Pressure effect on magnetic phase transition and spin-glass-like behavior of $GdCo_2B_2$*

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We systematically investigate the effect of pressure on the magnetic properties of $GdCo_2B_2$ on the basis of alternating current (AC) susceptibility, AC heat capacity and electrical resistivity measurements under pressures up to 2.2 GPa. A detailed magnetic phase diagram under pressure is determined. $GdCo_2B_2$ exhibits three anomalies that apparently reflect magnetic phase transitions, respectively, at temperatures $T_C = 20.5$ K, $T_1 = 18.0$ K and $T_N = 11.5$ K under ambient pressure. Under pressures up to 2.2 GPa, these anomalies are observed to slightly increase at T_C and T_1, and they coincide with each other above 1.6 GPa. Conversely, they decrease at T_N and disappear under pressures higher than 1.4 GPa. The results indicate that the low-temperature magnetic phases can be easily suppressed by pressure. Moreover, the spin-glass-like behavior of $GdCo_2B_2$ is examined in terms of magnetization, aging effect and frequency dependence of AC susceptibility. A separation between the zero-field-cooled (ZFC) and field-cooled (FC) magnetization curves becomes evident at a low magnetic field of 0.001 T. A long-time relaxation behavior is observed at 4 K. The freezing temperature T_f increases with frequency increasing.

Keywords: $GdCo_2B_2$, high pressure effect, phase diagram, spin-glass-like behavior

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1. Introduction

The intermetallic compound $GdCo_2B_2$ was first reported by Niihara *et al*. in 1973; it has a body-centered tetragonal crystalline structure (space group *I*4/*mmm*) and its lattice parameters are $a = 3.573 \pm 0.003$ Å and $c = 9.540 \pm 0.005$ Å.[1] Felner reported that $GdCo_2B_2$ is a ferromagnetic material below the Curie temperature $T_C = 26$ K in a magnetic field of 0.1 T.[2] Magnetic susceptibility measurements in a high-temperature region up to 800 K showed that Co in this compound has no magnetic moment.[3] In 2009, Li *et al*. proposed that this material be ordered antiferromagnetically under the Néel temperature, $T_N = 15$ K, based on its magnetization in a field of 0.1 T as a function of temperature.[4] Recently, a rather complicated magnetic phase diagram of single-crystal $GdCo_2B_2$ has been reported by Pospíšil *et al*.; this diagram shows four magnetic transitions at temperatures of 22, 18.5, 13, and 7 K, respectively.[5] The conformal complex magnetic phase diagram strongly suggests the existence of complicated magnetic interactions in this material.

High pressure is recognized as one of the most powerful tools for realizing the intrinsic physical properties of materials; as is well known, the magnetic properties of the 4f and 5f electrons in rare-earth and uranium intermetallic compounds are very sensitive to pressure.[6–8] For example, the unconventional superconductivity of 5f electrons in itinerant ferromagnetic UGe_2 under high pressure has been extensively studied.[7] Previously, we have reported the DC magnetization and magnetic susceptibility each as a function of temperature in $GdCo_2B_2$ under high pressure.[9] By increasing the pressure up to 1.27 GPa, T_C increased slightly from 22.2 K to 26.5 K and the antiferromagnetic (AFM) ordering was totally suppressed above 2.0 K.

As pointed out by the authors above, Ruderman–Kittel–Kasuya–Yosida (RKKY) indirect exchange interaction plays an important role in determining the magnetic properties of this material. The effective interatomic 4f magnetic interactions are transferred by the Fermi sea surrounding the conduction electrons. The application of high pressure changes the interatomic distances and can change the alignment of the magnetic moments. High pressure can also change the band structure of the conduction electrons by changing the density of states. By conducting experiments under high pressure, we can apprehend how these changes affect the magnetic ordering temperature of $GdCo_2B_2$.

