

# Successive magnetic transitions and multi-step magnetization in GdBC

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## Abstract

We report the results of the magnetization measurements in the GdBC single crystal using a pulsed-magnet system up to 30 T and a SQUID magnetometer up to 5 T. The magnetization for the  $b$  axis at 4.2 K shows three steps at 1, 5 and 15 T, being saturated above 23 T. The saturation moment is almost  $7 \mu_B/\text{Gd}$ . Temperature dependence of the step fields is obtained for all axes. These imply that GdBC has the successive antiferromagnetic transitions with the complex magnetic structures in spite of the simple spin system of  $\text{Gd}^{3+}$ .

*Key words:* successive transitions; high field magnetization; GdBC; magnetic phase diagram

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Recently, the materials containing boron and carbon have been highlighted. Among the ternary borocarbides, there have been no experimental data on the magnetic properties of  $R\text{BC}$  ( $R$ : rare-earth elements). Then, we focus attention especially on GdBC, which has a simple spin due to the orbital momentum  $L = 0$  in  $\text{Gd}^{3+}$ . GdBC crystallizes in the orthorhombic YBC-type structure [1]. The antiferromagnetic-like transition temperature,  $T_N = 45$  K is inferred by the magnetic susceptibility, resistance and heat capacity measurements done by our group[2]. Another magnetic transition may occur around  $T_m = 25$  K, where the susceptibility shows a broad peak and the heat capacity shows a small anomaly. In order to clarify the magnetic phase diagram of GdBC, in this study, the magnetization measurements were performed using a pulsed-magnet system and a SQUID magnetometer.

A single crystal of GdBC was grown by a Czochralski pulling method in a tri-arc furnace and confirmed by x-ray diffraction measurements. The magnetization measurements up to 30 T were performed by our home-made pulsed magnet system with a 46.44kJ capacitor bank. The time duration to maximum field is 3ms. A conventional induction method by pickup coils is used

for the magnetization measurements. The signal voltages induced in the pickup coils are stored in a digital oscilloscope and integrated numerically to obtain the magnetization  $M$ . The sample temperature is controlled by a Au(Fe)-silver thermocouple, two heaters, and a rotary pump from 1.5 K to 300 K. The dc mag-

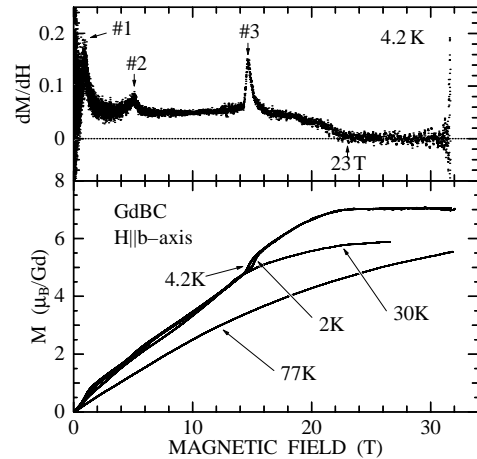


Fig. 1. High-field magnetization curves for the  $b$  axis of GdBC at 2, 4.2, 30, and 77 K. The  $dM/dH$  vs.  $H$  curve at 4.2 K is also shown in upside.

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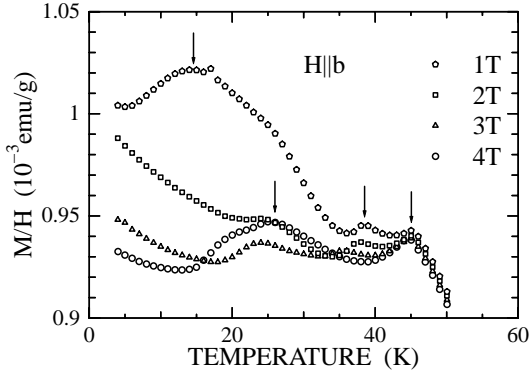


Fig. 2. The  $M/H$  vs.  $T$  curves of GdBC for the  $b$  axis.

netization measurements up to 5 T were performed by a conventional SQUID magnetometer.

