Long-range antiferromagnetic order in the frustrated XY pyrochlore antiferromagnet Er$_2$Ge$_2$O$_7$


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A cubic Er$_2$Ge$_2$O$_7$ pyrochlore was prepared under high-pressure and high-temperature conditions and its magnetic ground state was investigated by measurements of specific heat, dc and ac magnetic susceptibility as functions of temperature, pressure, and magnetic field. We found that Er$_2$Ge$_2$O$_7$ undergoes a long-range antiferromagnetic transition at $T_N \approx 1.4$ K, which can be further enhanced by applying external physical pressure. On the other hand, application of external magnetic fields suppresses the antiferromagnetic order to zero temperature around $H_c \approx 2.3$ T, where a magnetic-field-induced spin-flop transition was observed. $H_c$ increases accordingly with increasing $T_N$ under external pressure. A comparison of the magnetic ground states and structural variations along the isosstructural series Er$_2$B$_2$O$_7$ ($B = $ Sn, Ti, Ge) together with the high-pressure study on Er$_2$Ge$_2$O$_7$ indicated that the magnetic properties of these highly frustrated XY pyrochlore antiferromagnets are very sensitive to the minute structural changes that determine the anisotropic exchange interactions and the local crystal-electric-field environments of Er$^{3+}$ ions.

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Recently, much attention has been paid to the pyrochlore compound Er$_2$Ti$_2$O$_7$, which has been regarded as a promising textbook example where the exotic “order-by-disorder” (OBD) mechanism plays a decisive role in selecting the long-range-ordered ground state [1–7]. In Er$_2$Ti$_2$O$_7$, the Er$^{3+}$ ions form a three-dimensional network of corner-sharing tetrahedra, i.e., the so-called pyrochlore lattice, and exhibit strong easy-plane anisotropy with local moments confined to planes orthogonal to the local $<111>$ axis of tetrahedron [2]. These facts make Er$_2$Ti$_2$O$_7$ an ideal experimental realization of a highly frustrated XY antiferromagnet on the pyrochlore lattice [2,8]. Earlier numerical simulations on the classical (111) XY pyrochlore antiferromagnet found a macroscopic degeneracy of the magnetic ground state, which can be lifted by finite-temperature thermal fluctuations, leading the system to a $q = 0$ conventional Néel state via the OBD mechanism [1]. This prediction was later confirmed experimentally in Er$_2$Ti$_2$O$_7$, which was found to develop a long-range antiferromagnetic order below $T_N \approx 1.173$ K [2]. In sharp contrast to the prediction of a coplanar $\psi_3$ state, however, the spin ordered state under zero field can be described almost entirely with a noncoplanar $\psi_2$ structure [2,9]. This discrepancy has left the OBD effect as the most favorable selection mechanism for the experimentally observed noncoplanar $\psi_2$ ground state. Such an OBD scenario was further reinforced by more recent theoretical investigations based on an effective pseudo-spin-1/2 Hamiltonian with anisotropic exchange interactions [4,5]. By varying the relative magnitude of these anisotropic exchange couplings $J_{ex} \equiv \{J_{\pm\pm}, J_{\pm\mp}, J_{\mp\mp}, J_{zz}\}$, Wong et al. [6] further presented comprehensive ground-state phase diagrams of XY pyrochlore magnets, which were found to be very sensitive to the minute changes of $J_{ex}$.