In our previous paper, a remarkable phenomenon was observed: the zero-field-cooled (ZFC) and field-cooled (FC) magnetic susceptibility curves were separated at 9 K below T_N, where the FC curve was subjected to a magnetic field of 0.1 T. Pospíšil *et al*. found the same phenomenon in single crystal $GdCo_2B_2$ and they also found that the phenomenon became more obvious in low magnetic fields. It appeared at 8.5 K in a magnetic field of 100 mT and at 13.5 K just below T_N at 5 mT along the *c* axis.[5] The separation phenomenon between the

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ZFC and FC curves is a common feature of spin glass (SG) with the essential ingredients of frustration and disorder. In $GdCo_2B_2$, this phenomenon is unexpected as no geometrical frustration exists given its crystalline symmetry. The SG behavior, however, has been found in some of the rare-earth compound families with body-centered tetragonal $ThCr_2Si_2$-type structures. As-grown single crystal URh_2Ge_2 was reported to be a three-dimensional (3D) Ising-like random-bond SG by Süllow *et al*. in 1997.[10] The SG behavior disappeared because of annealing effects, implying that atomic disorderings of Rh and Ge are the origin of SG in URh_2Ge_2.[11] $PrAu_2Si_2$ was also found by Hemberger *et al*. in 1999 to be a canonical SG with a freezing temperature of 3 K.[12] In this compound, a frustration relates to the singlet ground state and the exchange coupling "avoided criticality" to the SG system.[13] SGs have been extensively studied by many researchers since the pioneering work by Cannella and Mydosh in 1972,[14] but still have unquestionable richness in condensed matter physics.

In the present paper, we perform precise measurements of AC susceptibility, AC heat capacity, and electrical resistivity to obtain more information about the phase transitions of $GdCo_2B_2$ by controlling the pressure of it. We define a detailed magnetic phase diagram based on these results. Moreover, we shed light on the SG-like behavior, namely, the separation phenomenon at low temperature. It is examined in terms of magnetization, aging effects, and frequency dependence of AC susceptibility measurements in order to clarify the nature of magnetic properties at low temperature. Finally, we discuss the relationship between magnetic phase transitions under pressure and SG-like behavior.

2. Experiments

High-quality polycrystalline $GdCo_2B_2$ was synthesized from high-purity Gd, Co, and B by an arc-melting method through using a tungsten electrode under an argon atmosphere. The sample was annealed at 1173 K for one week in an evacuated quartz tube. The sample was proved to be of a single phase with a body-centered tetragonal $ThCr_2Si_2$-type (space group *I*4/*mmm*) structure by an x-ray diffraction (XRD) experiment. Lattice parameters *a* and *c* were evaluated to be 3.577 Å and 9.536 Å, respectively. These results were consistent with those previously reported.[1]

The effect of pressure was investigated through AC susceptibility, AC heat capacity, and DC electrical resistivity measurements with a laboratory-made CuBe–NiCrAl hybrid piston cylinder pressure cell.[15] Daphne 7373 oil was used as a pressure-transmitting medium. Heat capacity measurement is known as an excellent method of observing the bulk properties of magnetic phase transitions, and it was performed using a typical Joule heating-type temperature-modulated method.[16,17] When one applies an electrical current with frequency ω to the sample, the Joule heating is supplied at a frequency of 2ω; thus, the temperature of the sample is modulated with a frequency of 2ω. As to the requirements for the experiment, the size of the sample was minimized into a size of 0.2 mm$\times$ 0.4 mm$\times$ 0.05 mm, a combination of 0.020 mmϕ Au and 0.025 mmϕ AuFe (Fe: 0.07 %) wires was used as a thermocouple to measure the modulated temperature, and a 0.020 mmϕ Au wire was used as a heater. The wires were spot-welded directly onto the sample together with two other Au wires to measure the electrical resistivity. Another piece of the sample was placed inside the compensated pick-up and modulation coils for AC susceptibility measurement with Sn as a manometer. In our laboratory-made system, all measurements could be made under the same pressure conditions.

The SG-like behavior at ambient pressure was examined through a series of experiments. These experiments were performed using a superconducting quantum interference device magnetometer MPMS-7 from Quantum Design, Inc. First, FC and ZFC magnetization each as a function of temperature were determined under various fields. Second, two types of measurements examined the aging effect. The first was of the time-dependence of ZFC magnetization at a selected temperature. The system was cooled from 50 K (much higher than the Curie temperature) to the selected temperature at a rate of 30 mK/s and then maintained at this temperature for 1800 s. Subsequently, the measurement of magnetization as a function of time was undertaken in a magnetic field of 0.01 T. The second experiment was the ZFC measurement with intermittent stops at the selected temperatures. The system was cooled from 50 K to 1.8 K at a rate of 30 mK/s, and the magnetization measurements were performed with intermittent stops of 1800 s at 2, 3, and 4 K in a magnetic field of 0.01 T. AC susceptibility measurements were conducted at four selected frequencies, namely 1, 10, 100, and 1000 Hz, to investigate the behavior of the freezing temperature.

