

Antiferromagnetic ordering and critical behavior induced giant magnetocaloric effect in distorted kagome lattice Gd_3BWO_9

Zhuoqun Wang,^{1,*} Xueling Cui^{1,*} Tim Treu² Jiesun Guo¹ Xinyang Liu,^{1,3,4} Marvin Klinger² Christian Heil² Nvsen Ma,¹ Xianlei Sheng,¹ Zheng Deng,^{3,5} Xingye Lu,⁶ Xiancheng Wang,^{3,5} Wei Li,^{4,7} Philipp Gegenwart² Changqing Jin,^{3,5} and Kan Zhao^{1,†}

¹*School of Physics, Beihang University, Beijing 100191, China*

²*Experimentalphysik VI, Center for Electronic Correlations and Magnetism, University of Augsburg, 86159 Augsburg, Germany*

³*Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China*

⁴*CAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China*

⁵*School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 100190, China*

⁶*Center for Advanced Quantum Studies, School of Physics and Astronomy, Beijing Normal University, Beijing 100875, China*

⁷*Peng Huanwu Collaborative Center for Research and Education, Beihang University, Beijing 100191, China*



(Received 18 April 2025; revised 31 July 2025; accepted 21 August 2025; published 16 September 2025)

We synthesize the high-quality Gd_3BWO_9 single crystal and investigate its low-temperature magnetic and thermodynamic properties. Below $T_N = 1.08$ K, the anisotropic behavior of magnetic susceptibilities reveals that the Gd^{3+} moments exhibit the dominant antiferromagnetic coupling along the c axis, while displaying a ferromagnetic arrangement in kagome plane. With pronounced magnetic frustration, in adiabatic demagnetization refrigeration experiments starting from initial conditions of 9 T and 2 K, Gd_3BWO_9 polycrystal reaches a minimum temperature of 0.151 K, significantly lower than its T_N . Due to the high density of Gd^{3+} ions ($S = 7/2$), the maximum magnetic entropy change reaches over $50 \text{ J kg}^{-1} \text{ K}^{-1}$ under fields up to 7 T in Gd_3BWO_9 , nearly 1.5 times as large as commercial sub-kelvin magnetic coolant $\text{Gd}_3\text{Ga}_5\text{O}_{12}$. The H - T phase diagram of Gd_3BWO_9 under $\mathbf{H} \parallel c$ exhibits field-induced critical behavior near the phase boundaries. This observation aligns with the theoretical scenario in which a quantum critical point acts as the endpoint of a line of classical second-order phase transitions. Such behavior suggests the importance of further investigations into the divergence of the magnetic Grüneisen parameter in the vicinity of critical field at ultralow temperatures.

DOI: [10.1103/716y-hdw5](https://doi.org/10.1103/716y-hdw5)

I. INTRODUCTION

Geometrically frustrated magnets are typically characterized by competing interactions of localized spins that provide a unique platform for exploring exotic quantum magnetic states. Typical examples are antiferromagnets where transition metal ions or $4f$ rare-earth ions form the kagome lattice, giving rise to strong electron correlations, spin-orbit coupling, and/or magnetic interaction [1–3]. In recent years, various antiferromagnets based on kagome lattice and its modifications have been extensively studied, including both insulators and metals, such as the quantum spin liquid candidates $\text{ZnCu}_3(\text{OH})_6\text{Cl}_2$ [4], quantum antiferromagnet $\text{BaCu}_3\text{V}_2\text{O}_8(\text{OH})_2$ [5], tripod-kagome-lattice dipolar magnet $\text{Dy}_3\text{Sb}_3\text{Zn}_2\text{O}_{14}$ [6,7], distorted kagome lattice heavy fermion system CePdAl [8–11] and kagome spin ice HoAgGe [12–14], and three-dimensional hyperkagome-lattice quantum spin liquid candidate $\text{PbCuTe}_2\text{O}_6$ [15,16].

