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Magnetization experiments down to 100 mK on single crystalline heavy-fermion $Ce_{0.95}La_{0.05}Ru_2Si_2$

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The heavy-fermion system $Ce_{0.95}La_{0.05}Ru_2Si_2$ undergoes a metamagnetic transition at $B^* \approx 5.3$ T. We have performed extensive low-temperature ($0.1\ K \leq T \leq 1.5$ K) magnetization measurements using a SQUID magnetometer. We observe that for fields above and below B^* ($B < 8T$) the magnetization is proportional to T^2. The results are compared with low-temperature ($0.3\ K \leq T \leq 2.0$ K) thermal-expansion experiments in magnetic fields up to 8 T, performed on the same single crystal. A simple scaling ansatz with one unique parameter describes the magnetic field behaviour on both sides of B^*.

The intermetallic compound $CeRu_2Si_2$ is widely studied because of its heavy-fermion properties (see for instance ref. [1] and references therein). Partial substitution of Ce for La in this compound induces a long-range antiferromagnetic order for La concentrations above 8% [2]. In this paper we focus on the compound $Ce_{0.95}La_{0.05}Ru_2Si_2$, that is on the verge of magnetic order. It can be characterized by a large coefficient of the linear temperature term in the electronic specific heat: $\gamma \approx 500$ mJ/molK^2 [3] (vs. $\gamma = 350$ mJ/molK^2 for pure $CeRu_2Si_2$). The zero-field ground state is expected to be non-magnetic. $Ce_{0.95}La_{0.05}Ru_2Si_2$ shows a metamagnetic transition at $B^* \approx 5.3$ T (vs. $B^* = 8$ T for pure $CeRu_2Si_2$), in the liquid helium temperature range, for a field applied along the tetragonal c axis.

To elucidate the origin of the anomalous low-temperatures properties, we have performed magnetization and thermal-expansion experiments in the vicinity of B^*. We will check the validity of the one parameter scaling ansatz (SA) [4,5] at low temperatures, where the magnetization and thermal expansion are simple functions of T.

The single-crystalline sample of $Ce_{0.95}La_{0.05}Ru_2Si_2$ was prepared by a tri-arc Czochralski technique and machined into an appropriate shape by means of spark erosion. The magnetization measurements were made using a high-field low-temperature SQUID magnetometer developed at the CRTBT. At the core of the system is a miniature dilution refrigerator [6]. A long copper tress holding the sample is attached to the cold finger of the mixing chamber. The sample is positioned in a highly uniform field of an 8 T magnet and can be displaced relative to the detection coils in order to obtain absolute values of M [7]. The coefficient of linear thermal expansion, $\alpha = (1/L)dL/dT$, has been measured using a sensitive three-terminal capacitance method, with a detection limit for length changes of ≈ 0.1 Å. The capacitance cell [8] has been machined of oxygen-free high conductivity copper, and was attached to the cold plate of a ^3He cryostat. Data points were taken through a slow-cooling run down to the lowest temperature of 0.3 K. Thermal expansion data ($T > 1.5$ K) in zero field, performed on the same sample, have been published in ref. [9].

Magnetization experiments on $Ce_{0.95}La_{0.05}Ru_2Si_2$ have been reported until now only for temperatures above 1.5 K [2]. In fig. 1 we show the temperature dependence of the magnetization at constant fields ($B \| c$) at very low temperatures, plotted vs. T^2. For all fields measured a T^2 law is obeyed in the low-temperature limit: $M = \beta T^2$. A change of sign of β occurs at B^*, which correlates with the occurrence of a maximum

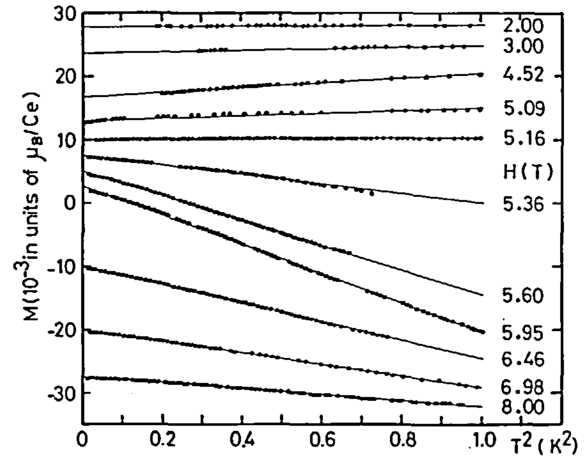

Fig. 1. The change in the magnetization ($B \| c$) of $Ce_{0.95}La_{0.05}Ru_2Si_2$ versus T^2 for magnetic fields as indicated. For clarity the curves have been offset vertically and arranged in descending order by field. (For the absolute valve of M see ref. [2].)

in $\gamma(B)$ (the linear term of the electronic specific heat) at B^* [3]. $\gamma(B)$ drops rapidly with B above B^*, i.e. when the magnetic response is purely local and the magnetic correlations have vanished.