3. Results

3.1. Pressure effect

3.1.1. AC susceptibility

The temperature dependence of the AC susceptibility is shown in Fig. 1. A driving AC field of 220 Hz and 5 Oe (1 Oe = 79.557 A·m^{-1}) is used. The inset shows the change of superconducting transition with temperature of Sn to determine the applying pressure at low temperature.[18] The compound exhibits three anomalies that apparently reflect magnetic phase transitions at temperatures of $T_C = 20.5$ K, $T_1 = 17.5$ K, and $T_N = 11.5$ K (all defined by the peak position of the χ_{AC}–T curves) under ambient pressure. This is in good agreement with the previously published work of Pospíšil *et*

al.[5] Among these anomalies, the peak at T_C was realized as a typical behavior of the Hopkinson effect and appeared just below the Curie temperature.[19,20] Under pressures up to 2.2 GPa, a slight increase is observed in T_C from 20.5 K to 21.5 K and in T_1 from 17.5 K to 21.5 K, where they coincided with each other. Conversely, T_N has a clear decrease from 11.5 K to 8.5 K under a pressure of 1.1 GPa and disappears under pressures higher than 1.4 GPa.

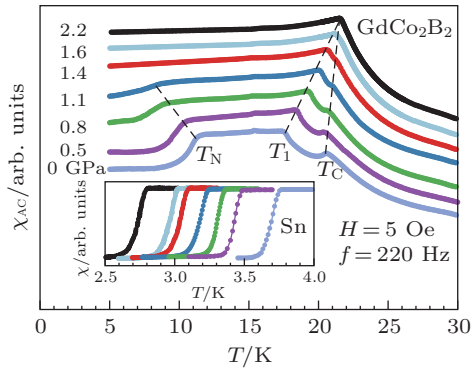


Fig. 1. (color online) Temperature dependences of the AC susceptibility under hydrostatic pressure for $GdCo_2B_2$. The curves under pressure shifted by the same value in order. The inset shows the temperature-dependent superconducting transition in the AC susceptibility measurement of the manometer Sn under pressure.

3.1.2. AC heat capacity

Figure 2 shows the AC heat capacity as a function of temperature under pressure. The phase transitions at temperatures T_C and T_1 at ambient pressure can be clearly seen. An additional broad hump appears in magnetic measurement at approximately 10 K instead of a clear transition at T_N. Pospíšil *et al*. have claimed that it is related to a Schottky contribution from the energy-splitting of the ground state $^8S_{7/2}$ by a ferromagnetic exchange field.[5] However, it is possible to comprehend that this broad hump originates from the SG as below. There are no significant signs of the freezing process in the heat capacity measurement of an SG.[21] In other words, the freezing temperature cannot be extracted from the magnetic specific heat. We underline that the pressure effect is observed and the results are almost the same as the measurements of

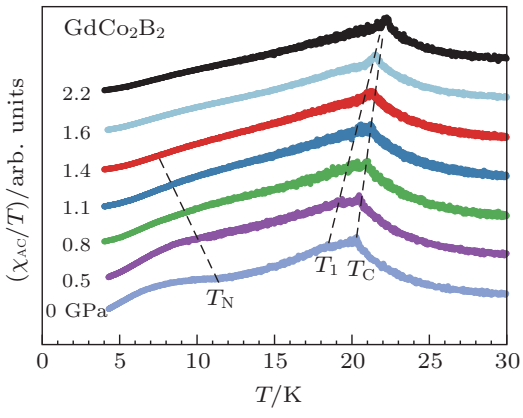


Fig. 2. (color online) Temperature dependences of the AC heat capacity under hydrostatic pressure for $GdCo_2B_2$. The curves under pressure shift by the same value in order.

susceptibility; T_C and T_1 increase from 20.3 K and 18.5 K to the same temperature of 22.2 K as pressure increases up to 2.2 GPa.

