Magnetic anisotropy study of UGe$_2$ in a static high magnetic field

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Abstract. UGe$_2$ has orthorhombic $C_{mmm}$ crystalline symmetry and shows ferromagnetic Heavy-Fermion (HF) Superconductor, which provides superconductivity under pressure in the range from 1.0 GPa to 1.5 GPa. Magnetic field dependence of magnetization shows strong magnetic anisotropy. When a magnetic field is applied parallel to easy axis ($a$-axis), magnetization presents ferromagnetic behavior. At 4.2 K, which is much lower than the Curie temperature $T_c = 54$ K, Spontaneous magnetization is $1.4 \mu_B$/U, and the magnetization gradually increase with increasing field. On the contrary, when a field is applied parallel to hard axis ($b$-axis or $c$-axis), magnetization increases linearly with increasing magnetic field. As for $H//b$-axis, magnetization is $0.23 \mu_B$/U even at 27 T. Magnetocrystalline anisotropy constant is obtained as $230 [T \mu_B] = 3.4 [kJ/kg]$ at 4.2 K. This value is comparable with rare-earth magnet Nd$_2$Fe$_14$B, which is typical strongly correlated ferromagnet.

1. Introduction

UGe$_2$ (orthorhombic $C_{mmm}$) is a ferromagnetic Heavy-Fermion (HF) Superconductor, which provides superconductivity under pressure in the range from 1.0 GPa to 1.5 GPa [1]. In this range of pressure, UGe$_2$ is in a ferromagnetic state. This is different behavior from other HF superconductors, which provide antiferromagnetism in a superconducting state. Aso et al. reported the temperature dependence of magnetic Bragg peak intensities $I_n(T)$ under pressure, and presented that below the characteristic temperature $T_x$, which is the transition or crossover temperature between FM1 and FM2 in the ferromagnetic phase, $I_n(T)$ exhibits a steep increase with decreasing temperature [2]. They proposed that this behaviour can be explained by a conventional Stoner model. Sato et al. evaluated the internal fields felt by itinerant electrons from the analysis of the temperature dependence of magnetic Bragg peak intensities [3]. The internal field is about 120 T at 0.1 MPa and decreases with increasing pressure, and finally tends to toward zero in the vicinity of the critical pressure $P_X = 1.2$
GPa, which is the pressure that $T_s$ goes to zero. Onuki et. al. studied about magnetization of UGe$_2$ single crystal up to 8 T [4]. The magnetization shows strong magnetic anisotropy. The purpose of this paper is precise investigation of magnetism, especially, magnetic anisotropy of UGe$_2$ single crystal. We studied about the field dependence of magnetization and evaluated anisotropic field, magnetic anisotropic energy and magnetic anisotropy constants.

2. Results and discussions

A single crystal was grown by the Czochralsky pulling method using a tetra-arc furnace. Magnetization measurements have been carried out using a home-made VSM and Hybrid Magnet HM-28T in High Field Laboratory for Superconducting Materials, Institute for Materials Research, Tohoku University and VSM-14T (Oxford Inst.) in Center for Low Temperature Science, Tohoku University. The absolute value of magnetization was calibrated by pure Nickel.

Fig. 1 shows the magnetic field dependence of the magnetization along easy axis ($H//a$-axis) and hard axis ($H//b$-axis). Magnetization shows strong magnetic anisotropy. When a magnetic field is applied parallel to easy axis ($a$-axis), magnetization presents ferromagnetic behaviour. At 4.2 K, which is much lower than the Curie temperature $T_c = 54$ K. Spontaneous magnetization $M_s$ is $1.40 \mu_B/U$, and the magnetization gradually increase with increasing field. On the contrary, when a field is applied parallel to hard axis ($b$-axis), magnetization increases linearly with increasing magnetic field, which is illustrated in Fig. 2. Experimental result of the magnetization along $b$-axis ($M_b$) can be approximated by linear line,

$$M_b = \alpha + \beta B \ [\mu_B/U], \ \alpha = 0.0331, \ \beta = 0.00763$$

The magnetization along $a$-axis and $b$-axis is different in Fig.1 and temperature dependence of magnetization is also different with each other, as shown in Fig.3. Therefore the anomalous magnetization along $b$-axis is supposed to be intrinsic one.