Despite these significant achievements in understanding the magnetically ordered state of Er$_2$Ti$_2$O$_7$, it remains elusive why the isosstructural Er$_2$Sn$_2$O$_7$ with a nearly identical Er$^{3+}$ pyrochlore lattice does not form a long-range-ordered state down to 100 mK [10–13]. A very recent neutron study on Er$_2$Sn$_2$O$_7$ revealed the existence of short-range correlations, in which the magnetic moments are arranged in the Palmer-Chalker configurations favored by the dipolar interactions [12,14]. A comparison of the crystal-electric-field (CEF) and the anisotropic exchange parameters between Er$_2$Sn$_2$O$_7$ and Er$_2$Ti$_2$O$_7$ indicated that the former compound has a stronger planar character of Er$^{3+}$ moment, but less anisotropic exchange couplings [12]. Variations of these microscopic parameters that influence the ground states of Er$_2$B$_2$O$_7$ ($B = $ Ti, Sn) should have a deep root on the minor structural changes in these closely related compounds. An intuitive expectation would connect with their different nearest-neighbor distance $R_{nn}$ between Er$^{3+}$ ions. Therefore, a systematic study on the magnetic ground states of Er$_2$B$_2$O$_7$ by spanning $R_{nn}$ to a large extent is indispensable in order to achieve a thorough understanding.

For this purpose, we have chosen to replace Ti$^{4+}$ (0.605 Å) and Sn$^{4+}$ (0.69 Å) with the much smaller Ge$^{4+}$ ion (0.53 Å) so as to exert a larger chemical pressure on the Er$^{3+}$ pyrochlore lattice. As reported earlier [15], high-pressure and
high-temperature (HPHT) synthesis is required in order to stabilize the cubic pyrochlore structure for Er2Ge2O7. In this paper, we report on the HPHT synthesis and the structural analysis of the cubic pyrochlore Er2Ge2O7, followed by detailed characterizations on the low-temperature magnetic properties of this XY pyrochlore antiferromagnet. As expected, the application of chemical pressure results in a global, uniform reduction of lattice dimension or $R_{\text{m}}$. Structural refinement on Er2Ge2O7 enables one to see subtle modifications of the local CEF environments of Er3+ ions along the series Er2B2O7 ($B = \text{Sn, Ti, Ge}$). Measurements of low-temperature specific heat and dc magnetic susceptibility revealed that like Er2Ti2O7 [2], Er2Ge2O7 also develops a long-range antiferromagnetic order below $T_N \approx 1.40 \text{ K}$, which is higher than the reported $T_N = 1.173 \text{ K}$ of Er2Ti2O7. In addition, we found that $T_N$ of Er2Ge2O7 can be further enhanced by applying external physical pressure, but $T_N$ tends to saturate with pressure. These results indicate that the magnetic ground state of XY pyrochlore antiferromagnets Er2B2O7 is very sensitive to structural changes. Furthermore, measurements of dc and ac magnetic susceptibility under different dc magnetic fields revealed the existence of quantum critical point around $T_B \approx 2.3 \text{ T}$, where the long-range ordered state gives way to a highly polarized state. The critical magnetic field $H_c$ was found to increase slightly with increasing $T_N$ under pressure.

The cubic Er2Ge2O7 pyrochlore in the present study was prepared under 7 GPa and 1000 °C by using a Walker-type multianvil module (Rockland Research Co.) in the Institute of Physics, Chinese Academy of Sciences. Another Er2Ge2O7 sample obtained under 8 GPa and 1100 °C at the University of Edinburgh shows similar results (not shown here). Phase purity of the obtained high-pressure products was examined by powder x-ray diffraction (XRD) at room temperature. Direct current magnetization was measured with a commercial Superconducting Quantum Interference Device (SQUID) magnetometer (Quantum Design) equipped with a home-made 3He insert [16]. Specific-heat data in the temperature range 0.5–30 K were collected by using a 3He option of the Physical Property Measurement System (PPMS, Quantum Design). Alternating current magnetic susceptibility under pressures up to ~20 kbar was measured by employing a primary-secondary-coil technique inside a self-clamped piston-cylinder cell, which was attached to commercial Heliox insert (Oxford Instruments). An excitation current of about 2 mA with a secondary-coil technique inside a self-clamped piston-cylinder cell, which was attached to commercial Heliox insert (Oxford Instruments). An excitation current of about 2 mA with a frequency of 317 Hz was applied to the primary coil during the measurements. The pressure inside the high-pressure cell was monitored by measuring the superconducting transition temperature of lead (Pb). Glycerin was used as the pressure transmitting medium.

