Magnetic and superconducting properties under high pressure in URu_2Si_2

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Abstract

URu_2Si_2 exhibits successive phase transitions at T_c(superconducting)$\sim$1.5 K and at T_0(hidden)$\sim$17 K at ambient pressure. We have made thermal expansion measurements under pressure for a well-characterized single crystalline sample of URu_2Si_2. We have observed that an additional anomaly appears between T_c and T_0 only under high pressures. From the pressure dependence of these temperatures, we have constructed a P-T phase diagram.

Key words: URu_2Si_2 ; superconductibity ; hidden order ; high pressure ; thermal expansion

URu_2Si_2 is a heavy fermion superconductor with a superconducting transition temperature T_c $\sim$1.5 K [1]. In addition to this transition, a sharp λ-like anomaly appears in the specific heat at T_0 $\sim$17.5 K. At the same temperature, there appears a clear inflection point in the magnetic susceptibility as a function of temperature, but it remains unclear what the principal order parameter is. On the other hand, neutron scattering experiments revealed a tiny ordered moment of only μ_0 $\sim$0.03 μ_B [2]. Recently, Amitsuka *et al.* reported elastic neutron scattering measurements under pressures of up to P= 28 kbar [3]. They found that the staggered moment μ_0 is stongly enhanced under pressure. Matsuda *et al.* performed NMR measurements under high pressures, and observed that signals corresponding to the paramagnetic and antiferromagnetic phases coexist below T_0 [4]. From the P-dependence of the signals, they suggested that the volume fraction of the antiferromagnetic region, coexisting in the real space with the paramagnetic region, increases with pressure. From these observations, we think that it is helpful to carry out thermal expansion measurements under high pressures for a deeper understanding of the nature of these phases.

Starting materials used for the present single-crystal growth was natural uranium metal, 4N pure ruthenium and 5N pure silicon. We prepared a single crystal by the Czochralski pulling method using a tetra-arc furnace in a pure argon atmosphere. The obtained single crystal was cut into several pieces, and they are referred to as #1 and #2 in this paper. Then they were annealed at 950 and 980 for a week in an evacuated quartz tube, respectively, and then cooled down slowly. We confirmed that these samples exhibit the superconducting transition at 1.2 K and 1.3 K, respectively. The pressure was generated by means of a copper-beryllium clamp-type cylinder. We used a piston made of tungsten-carbide. Pressure transmitting medium was a 1:1 mixture of Fluorinert FC70 and FC77. We measured the superconducting transition temperature of indium and lead by the ac magnetic susceptibility to determine a pressure at low temperature. Thermal expansion was measured using strain gage technique with a copper as a dummy.

Figure 1(a) shows the temperature dependence of the thermal expansion $dl/l(T)$ along the a-axis direction under external pressures for sample #1. At ambient pressure, the slope of $dl/l(T)$ changes at $T_0 \simeq 17.0$ K, which is consistent with the results in the literature

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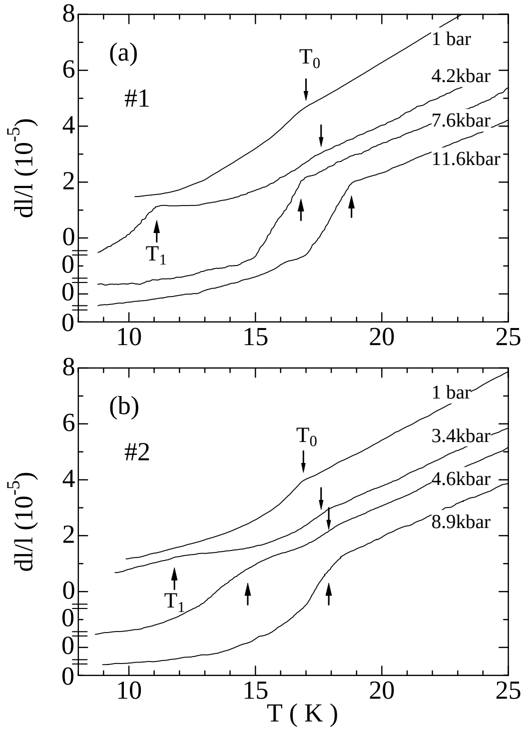

Fig. 1. (a)Temperature dependence of thermal expansion parallel to the *a*-axis under external pressures for sample #1. (b)Temperature dependence of thermal expansion parallel to the *a*-axis under external pressures for sample #2.