Figure 1 shows the high field magnetization curves for the  $b$  axis of GdBC at 2, 4.2, 30, and 77 K, and the differential magnetization curve at 4.2 K. The  $dM/dH$  curve clearly shows three peaks at 1, 5, and 15 T denoted by #1, #2, and #3, respectively. The magnetization curves in the temperature at 2 and 4.2 K show three-step jumps and the complete saturation at 23 T. The saturation moment is almost  $7 \mu_B/\text{Gd}$ , which is in agreement with the free ion's value of  $\text{Gd}^{3+}$ . The magnetization values at the second and the third jumps are about 2 and  $5 \mu_B/\text{Gd}$ , respectively. At 30 K, the magnetization curve shows two-step jumps at 3.4 and 12.9 T, while it shows no anomaly but a monotonic increase at 77 K.

Figure 2 shows the temperature dependence of  $M/H$  for the  $b$  axis using SQUID magnetometer in the temperature range below 50 K under the several magnetic field. The data show the complex temperature dependence below 45 K. For the data at 1 T, three peaks are seen at 14.5, 38.5, and 45 K. With increased magnetic field, the peak around 15 K decreases abruptly, and a new peak appears around 24 K. Above 45 K, no remarkable difference between the data for several magnetic field was seen, which suggests a simple paramagnetic state above 45 K.

The magnetization measurements up to 5 T at several temperatures using a SQUID magnetometer were also performed. Small jumps in the magnetization curves were observed for the  $b$  axis. The  $H$ - $T$  phase diagram of GdBC for the  $b$  axis was obtained from these magnetization measurements as shown in Fig. 3. Four different magnetic phases divided by three boundary lines appear in the figure. The outer region from the #3 line may be paramagnetic. The inner three phases may have a complex magnetic structures, which are not clear at all.

For  $a$  and  $c$  axes, the magnetization were measured up to 5 T. The results summarized to the  $H$ - $T$  phase

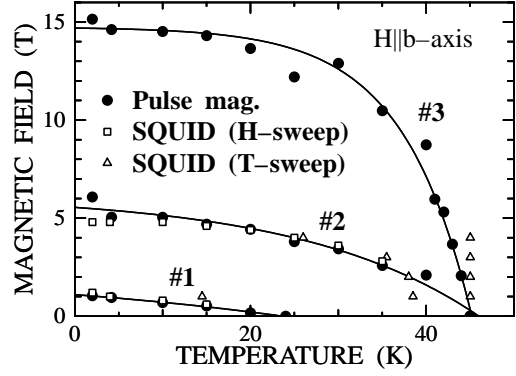


Fig. 3.  $H$  -  $T$  phase diagram of GdBC for the  $b$  axis.

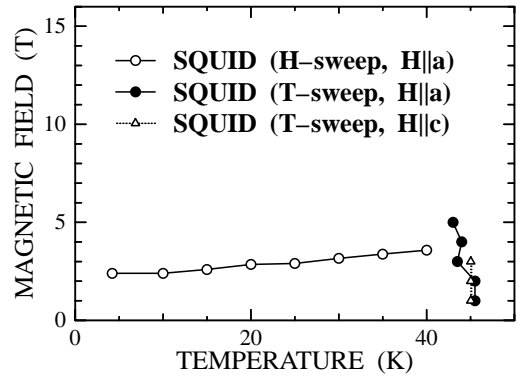


Fig. 4.  $H$ - $T$  phase diagrams of GdBC for the  $a$  and  $c$  axes.

diagrams are shown in Fig. 4. A clear phase boundary around 3 T appears for the  $a$  axis. No anomaly was observed for the  $c$  axis except for 45 K, which suggests that the  $c$  axis is the magnetically hard axis.

In conclusion, the multi-step magnetization in GdBC for the  $b$  axis was observed from the magnetization measurements. The  $H$ - $T$  phase diagrams of GdBC for each axes were obtained. These imply that GdBC has the successive antiferromagnetic transitions with the complex magnetic structures in spite of the simple spin system of  $\text{Gd}^{3+}$ . The cause of the complex structures may exist in the magnetic frustration due to the competed exchange interactions in the double-layer structure of GdBC. We note that it is very important to clarify the magnetic structures at first by the measurements such as the neutron diffraction, NMR, ESR, and others.

## References

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