The powder XRD pattern shown in Fig. 1(a) confirmed that the as-obtained Er2Ge2O7 sample is single phase with the cubic pyrochlore structure. To extract more structural information, we have refined the XRD pattern in a cubic Fd-3m (No. 227) space group with the Er atom at 16d (1/2, 1/2, 1/2), the Ge atom at 16c (0, 0, 0), the O1 atom at 48f (x, 1/8, 1/8), and the O2 atom at 8b (3/8, 3/8, 3/8) site, respectively. The structural parameters after refinements are given in Table I together with those of Er2Ti2O7 (Ref. [17]) and Er2Sn2O7 (Ref. [18]) for comparison. The obtained lattice parameter $a = 9.8782(2)$ Å is consistent with the value reported previously [15], and is much smaller than that of Er2Ti2O7 ($a = 10.074$ Å) [17] and Er2Sn2O7 ($a = 10.35$ Å) [18]. As shown in Fig. 1(b) and Table I, with decreasing the ionic radius (IR) of B4+ ions along the Er2B2O7 series, the cubic lattice parameter $a$ and the corresponding $R_{\text{m}} = (\sqrt{2}/4)a$ decrease linearly, signaling a progressive increment of chemical pressure on the Er3+ pyrochlore lattice by reducing the B4+-ion size.

In addition to the global, uniform reduction of lattice dimension upon the application of chemical pressure along the Er2B2O7 series, the local coordination around Er3+ ions also experiences subtle modifications, which should have a nontrivial impact on the CEF and in turn on the anisotropic magnetic degree of freedom of Er3+ ions. In the Er2B2O7 pyrochlores, the Er atoms are coordinated by six O1 and two O2 atoms; the much shorter Er-O2 bonds produce a pronounced axial distortion along the local (111) direction. In general, this distortion increases with decreasing $x$ [8], which is indeed observed along this series Er2B2O7 ($B = \text{Sn, Ti, Ge}$). As shown in Table I, however, variation of $x$

![FIG. 1. (Color online) (a) Powder XRD pattern of Er2Ge2O7 after Rietveld refinement. (b) Lattice parameter $a$ and the Er-O bond-length ratio $\rho = (\text{Er-O2})/(\text{Er-O1})$ characterizing the axial distortion of ErO6 polyhedra in the series of Er2B2O7 ($B = \text{Sn, Ti, Ge}$) as a function of ionic radius (IR) of B4+ ions.](image-url)

![TABLE I. Comparison on the structural parameters of cubic pyrochlores Er2B2O7 ($B = \text{Ge, Ti, Sn}$).](table-url)
values as a function of IR is not uniform: Δχ/IR is 0.076/Å from Er2Sn2O7 to Er2Ti2O7, but it is only 0.024/Å from Er2Ti2O7 to Er2Ge2O7. Here, we introduce an Er-O bond-length ratio ρ ≡ (Er-O2)/(Er-O1) to further characterize this axial distortion; the smaller ρ, the stronger axial distortion. As seen in Fig. 1(b), with reducing IR(B2) in this series, ρ does not decrease linearly as the lattice constant a does, but tends to level off, which implies that the local CEF environments might change only slightly with further applying chemical or physical pressure. It is worth noting that ρ scales linearly with x.

The availability of Er2Ge2O7 enables us to check the magnetic ground state of XY pyrochlore antiferromagnet with a much reduced lattice dimension and a stronger local structural distortion. The main panel of Fig. 2 displays the temperature dependence of the dc magnetic susceptibility χ(T) of Er2Ge2O7 between 0.7 and 30 K measured under H = 0.1 T after zero-field-cooling (ZFC) from room temperature. A cusplike anomaly at about 1.4 K was clearly observed, in excellent accordance with the measured χ(T) shown in Fig. 2, further confirming a second-order phase transition to an antiferromagnetically ordered state below TN.