3.1.3. Electrical resistivity

Electrical resistivity ρ versus temperature under pressure is shown in Fig. 3. Broad changes at approximately T_C and T_1 can be found from 17.5 K to 21.0 K and an anomalous flat change at T_N is clearly seen at approximately 12.0 K under ambient pressure. With increasing pressure, the starting temperature of the broad change shifts upward to 22.0 K while T_N decreases and disappears completely above 1.4 GPa. These behaviors are in good agreement with the other measurements discussed above.

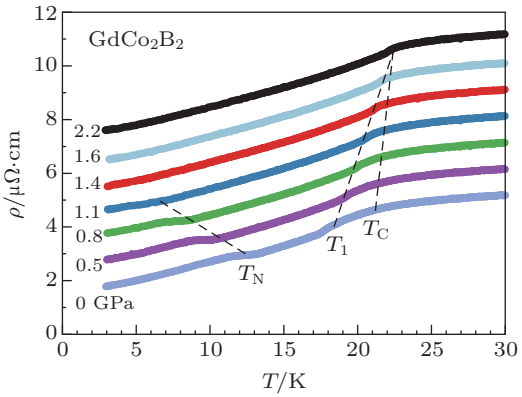


Fig. 3. (color online) Temperature dependences of the electrical resistivity ρ under hydrostatic pressure for $GdCo_2B_2$. The data are shifted by an order of 1 μΩ/cm under pressure.

3.2. Spin-glass-like behavior

3.2.1. ZFC and FC magnetization

As is well known, SG behavior has the characteristic separation of the ZFC and FC magnetization curves below a characteristic temperature as a signature. Figure 4 shows the temperature dependences of both ZFC and FC magnetizations in magnetic fields of 0.001, 0.005, and 0.01 T. It can be clearly seen that the separate phenomena become obvious under low magnetic fields. As the magnetic field decreases, the separating temperature increases to T_1 (see the inset of Fig. 4). This suggests that SG-like behavior is realized below this separating temperature T_1.

3.2.2. Hysteresis loops

Figure 5 shows the hysteresis loop in magnetization measurements M as a function of magnetic field H at 2 K. At ambient pressure, an isothermal "S"-shape $M(H)$ is observed after the ZFC procedure. The existence of a very small coercive field of 0.006 T reveals that this compound is a soft ferromagnet. Another interesting phenomenon that can be noticed is that the magnetization curves in the two field-increasing processes are crossed at 0.035 T as shown in inset (a) of Fig. 5. This phenomenon was discovered by Monod *et al*. in 1979

as evidence of cooperative behavior among a large number of frozen spins.[22] In particular, the complicated behavior may occur in a system where mixed ordering produced by competition between SG and ferromagnetic orderings exists.[23] As seen in inset (b) of Fig. 5, the hysteresis loop almost disappears under a pressure of 1.27 GPa as noted in our previous paper.[9]

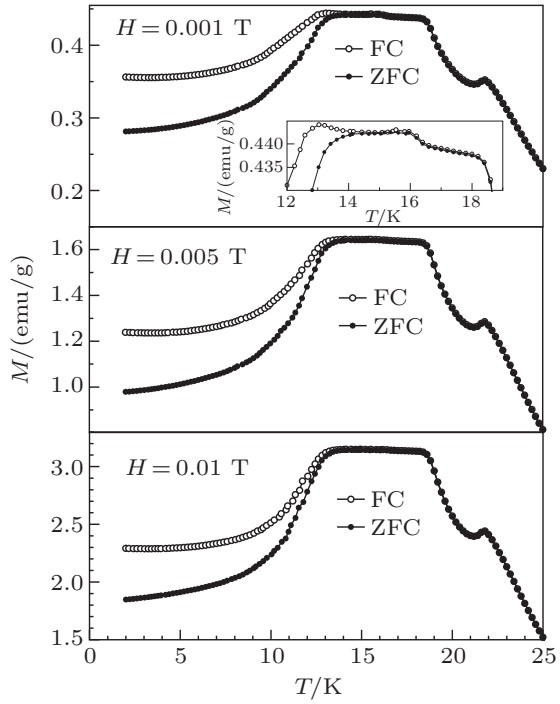


Fig. 4. Variations of FC and ZFC magnetization with temperature in selected magnetic fields of 0.001, 0.005, and 0.01 T in the temperature range from 2 K to 25 K.

