and R is a constant, whereas the cubic term KT^3 describes interband scattering processes.[13] A least-squares fitting of the experimental data to Eq. (1) yields the following parameters: $\rho_0 = 91$ $\mu\Omega$ cm, $\Theta_D = 149$ K, $R = 0.064$ $\mu\Omega$ cm/K and $K = 1.5\times10^{-7}$ $\mu\Omega$ cm/K^3. Assuming that $\rho_{ph}(\mathrm{UCu_5In}) = \rho_{ph}(\mathrm{ThCu_5In})$ the magnetic contribution to the electrical resistivity of UCu$_5$In was derived and the result of this subtraction is given in Fig. 1(b) as a sum $\rho_m(\mathrm{UCu_5In}) + \rho_0(\mathrm{UCu_5In})$ (because the resistivity of UCu$_5$In does not show any tendency to saturation down to the lowest temperature measured, the term ρ_0 could not be determined). Most interesting from this figure is that UCu$_5$In can be treated as a dense Kondo system exhibiting a negative temperature coefficient in the paramagnetic region. A broad maximum in $\rho_m(T)$ that occurs around 100 K may thus be interpreted as a result of the Kondo effect in the presence of strong crystal-field interactions. According to the relevant theory developed by Cornut and Coqblin,[14] the temperature of this maximum may correspond to the overall splitting Δ_{CF} of the ground multiplet of the uranium ions under the crystalline field potential.

At the first glimpse, a salient behavior of the resistivity of UCu$_5$In in the ordered region might be associated to scattering of the conduction electrons on the boundaries of a new ''magnetic'' Brillouin zone. However, this mechanism requires the magnetic unit-cell volume to be larger than the chemical one. As found in the recent neutron-diffraction studies,[12] this is not the case of UCu$_5$In and therefore the low-temperature maximum in $\rho_m(T)$ must have had a different origin, e.g., it may be a hallmark of the opening a gap on part of the Fermi surface due to spin-density-wave (SDW) formation as, for example, in Cr and its alloys[15]. This exciting possibility calls for further experimental characterization of UCu$_5$In, especially on single crystals, which is planned for the near future.

Upon applying magnetic field ($B\perp i$) the electrical resistivity of UCu$_5$In increases in the whole temperature region. As an example, in the inset to Fig. 2 it is shown the low-temperature resistance measured in a field of 80 kOe and compared to the zero-field data. The transverse magnetoresistivity (MR) $\Delta\rho/\rho$, defined as

$$\Delta\rho/\rho = \frac{\rho(B) - \rho(B=0)}{\rho(B=0)}\cdot 100\% \tag{2}$$

is positive and reaches at $T = 4.2$ K and $B = 8$ T a value of about 7% (see Fig. 2). According to Yamada and Takada,[16] MR of an antiferromagnet is positive in magnetic fields being lower than the critical value of spin-flip or metamagnetic transitions. Apparently, this latter condition is fulfilled in UCu$_5$In, as evidenced in the inset to Fig. 1(a) by a linear behavior of $\sigma(B)$. However, in contrast to the predictions of the authors of Ref. 16, no B^2 dependence of $\Delta\rho/\rho$ is observed for this compound in the ordered region. Instead, the measured $\Delta\rho/\rho(B)$ dependencies exhibit a clear downward curvature. This behavior can be qualitatively understood if one takes into account a Kondo-like character of UCu$_5$In. For a Kondo system MR is always negative and has a concave-type dependence on magnetic field.[17] Thus a superposition of positive magnetoresistivity due to the antiferromagnetic ordering and negative one due to Kondo effect may lead to the behavior observed for UCu$_5$In at the lowest temperatures. However, a similar S-shaped field dependence of

