High field study of the magnetic phase transition of URu$_2$Si$_2$

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Abstract

We investigate the phase transition of URu$_2$Si$_2$ at $T_0 = 17.5$ K by thermal expansion and heat capacity in magnetic fields, $H$, up to 25 T. At $T_0$ an energy gap of $\Delta \approx 115$ K opens, which decreases to 65 K in 25 T. The $H$ dependence of $T_0$ scales with $\Delta$, whereas a different $H$ dependence and energy scale was observed for the ordered dipole moment. The anomalous $H$ dependence of the thermal expansion coefficients may discriminate between the various scenarios for the primary order parameter of URu$_2$Si$_2$.

Keywords: URu$_2$Si$_2$; Antiferromagnetism; High magnetic field
The experiments have been performed on annealed single crystalline URu$_2$Si$_2$. Thermal expansion up to 25 T was measured with a capacitive method, using RuO$_2$ and capacitance thermometry. The heat capacity was recorded up to 16 T using a pulse method. The magnetic field was only applied along the easy c axis. Fig. 1 displays $\alpha$ parallel to the a and c axes, recorded at fields of 0, 10, 14, 18 and 25 T. The $H = 0$ data are in good agreement with literature [10]. Cooling through $T_0$, the a axis contracts, while the c axis length increases. Interestingly, and unexpectedly for a regular magnetic ordering, the anomaly grows and remains very sharp upon increasing $H$. Below $T_0$, the data can be well described by an (dominating) exponential $T$ dependence, in addition to the linear and cubic terms for the electronic and phonon contributions:

$$\alpha = \alpha_0 + AT + BT^3 + C \exp(-\Delta/T).$$  \hfill (1)

In Fig. 2 the gap as derived from the volume expansion, $\alpha_v = \frac{1}{2}(2\alpha_a + \alpha_c)$, is shown versus $H$. The magnitude of $\Delta H=0$ is the same as obtained from infrared reflectance, vacuum tunneling, nonlinear susceptibility, heat capacity and neutron scattering. $\Delta$ decreases quadratically with $H$, with a critical field $\mu_0H_0 = 37 \pm 2$ T, consistent with Ref. [7].

The $T_0(H)$ phase boundary found in Ref. [7] has been verified by a collection of magnetostriction curves [9]. From the ratio of the jumps at $T_0$ of thermal expansion and specific heat, $c$ (not shown), the initial uniaxial pressure dependence can be calculated through the Ehrenfest relation:

$$\left(\frac{\partial T_0}{\partial P_{a,c}}\right)_{B,B'} = \frac{V_m \partial \alpha_{a,c}}{\Delta(c/T)}. \hfill (2)$$

The $c/T$ jumps at $T_0$ vary slowly from 0.30 J/mole-K$^2$ at $H = 0$ to 0.33 J/mole-K$^2$ at 16 T [9]. By using $V_m = 4.95 \times 10^{-5}$ m$^3$/mole, and assuming that $\Delta(c/T)$ at 18 T and 25 T does not change significantly from the 16 T value, we can derive the pressure derivatives as shown in Fig. 3. The pressure dependences are almost $H$-independent up to about 15 T, but increase strongly at high fields. Note that the anisotropy, reflected in the directly measured $c/a$ ratio (not shown), changes in a similar way [9], which is a further indication that the above assumption on $c/T$ is reasonable. The question arises whether this anomalous high-field behavior is due to the diminishing gap, allowing for cross-gap excitations, or perhaps related to the vanishing ordered moment. The observed decrease of $\gamma = c/T$ at 2 K upon increasing $H$ [9] makes the first possibility unlikely.

We have presented the first thermal expansion experiments on URu$_2$Si$_2$ in magnetic fields up to
25 T. While confirming the equivalent field dependence of $T_0$ and $\Delta$ found in resistivity, the gap derived from $\alpha_T$ equals that found in tunneling and neutron scattering, and decreases by 45% at 25 T. The $c/a$ ratio and, possibly also the uniaxial pressure dependence of $T_0$, have qualitatively different behaviors in low fields ($\mu_0 H < 15$ T) and high fields ($\mu_0 H > 15$ T). Such behavior would be consistent with the presence of an extra energy scale of about 15 T, proposed to relate to the disappearance of the staggered moment. More experiments in this field range are necessary to substantiate such speculations and could eventually enable us to identify the primary order parameter of URu$_2$Si$_2$.

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References

[9] A full account of this work will be published elsewhere.