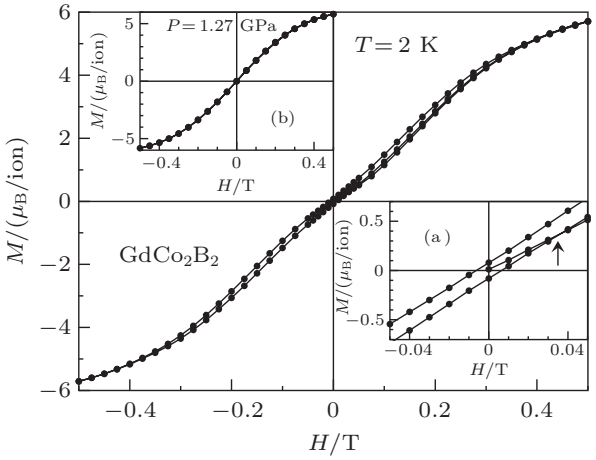


Fig. 5. Hysteresis loop in magnetization measurement as a function of magnetic field at 2 K. Inset (a) displays the hysteresis loop at 2 K in the field range from −0.05 T to 0.05 T. Inset (b) shows the hysteresis loop at 2 K under pressure of 1.27 GPa.

3.2.3. Aging effect

Another crucial feature of the SG behavior is the existence of aging processes on all time scales in the isothermal process. The time dependences of the ZFC magnetization in a magnetic field of 0.01 T are measured as mentioned in Section 2. Figure 6 shows the variations of magnetization $M(t)$ with time t at 4 K for $GdCo_2B_2$ in different magnetic fields. We have plotted it as $M(t)/M(0)$ versus t. The aging behavior of $M(t)$ for $GdCo_2B_2$ could be fitted to a logarithmic function:

$$M(t) = M_0 + S\ln(t/t_0 + 1), \tag{1}$$

where M_0 and S, called the initial zero-field magnetization and magnetic viscosity respectively, are the fitting parameters depending on the temperature. The parameter t_0 depends on the measuring conditions and has only limited physical relevance.[24–26] The best fitting results obtained using the least-squares method are shown by the solid lines in Fig. 6. The values of magnetic viscosity are estimated as 0.0021 emu/g under ambient pressure with $M_0 = 1.8853$ emu/g and $t_0 = 213.3$ s, 0.0019 emu/g under 0.7 GPa with $M_0 = 2.5719$ emu/g and $t_0 = 208.6$ s, and 0.0014 emu/g under 1.2 GPa with $M_0 = 3.3880$ emu/g and $t_0 = 193.7$ s, respectively. It is emphasized that the characteristic phenomena of magnetic relaxation on a macroscopic time scale can be observed for all SGs, including U_2NiSi_3,[27] $CeIr_3Si_2$,[28] $Gd_{2-x}Y_xPdSi_3$,[29] and R_2PdSi_3 (R = Nd, Tb and Dy).[26] Figure 7 shows the time-dependence of ZFC magnetization with one intermittent stop at 4.5 K and the two-stop transfers from 4 to 4.5 K after 4300 s. As clearly seen in the figure, state A in the one-stop process and state B in the two-stop process are identical. A similar behavior was reported in the $Fe_{0.5}Mn_{0.5}TiO_3$ system and well analyzed by the simple Edwards–Anderson (EA) model SGs.[30]

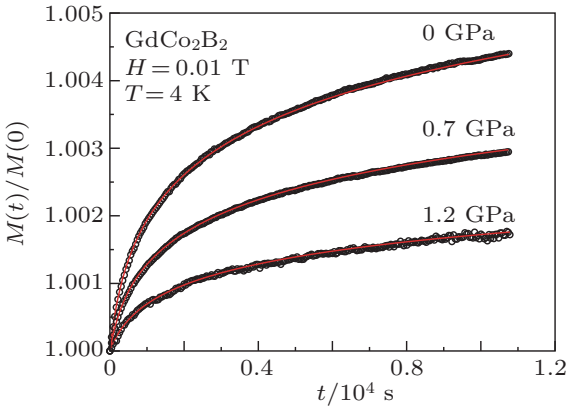


Fig. 6. (color online) Values of magnetization $M(t)$ each as a function of time t, plotted as $M(t)/M(0)$ versus t at 4 K for $GdCo_2B_2$ under pressures of 0, 0.7, and 1.2 GPa. The solid lines represent least-squares fits using equation $M(t) = M_0 + S\ln(t/t_0 + 1)$.