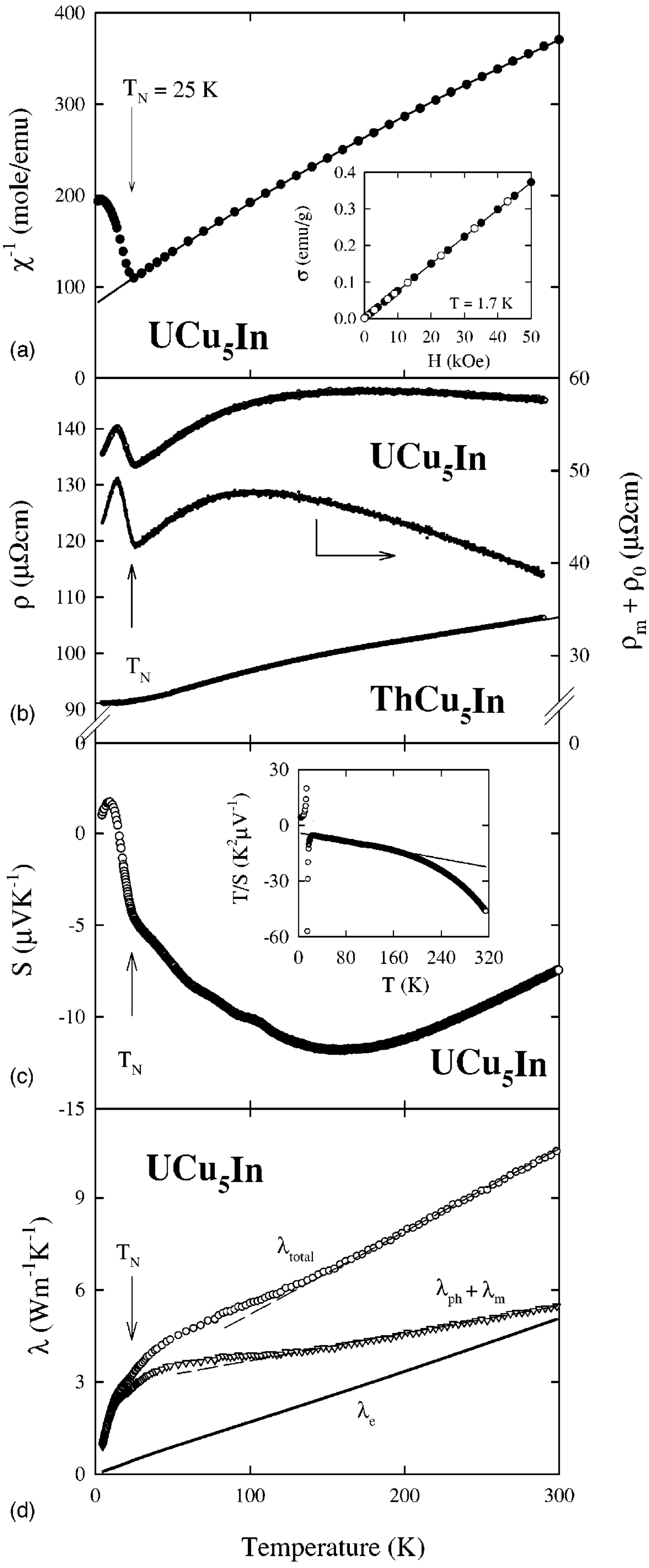

FIG. 1. (a) Temperature dependence of the inverse molar magnetic susceptibility of UCu$_5$In. The solid line is a fit of $\chi^{-1}(T)$ to the modified Curie-Weiss law with the parameters given in the text. The inset shows the field variation of the magnetization, measured at 1.7 K with increasing (full circles) and decreasing (open circles) magnetic field. (b) Temperature dependence of the electrical resistivity of UCu$_5$In, compared to that of nonmagnetic ThCu$_5$In. The solid line is a fit of the latter $\rho(T)$ to Eq. (1) with the parameters given in the text. In the figure there is also shown the temperature variation of the magnetic contribution to the total electrical resistivity of UCu$_5$In derived from Eq. (2) (enlarged by the residual resistivity; right-hand scale). (c) Temperature dependence of the thermoelectric power of UCu$_5$In. The inset presents the function T/S vs T. The solid line marks a $T/(1+T/T^*)$ dependence of the thermopower in the range 30–160 K with $T^* = 64$ K. (d) Temperature dependence of the thermal conductivity of UCu$_5$In (circles). The main contributions to $\lambda_{total}(T)$, i.e., the electronic (solid lines) and the phonon (triangles) components (the latter enlarged in the ordered region by the magnon component), were derived as described in the text.

