High pressure magnetic measurements on strongly correlated electron systems with a miniature ceramic anvil high pressure cell

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Abstract. We have designed a miniature ceramic anvil high pressure cell (mCAC) for magnetic measurements at pressures up to 12.6 GPa in a commercial superconducting quantum interference (SQUID) magnetometer [1-3]. The simplified mCAC without anvil alignment mechanism is easy-to-use for researchers who are not familiar with high-pressure technology and magnetic measurements can be done above 10 GPa. Here, we show one additional modification in the mCAC. This modification enables more precise magnetic measurements on samples with smaller magnetization. We confirm the spontaneous dc magnetization in the pressure-induced ferromagnetic phase in YbCu₂Si₂ by high pressure magnetic measurements with the mCAC. The pressure-induced phase has the strong uniaxial Ising-type anisotropy.

1. Introduction

Magnetic measurement at high pressure is an important experimental method for the study of magnetic properties of materials at high pressure. Recently, we have proposed a miniature ceramic-anvil high-pressure cell for magnetic measurements at pressures above 10 GPa in a commercial superconducting quantum interference (SQUID) magnetometer [1-3]. This cell is abbreviated mCAC. See [1-3] for details on the mCAC and the current status of the pressure cells developed for the SQUID magnetometer. The mCAC has several advantages. The anvils are made of inexpensive composite ceramic (FCY20A, Fuji Die Co.). The simplified mCAC without anvil alignment mechanism is easy-to-use for researchers who are not familiar with high-pressure technology. In this paper, we report one additional modification made to the mCAC. This modification enables more precise measurements on samples with smaller magnetization. Furthermore, we report results of magnetic measurements on the rare earth compound YbCu₂Si₂ which shows a pressure-induced magnetic phase.

YbCu₂Si₂ crystallizes into the tetragonal ThCr₂Si₂-type structure. This is a paramagnetic compound with a moderately high value of the linear specific heat coefficient $\gamma = 135 \text{ mJK}^{-2}\text{mol}^{-1}$ [4]. Previous high pressure studies suggested a pressure-induced magnetic phase above 8 GPa [5-7]. The ac-magnetic susceptibility $\chi_{ac}$ and calorimetry $C_{ac}$ under magnetic field suggested a ferromagnetic transition [8]. Previously, we reported observation of the dc spontaneous magnetization in pressure-induced phase at 10.5 GPa [2]. The magnetic field was
applied along the magnetic easy $c$ axis in the tetragonal structure. To study the anisotropy of the magnetic property in the pressure-induced phase, we measure the magnetization under magnetic field along the magnetic hard $a$ axis in this study. It was difficult to measure the magnetization for the hard axis with the former version of the mCAC since the value of the magnetization is far smaller than that for the easy axis. The present modification to the mCAC makes it possible to obtain reliable magnetization data under magnetic field applied along the hard $a$-axis.

2. Modification to the mCAC
Figure 1 shows photographs of (a) the miniature ceramic anvil high pressure cell (mCAC), (b) the central part of the mCAC, and (c) schematic illustration of the Cu-Be gasket and ceramic anvils in the mCAC. $\phi_1$: culet size of the anvil. $\phi_2$: diameter of the sample space. $z$: thickness of the gasket.

3. Results and Discussion
We have measured the magnetization under high pressure in YbCu$_2$Si$_2$ to study the magnetic anisotropy in the pressure-induced phase. Two single crystals were measured under magnetic field applied parallel to the magnetic easy $c$-axis (the [001] direction) and the hard $a$-axis ([100] direction) in the tetragonal crystal structure. Detail of the sample preparation is given in reference [4]. The sizes of the single crystal samples were $0.11 \times 0.09 \times 0.03$ mm$^3$ and $0.10 \times 0.09 \times 0.02$ mm$^3$ for magnetic measurements under magnetic field along the $c$-axis and the $a$-axis, respectively. The 0.6 mm cult anvils were used. The Cu-Be gasket was preindented to $z_1 = 0.08$ mm from the initial thickness of $z_0 = 0.30$ mm. The sample and a pressure manometer lead (Pb) were placed in the sample space filled with the pressure-transmitting medium glycerin.
as shown in figure 1 (c) [9]. The pressure values at low temperatures were determined by the pressure dependence of the superconducting transition temperature in Pb [10].

