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Resistivity and magnetoresistance studies of the compound $SmCu_6$

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Abstract. The temperature dependence of the resistivity (ρ) and the magnetoresistance ($\Delta\rho/\rho(0)$) have been measured for polycrystalline $SmCu_6$ and $LaCu_6$ compounds. In $SmCu_6$ the resistivity exhibits a sharp drop at the antiferromagnetic transition temperature, $T_N = 9.5$ K. In the region where $T > T_N$, the temperature dependence of the resistivity follows $\rho(T) = \rho_0 + \alpha T(1-(T/T_0)^2)$ where the second term is the phonon contribution to the resistivity within the s–f interaction model. The magnetic field and temperature dependence of $\Delta\rho/\rho(0)$ for $T < T_N$ is suggested to arise from combination of two terms: (i) the orbital motion of the electrons ($\propto H^2$); and (ii) an intrinsic term characteristic of the antiferromagnetic state of the compound ($\propto H$).

1. Introduction

The RCu_6 (where R = rare earth) class of intermetallic compounds show a wide variety of interesting physical phenomena. Among them, $CeCu_6$ is a heavy-fermion compound which does not exhibit either magnetic ordering or superconductivity [1], $PrCu_6$ shows nuclear magnetic ordering with a non-magnetic ground state [2], and $NdCu_6$ undergoes a metamagnetic transition with four discontinuous steps in magnetization [3] and magnetoresistance [4]. Both $SmCu_6$ and $GdCu_6$ order antiferromagnetically, below $T_N = 9.5$ K [5, 6] and 16 K [7], respectively.

In this paper, we present measurements on polycrystalline $SmCu_6$ made to study the effect of magnetic ordering on the temperature dependence of the resistivity (ρ) and the magnetoresistance (MR). We observe that: (i) the temperature dependence of ρ in the high-temperature regime ($T > T_N$) is described by an electron–phonon scattering mechanism within the s–f interaction model; and (ii) the magnetic field and temperature dependence of the MR deviates from Kohler's rule. The variation of the MR with magnetic field and temperature could be ascribed to there being a normal magnetoresistance part and an antiferromagnetic contribution to the compound.

2. Experimental details

The samples $SmCu_6$ and $LaCu_6$ were prepared by arc melting the stoichiometric composition in flowing Ar gas. They were each drawn in the form of a rod for resistivity measurements and then sealed in a quartz capsule and annealed at 973 K for four days. X-ray measurements revealed the samples to be of single phase. The resistivity and longitudinal magnetoresistance measurements were made using the standard four-probe dc measurement technique.

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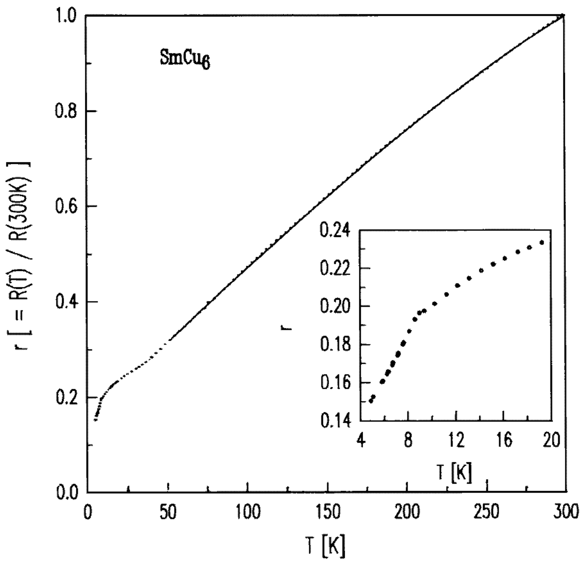

Figure 1. The temperature dependence of the normalized resistance r $(=R(T)/R(300\ \mathrm{K}))$ of $SmCu_6$. The inset shows r in the low-temperature region.