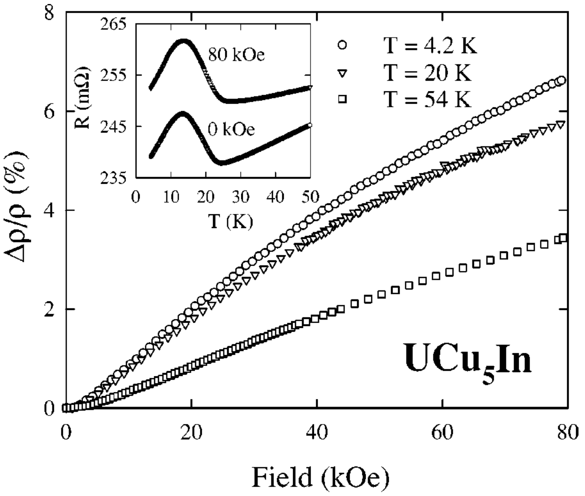

FIG. 2. Field dependence of the magnetoresistivity of $\mathrm{UCu_5In}$, measured at 4.2, 20, and 54 K. The inset shows the low-temperature variations of the electrical resistance measured in zero field and in 80 kOe.

$\Delta\rho/\rho$ with the positive sign persists also well above T_N. For example, as seen from Fig. 2, the magnetoresistivity measured at 54 K is positive and still fairly large (about 3.5% in 8 T). Such a behavior cannot be accounted for by invoking scattering of the conduction electrons on disordered magnetic moments because this mechanism always yields negative magnetoresistivity.[16,17] It seems also unlikely that a negative spin-fluctuation contribution to $\Delta\rho/\rho$ in the paramagnetic state is dominated in $\mathrm{UCu_5In}$ by a positive term arising from the influence of magnetic field on the Fermi surface because the latter becomes non-negligible only in alloys exhibiting quite large electronic mean free path, i.e., in good electrical conductors. Just in opposition, large resistivity of $\mathrm{UCu_5In}$ indicates that this compound is rather a poor metal. On the other hand, large positive values of MR have recently been observed for some paramagnetic,[18] antiferromagnetic,[19] and ferromagnetic[20] compounds having a layered crystal structure. For these phases the positive magnetoresistance is thought to result from to the presence of nonmagnetic layers, which imply a scattering mechanism similar to the interface effect characteristic of multilayers.[21] As the crystallographic unit cell of $\mathrm{UCu_5In}$ contains particularly many nonmagnetic atoms which may be viewed as forming wavy planes, it seems that also in this compound the latter effect may play some role, and thus gives rise to the observed behavior of MR in both the paramagnetic and ordered regions. Another possible mechanism leading to a positive MR is a so-called magnetic precursor effect proposed recently to explain anomalous electronic transport and thermodynamic properties of some Gd-based intermetallics.[22] According to Mallik and co-workers,[22] in some metallic materials there develops ''magnetic disorder-induced localization of electrons'' before a long-range magnetic order sets in and this effect may give rise to the appearance of significant magnetic contribution to the electrical resistivity and the specific heat, already well above the magnetic phase transition. In ferromagnetic compounds like those studied in Ref. 22 this mechanism implies a negative magnetoresistance at temperatures far above T_C but in antiferromagnetic $\mathrm{UCu_5In}$ it would yield a positive MR, as is observed experimentally even at $T=54$ K.

The results of thermoelectric power (TEP) measurements are shown in Fig. 1(c). At room temperature TEP is negative (about $-7\,\mu$V/K) and on cooling down to about 200 K the $S(T)$ variation shows as an almost linear behavior. Subsequently, $S(T)$ goes through a broad negative minimum near 160 K (approximately $-12\ \mu$V/K), and on further cooling TEP decreases in its absolute value. The antiferromagnetic phase transition at $T_N=25$ K manifests itself as a pronounced kink in $S(T)$. In the ordered region TEP changes its sign at 15 K and finally exhibits a positive peak centered at 9 K. Below this temperature the thermopower shows a tendency to fall rapidly towards zero.

