Anisotropy of magnetic susceptibility of URu$_2$Si$_2$ under pressure

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Abstract. We have carried out measurements of magnetic susceptibility on a single crystal of the heavy fermion compound URu$_2$Si$_2$ under pressure up to 0.7 GPa. The external magnetic fields were applied parallel to $a$- and $c$-axes. Hidden order transition at $T_0$ and first-order phase transition between hidden ordered phase and large-staggered-moment antiferromagnetic phase at $T_M$ are observable in both measurements. Temperature dependence of magnetic susceptibility of $a$- and $c$-axes exhibits a kink and a drop at $T_0$ and $T_M$, respectively. However, the magnitude of the variation on $a$-axis at $T_0$ and $T_M$ were about one tenth of those on $c$-axis, respectively. We conclude that the HO phase has a similar anisotropy to that of AFM phase.

1. Introduction
URu$_2$Si$_2$ is a heavy fermion superconductor with a superconducting transition temperature $T_c$ $\sim$ 1.5 K under ambient pressure[1]. Furthermore the compound undergoes a successive phase transition(a hidden order transition) at $T_0$ $\sim$ 17.5 K. Since the discovery of a development of the antiferromagnetic(AFM) staggered moment with increasing pressure[2], many investigations under pressure have been carried out so far. Nuclear magnetic resonance(NMR) experiments suggested that the sample consisted of the AFM and hidden order(HO) regions below $T_0$: the spatially inhomogeneous AFM volume fraction develops by applying pressure[3]. Thermal expansion measurements revealed an existence of the first order transition between HO and AFM phases at $T_M$ and the pressure($P$) dependence of $T_M$[4]. The simultaneous neutron scattering and thermal expansion measurements were carried out in order to detect the successive phase diagram through the eyes of microscopic and macroscopic[5]. Moreover, there are some studies of superconducting phase; the superconductivity exists in only HO phase but not in AFM phase[6], and two distinct superconducting gap structures with different nodal topology are suggested[7]. However, a question for the nature of hidden order parameter still remains. There is a large anisotropy for URu$_2$Si$_2$ on magnetization under ambient pressure. It would be important to reveal the anisotropy of magnetization for understanding the ordered ground states. Detailed measurements of temperature($T$) dependence of magnetic susceptibility for $a$-axis($\chi_a(T)$) under pressure have never been reported, because $\chi_a(T)$ is too small. Here we report about anisotropy of magnetic susceptibility of URu$_2$Si$_2$ under pressure.
2. Experiments

We first synthesized a polycrystalline material by melting a stoichiometric amount of constituent elements, each of which has the purity of 99.9 %, 99.99 %, and 99.9999 % for natural U, Ru, and Si, respectively. Then we grew a single crystal by the Czochralski pulling method from the polycrystal under high purity argon atmosphere. The obtained single crystal was cut into several small pieces. Typical size of the sample is about $\sim 2\, \text{mm}^3$. Before magnetic measurements, thermal expansion measurements were carried out to choose the sample which showed a distinct anomaly at $T_M$. The anomaly of $T_M$ exhibits a sample quality because of its strong sample dependence. We measured the dc magnetic susceptibility by using commercial SQUID magnetometer (MPMS). The pressure was generated by means of a copper-beryllium clamp-type cylinder with a piston made of zirconia. Pressure transmitting medium was a Dafune7373. We determined the pressure by measuring the superconducting transition temperature of an indium.

3. Results

We performed the measurements of $\chi_a(T)$ and $\chi_c(T)$ in several magnetic fields ($H$) of 1, 2, 5, and 10 kOe applied parallel to the $a$ and $c$-axes. There were little $H$ dependence on the whole our measurements of $\chi_a(T)$ and $\chi_c(T)$, we present the results of $H = 1\, \text{kOe}$ in figure 1 and 2. First, we focus on the results of the $\chi_c(T)$. Our results of $\chi_c(T)$ under pressure agree to the previous work, which reported the $T$ dependence of the $T$ derivative of the dc magnetization, $dM/dT(T)$[6]. We observed the anomalies of phase transition at $T_0$ and $T_M$, respectively. $\chi_c(T)$ of 0.30 GPa decreases with decreasing $T$ down to $T_0$, then it shows a sharp kink at $T_0$. After rapid decreasing below $T_0$, the decreasing rate becomes slower and exhibits little $T$ dependence.
It slightly shows a paramagnetic behavior at lower temperature (not shown). When $P$ increases to 0.51 GPa, the anomaly of $T_M$ appears. It is a stair-like anomaly with a transition width of $\sim 3$ K. The width becomes sharper at higher pressure as seen in the previous experiments of thermal expansion and electrical resistivity[4, 8]. More noteworthy is a magnitude of the magnetic susceptibility parallel to the $a$-axis cannot be argued. The data of the magnetic susceptibility parallel to the $a$-axis are slightly shifted downward, for clarity. Down-pointing and up-pointing arrows indicate $T_0$ at 0.38 GPa and $T_M$ at 0.65 GPa, respectively.

Next, we discuss about $\chi_a(T)$ shown in Fig. 2. First of all, there is little doubt that magnitude of $\chi_a(T)$ keeps very small with increasing $P$. The variations of $\chi_a(T)$ are also small. These anisotropic behaviors remain at higher pressures. According to the neutron scattering experiments, the staggered moment of ordered state orients to the $c$-axis[2], which is consistent with our results of large anisotropy of magnetic susceptibility in the AFM phase. On the other hand, a kink and a drop anomalies of $\chi_a(T)$ are found to be similar to those of the $\chi_c(T)$, as see in fig. 1(a). The ratio of $\Delta \chi_{a, PM\rightarrow HO}$ to $\Delta \chi_{a, PM\rightarrow AFM}$ almost agrees with that of $\Delta \chi_{c, PM\rightarrow HO}$ to $\Delta \chi_{c, PM\rightarrow AFM}$. If the measured sample has a mis-configuration of $\sim 5$ degrees from the $a$-axis,
these anomalies which was observed on our results of $\chi_a(T)$ below $T_0$ may be explained as a contribution from $\chi_c(T)$. However $\chi_a(T)$ shows no broad peak around 60 K. The broad peak is also characteristic behavior for $\chi_c(T)$. Therefore we consider that $\chi_a(T)$ exhibits quite small anomalies compared to that of $\chi_c(T)$.

4. Discussions

Our present result of the magnitude of the $\chi(T)$ indicate that the HO phase has a similar anisotropy to that of AFM phase. At least in AFM phase, the ordered local moment was observed. However, heavy fermion liquid states is achieved just above $T_0$; specific heat shows the linear dependence as plotted $C/T$ vs. $T^2$[1, 9], nuclear spin-lattice relaxation time$(1/T_1)$ follows the Korringa law[10]. Heavy fermion liquid behavior remains even at high pressure[11], namely, it is achieved just above antiferromagnetic phase transition temperature. We need to account for the experimental results with seemingly unreasonable behaviors. Although the hidden order parameter which is exhibited below second order phase transition at $T_0$ is still open question, we revealed an anisotropy of magnetic susceptibility of both ordered phases with useful hints to solve the hidden order parameter.

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