Unusual ferromagnetic behavior in UGe_2

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Abstract

We have measured magnetization curves of the pressure-induced ferromagnetic superconductor UGe_2 at temperatures down to 0.5 K under various pressures. The ferromagnetic hysteresis loop is smooth down to about 1 K, but on further decreasing temperature, the hysteresis suddenly changes into a staircase-like curve, and the jump occurs at regular interval of magnetic field. We ascribe this novel finding to the macroscopic quantum tunneling effect (MQT). An analysis based on MQT suggests tiny magnetic domain formation whose size is smaller than the superconducting coherence length.

Key words: ferromagnetism; heavy fermion superconductor; macroscopic quantum tunneling; UGe_2; magnetization

UGe_2 crystallizes in the orthorhombic $ZrGa_2$ structure, and orders ferromagnetically below the Curie temperature T_{Curie}~53 K [1]. The magnetization curve at 4.2 K indicates strong uniaxial anisotropy: the magnetization along the easy axis (a-axis) is saturated to a value of about 1.5 μ_{B} per uranium atom at a field as low as 0.1 T, while along the hard axes (b- and c-axis) a field of 100 T is required for the saturation of magnetization [1]. From these values, we can evaluate a uniaxial anisotropic constant $K_1 \sim 2 \times 10^{-8}$ erg/cm^3. The Curie temperature of UGe_2 decreases monotonically with pressure, and disappears at around 16 kbar [2]. Saxena *et al.* found that UGe_2 also exhibits superconductivity below 1 K in pressure range between ~10 and ~16 kbar [3]. It seems that both the ferromagnetism and superconductivity are inhomogeneous, and they coexist cooperatively. However, in general, ferromagnetism and superconductivity are mutually repulsive. Recently, we measured the ac susceptibility χ_{ac} of UGe_2 and have indicated that the superconductivity is inhomogeneous. Furthermore, the peak of $\chi_{\mathrm{ac}}(T)$ at T_{Curie} broadens at pressures where the superconductivity sets in, and thus we have suggested that the ferromagnetism is also inhomogeneous under pressure, and that both orderings coexist competitively.

The purpose of this paper is to investigate detailed nature of ferromagnetic properties of UGe_2. In order to achieve this purpose we have measured static magnetization at temperatures down to 0.5 K and at pressures up to 11.5 kbar.

A single crystal was grown by the Czochralski pulling method using a tetra-arc furnace. A residual resistivity ratio of the sample used here is ~80. The magnetization was measured by using a laboratory-made vibrating sample magnetometer with the field applied along the a-axis, and the sample was immersed in liquid ^{3}He. The pressure was generated by a beryllium-copper piston-cylinder clamp device using Fluorinert as a pressure transmitting medium.

Figure 1(a) shows the ferromagnetic hysteresis loops of UGe_2. At ambient pressure, the hysteresis begins to appear just below T_{Curie}. The hysteresis curve remains to be smooth down to ~1.5 K as is usually observed in normal ferromagnets, which is shown byt the full line in Fig. 1(a), though a coercive force H_0 increases with decreasing temperature. However, on further decreasing temperature down to 0.5 K, the hysteresis curve abruptly changes into a staircase-like curve as shown by closed circles in Fig. 1(a). The staircase-like hysteresis

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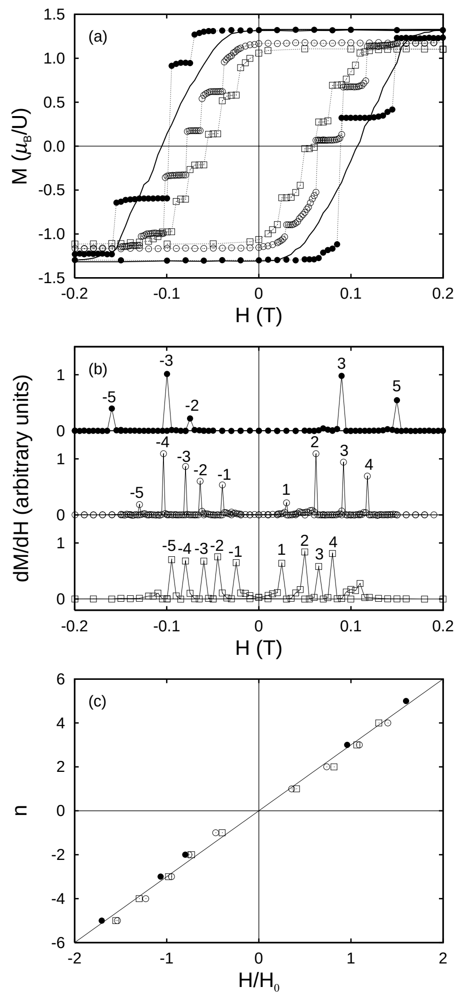

Fig. 1. (a) Magnetization hysteresis loops of UGe_2 at low temperatures under pressure. Symbols are defined as follows; (—) ambient pressure at 1.5 K, (•) ambient pressure at 0.5 K, (∘) 9.5 kbar at 0.5 K, (□) 11.5 kbar at 0.5 K. The dashed lines are guide to the eye. (b) Derivative of the magnetization at 0.5 K in Fig. 1(a) with respect to H as a function of H. Each peak is labeled in the figure by a step number (see text for details). (c) Step number n is plotted against H/H_0, where H_0 is a coercive force for each pressure. The solid line represents a function of $n = 3(H/H_0)$.

curves were also observed under pressure as shown by open circles (9.5 kbar) and open squares (11.5 kbar). We note here that H_0 decreases with increasing pressure.

Figure 1(b) is a derivative of magnetization at 0.5 K shown in Fig. 1(a) with respect to H as a function of H. We can see the magnetization jump occurs at relatively regular field. Here, we index these peaks as step number n with $n = 0$ at zero field, as denoted in the figure.

Figure 1(c) shows a plot of the step number n vs H/H_0 at pressures 0, 9.5 and 11.5 kbar. All data lie on the straight line of $n = 3(H/H_0)$, indicating the magnetization jump occurs regularly at every $H_0/3$. Slight deviations from the straight line may come from residual field of a superconducting magnet and subtle difference in experimental conditions.

Since these staircase-like hysteresis loops are observed only below 1 K and the jump occurs at regular field interval, they can be attributed to a quantum mechanical effect, such as the macroscopic quantum tunneling effect (MQT) [5]. Although this type of magnetization jump was already observed in a simple ensemble of non-interacting molecules such as $Mn_{12}O_{12}(CH_3COO)_{16}(H_2O)_4$ [6], UGe_2 may be the first example showing the magnetization jump at regular intervals of field in macroscopic materials. In our analysis [5], the magnetization jump occurs at $H = n(d_1/g_{\rm eff}\mu_{\rm B})$, where $g_{\rm eff}$ is an effective g factor and d_1 is a uniaxial anisotropic constant per domain and is related to macroscopic anisotropic constant K_1 via $K_1 = d_1 J^2/V$ (J is the total angular momentum of one domain and V is its volume). From this relation, we can estimate a domain size. When the magnetization jump occurs at every about 0.03 T for 9.5 kbar, we obtain tiny domain size of about 40 Å, whose size is smaller than the superconducting coherence length of UGe_2 (130 – 200 Å) [7]. If these tiny domains align adversely, it is possible that magnetic field produced by ferromagntism is cancelled out in a scale of superconducting coherent length. In contrast to this, such domain structure formation may result in pair-breaking effect. In order to examine the relationship between the magnetization jump and superconductivity, magnetization measurements under higher pressures are in progress.

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