3. Results and discussion

In figure 1 we show a plot of the normalized resistance r $(=R(T)/R(300\ \mathrm{K}))$ as a function of temperature. The resistivity of the sample at 300 K is 28 $\mu\Omega$ cm and the residual resistivity ratio (RRR) $(=\rho(300\ \mathrm{K})/\rho(5\ \mathrm{K}))$ is 6. The value of the RRR is significantly smaller than that reported for polycrystals ($\sim$35) [5] and single crystals ($\sim$80) [6] of this compound. The resistance decreases as temperature is lowered and exhibits a sharp drop at T_N (=9.5 K) (see the inset of figure 1). This behaviour is attributed to the freezing of the spin degrees of freedom in the antiferromagnetic state. Below T_N, a distinct change in the resistance behaviour occurs. However, a Cr-type anomaly associated with the superzone effects is not observed. Instead this behaviour is of the type observed for TbAgSn [8]. In the antiferromagnetic state the resistance varies with temperature as $T^{3/2}$. Since there are too few data points below T_N we do not emphasize this. In the high-temperature region ($T > 50$ K) the resistance behaviour is anomalous. It does not vary linearly as expected from the Bloch–Grüneisen relation, but shows a negative curvature. Such behaviour has also been observed in transition metals, non-magnetic rare-earth metals, and compounds ($LaPd_2Ga_3$) [9]. Mott and Jones [10] attributed such a behaviour observed for transition metals to the lowering of the s–d scattering probability as the temperature is increased. A term proportional to T^3 in addition to the phonon term was suggested to take into account the rapid change in the density of states at the Fermi level. Similar negative curvature of $\rho(T)$ has also been observed for $La_3Rh_3Si_5$ and explained on the basis of the parallel resistor model [11]. It is found that the negative curvature of $\rho(T)$ is observed in all of the RCu_6 compounds (where R = La, Nd, Sm, Gd) except $CeCu_6$ and $PrCu_6$ [5]. The exact sources of such behaviours are not clear. Since the high-temperature behaviours are very similar in $LaCu_6$ and $SmCu_6$, we assume that the electron–phonon interaction essentially describes the $\rho(T)$-behaviour. Therefore, we have fitted the temperature dependence of the resistivity, for $50 < T < 300$ K, to an expression of the form

$$\rho(T) = \rho_0 + \alpha T(1 - (T/T_0)^2)$$

where ρ_0 is the temperature-independent term and the second term is the phonon contribution obtained within the s–f interaction model [12]. The coefficient α incorporates the first and second derivatives of the density of states at the Fermi level and T_0 is identified with the degeneracy temperature. The continuous line through the data points indicates the fitted line. The values of the coefficients that we obtain are $\alpha = 0.907\ \mu\Omega$ cm K^{-1} and $T_0 = 886.7$ K. The values of α and T_0 compare with those found in the case of rare-earth metals (for La, $\alpha = 0.3\ \mu\Omega$ cm K^{-1} and $T_0 = 520$ K) [12]. We find that the same expression also holds good in the case of $LaCu_6$ in the same temperature region, with the value of $\alpha = 0.166\ \mu\Omega$ cm K^{-1} and $T_0 = 1097$ K.

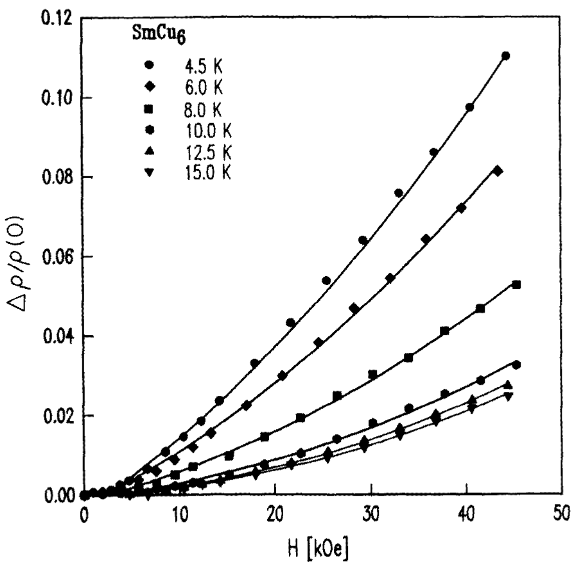

Figure 2. The magnetic field dependence of the magnetoresistance of $SmCu_6$ at various temperatures. The continuous lines are the fits to the equation discussed in the text.

The magnetoresistance (MR), $\Delta\rho/\rho(0)$ $(=\overline{\rho(H) - \rho(0)}/\rho(0))$, as a function of magnetic field at various temperatures is shown in figure 2. It is positive both above and below the ordering temperature. The value of $\Delta\rho/\rho(0)$ at 4.5 K and 44 kOe is $\sim$0.11 and is significantly smaller than that reported in single crystals of $SmCu_6$: $\Delta\rho/\rho(0) \sim 13$ at 1.3 K and 75 kOe [6]. This large difference in $\Delta\rho/\rho(0)$ is presumably due to the significant difference in the RRR between the single-crystal and the polycrystalline samples reported here. The magnitude of $\Delta\rho/\rho(0)$ decreases sharply as the temperature is increased, and becomes nearly temperature independent for $T > T_N$ having a value of 0.02. The field dependence of the MR is found to vary as H^n, where n increases from 1.2 at 4.4 K to 1.7 at 15 K. This behaviour is consistent with the data on single crystals of $SmCu_6$ where at 1.3 K the value of $n \sim 1$ [6]. There appears to be systematic deviation from Kohler's rule—as against the case of $LaCu_6$. In figure 3 we show a plot of $\Delta\rho/\rho(0)$ versus H for the case of $LaCu_6$ at temperatures between 4.5 and 10 K. It exhibits a nearly temperature-independent