[6,7]. When P increases to 4.2 kbar, the anomaly shifts slightly to the higher temperature side and becomes smaller in magnitude. We note that a new anomaly appears at $T_1 \simeq 11.1$ K. With increasing pressure to 7.6 kbar, the anomaly at T_0 becomes unclear, while the anomaly at T_1 remains evident. At P=11.6 kbar, there exists only one anomaly around 19 K, probably corresponding to the anomaly at T_1. This pressure dependence of T_0 and T_1 is plotted in Fig. 2.

In Fig. 1(b), we plot the temperature dependence of $dl/l(T)$ along the a-axis direction for sample #2. At P= 3.4 kbar, we observe a broad hump at $T_1 \sim 11.8$ K and a kink at $T_0 \simeq 17.6$ K. With increasing pressure to 4.6 kbar, the lower temperature anomaly shifts to $T_1 \sim$ 14.7 K and the higher temperature one to $T_0 \simeq 17.9$ K. Then at P= 8.9 kbar, we observe only one anomaly at 17.9 K, which probably corresponds to the anomaly at T_1. We summarize in Fig. 2 these P-dependence of T_0 and T_1.

When we compare the anomaly at T_1 of the two samples, its magnitude seems to depend on a sample; the anomaly for sample #2 with higher T_c seems to be less evident. We also note that the anomaly at T_1 becomes evident with increasing pressure, in contrast to that at T_0.

Fisher *et al.* performed specific heat measurements

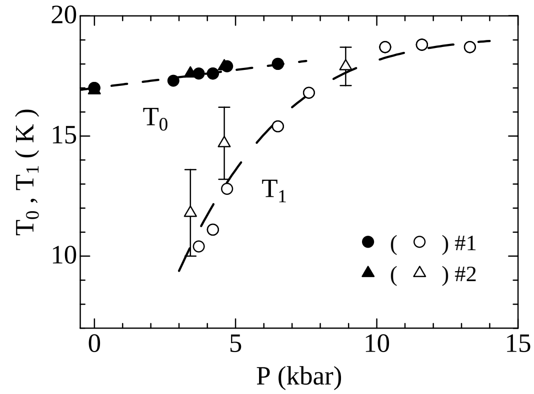

Fig. 2. Pressue dependence of the characteristic temperatures T_0 and T_1 for sample #1 and #2.

under pressures of up to 5.8 kbar [5]. They argued that the anomaly at T_0 broadens and diminishes in amplitude with increasing pressure. In their plot of the heat capacity from 12 to 20 K, only one anomaly is visible. Considering the "phase boundary" at T_1 given in Fig. 2, however, we expect that an additional anomaly would appear in the heat capacity at $T \sim$14 K. The origin of this discrepancy is not clear at present, although it may be ascribed to the sample dependence. On the other hand, Kagayama *et al.* made thermal expansion measurements at ambient pressure and 10 kbar [6]. They detected an anomaly at $\sim$16 K and $\sim$19 K for P= 0 and 10 kbar, respectively. The magnitude of the jump of the thermal expansion coefficient at 10 kbar is larger than that at ambient pressure. Considering again the P-T diagram given in Fig. 2, the anomaly observed at 10 kbar probably corresponds to that at T_1 observed in this study. In other words, it seems that they observed switching of the transition from T_0 to T_1. In this respect, there may be no discrepancy between our results and those reported by Kagayama *et al.*

In order to reveal the nature of the "transition" at T_1 as well as T_0, the magnetic susceptibility experiment can be a good probe. Such measurements under pressure is in progress.

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