In order to extract the magnetic contribution Cm and to estimate the entropy associated with this transition, we measured (C(T)) of an isostructural, nonmagnetic Lu2Ge2O7 pyrochlore as the lattice standard Clat. After subtracting Clat from the measured Ctotal, we obtained the specific-heat contribution from the magnetic Er3+ ions, CEr. As shown in Fig. 3(a), besides the low-temperature peak, there exists a substantial contribution above 10 K associated with the Er3+ CEF levels, CCEF. As the 16-fold degeneracy of Er3+ (J = 15/2) is expected to split into eight doublets in the D3d symmetry, we have tried to simulate the CCEF by considering the first two doublets (two doublets) or the first three doublets (three doublets), respectively. As can be seen, the latter gives a better description to CEr between 15 and 30 K, but both underestimate the measured (C(T)) below 15 K. From the best fitting, the first and second excited doublets are found to be located at 73(6) K and 150(70) K, respectively. The large uncertainty of the second excited doublet arises from the limited fitting range, but the estimated value for the first excited doublet, ~6.3 meV, agrees in general with that of Er2Ti2O7 and Er2Sn2O7 determined from neutron scattering measurements [2,12,13].
Finally, $C_m$ is obtained by $C_m = C_{\text{total}} - C_{\text{CEF}}$, and is shown in Fig. 3(b). The magnetic entropy $S$ obtained by integrating $C_m/T$ almost saturates to its ideal value of $R\ln(2S+1)$ with $S = 1/2$. This points to the effective $S = 1/2$ pseudo-spin character of the magnetic Er$^{3+}$ ions with a Kramers doublet ground state [20]. In addition, greater than 50% of the entropy is found to release above $T_N$, suggesting the existence of profound short-range spin correlations before finally establishing the long-range order. On the other hand, $C_m$ below $T_N$ follows nicely the $T^3$ dependence at least up to 1.1 K, as shown in Fig. 3(c). A linear fitting to $C_m = \sigma T^3$ yields a coefficient $\sigma = 3.14$ J/(mol Er K$^4$). Similar behavior has also been observed in Er$_2$Ti$_2$O$_7$ [2,20].

The observation of a higher $T_N = 1.4$ K in Er$_2$Ge$_2$O$_7$ than that of 1.17 K in Er$_2$Ti$_2$O$_7$ indicated that the chemical pressure applied on the Er$^{3+}$ pyrochlore lattice can promote the long-range antiferromagnetic ordering. This finding motivated us to check if the $T_N$ of Er$_2$Ge$_2$O$_7$ can be further enhanced by applying external physical pressure. Figure 4 displays the ac magnetic susceptibility $\chi'(T)$ of Er$_2$Ge$_2$O$_7$ measured below 2 K under zero magnetic field in the presence of different pressures up to 19.7 kbar. As can be seen, the overall feature of $\chi'(T)$ resembles that of dc $\chi(T)$ data shown in Fig. 2. We defined $T_N$ as the maximum of $\chi'(T)$. At ambient pressure, the measured $T_N = 1.376$ K agrees well with that determined from $\chi(T)$ and $C(T)$. With increasing pressure, $T_N$ shifts gradually to higher temperatures and reaches 1.461 K at 19.7 kbar. The pressure dependence of $T_N(P)$ is shown in the main panel of Fig. 4(b). As can be seen, $T_N$ does not increase linearly with pressure, but seems to saturate with further applying pressure. Thus, the combined chemical and physical pressure study indicated that the long-range antiferromagnetic transition temperature is sensitive to structural changes, but exhibits a complex behavior. We will return to this point below.