In view of strong combined effects of Kondo and CEF scattering, evidenced for $\mathrm{UCu_5In}$ in the resistivity studies, the usual treatment of $S(T)$ in terms of phonon drag, appropriate for pure and simple materials, seems to be not significant here due to the dominance of the Umklapp processes. Hence the high-temperature negative minimum in $S(T)$ may rather be attributed to Kondo effect, which involves excited CEF states.[23] Consequently, the temperature of this minimum may be considered as a rough estimate of crystal-field splitting Δ_{CF}, yielding, however, a slightly higher value than Δ_{CF} derived from the resistivity data. This discrepancy probably reflects the intrinsic difference between $\rho(T)$ (always positive) and $S(T)$ (both signs possible) with respect to the combination of Kondo and CEF scattering effects. It is worth noting that similar behavior of TEP as in $\mathrm{UCu_5In}$ was found for U-based heavy fermion compounds $\mathrm{U_3Ni_3Sn_4}$ and $\mathrm{U_3Au_3Sn_4}$,[24] $\mathrm{UPt_3}$,[25] and $\mathrm{UCu_5}$.[26] Also, for the heavy fermion antiferromagnets $\mathrm{UNi_2Al_3}$ and $\mathrm{UPd_2Al_3}$,[27] the absolute value of $S(T)$ generally increases steadily with increasing temperature. On the other hand, antiferromagnetic and metallic but not heavy-fermion compound UPdSn,[28] exhibits a large resemblance in $S(T)$ to some Ce-based Kondo lattices, for which a broad high-temperature (100–200 K) positive maximum due to CEF effect is observed.[23]

In the inset to Fig. 1(c) we have plotted T/S against T. As seen, this dependence is approximately linear below 160 K down to temperatures near T_N. Thus at least in this region $S(T)$ can be phenomenologically described by the general expression[27]

$$S(T)=\frac{AT}{1+T/T^*}, \tag{3}$$

where A is a constant and T^* is a characteristic temperature being related to the temperature of resistivity maximum. The values of A and T^* determined for $\mathrm{UCu_5In}$ are $-0.2\ \mu\mathrm{V/K^2}$ and 64 K, respectively, i.e., they are markedly different from those reported for $\mathrm{UPt_3}$ ($-1.25\ \mu\mathrm{V/K^2}$ and 10 K, respectively),[27] possibly because of much weaker (if any) CEF effect in the latter compound. Interestingly, a similar phenomenological analysis of TEP determined for a series of heavy-fermion compounds $\mathrm{UNi_2Al_3}$, $\mathrm{UPd_2Al_3}$, $\mathrm{UCu_{4+x}Al_{8-x}}$, and $\mathrm{UBe_{13}}$ gives positive and less than unity values of A.[27]

In the antiferromagnetic region the thermopower of $\mathrm{UCu_5In}$ exhibits a maximum and this feature can probably be related to effective scattering of conduction electrons on CEF ground state only.[23] Somewhat below T_{N}, TEP changes its sign, which may reflect a change in the density of states near the Fermi level due to a reconstruction of the Fermi surface.

C. Thermal properties

As is apparent from Fig. 1(d), the thermal conductivity $\lambda(T)$ of $\mathrm{UCu_5In}$ rises continuously with increasing temperature, rather rapidly below T_N and almost linearly at ambient temperatures. At the magnetic phase transition $\lambda(T)$ exhibits only a small dip, while near 150 K it slightly changes its slope. This latter anomaly occurs at a similar temperature as that of a broad negative minimum in $S(T)$ and may be consequently considered as a crystal-field effect.

