# AC magnetic susceptibility measurements on $UGe_2$


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**Abstract**

We have measured ac magnetic susceptibility of the ferromagnet $UGe_2$ which shows superconductivity in an external pressure range, $P_1 \leq P \leq P_2$, in the ferromagnetic state. When $P$ is close to $P_1$ ($\sim$ 8 kbar in the present study) in the superconducting phase, the ac magnetic susceptibility indicates an imperfect superconducting shielding effect and shows nearly the perfect shielding effect around $\sim$ 12 kbar, while a superconducting onset temperature seems to be almost independent of the pressure.



*Key words:* $UGe_2$ ; heavy fermion ; superconductivity ; ac magnetic susceptibility


$UGe_2$ is a ferromagnet with the Curie temperature $T_{\rm Curie}$ of about 53 K at ambient pressure. When an external pressure $P$ is applied, $T_{\rm Curie}$ shows monotonic decrease with increasing pressure and seems to vanish at around 16 kbar. Interestingly, superconductivity appears in the pressure range between about 10 and 16 kbar[1]. The superconducting transition temperature $T_{\rm SC}$ exhibits a maximum, $\sim$0.8 K, around 12 kbar. In contrast to rare-earth magnetic superconductors such as $ErRh_4B_4$, on the other hand, it is argued that both of the long-ranged ordered states in $UGe_2$ are carried by 5f electrons of uranium atoms[1,2]. In such a ferromagnetic superconductor, we expect that superconducting electrons detect a non-vanishing internal field. Thus, it is quite surprising that the ferromagnetism with a local moment larger than 1 $\mu_{\rm B}$ per uranium atom coexists with the superconductivity in $UGe_2$.

Very recently, unusual magnetization behavior was observed; $UGe_2$ shows a continuous hysteresis loop at 4.2 K, as is usual. However, below $\sim$1 K, it shows a staircase like curve[3,4], which may be related to the superconductivity of odd parity pairing in this compound[3].

These interesting features of $UGe_2$ raise a question concerning to the nature of the coexistence of ferromagnetism and superconductivity; are both of them homogeneous in the real space? To resolve this question, in our previous paper we measured ac and dc magnetizations at pressures of up to $\sim$13 kbar using a $^3$He cryostat, and suggested that the superconductivity coexists in a competitive way with the ferromagnetism[5]. In the present paper, we have made measurements of the ac magnetic susceptibility using a $^3$He/$^4$He dilution refrigerator as well as the $^3$He cryostat.

A polycrystalline material was first prepared by melting stoichiometric amount of natural uranium and germanium of high purity. Then single crystals were grown by the Czochralski pulling method using a tetra-arc furnace in a pure argon atmosphere. We did not make additional heat treatment. In order to characterize the obtained single crystal we measured the electrical resistivity of the ingot, and observed that a residual resistivity ratio is about 290. The ac magnetic susceptibility was measured in terms of a conventional Hartshorn bridge circuit in a frequency of 100 Hz. A modulation field was applied along the crystallographic $a$-axis, which is the easy axis of magnetization. A peak-to-peak amplitude of the modulation field was $\sim$0.1 Oe. The pressure was generated


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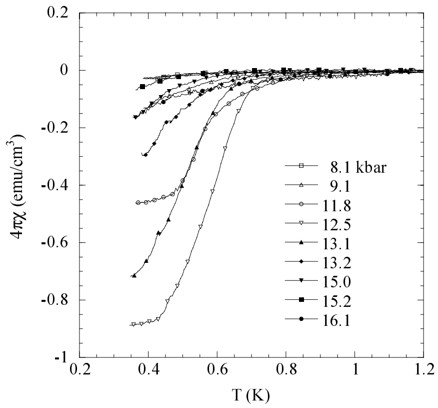


Fig. 1. Temperature dependence of ac magnetic susceptibility around $T_{SC}$ measured by using a $^3$He cryostat.

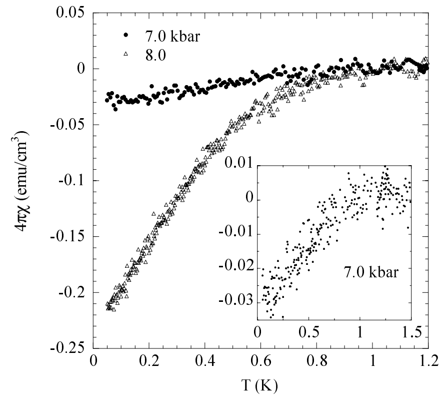


Fig. 2. Temperature dependence of ac magnetic susceptibility around $T_{SC}$ measured by using a $^3$He/$^4$He dilution refrigerator. Inset shows the data taken at 7.0 kbar in an expanded scale.

by means of a copper-beryllium (CuBe) clamp-type cylinder. Pressure transmitting medium was a 1:1 mixture of Fluorinert FC70 and FC77. We measured a superconducting transition temperature of indium and lead to determine a pressure at low temperatures. The accuracy of the estimated pressure was evaluated as about ±0.5 kbar.

Figure 1 shows the temperature dependence of the real part of ac magnetic susceptibility. The measurement was carried out using the $^3$He cryostat. We used a piston (that is a part of the pressure cell) made of a tungsten carbide. Since we did not determine a demagnetizing factor for the sample because of its irregular shape, the absolute value of the magnetic susceptibility is considered to be a rough measure of the shielding effect. As may be seen from the figure, the superconducting diamagnetic susceptibility is clearly observed above 9.1 kbar. At $P = 12.5$ kbar, the absolute value of diamagnetic susceptibility shows a steep increase and saturates at a value of about 0.9. We note that around this pressure the superconducting transition temperature $T_{SC}$ exhibits the maximum.

In the above measurement, the lowest accessible temperature was about 0.35 K, which was not enough to study whether or not the diamagnetic susceptibility saturates at a lower temperature. In order to check it, we measured the ac magnetic susceptibility using the dilution refrigerator with a cupper-beryllium piston. The obtained results are plotted in Fig.2. At $P = 7.0$ kbar, the superconducting diamagnetism is very weak, only a few % of the perfect shielding. At $P = 8.0$ kbar, it is clearly observed: The onset temperature of the superconductivity seems to be nearly the same as that at 12.5 kbar given in Fig.1. However, the magnitude of the diamagnetic susceptibility is small, about $-0.2$ at 50 mK, and the temperature dependence is very gradual. (Here one may notice that this value is rather larger than that at 8.1 kbar in Fig.1. We think that this may be due to a "pressure hysteresis" effect; $T_{SC}$ seems to change every time the sample is pressurized from the zero pressure.) This feature of non saturation behavior even at a very low temperature confirms our previous conclusion that some part of a sample remains to be in normal state when the pressure is close to the lower boundary between the normal and superconducting phases[5].

Let us come back to the data taken at 7.0 kbar. As may be seen from an inset of Fig.2, the superconducting onset temperature is as high as ∼0.8 K again, although the diamagnetism is very small. This may suggest that the superconducting onset temperature is not strongly dependent on pressure, and that only a superconducting volume fraction varies with pressure. We think that such a feature has not been recognized so far, and detailed experiments in a wider pressure range are in progress.

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