Figure 2 shows the temperature dependence of the magnetic susceptibility $\chi$ at 1 bar, 5.0 and 11.5 GPa under magnetic field applied along the magnetic hard $a$-axis ($H || a$). The inset of figure 2 shows $\chi$ at 1 bar, 5.2 and 10.5 GPa for magnetic field under magnetic field along the magnetic easy $c$-axis ($H || c$) [2]. The magnetic susceptibility shows a monotonic temperature dependence at 1 bar. The application of the pressure induces a low temperature upturn when the magnetic field was applied along the easy $c$-axis. The susceptibility for $H || c$ at 10.5 GPa increases largely with decreasing temperature below 5 K, suggesting a ferromagnetic ordering.

Figure 2. Temperature dependences of the magnetic susceptibility $\chi$ at 1 bar, 5.0 and 11.5 GPa under magnetic field applied along the magnetic hard $a$-axis. The inset shows $\chi$ at 1 bar, 5.2 and 10.5 GPa for magnetic field under magnetic field along the magnetic easy $c$-axis [2].

Figure 3. Magnetic field dependences of the magnetization at 1 bar, 5.0 and 11.5 GPa under magnetic field applied along the magnetic hard $a$-axis. The inset shows the magnetization data at 1 bar, 5.2 and 10.5 GPa for magnetic field under magnetic field along the magnetic easy $c$-axis [2].
Meanwhile, the pressure effect on $\chi$ for $H \parallel a$ is weak. The value of $\chi$ at 11.0 GPa is about 30 times smaller than that for $H \parallel c$ at the lowest temperature 2.0 K, suggesting the strong uniaxial magnetic property in the pressure-induced phase.

Figure 3 shows the magnetic field dependence of the magnetization at 1 bar, 5.0 and 11.5 GPa under field applied along the magnetic hard $a$-axis ($H \parallel a$). The inset of figure 3 shows the magnetization data at 1 bar, 5.2 and 10.5 GPa for field along the magnetic easy $c$-axis ($H \parallel c$) [2]. The magnetization increases monotonically with increasing magnetic field at 1 bar. When magnetic field was applied along the magnetic easy $c$-axis, the application of the pressure induces a non-linear increase in magnetization at low fields. The magnetization at 10.5 GPa shows a typical ferromagnetic behavior. It is concluded that the pressure-induced magnetic transition in YbCu$_2$Si$_2$ is ferromagnetic. Similar to the magnetic susceptibility data, the pressure effect on the magnetization is weak when magnetic field was applied along the magnetic hard $a$-axis. These results suggests that the pressure-induced ferromagnetic phase has the strong uniaxial Ising-type anisotropy.

The spontaneous magnetic moment was estimated as $0.36 \pm 0.05 \mu_B$/Yb at 2.0 K and 10.5 GPa from the magnetization data for $H \parallel c$. This value is less than half of that determined in the Mössbauer experiment where it was estimated as $1.25 \mu_B$/Yb. The Mössbauer spectra in the pressure-induced phase were fitted by a superposition of a magnetic and nonmagnetic component in the pressure-induced phase, suggesting an electronic phase separation between the ferromagnetic and paramagnetic states [7]. The smaller spontaneous magnetic moment in the macroscopic magnetic measurement is due to this spatially phase separation.

4. Summary
In summary, we made one modification to a mCAC designed previously by us. There are remaining drops of a residual pressure-transmitting medium overflowed from the sample space in the former version of the mCAC. This residual drops cause errors in the estimation of the background magnetization. In the new version, the drops can be removed through a hole made in the central part in the cylinder. This modification enables more precise magnetic measurements on samples with smaller magnetization. We have studied the anisotropic magnetic property of the pressure-induced phase in YbCu$_2$Si$_2$. We confirm the spontaneous dc magnetization in the pressure-induced ferromagnetic phase with the mCAC. It is found that the pressure-induced phase has the strong uniaxial Ising-type anisotropy.

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