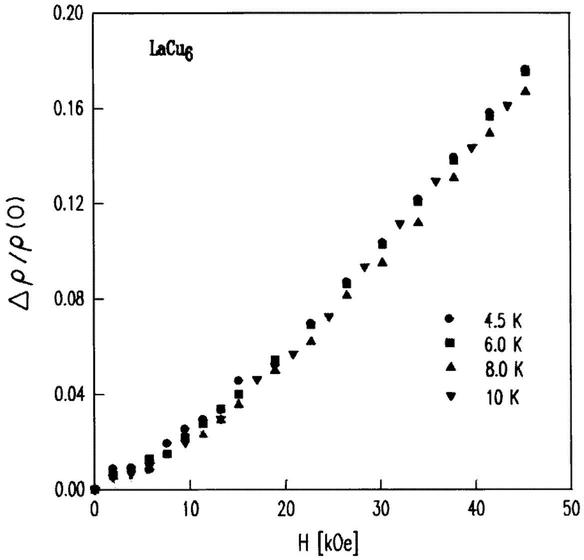

Figure 3. The magnetic field dependence of the magnetoresistance of $LaCu_6$ at various temperatures.

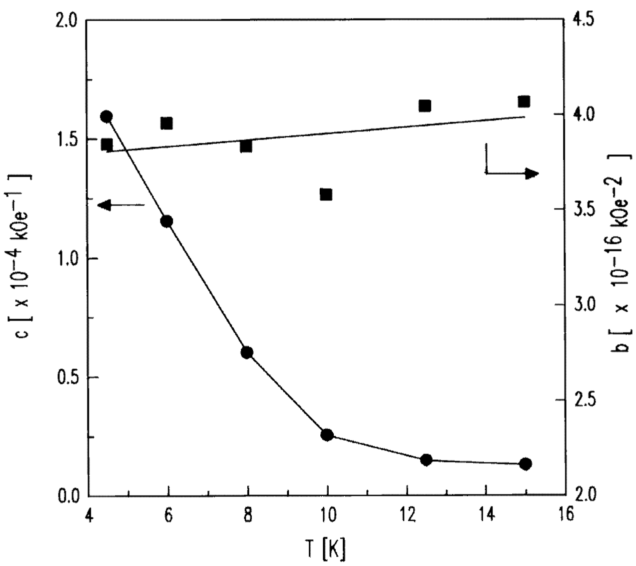

Figure 4. The variation of the coefficients b and c (defined in the text) with temperature for $SmCu_6$.

behaviour consistent with Kohler's rule:

$$\Delta\rho/\rho(0) = f(H/\rho(0, T)).$$

Since $\rho(0, T)$ is nearly temperature independent in the region of 4.5 and 10 K, the magnitude of $\Delta\rho/\rho(0)$ is constant. In the case of $SmCu_6$ the plot of $\Delta\rho/\rho(0)$ versus $\log(H/\rho(0, T))$

does not collapse to a single line (figure not shown). This suggests that the magnetic field influences the scattering rate in addition to creating cyclotron orbits in the antiferromagnetic state of this compound. To take this into account we analyse the MR in $SmCu_6$ in the following manner. This form of field and temperature dependence is attributed as arising due to two contributions: (i) from the orbital motion of the electrons; and (ii) from an intrinsic term characteristic of the antiferromagnetic state. In order to isolate the two contributions, we have fitted the MR curves to an expression of the form

$$\Delta\rho/\rho(0) = b'(H/\rho(0, T))^2 + cH.$$

The first term is attributed to the cyclotron motion of the electrons (Kohler's law in the limit of weak magnetic fields), and the second term is that due to the antiferromagnetic state. The continuous lines in figure 2 are the fits to the data. In figure 4 we plot the variation of the coefficients b $(= b'(\rho(0, T))^2)$ and c as functions of temperature. The coefficient b, which is independent of the magnetic state, remains constant at all temperatures, whereas the coefficient c is found to decrease sharply as temperature is increased and is negligibly small above T_N. This indicates that the temperature and field dependences of the MR in this compound are strongly influenced by the magnetic state of the compound. A similar linear term, in addition to the quadratic term, in the field dependence of the MR in the antiferromagnetic state has also been found in the case of α-Mn below its Néel temperature, T_N [13].

4. Conclusions

The resistivity decreases as the temperature is lowered, and exhibits a sharp drop in value below the antiferromagnetic ordering temperature, $T_N = 9.5$ K, due to the freezing of spin degrees of freedom. In the range $50 < T < 300$ K the temperature dependence of the resistivity is fitted to an expression of the form $\rho(T) = \rho_0 + \alpha T(1 - (T/T_0)^2)$, where the second term is the phonon contribution to the resistivity within the s–f interaction model. The magnetoresistance is positive both below and above T_N. However, for $T < T_N$, the MR shows a large temperature dependence. The behaviour is shown to be due to a combination of orbital motion of the electrons and an intrinsic term characteristic of the antiferromagnetic state of the compound.

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