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Magnetovolume study of the metamagnetic transition of $CeRu_2Si_2$ below 1 K

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We report magnetostriction and thermal-expansion measurements on a single-crystalline sample of the heavy-fermion compound $CeRu_2Si_2$ in the temperature interval $0.1 < T < 1.3$ K and in fields along the tetragonal axis up to 12 T, in order to study the metamagnetic-like transition. The width of the field-induced transition (at ~7.7 T) as observed by magnetostriction narrows on cooling and seems to remain finite at $T = 0$ K indicating that the transition remains continuous for the present sample.

1. Introduction

The compound $CeRu_2Si_2$ is one of the most intriguing among the rare-earth ternaries with the tetragonal $ThCr_2Si_2$ structure. Because of its large coefficient of the term linear in temperature of the electronic specific heat ($\gamma \sim 350$ mJ/mol K^2 [1]), $CeRu_2Si_2$ is classified as a heavy-fermion system. The low-temperature Fermi-liquid behaviour with a large renormalization factor for the effective mass of the quasiparticles arises from a pronounced interplay of on-site Kondo-like fluctuations and antiferromagnetic intersite correlations, as evidenced by neutron-scattering experiments [2]. The onset of the magnetic interactions below ~70 K is accompanied by a large reduction of the volume ($(\Delta V/V) = -0.5 \times 10^{-3}$ between 70 and 0 K) as was shown, recently, by thermal-expansion measurements [3]. The coefficient of volume thermal expansion (α_V) attains a large maximum value at 9 K, close to the temperature at which also the electronic specific heat and the susceptibility pass through a maximum. The strong coupling of the heavy-fermions to the lattice is futhermore reflected in the extraordinary large electronic Grüneisen parameter $\Gamma_e \sim 160$ in the limit $T \to 0$ K [3, 4].

Much attention has been focused on $CeRu_2Si_2$ because of the field-induced metamagnetic-like transition, that occurs at $B^* \sim 8$ T in the liquid-helium temperature range for a field along the tetragonal axis [5]. Neutron-scattering experiments in field [2] have shown that the sudden increase of the magnetization at B^* coincides with a collapse of the intersite correlations. The metamagnetic-like transition is furthermore accompanied by a large volume increase ($\Delta V/V \sim 10^{-3}$) as evidenced by magnetostriction [3] and thermal expansion measurements in field [6]. More precise: the large positive anomaly in α_V at 9 K shifts towards lower temperatures with increasing field ($B < B^*$), where it becomes very sharp and then suddenly changes sign at B^*. For fields $B > B^*$, α_V is negative and has a minimum, the position of which increases in temperature with field. Using a simple scaling law, the enhancement of the effective mass at the metamagnetic-like transition could be calculated from the linear temperature coefficient of $\alpha_V(B) = a(B)T$ (see, e.g., ref. [6]): $m_{eff}(B^*)/m_{eff}(B = 0) = 1.27$.

However, since our previous measurements were performed only for $T > 1.3$ K, the true Fermi-liquid behaviour was not probed reliably yet. In the present paper we investigate the

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volume effect at the metamagnetic-like transition below $T = 1.3\ K$, by means of magnetostriction measurements and thermal expansion measurements in field ($0.1 < T < 1.2$ K, $B < 12$ T).

2. Experimental details

A single-crystalline batch of $CeRu_2Si_2$ was grown in a tri-arc furnace by the Czochralski technique. The as-grown sample was shaped by means of spark erosion into the proper shape, i.e., a parallelepiped with edges ~3 mm. The coefficient of linear magnetostriction $\lambda' = L^{-1}(dL/dB)$, and the coefficient of linear thermal expansion, $\alpha = L^{-1}(dL/dT)$ were measured using a sensitive three-terminal capacitance method. The sample was placed in a parallel-plate capacitance cell, made of oxygen-free high-conductivity copper. Measurements were performed in a dilution refrigerator equipped with a 12 T superconducting coil. The cell was thermally anchored to the copper tail of the mixing chamber. A zero-field region is available at the level of the mixing chamber, allowing for accurate thermometry. More details can be found elsewhere [7].