Quite recently, the rare-earth-based systems R_3BWO_9 ($\text{R} = \text{Pr}, \text{Nd}, \text{Sm}, \text{Gd}, \text{Tb}, \text{Dy}, \text{Ho}$) have attracted considerable attention as searching for new kagome antiferromagnets [17]. These compounds crystallize in a hexagonal coordinated

structure with space group $P6_3$ (no. 173), where the R^{3+} ions are connected by oxygen ions and form a distorted kagome lattice in the ab plane [Fig. 1(a)] and stack in an AB-type arrangement along the c axis [Fig. 1(b)]. Notably, the interlayer separations between R^{3+} ions are slightly smaller than the intralayer distances [Fig. 1(b)], which enhances the three-dimensional nature of the magnetic interaction in R_3BWO_9 [17]. The non-Kramers system Pr_3BWO_9 has been identified as a frustrated quantum Ising magnet [18,19]. The Kramers system Nd_3BWO_9 exhibits short-range correlations below 1 K and enters the long-range magnetic order state below 0.3 K, accompanied by anisotropic field-induced metamagnetic quantum criticalities. The rich magnetic behavior of Nd_3BWO_9 can be understood through the Ising model composed of twisted triangular spin tubes [20–22]. For Sm_3BWO_9 , a magnetic phase transition occurs at 0.75 K and nuclear magnetic resonance spectra reveal an incommensurate magnetic order [23]. The polycrystalline studies of Gd_3BWO_9 demonstrate a giant magnetocaloric effect (MCE) while the magnetic structure remains unclear [24,25]. Therefore, investigating the anisotropic properties of Gd_3BWO_9 single crystals is crucial for understanding the microscopic mechanism of the MCE.

In this article, based on the magnetic susceptibilities along the a and c axes, we demonstrate that the Gd^{3+} moments are aligned antiferromagnetically along the c axis and

*These authors contributed equally to this work.