In our previous experiments [9] we have observed that the linear coefficients of thermal expansion, $\alpha_{\|}$ and $\alpha_{\perp}$ ($\|$ and $\perp$ to the c-axis), of $Ce_{0.95}La_{0.05}Ru_2Si_2$ are almost proportional at low temperatures: $\alpha_{\|} \approx 2.5\alpha_{\perp}$. In the present experiment we have measured only the dilatation along the c-axis for $B \| c$. Using the aforementioned proportionality, the volume effect has been calculated from $\alpha_v = \alpha_{\|} + 2\alpha_{\perp}$. This is shown in Fig. 2 in a plot of α_v vs. T. A linear temperature behaviour is achieved only below 500 mK for $B \approx B^*$. The change of sign in α_v in the vicinity of B^* correlates again to the presence of a maximum in $\gamma(B)$ [3] and the huge pressure variation of B^* [10].

It has been claimed that the field dependence of the thermal expansion, susceptibility and specific heat can be interrelated self-consistently assuming an entropy governed by a single pressure dependent energy scale (i.e. as a function of $T/T^*(P)$ and $B/B^*(P)$) [4,5]. For example, in the low temperature limit, the linear temperature term of the volume expansion $a(B) = \alpha_v(B)/T$, is connected with the field dependence of $\gamma(B)$ by the relation [5]:

$$a(B) = \frac{\Omega}{V_0}\left(\gamma_M + B\frac{\partial\gamma_M}{\partial B}\right), \tag{1}$$

where V_0 is the molar volume and $\Omega \approx 220$ Mbar^{-1} is the effective Grüneisen parameter [9,11]. γ_M is the linear specific heat coefficient obtained from the standard Maxwell relation, $\partial\gamma_M/\partial B = 2(\partial M/\partial T^2)$, where in the low temperature limit, at constant field, M obeys at T^2 law. Using the field dependence of β (fig. 1, where we have evaluated β in the temperature interval 100–400 mK) $a(B)$ is calculated from eq. (1) and compared with the experimental values deduced from fig. 2 (see fig. 3). Excellent agreement is found up to B^*, the coincidence being less above B^*.

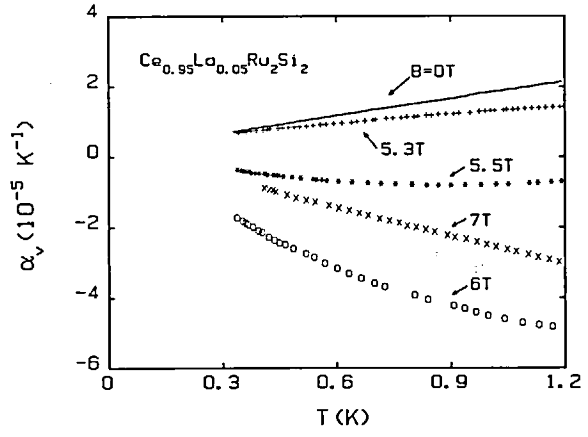

Fig. 2. Coefficient of volume expansion (α_v) of $Ce_{0.95}La_{0.05}Ru_2Si_2$ for magnetic fields ($B \| c$) as indicated.

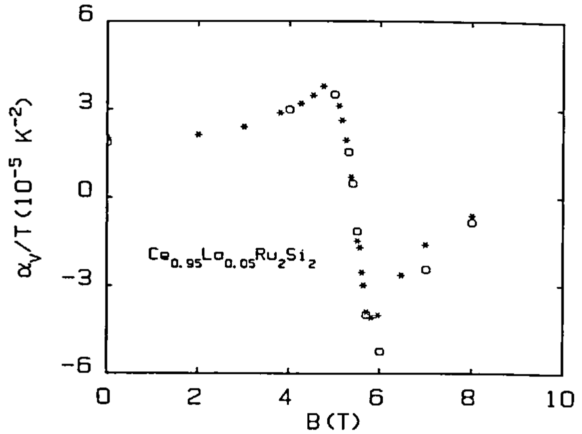

Fig. 3. Field dependence of the term linear in temperature of the volume expansion $a = \alpha_v/T$ for $B \| c$, for $Ce_{0.95}La_{0.05}Ru_2Si_2$, (o) as measured, (*) as calculated using eq. (1).

In summary, a comparison of thermal-expansion and magnetization data for $Ce_{0.95}La_{0.05}Ru_2Si_2$ gives further support for the existence of a single energy parameter for this heavy fermion system. Low-temperature experiments are in progress to verify in more detail the scaling ansatz in pure $CeRu_2Si_2$.

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