3. Results

The coefficient of linear magnetostriction for a field and elongation direction along the tetragonal (c) axis, $\lambda'_{\parallel}$ has been measured at 0.12, 0.34, 0.60, 0.80 and 1.30 K. Assuming $\lambda'_{\parallel} \sim 3\lambda'_{\perp}$, as followed from our earlier experiments at 1.3 and 4.2 K [3], we have calculated the coefficient of volume magnetostriction from $\lambda'_V = \lambda'_{\parallel} + 2\lambda'_{\perp} \simeq \frac{5}{3}\lambda'_{\parallel}$, where the subscripts $\parallel$ and $\perp$ refer to elongations along and perpendicular to the tetragonal axis (the field is oriented along this axis). The integrated values of λ'_V, i.e., the magnetostriction λ_V, is shown for various temperatures in fig. 1. As follows from fig. 1, the width of the transition narrows with decreasing temperature, but the total volume change remains constant ($\Delta V/V = 1.8 \times 10^{-3}$ at 12 T). It also appears that B^* has still a weak temperature variation below

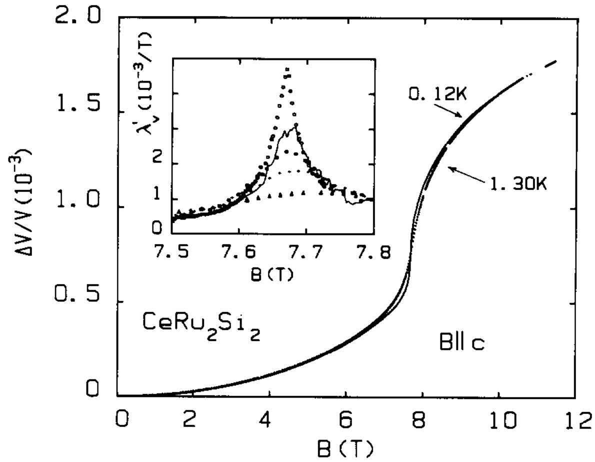

Fig. 1. Volume magnetostriction, λ_V, for $CeRu_2Si_2$ for $B \parallel c$ at temperatures as indicated. The inset shows λ'_V at different temperatures: (▲) 1.3 K, (+) 0.8 K, (●) 0.6 K, (—) 0.34 K, and (O) 0.120 K.

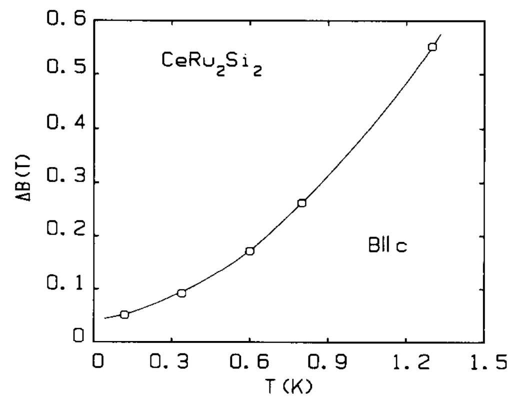

Fig. 2. The width of the metamagnetic transition ($B \parallel c$) for $CeRu_2Si_2$, taken at the half maximum in λ'_V at B^*.

1.3 K, follows from the inset in fig. 1. The temperature variation of the width of the metamagnetic transition ΔB, determined from the inset in fig. 1, is shown in fig. 2. Extrapolating the data in figs. 1 and 2, it follows that $B^* \simeq 7.66$ T and $\Delta B \simeq 0.04$ T at 0 K. Thus the width of the transition remains finite at $T = 0$ K, implying that the transition stays continuous for this sample.

The coefficient of linear thermal expansion for a field and dilatation direction along the c axis, $\alpha_{\parallel}$, has been measured for $B = 7.500$, 7.614,

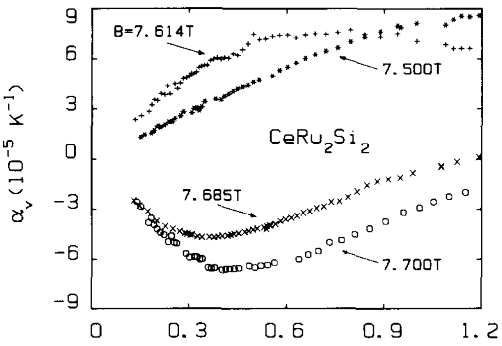

Fig. 3. α_V in the vicinity of B^* for $CeRu_2Si_2$ for magnetic fields ($B \| c$) as indicated.

7.685 and 7.700 T in the temperature interval $0.12 < T < 1.3$ K. Assuming $\alpha_\| = 3\alpha_\perp$, as followed from our previous experiments above 1.3 K [8], we have calculated the coefficient of volume expansion, α_V, from $\alpha_V = \alpha_\| + 2\alpha_\perp \simeq \frac{5}{3}\alpha_\|$, where the subscripts $\|$ and $\perp$ refer the dilatations along and perpendicular to the field ($B \| c$). The results are shown in fig. 3. Note the large change in α_V when the field is increased from 7.614 T to just 7.685 T. From the concurrent rapid variation of $a_B(=\alpha_V/T)$ with field, a specific-heat enhancement of 62% at B^* is calculated using the scaling Ansatz as described in ref. [6]. The temperature T_m where the extremum in α_V occurs attains a sharp minimum at B^*; however, the exact shape of $T_m(B)$ near B^* cannot be determined from the present data (the lowest value obtained for T_m equals 340 mK at $B = 7.685$ T).