In general, the total measured thermal conductivity of a magnetic solid is usually expressed as a sum of electronic λ_e, phonon λ_{ph}, and magnon λ_m, components. The electronic contribution comes from the scattering of conduction electrons on lattice imperfections, phonons and magnetic moments. Its temperature variation can be derived on the basis of the Wiedemann-Franz law from the measured electrical resistivity versus temperature function:

$$\lambda_e(T)=\frac{L_0 T}{\rho(T)}, \tag{4}$$

where the Sommerfeld value $L_0=2.45\times10^{-8}\ \mathrm{W\,\Omega/K^2}$. The $\lambda_{ph}(T)$ contribution originates from collisions of phonons on impurities and/or defects present in the lattice, conduction electrons, other phonons, and magnetic moments. In turn, the magnon component is due to interactions of spin-wave excitations with both electrons and phonons. This contribution appears in the magnetically ordered region only, and its magnitude at the lowest temperatures can be comparable to those of λ_e and λ_{ph}. The difference $\lambda_{total}(T)-\lambda_e(T)$ is usually regarded as an estimate of the phonon contribution, enlarged in the magnetically ordered region by the magnon component. The scattering of electrons and phonons on lattice imperfections is elastic and these two mechanisms are dominant at low temperatures. In contrast, the electron-phonon and phonon-phonon interactions dominate at elevated temperatures, they have both elastic and inelastic character being described by the normal- and Umklapp-type processes, respectively.[29]

The calculated contributions $\lambda_e(T)$ and $\lambda_{ph}(T)+\lambda_m(T)$ for $\mathrm{UCu_5In}$ are given in Fig. 1(d). Because of the aforementioned small temperature dependence of the electrical resistivity of this compound, the electronic thermal conductivity is almost proportional to temperature. Thus in the paramagnetic region the phonon contribution increases with rising temperature in a manner characteristic of a number of cerium dense Kondo compounds, e.g., $\mathrm{CeCu_2Si_2}$, $\mathrm{CeAl_3}$, or $\mathrm{CeCu_6}$.[30] It is worth mentioning that a linear temperature dependence of λ_{ph} has been predicted theoretically by Zimmermann[31] for materials characterized by the predominant phonon wavelength being larger than the electronic mean free path, i.e., those being rather poor metallic conductors. The relatively large electrical resistivity of $\mathrm{UCu_5In}$ strongly suggests that this compound may indeed belong to this class of intermetallics.

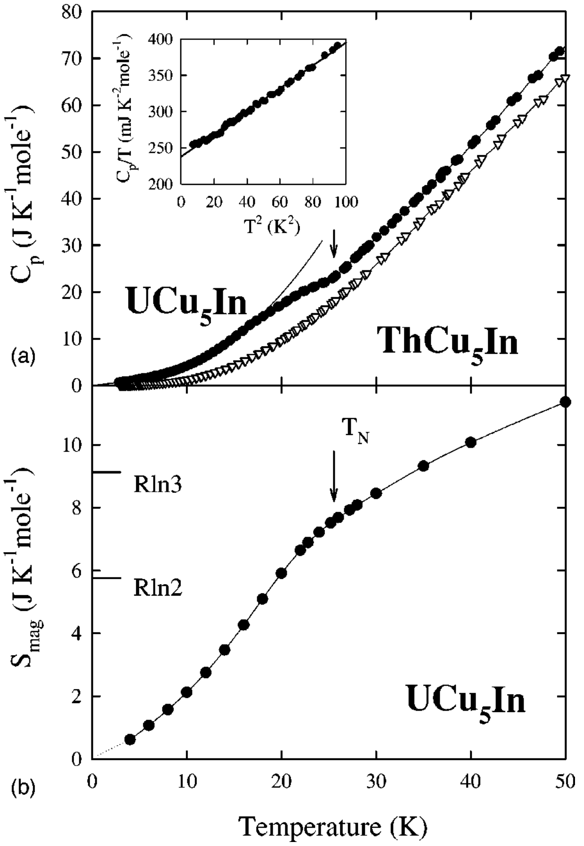

FIG. 3. (a) Low-temperature specific heat of $\mathrm{UCu_5In}$, as compared to that of $\mathrm{ThCu_5In}$. The solid line is a fit of $C_p(T)$ to Eq. (6) with the parameters given in the text. The arrow marks the antiferromagnetic phase transition. The inset shows the specific heat of $\mathrm{UCu_5In}$ as a function C_p/T vs T^2. The solid line is a fit of $C_p(T)$ according to Eq. (5) with the parameters given in the text. (b) Temperature variation of the magnetic entropy in $\mathrm{UCu_5In}$.