Figure 8 shows the temperature dependence of the ZFC magnetization with intermittent stops at 2, 3, and 4 K for 1800 s, and that of the normal heating process. The magnetization increases even as the temperature stays constant, and when the heating restarts, it increases slowly and reaches that of the normal heating process. This phenomenon is well known as the "memory effect" in SG materials.[31]

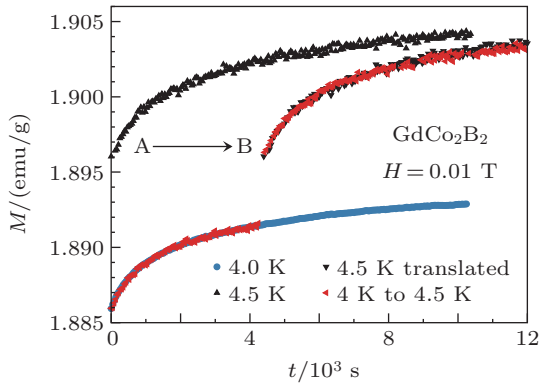


Fig. 7. (color online) Time dependences of ZFC magnetization with one stop at 4.0 K and 4.5 K, and a two-stops transfer from 4.0 K to 4.5 K with waiting time $t_w = 4300$ s.

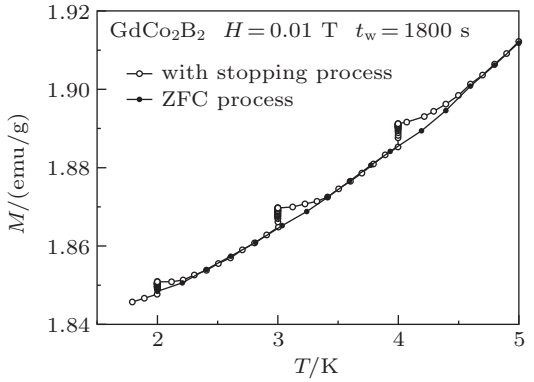


Fig. 8. Temperature dependence of ZFC magnetization with intermittent stops at 2, 3, and 4 K for 1800 s (empty symbols) and that of a normal ZFC process (solid symbols).

3.2.4. AC susceptibility

Figure 9 shows the variations of real part (χ') of the AC susceptibility at four selected frequencies, namely 1, 10, 100, and 1000 Hz in a driving magnetic field of 0.1 mT. The peaks of χ' corresponding to the magnetic orderings at T_C, T_1, and T_N are in good agreement with those of the AC susceptibility measurement in the laboratory-made system mentioned in Subsubsection 3.1.1. The Hopkinson peak just below the Curie temperature appears at T_C without frequency dependence.[19] However, frequency dependence, which is known as a common feature of SG, is realized below T_1. The AC susceptibility of SG generally has a cusp at freezing temperature. Interestingly, however, the cusp does not appear below the characteristic temperature T_1 in this material, because the molecular field caused by ferromagnetic interaction plays the same role as the external field. Below T_N, it decreases rapidly with temperature decreasing at approximately 13 K and becomes flat in the temperature region below 10 K, which is similar to low-field DC magnetization measurements. The value of freezing temperature T_f shifts towards higher temperature with higher frequency — a phenomenon characteristic of SGs.[32] To understand this nature, we use the conventional SG formula to analyze our data. According to the power law

$$\tau/\tau_0 = [(T_f - T_g)/T_g]^{-z\nu}, \quad (2)$$

where T_f, shown in the inset (a) of Fig. 9, is the frequency-dependent freezing temperature at which the maximum relaxation time τ corresponds to the selected frequency f ($\tau = 1/f$), T_g is the SG transition temperature that is determined by extrapolating the curve of T_f as a function of f to zero frequency, τ_0 is the characteristic time constant of the SG, ν is the critical exponent which describes the growth of the correlation length, z is the dynamic exponent that describes the slowing down of the relaxation. Inset (b) of Fig. 9 shows $\ln(\tau)$ versus $\ln[(T_f - T_g)/T_g]$. An excellent fit to the power law is estimated as $T_g = 18.77$ K, $\tau_0 = 1.7 \times 10^{-15}$ s, and $z\nu = 6.4$. The fitting parameters are within the range of typical values for known SG systems, for which $z\nu \sim 6$–12 and $\tau_0 \sim 10^{-12}$–10^{-15} s.[32–35] A cusp that can be noticed at about 16.5 K is most likely from impurities, since it does not appear in DC magnetization nor single crystal measurement.[5]