†Contact author: kan_zhao@buaa.edu.cn

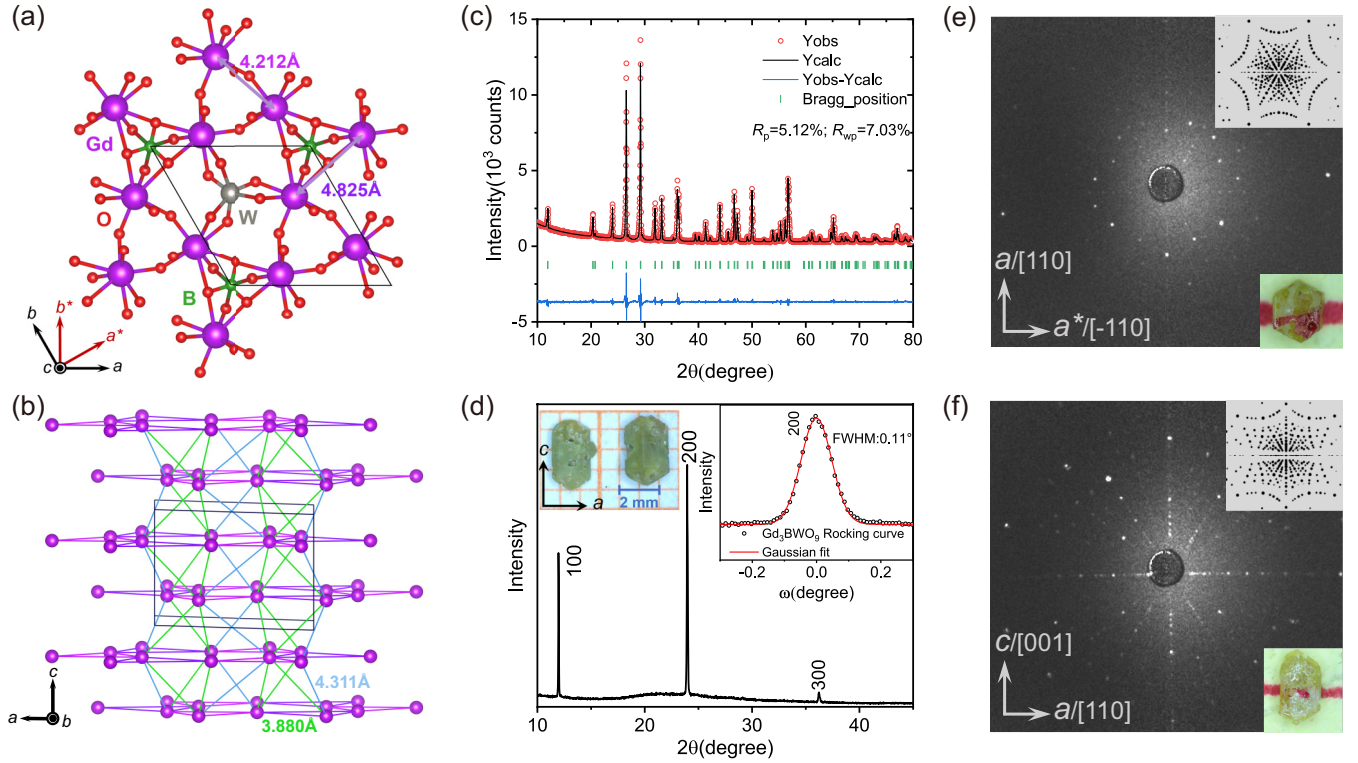


FIG. 1. Crystal structure of Gd_3BWO_9 . (a) The schematic structure of Gd_3BWO_9 reflecting the distorted kagome lattice in the crystallographic ab plane. (b) The well-separated distorted kagome planes are stacked along the c axis of Gd_3BWO_9 . (c) The experimental XRD patterns of Gd_3BWO_9 powder. (d) X-ray diffraction pattern of Gd_3BWO_9 single crystal. Left inset: an optical image of typical single crystals. Right inset: the rocking curve (black line) of the (200) Bragg peak, together with the Gaussian fitting (red line) of Gd_3BWO_9 . (e), (f) The experimental and simulated Laue diffraction patterns of the ab and ac plane of Gd_3BWO_9 , respectively.

ferromagnetically in the ab plane below $T_N = 1.08$ K. Below T_N , the metamagnetic transitions of the Gd_3BWO_9 single crystal are identified through magnetization and thermodynamic measurement under $\mathbf{H} \parallel c$. We continue to construct a phase diagram of magnetic entropy as a function of temperature and magnetic field along the c axis, revealing a giant MCE at low temperature. Our work on the Gd_3BWO_9 single crystal offers significant insights into its microscopic magnetic structure, magnetic critical behavior, and the associated giant MCE.

II. EXPERIMENT

The polycrystalline Gd_3BWO_9 is synthesized using a standard solid-state reaction method by mixing stoichiometric amounts of predried Gd_2O_3 , H_3BO_3 , and WO_3 . The powders are ground together and sintered in air at 1200°C for 36 h, with several intermittent regrindings. High-quality single crystals of Gd_3BWO_9 were grown via flux method analogous to Ref. [26]. Yellow transparent single crystals with six hexagonal facets are obtained and have a typical mass ranging from a few milligrams to 100 mg [inset of Fig. 1(d)]. The X-ray diffraction (XRD) patterns and rocking-curve scans are collected using a Bruker D8 ADVANCE diffractometer with $\text{Cu-K}\alpha$ radiation ($\lambda = 1.5406 \text{ \AA}$) at room temperature. Crystal orientation verification is performed using a Laue X-ray alignment system (Photonic Science Ltd.). The magnetic susceptibility and magnetization are measured as a

function of the applied field (0 to 7 T) and temperature (0.4 to 300 K) using a Magnetic Property Measurement System SQUID magnetometer (MPMS, Quantum Design) equipped with a ^3He -refrigerator insert. Specific heat measurements are performed using a Physical Property Measurement System (PPMS, Quantum Design) under applied magnetic fields of 3 T and 7 T with a ^3He option and in zero field (0 T) with a ^3He – ^4He dilution refrigerator.

For the adiabatic demagnetization refrigeration (ADR) experiment in PPMS, we used a 4.38 g cylindrical pellet of 15 mm diameter and 4 mm thickness containing equal weights of Gd_3BWO_9 and silver powder. The pressed pellet was sintered at 800°C to further improve the thermal conductivity. The sample temperature was measured using a custom-built thermometer based on a commercial ruthenium oxide chip resistor. This thermometer was calibrated against a known reference thermometer and read out with a Lake Shore Model 372 AC resistance bridge, equipped with a Model 3726 scanner, operating at an AC excitation of 1 nA.