We further explored the stability of the long-range antiferromagnetic order under external magnetic fields at each pressure. Figures 5(a)–5(d) present the ambient-pressure ac $\chi'(T)$ data of Er$_2$Ge$_2$O$_7$ under different magnetic fields $H_{dc}$ up to 6 T. As can be seen in Fig. 5(a), the $\chi'(T)$ under $H_{dc} = 0.1$ T resembles the dc $\chi(T)$ curve shown in Fig. 2, showing a relatively broad cusplike anomaly around $T_N = 1.4$ K followed by a low-temperature upturn. This comparison thus confirms our ac susceptibility data obtained by using a home-made primary-secondary coil. The small peaklike feature in the zero-field $\chi'(T)$ curve smears out immediately upon the application of external fields. With increasing $H_{dc}$, the evolution of $\chi'(T)$...
can be divided into four regions: (1) for $0 \leq H_d \leq 0.2$ T, $T_N$ remains essentially constant; $\chi^\prime(T)$ is nearly unchanged for $T > T_N$, but is enhanced dramatically for $T < T_N$; (2) for $0.3 \leq H_d \leq 1.0$ T, $T_N$ decreases slightly and the low-temperature upturn in $\chi^\prime(T)$ is suppressed gradually; (3) for $1.0 \leq H_d \leq 2.3$ T, the cusplike anomaly of $\chi^\prime(T)$ at $T_N$ transforms to a broad maximum, which shifts progressively to lower temperatures with increasing $H_d$ and completely disappears around $2.3$ T; (4) for $2.3 < H_d \leq 6.0$ T, no anomaly can be discerned in $\chi^\prime(T)$ and the magnitude of $\chi^\prime(T)$ in the measured temperature region drops quickly. Similar features were observed for $\chi(T)$ data under different high pressures. The evolution of $\chi^\prime(T)$ in these four regions can be tracked by monitoring the field dependence of $\chi^\prime(T)$ at $T = 0.35$ K, the lowest temperature of our present study. As shown in Fig. 5(e), $\chi^\prime(H)$ curves at different pressures all exhibit a double-peak structure: the first peak corresponds to the initial enhancement of $\chi^\prime(T)$ below $T_N$ under low $H_d$, and the second peak to the critical magnetic field $H_c$ where $T_N$ is suppressed to below 0.35 K. As can be seen, upon application of external pressure, the first peak does not exhibit noticeable change, whereas the second peak moves gradually to higher temperatures, consistent with the enhancement of $H_c$ with pressure. Finally, the field dependencies of $T_N(H)$ determined from $\chi^\prime(T)$ data at different pressures are summarized in Fig. 5(f). It is clear that both $T_N$ and $H_c$ increase with pressure. These results demonstrated that, on the one hand, the application of external magnetic field destabilizes the long-range antiferromagnetic order, leading to a zero-temperature quantum critical point around $H_c = 2.3$ T at ambient pressure, and on the other hand, the application of physical pressure stabilizes the long-range antiferromagnetic order, leading to an enhancement of both $T_N$ and $H_c$.

In order to gain insights into the high-field phase above $H_c$, we turn to the temperature and field dependence of dc magnetization. As shown in Fig. 6(a), the dc $\chi(T)$ data under different magnetic fields resemble those of ac $\chi^\prime(T)$ data shown in Figs. 5(a)–5(d). The $\chi(T)$ curve measured under $H = 4$ T $> H_c$ exhibits a ferromagnetic like saturation behavior, which suggested that the sample enters a highly polarized state under $H > H_c$. This is confirmed by the $M(H)$ measurement below $T_N$. As shown in Fig. 6(b), the $M(H)$ curve measured at $T = 0.6$ K displays a clear slope change around $H_c = 2.3$ T, which corresponds to a sharp peak in the $dM/dH$ curve and signals a field-induced spin-flip transition from an antiferromagnetic state for $H < H_c$ to a highly polarized state for $H > H_c$. The weak peak located around 0.2 T in both $dM/dH$ and $\chi^\prime(H)$ curves might be associated with the alignment of magnetic domains.