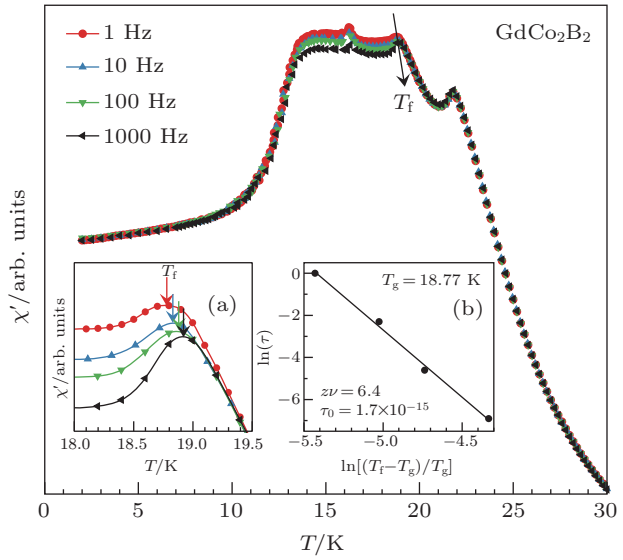


Fig. 9. (color online) Variations of the real (χ') part of AC susceptibility with temperature for $GdCo_2B_2$ at frequencies of 1, 10, 100, and 1000 Hz. Inset (a) shows the detail of freezing temperature T_f. Inset (b) shows $\ln(\tau)$ as a function of $\ln[(T_f - T_g)/T_g]$.

4. Discussion

First, the magnetic properties under high pressure are discussed. Figure 10 shows the magnetic phase diagram under high pressure determined by our experimental results. It shows that the $GdCo_2B_2$ compound exhibits three anomalies that apparently reflect magnetic phase transitions at temperatures $T_C = 20.5$ K, $T_1 = 18.0$ K, and $T_N = 11.5$ K under ambient pressure. We define these three areas at temperatures between T_C and T_1 and T_1 and T_N, and below T_N as I, II, and III, respectively. It is realized that only phase II survives and expands its temperature range with increasing pressure. The triangular shape of phase I becomes narrow and disappears above 1.6 GPa. The temperature of the boundary between phases II and III decreases monotonically with increasing pressure and is invisible above 1.4 GPa.

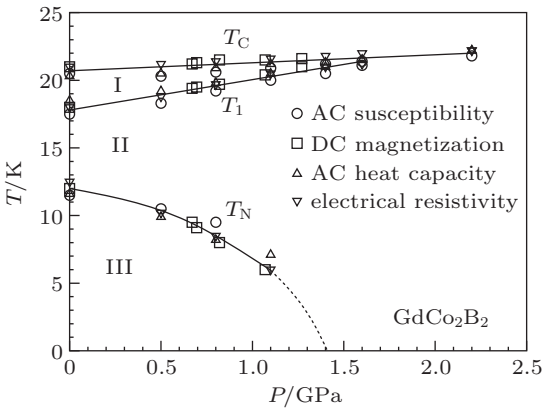


Fig. 10. The magnetic phase diagram of $GdCo_2B_2$ under pressure. □ is from the DC magnetization measurements (see Ref. [9]); ○ is from the AC susceptibility measurements; △ is from AC heat capacity measurements; and ▽ is from the electrical resistivity measurements.

Second, we discuss the SG-like behavior of $GdCo_2B_2$. The results in Subsection 3.2 prove the existence of SG-like behavior at low temperature and under ambient pressure.

No geometrical frustration exists in $GdCo_2B_2$, given its crystalline symmetry. Thus this behavior is unexpected. It is fascinating that the SG-like behavior appears in a non-frustrated system such as $GdCo_2B_2$ with the symmetry described by the space group $I4/mmm$. One possibility is the presence of frustration from the geometric disorders between Co and B atoms as discussed in URh_2Si_2, but this can be negated since the sample is well annealed. Recently, Motoya *et al*. observed a long-time variation in the magnetic structure of a non-diluted uniform magnet, $CeIr_3Si_2$.[36] Similar behaviors were also studied in intermetallic compounds $PrCo_2Si_2$ and $TbNi_2Si_2$ by the same authors.[37] The long-time variations in the magnetic structure of these materials were reported to originate from frustrating magnetic interactions.