4. Discussion

An important result from the present experiments is the strong reduction, in the vicinity of B^*, of the temperature interval where α_V is linear in T. Thus the temperature range where the characteristic Fermi-liquid behaviour is observed is strongly reduced near the metamagnetic-like transition. Correspondingly, the temperature of the extremum in the volume thermal expansion (T_m) passes through a sharp minimum. The fact that even the present low-temperature measurements do not allow for an accurate determination of $T_m(B)$ in the vicinty of B^* is largely caused by the weak temperature dependence of B^* itself. The prime question whether T_m drops to 0 at B^* remains, therefore, unsettled, given the data in fig. 3. However, this question is closely related to the order of the transition. Since the transition seems to remain continuous at $T = 0$ K (fig. 2), it is likely that T_m remains finite at B^*. Of next importance is then to search for mechanisms that explain why the transition remains continuous. A first possibility is a certain sample imperfection as ρ_0 equals 1.7 μΩ cm (at $B = 0$ T) and rises up to 2.8 μΩ cm at B^* [5]. However, a systematic study of the narrowness of the transition in various samples with different ρ_0 values has not been performed yet. A considerable broadening of the transition occurs when $CeRu_2Si_2$ is doped with 5% La ($B^* \sim 5.3$ T) [8, 9]. This lends support to the idea that the inhomogeneities of the sample play a role. From a physical point of view, a more appealing second possibility is that quantum fluctuations prevent a first order phase transition at $T = 0$ K. However, given the present experimental information this cannot be evidenced. Microscopic inelastic neutron-scattering experiments at very low temperatures would be very helpful to investigate this hypothesis. Finally, we mention that the data have not been corrected for demagnetizing effects (~20%). Further detailed studies should take such a correction into account.

As mentioned above, $\gamma(B)$ can be calculated from the data in fig. 3 using the scaling Ansatz (see ref. [6]). An enhancement of 62% is found at B^*, which is considerably larger than our previous estimate [6], as the lowest temperature was only 1.3 K. A similar value for $\gamma(B^*)$ has recently been determined for the T^2 term in the magnetization using Maxwell relations [10]. It appears that $\gamma(B^*)$ extrapolates to a critical value, $\gamma_c(B^*) = 650$ mJ/mol K^2, that is close to the value for which long-range antiferromagnetism occurs on La doping, indicating a close relation between the electronic and magnetic instability [7].

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References

[1] M.J. Besnus, J.P. Kappler, P. Lehmann and A. Meyer, Solid State Commun. 55 (1985) 779.
[2] J. Rossat-Mignod, L.P. Regnault, J.L. Jaccoud, C. Vettier, P. Lejay, J. Flouquet, E. Walker, D. Jaccard and A. Amato, J. Magn. & Magn. Mater. 76–77 (1988) 376.
[3] A. Lacerda, A. de Visser, P. Haen, P. Lejay and J. Flouquet, Phys. Rev. B 40 (1989) 8759.
[4] J.M. Mignot, J. Flouquet, P. Haen, F. Lapierre, L. Puech and J. Voiron, J. Magn. & Magn. Mater. 76–77 (1988) 97.
[5] P. Haen, J. Flouquet, F. Lapierre, P. Lejay and G. Remenyi, J. Low Temp. Phys. 67 (1987) 391.
[6] A. Lacerda, A. de Visser, L. Puech, P. Lejay, P. Haen, J. Flouquet, J. Voiron and F.J. Ohkawa, Phys. Rev. B 40 (1989) 11429.
[7] C. Paulsen, A. Lacerda, L. Puech, P. Haen, P. Lejay, J.L. Tholence, J. Flouquet and A. de Visser, J. Low Temp. Phys. 81 (1990) 299.
[8] A. Lacerda, A. de Viser, L. Puech, P. Lejay, P. Haen and J. Flouquet, J. Appl. Phys. 67 (1990) 5212.
[9] C. Paulsen, A. Lacerda, A. de Visser, K. Bakker, L. Puech and J.L. Tholence, in: The Proc. of the Yamada Conf. XXV on Magnetic Phase Transition (Osaka, April 13–16, 1990) J. Magn. & Magn. Mater., in print.
[10] C. Paulsen, A. Lacerda, J.L. Tholence and J. Flouquet, in: The proceedings of the XIX Conf. on Low Temperature Physics (Brighton, August 16–22, 1990) Physica B 165–166 (1990) 433.