Our detailed characterizations on the cubic Er$_2$Ge$_2$O$_7$ pyrochlore thus confirm that it develops into long-range antiferromagnetic order below $T_N = 1.4$ K, with several similar characteristics as its sister compound, Er$_2$Ti$_2$O$_7$, as detailed below: (1) the $\chi(T)$ data evidences a continuous, second-order phase transition; (2) the magnetic specific heat follows the $C_m \sim T^3$ dependence below $T_N$; (3) the magnetic entropy saturates to the expected value of $R\ln2$ for $S = \frac{1}{2}$; (4) a quantum critical point (QCP) can be reached by suppressing the $T_N$ smoothly to zero temperature via the application of external magnetic fields. It has been well known that the first two observations contradict classical theories [2], which predicted a first-order transition with a constant density of low-lying excitations. Very recent studies have achieved significant progress on this problem. Zhitomirsky et al. [4] calculated the low-energy excitation spectrum of Er$_2$Ti$_2$O$_7$ based on an effective “pseudodipolar” spin-1/2 model, and found a gapless mode with linear dispersion, which can account for the experimentally observed $C_m \sim T^3$ dependence as well as the inelastic neutron spectrum. Savary et al. [5] proposed that the slope $\sigma$ is related to the mean-spin-wave velocity $\bar{v}$ of the pseudo-Goldstone mode, i.e., $\sigma = k_B^2 \pi^2 a^2/120 \bar{v}^3$. By using the experimental values of $\sigma$ (Er$_2$Ge$_2$O$_7$) = $3.14$ J/(mol Er K$^4$) obtained in the present study and the $\sigma$ (Er$_2$Ti$_2$O$_7$) = $4.6$ J/(mol Er K$^4$) [5], as well as the lattice constants shown in Table 1, we can estimate that $\bar{v}$ of Er$_2$Ge$_2$O$_7$ is about 1.11 times that of Er$_2$Ti$_2$O$_7$, roughly consistent with the ratio of $T_N$, i.e., 1.19, since the velocity $\bar{v}$ is roughly proportional to the overall exchange interactions (see Supplemental Material of Ref. [5]). Based on an effective pseudo-spin-1/2 Hamiltonian with anisotropic exchange interactions, the experimentally observed noncoplanar $\psi_2$ state for Er$_2$Ti$_2$O$_7$ has recently been confirmed to be selected by the quantum fluctuations via the OBD mechanism [4–6]. The importance of quantum fluctuations is consistent with the observation (3), which points to an effective $S = 1/2$ pseudo-spin character of the ground state Kramers doublet of Er$^{3+}$ ions. By means of single-crystal neutron scattering measurements, Ruff et al. [3] have shown explicitly that the magnetic-field-induced QCP in Er$_2$Ti$_2$O$_7$ corresponds to a smooth transformation from the noncoplanar $\psi_2$ structure to a highly polarized XY state. Although neutron scattering measurements are needed to determine if Er$_2$Ge$_2$O$_7$ adopts a similar magnetic structure as Er$_2$Ti$_2$O$_7$, our magnetization curves shown in Fig. 6 as well as the field-induced QCP states of Er$_2$Ge$_2$O$_7$ offers us an excellent opportunity to look into the critical factors governing the magnetic ground state of the Er$_2$B$_2$O$_7$ series, a family of $XY$ pyrochlore antiferromagnets. As mentioned earlier, although short-range

