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SPECIFIC HEAT AND ELECTRICAL RESISTIVITY OF $CeCu_6$ BELOW 1 K

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Results of measurements of the electrical resistivity ρ between 0.04 and 1 K and the specific heat c_p between 0.06 and 1 K of annealed polycrystalline $CeCu_6$ are reported. ρ varies proportional to T^2 below 0.1 K but is linear in T above 0.6 K. The specific heat is proportional to T below 0.5 K and the electronic specific-heat parameter $\gamma = 1.53$ J/mole K^2.

Recent work reported by two different groups[1 2] has shown that $CeCu_6$ has many of the properties believed to be characteristic of materials which are now often denoted as dense Kondo- or heavy-electron systems. The reported properties of this compound are remarkably similar to those of $CeAl_3$. Among them we mention the electrical resistivity which in both cases increases with decreasing temperature below room temperature, reaches a maximum below 50 K and then decreases at still lower temperatures down to 1 K and below[3 5]. In specific-heat experiments, a strong increase of the c_p/T ratio is observed for both substances below 8 K, reaching a value of about 0.85 J/mole K^2 at 1.8 K with a still steep and negative slope at this temperature[2 6]. Since it seemed quite natural to check for more similarities of these two materials at even lower temperatures, in this letter we report on measurements of the electrical resistivity ρ and the specific heat c_p of $CeCu_6$ below 1 K.

For these experiments, polycrystalline $CeCu_6$ was prepared by arc-melting the pure elements together in a water-cooled arc furnace under argon atmosphere. The sample was subsequently annealed for four days at 750°C. This annealing procedure had no apparent effect on the magnitude or temperature dependence of the specific heat above 1 K. It proved, however, to be of paramount importance for the low-temperature behaviour of the electrical resistivity. To illustrate this effect, we show ρ(T) measured on a small piece cut from the annealed sample between 1 and 300 K in Fig. 1. It is characteristically different from previously published ρ(T) curves for polycrystalline material[2] and, at liquid-helium temperatures, also lower resistivity values than those reported from experiments on single crystals are observed[1]. X-ray measurements on both annealed and unannealed material gave essentially the same pattern with line broadening at large angles, probably due in part to cold working on the sample when preparing the X-ray specimen.

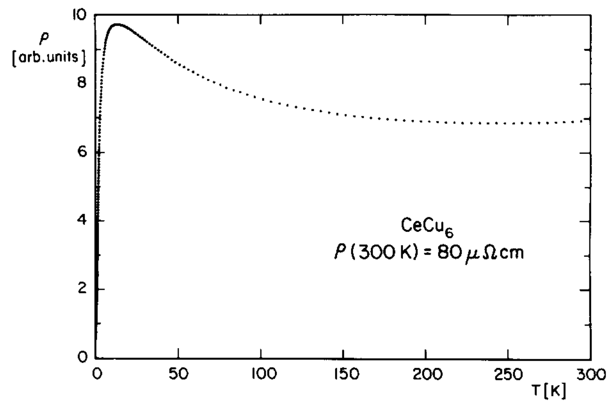

Fig. 1: Temperature dependence of the electrical resistivity of annealed $CeCu_6$ between 1.3 and 300 K.

The results of our resistivity measurements below 1 K are shown in Fig. 2. With decreasing temperature, ρ first decreases linearly with T, amazingly extrapolating to zero resistivity at T = 0 K. Below 0.6 K, however, ρ(T) deviates from this behaviour and approaches a residual resistivity of 7.2 μΩcm at zero temperature. It is not possible to express ρ(T) as a simple power law in temperature below 0.6 K. It is only below 0.1 K that there is any suggestion of a T^2 dependence of the resistivity as it is, of course, expected for quasiparticle scattering in a Fermi liquid for temperatures well below the Fermi temperature T_F and was clearly observed in $CeAl_3$ below 0.3 K[4]. In the mentioned limited temperature range, the coefficient of the T^2 term for our sample of

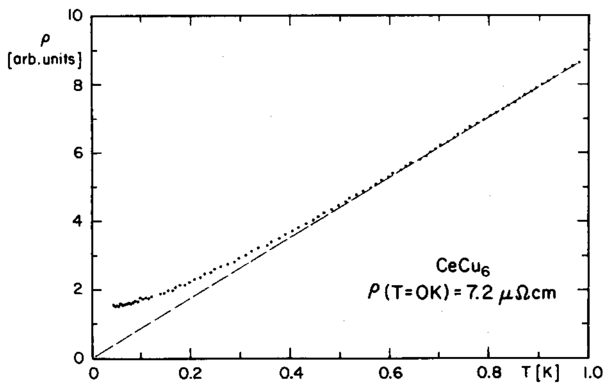

Fig. 2: Temperature dependence of the electrical resistivity of annealed $CeCu_6$ between 0.04 and 1 K.