The low-temperature specific heat of $\mathrm{UCu_5In}$ is presented in Fig. 3(a). Rather surprisingly $C_p(T)$ reveals only small, very broad anomaly, which spreads out from the antiferromagnetic phase transition at $T_{\mathrm{N}}=25$ K down to about $T_{\mathrm{N}}/2$. However, as is also apparent from Fig. 3(a), in the ordered region there is a marked difference between $C_p(T)$ of $\mathrm{UCu_5In}$ and that of its isostructural nonmagnetic counterpart $\mathrm{ThCu_5In}$, indicating still not released entropy. For the latter compound the specific heat decreases smoothly with decreasing temperature and below 10 K it follows the formula

$$C_p(T)=\gamma T+\beta T^3 \tag{5}$$

with the parameters: $\gamma=6\ \mathrm{mJ/(mole\,K^2)}$ and $\beta=1.1\ \mathrm{mJ/(mole\,K^4)}$, describing the electronic and lattice contributions, respectively. In the same temperature range the specific heat of $\mathrm{UCu_5In}$ can also be approximated by Eq. (5) with the parameters: $\gamma = 237$ mJ/(mole K^2) and $\beta = 1.6$ mJ/(mole K^4) [see the inset to Fig. 3(a)]. In this case, however, Eq. (5) represents the $C_p(T)$ variation being rather characteristic of antiferromagnetic spin waves. Alternatively, the low-temperature ($T < 17$ K) specific heat of $\mathrm{UCu_5In}$ can be described [note the solid line in Fig. 3(a)] by the formula

$$C_p(T) = aT + bT^3 + fT^{3/2}\exp\left(-\frac{\Delta}{T}\right), \qquad (6)$$

appropriate for magnets exhibiting a gap Δ in their spin-waves spectrum.[32] The least-squares fitting procedure yields the following values of the parameters: $a = 231$ mJ/(mole K^2), $b = 0.7$ mJ/(mole K^4), $f = 315$ mJ/(mole $\mathrm{K}^{5/2}$), and $\Delta = 22$ K. It is worth noting that regardless of the analysis form the enhanced C/T ratio in $\mathrm{UCu_5In}$, obtained from the extrapolation to $T = 0$ K, may be taken as $\gamma(0)$ giving a rough estimate of the Kondo temperature T_K of about 24 K.

In order to derive the entropy S in $\mathrm{UCu_5In}$ it was assumed that the low-temperature lattice contribution to the total measured specific heat can be approximated by $C_p(T)$ measured for $\mathrm{ThCu_5In}$. On this basis, the $S(T)$ variation was calculated and presented in Fig. 3(b). The entropy released at T_N amounts to about 7.5 J/(mole K) and is larger than $R\ln 2$ expected for a doublet ground state. However, it must be noted that so-derived $S(T)$ does not have a purely magnetic origin but contains also the electronic contribution. Furthermore, the entropy increases considerably above T_N and reaches at 50 K (the upper limit of our analysis) a value of about 11.3 mJ/(mole K), i.e., it is somewhat larger than $R\ln 3$. This finding emphasizes a role of crystal-field effect in the compound studied.

Finally, Fig. 4(a) shows the temperature-dependent relative length change determined with respect to the sample length measured at 5 K. As is the case of $C_p(T)$, the magnetic phase transition does not manifest itself as a notable anomaly in $\Delta L/L(T)$. However, a careful inspection of this curve shows that there is a slight change in its slope at T_N and a broad hump is formed that extends to about 15 K. In Fig. 4(b) there is presented the temperature variation of the linear thermal-expansion coefficient α of $\mathrm{UCu_5In}$, derived from $\Delta L/L(T)$. In the paramagnetic region α decreases smoothly with decreasing temperature but has a negative curvature in contrast to normal metals. Also the magnitude of the thermal expansion is much larger than that expected for metals. Both these features are, however, characteristic of heavy-fermion systems.[33] As is apparent from Fig. 4(b), the onset of antiferromagnetism manifests itself as a small dip in $\alpha(T)$. At low temperatures the thermal-expansion coefficient of metals may be considered in analogy to the heat capacity as a sum of electronic and phonon contributions, i.e.,