FIG. 6. (Color online) (a) Temperature dependence of the dc magnetic susceptibility $\chi(T)$ under different magnetic fields up to 4 T. (b) Magnetization curve $M(H)$ and its derivative $dM/dH$ measured at $T = 0.6$ K.
correlations with the Palmer-Chalker configurations have been detected in Er₂Sn₂O₇,[11,12] it does not show any long-range order down to 100 mK. In contrast, Er₂Ti₂O₇ undergoes an antiferromagnetic transition at $T_N = 1.173$ K [2]. The observed higher $T_N$ in Er₂Ge₂O₇ clearly indicated that the application of chemical pressure plays an important role in determining the magnetic ground state. This conclusion is further supported by our high-pressure $\chi'(T)$ results shown in Fig. 4, where the application of physical pressure can further enhance $T_N$ of Er₂Ge₂O₇. This is understandable since the strength of exchange interactions $J_{\text{ex}}$ including the nearest- and the next-nearest-neighbor ones should be reinforced dramatically with decreasing $R_{\text{nn}}$. Earlier numerical calculations by Bramwell et al. [1] have predicted that the long-range order of $XY$ pyrochlore antiferromagnets takes place at $T_N \sim 0.1 J_{\text{ex}}$. Recent investigations have realized the importance of anisotropic exchange interactions for the $XY$ pyrochlore antiferromagnets; the ground-state phase diagrams were found to be very sensitive to the minute change of the relative magnitude of these anisotropic exchange couplings $J_{\text{ex}} \equiv \{ J_{\text{xx}}, J_{\text{kk}}, J_{\text{kk}}, J_{\text{zz}} \} [6,7]$. As shown in Fig. 1(b), the effect of chemical pressure applied on the Er₃⁺ pyrochlore lattice via reducing the IR of B₄⁺ ions is at least twofold: (1) a global, uniform reduction of lattice dimension that reduces the nearest-neighbor Er³⁺ distance $R_{\text{nn}}$ and (2) a strengthening of the local axial distortion of ErO₈ polyhedron that can change the local CEF environment of Er³⁺ ions. Both factors are expected to change effectively the relative magnitude of these four independent anisotropic exchange couplings $J_{\text{ex}}$, and thus $T_N$.

Although our combined chemical and physical pressure studies demonstrated unambiguously an intimate correlation between $T_N$ and structural changes, we cannot reach a simple relationship between $T_N$ and $R_{\text{nn}}$. By using a bulk modulus $B_0 = 228 (4)$ GPa determined from our high-pressure XRD measurements on Er₂Ge₂O₇, we have determined $R_{\text{nn}}(P)$ and plotted the $T_N$ of Er₂Ge₂O₇ as a function of $R_{\text{nn}}$ in the inset of Fig. 4(b). As can be seen, the ambient-pressure data of Er₂Ti₂O₇ does not fall on the extrapolated curve of $T_N(R_{\text{nn}})$ of Er₂Ge₂O₇. This observation indicated that in addition to $R_{\text{nn}}$, the subtle changes of local CEF environment also influence dramatically $J_{\text{ex}}$ and $T_N$. Although the resolution of our high-pressure XRD does not allow us to extract reliable information regarding the local distortion, the observations that both the Er-O bond-length ratio $\rho = (\text{Er-O2})/(\text{Er-O1})$ in Fig. 1(b) and $T_N(P)$ in Fig. 4(b) tend to saturate with reducing $R_{\text{nn}}$ imply an important correlation between $T_N$ and the local distortions of Er³⁺ ions. To gain a better understanding, future studies on the solid solutions of Er₂(Ge₁₋ₓTiₓ)₂O₇ are planned with a focus on the detailed evolutions of $T_N$ and local structural changes.

In summary, we have prepared the cubic Er₂Ge₂O₇ pyrochlore under 7 GPa and 1000 °C and characterized in details its magnetic ground state by measuring low-temperature specific heat, dc and ac magnetic susceptibility under external pressure and magnetic fields. We found that Er₂Ge₂O₇ forms a long-range antiferromagnetic order below $T_N \approx 1.4$ K, with similar characteristics as the well-studied Er₂Ti₂O₇. The application of external magnetic fields suppresses the antiferromagnetic order continuously to zero temperature and leads to a highly polarized state above $H_c \approx 2.3$ T. On the other hand, the application of physical pressure can stabilize antiferromagnetic order, leading to higher $T_N$ and $H_c$. Neutron scattering experiments are planned to determine the magnetic structure and excitations of this $XY$ pyrochlore antiferromagnet.

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