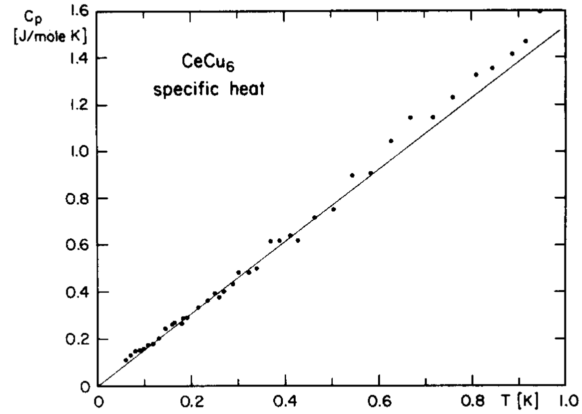

Fig. 3: Temperature dependence of the specific heat of annealed $CeCu_6$ between 0.06 and 1 K.

$CeCu_6$ is 111 $\mu\Omega cm/K^2$, roughly a factor of three larger than that observed in $CeAl_3$ [4]. Apart from a clearly higher residual resistivity in our case as compared to that observed in $CeAl_3$, we only have a weak case for a T^2 law of $\rho(T)$ because the temperature interval for its approximate validity is obviously too narrow to come to a definite conclusion. It is, however, clear that in both cases of $CeCu_6$ and $CeAl_3$ the electrical resistivity is still varying considerably below 1 K, very atypical for ordinary metals and pointing to efficient scattering processes in that temperature range. As shown in Fig. 1, the peak resistivity of $CeCu_6$ at 13 K is about 100 $\mu\Omega$cm, considerably less than that of $CeAl_3$ at its peak temperature of 35 K [5]. Interestingly, this reduction of the peak temperature for $CeCu_6$ as compared to that of $CeAl_3$ is approximately the same as that observed for the respective temperature intervals where a T^2 dependence of the electrical resistivity is established. The same factor of three is recognized in the ratio of the T^2 coefficients for ρ, the scaling between the two compounds being inversed in this case, however.

The specific-heat data obtained for temperatures less than 1 K are shown in Fig. 3. It may readily be seen that the large electronic specific-heat parameter γ suggested by earlier measurements at temperatures above 1.5 K [2] is indeed borne out. The limiting value as T approaches 0 K is 1.53 J/mole K^2, very close to that reported previously for $CeAl_3$ [4]. It is also clear from Fig. 3 that the c_p/T ratio is temperature dependent above 0.5 K, as it increases above the mentioned value for $T \rightarrow 0$ K and, when taking into account the data published in ref. 2, must pass through a maximum in the vicinity of 1 K. A temperature dependence of this kind for c_p/T has recently been reported for $CeAl_3$ with a peak of c_p/T near 0.5 K [7]. The existence of this peak, which had already been observed in earlier work[8] has been interpreted in ref. 7 as evidence for a coherence effect in the electronic energy spectrum of a dense Kondo system. From our data this evidence is much less well developed in $CeCu_6$. Moreover, the scaling behaviour that may be recognized when comparing the electrical resistivities of $CeCu_6$ and $CeAl_3$ does not seem to be reflected in the low-temperature specific heats of the two compounds.

Taking all the presented data together, $CeCu_6$ seems to fit comfortably into the framework provided by current thinking of dense Kondo- or heavy-electron Ce-based systems[9]. The lack of any phase transition, magnetic or superconducting, is another analogy with $CeAl_3$. However, the limiting Fermi-liquid behaviour appears to occur at lower temperatures for $CeCu_6$, at least as it is indicated by $\rho(T)$. It might be of interest to investigate, how much of the qualitative differences in the properties of $CeCu_6$ and $CeAl_3$ may be ascribed to crystal-electric-field effects. In both compounds, the 4f electron $J = 5/2$ Hund's rule ground state of the Ce^{3+} ions is split into three doublets because of the symmetries of the respective crystal-lattice structures, hexagonal in the case of $CeAl_3$ [10] and orthorhombic for $CeCu_6$ [11]. Differences in the separation of these energy levels might, in part, account for the differences observed in the $\rho(T)$ data. Since the published specific-heat results[2] and the apparent dependence of $\rho(T)$ upon annealing in $CeCu_6$ rather contradict than support this conjecture, inelastic neutron-scattering experiments are clearly called for and the availability of single crystals[1] will certainly greatly facilitate such measurements in comparison with $CeAl_3$ [12], where still only polycrystalline material is available. The same holds for other important experiments such as investigations of possible anisotropies in the physical properties which may now be peformed on $CeCu_6$, a system so much alike the prototype metallic compound $CeAl_3$, showing Fermi-liquid behaviour of its electronic subsystem at very low temperatures.

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