As for $H//b$-axis, magnetization is $0.23 \mu_B/U$ even at 27 T. The anisotropic magnetic field $B_a=\mu H_A$ is about 370 T, which is derived by the extrapolation of $M_b$ to the spontaneous magnetization $M_s$ for $a$-axis. Magnetic anisotropy energy $E_A$ is calculated by the area surrounded by magnetization for $H//a$-axis and $H//b$-axis.

The obtained value is 800 J/mole = 260 T$\mu_B$, which is much larger than usual ferromagnetic Fe or Ni alloys.
Magnetic anisotropy energy $E_A$ is written as

$$E_A = K_1(\alpha_1^2+\alpha_2^2+\alpha_3^2) + K_2\alpha_1^2\alpha_2^2 + \cdots$$

where $K_1$ and $K_2$ are magnetocrystalline anisotropy constants. Magnetization result indicates the magnetic moment is almost directed to $a$-axis. Therefore Eq. (3) is rewritten as [5]

$$E_A = -\mu_0 M_S H_A \cos \theta = -\mu_0 M_S H_A (1 - \frac{1}{2} \theta^2 + \frac{1}{24} \theta^4 - \cdots) = E_0 + K_1 \theta^2 + K_2 \theta^4 + \cdots$$

where $M_S$ is an spontaneous magnetization, $\theta$ is an angle between magnetic moment and $a$-axis. The third term $K_2 \theta^4$ of Eq. (4) is quite smaller than the second term $K_1 \theta^2$. Then we will discuss about the magnetocrystalline anisotropy constant $K_1$.

$K_1$ is evaluated from the field dependence of magnetization by using the relation [6]

$$K_1 = \mu_0 M_S H_A / 2$$

Thus $K_1$ is obtained as $230 \, T \mu_B = 3.4 \, kJ/kg$ at $4.2 \, K$.

![Fig. 3 Temperature dependence of the magnetization of UGe$_2$ at 1 T.](image1)

![Fig. 4 Temperature dependence of the magnetocrystalline anisotropy constant $K_1$.](image2)

Koyama et al. studied about magnetic anisotropy of hexagonal crystal Nd$_2$Fe$_{14}$, which is typical strongly correlated ferromagnet [7]. Normally, Nd is highly anisotropic element in rare-earth elements. The anisotropic constants are $K_1 = -7.4 \, kJ/kg, K_2 = 3.3 \, kJ/kg$. These values are same extent as UGe$_2$. This result indicates that UGe$_2$ is highly anisotropic ferromagnet like rare earth ferromagnets.

Furthermore, temperature dependence of magnetization at the field of 1 T has been carried out, as shown in Fig.3. For $H//a$-axis, it is as same as former dc magnetization result [8]. Magnetization increases with decreasing temperature. Arrow indicates Curie temperature $T_C = 54 \, K$. Therefore, the $M$-$T$ curve along $a$-axis in Fig.3 indicates spontaneous magnetization along $a$-axis $M_S$ in Eq. (5) at each temperature. As for the $M$-$T$ curve along $b$-axis, steep increase has been observed around $T_C$. Below 40 K, magnetization is almost constant. Therefore the magnetization curve for $b$-axis is supposed to be as same as that at 4.2 K, which is shown in Fig.2. Then the anisotropic magnetic field $H_A$ is proportional to the difference between $M_S$ and $M_b$ at 1 T in Fig.3 and Eq. (5) can be rewritten as,

$$K_1 = \mu_0 M_S H_A / 2 \propto \mu_0 M_S (M_S - M_b)$$

Fig. 4 shows temperature dependence of $K_1$, which is evaluated by Eq. (5). $M_S$ is defined to the magnetization for $H//a$-axis at 1 T in Fig.3. Zener proposed that $K_1$ is written as [9]

$$K_1(T)/K_1(0) \propto (M_S(T)/M_S(0))^{1+(n+1)/2}$$

As for UGe$_2$, $n = 1$, and this is smaller than Co ($n=2$) or Fe ($n=4$). This analysis indicates magnetic anisotropy in UGe$_2$ remains until high temperature. Magnetization curves in Fig. 1 and Fig. 3 also reflect the strong magnetic anisotropy.
3. Summary
Magnetization investigations has been carried out. Magnetization for $a$-axis indicates typical ferromagnetic property. On the other hand, magnetization for $b$-axis is quite smaller than easy $a$-axis. Magnetocrystalline anisotropy constant is same extent as rare-earth ferromagnet Nd$_2$Fe$_{17}$, which indicates that UGe$_2$ is highly anisotropic ferromagnet.

References

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