The splitting of ZFC and FC magnetization curves and the cusp-like behavior in the ZFC magnetization are the features for spin glass or cluster glass system or the coexistence of antiferromagnetism with ferromagnetism.[38–40]

One of the scenarios to understand the SG-like behavior of this compound is the existence of competition between complicated FM and AFM interactions distributed randomly throughout the compound. This can be understood from pervious papers, which claimed the transition at around 11.5 K as Néel ordering.[4,5] We note that SG-like behavior starts at T_1 as discussed in Subsection 3.2.1; thus, the AFM interaction starts at T_1 and becomes larger from T_N.

In this scenario, we discuss the relationship between magnetic phase transitions under pressure and SG-like behavior. The interaction between the localized 4f spins is of RKKY type. In the case of $GdCo_2B_2$, Gd^{3+} ions are responsible for its magnetic orders as mentioned in the Introduction. The FM order is mainly determined by the nearest-neighbor interaction J_1 between Gd^{3+} ions, and the AFM order is mainly determined by the next-nearest-neighbor interactions J_2 between the spins of the Gd^{3+} ions. A small decrease is caused in unit cell size by increasing pressures up to 2.2 GPa. The lattice becomes shorter, which causes the FM interaction (and J_1) to be strengthened and the AFM (and J_2) weakened. As a result, T_C increases while T_N decreases and disappears with increasing pressure. The competition between FM and AFM interactions is also weakened in this process. As a response to it, the SG-like behavior of $GdCo_2B_2$ is apparently suppressed by pressure. As shown in Fig. 6, at $t = 10^4$ s, the relative increases in the magnetization change, $M(t)/M(0)$, are reduced by 0.14% and 0.26% under pressures of 0.7 GPa and 1.2 GPa, respectively, compared with those at ambient pressure. Also, the relaxation time is shortened under pressure. These results are identical to the above analyses and support the explanation to the SG-like behavior of $GdCo_2B_2$, i.e., the competition between complicated FM and AFM interactions distributed randomly throughout the compound.

Other scenarios should be considered following our new results, especially, the large magnetization below around 11.5 K (see Fig. 4) and the hysteresis loops at 2 K (see Fig. 5), which suggest the material shows ferromagnetism in bulk below around 11.5 K. Thus, this reflects that the material does show glassy magnetic behavior below around 11.5 K.[41,42] The glassy magnetic behavior is also supported by the results of the heat capacity, aging effect and the frequency dependence of ac susceptibility at low temperature, which are shown in Figs. 2, and 6–9. In this case, on one hand, the small difference between ZFC and FC magnetizations with the decreasing of FC magnetization below around 13 K in Fig. 4 does not support the typical cluster glass state in this compound. Also, according to Fig. 9, the value of τ_0 is much shorter than that of the cluster glass state (10^{-5} s) but in agreement with that for a classical SG.[43–45] On the other hand, the results in Figs. 4 and 5 suggest that this material at low temperature is not in the classical SG state, which shows small magnetization and no magnetic hysteresis. Anyway, these behaviors should be supported by the existence of mixed ordering state competition between SG and ferromagnetism at low temperature as discussed in Subsubsection 3.2.2.

In this stage, we cannot affirm the origin of the SG-like behavior in $GdCo_2B_2$, and have not clarified the magnetic structure in $GdCo_2B_2$ either. Such a clarification is required to understand both the SG-like behavior of non-geometrical frustrated compound with symmetry described by the space group $I4/mmm$ and the pressure effects on magnetic phases. Unfortunately, it is very difficult to determine the structure by neutron scattering because of the large absorption cross-sections of Gd and B. We are planning to perform x-ray resonant magnetic scattering. It may be interesting to investigate the uniaxial pressure effect for single crystal $GdCo_2B_2$, be-

cause the weak-but-significant magneto-crystalline anisotropy of as-grown single crystal $GdCo_2B_2$ was reported by Pospíšil *et al*.[5] Further investigations on single crystal $GdCo_2B_2$ are expected to provide more information for understanding these interesting properties on this compound.

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