$$\alpha(T) = AT + BT^3. \qquad (7)$$

In this representation the coefficient A is roughly proportional to the electronic specific-heat coefficient and thus to the density of states at the Fermi level. In the inset to Fig. 4(b) there is shown the ratio α/T plotted against T^2. It is evident from this figure that α/T below about 7 K starts to rise rapidly on cooling [being in some contrast to the low-temperature behavior of C/T; compare the inset to Fig. 3(a)], which may be interpreted as a signature of a large enhancement of $N(E_F)$ at low temperatures. As expected, the behavior of α at high temperatures is dominated by a phonon contribution.

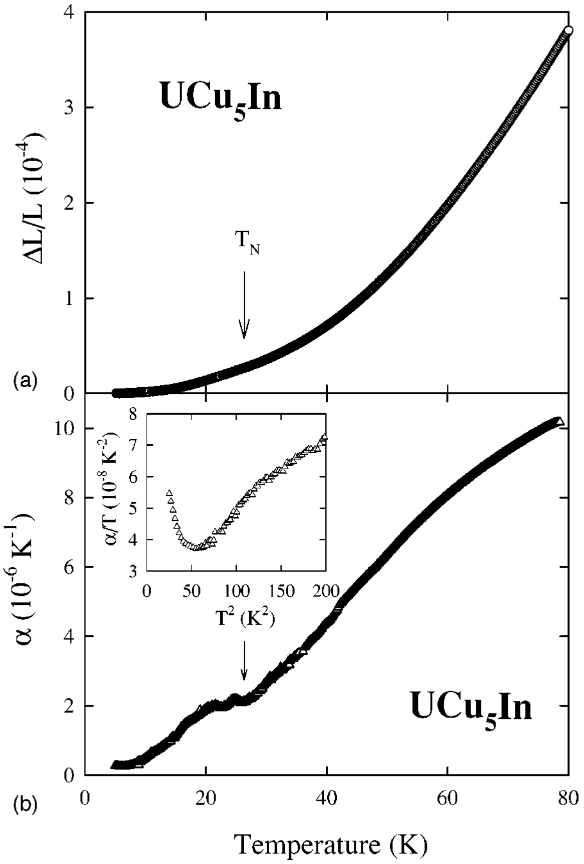

FIG. 4. (a) Temperature dependence of the relative length change with respect to the sample length at 5 K for polycrystalline $\mathrm{UCu_5In}$. (b) Temperature variation of the thermal-expansion coefficient for $\mathrm{UCu_5In}$. The inset shows the thermal expansion as a function α/T vs T^2.

IV. CONCLUSIONS

The ternary intermetallic compound $\mathrm{UCu_5In}$, crystallizing with the orthorhombic $\mathrm{CeCu_5Au}$-type structure, exhibits a localized magnetic behavior at elevated temperatures and orders antiferromagnetically at $T_{\mathrm{N}} = 25$ K. The electrical and heat transport properties have a typical semimetallic character with pronounced Kondo-like and crystal-field features. Interestingly, both the specific heat and the thermal expansion show only small anomalies at T_{N}, characteristic of spin-density-wave (SDW) materials. Furthermore, the specific heat exhibits a considerable enhancement at low temperatures, yielding $\gamma(0)$ of about 240 mJ/mole K^2. On the basis of all these experimental data it is proposed that $\mathrm{UCu_5In}$ is a moderate heavy-fermion antiferromagnet. Another interesting finding for $\mathrm{UCu_5In}$ is a fairly large positive magnetoresistance observed well above T_N. The latter phenomenon has been tentatively ascribed in the present paper to magnetic precursor effects or/and interfacelike mechanisms associated with the presence in the crystal structure of UCu_5In nonmagnetic layers. Further experimental work, aimed at verifying this hypothesis on well-defined single crystalline specimens, is presently under way.

ACKNOWLEDGMENTS

The authors are indebted to B. Waszkiewicz and D. Badurski for assistance in thermopower and electrical resistivity measurements, respectively. This work was sponsored by the Polish Committee for Scientific Research (KBN) within Project No. 2 P03B 150 17.

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