III. RESULT AND DISCUSSION

A. Crystal structure

Figure 1(c) shows the room-temperature powder X-ray diffraction pattern and Rietveld refinement of Gd_3BWO_9 . The observed profile aligns well with the simulation, yielding refinement reliability factors $R_p = 5.12\%$ and $R_{wp} = 7.03\%$. The structural parameters determined from the Rietveld

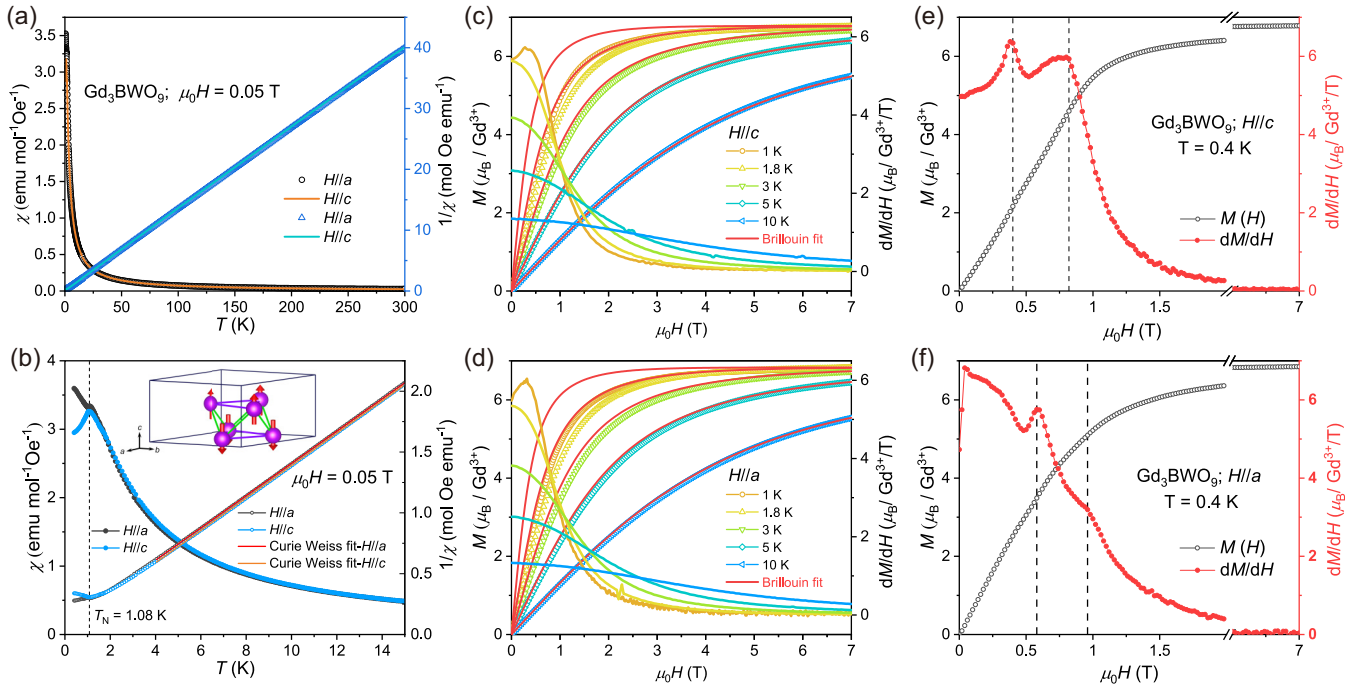


FIG. 2. Magnetic properties of Gd_3BWO_9 under $\mathbf{H} \parallel a$ and $\mathbf{H} \parallel c$. (a) The susceptibility $\chi(T)$ and the inverse magnetic susceptibility $1/\chi(T)$ of Gd_3BWO_9 for $\mathbf{H} \parallel a$ and $\mathbf{H} \parallel c$ under 500 Oe. (b) The low-temperature part of (a). The inset of (b): a schematic of the magnetic structure in Gd_3BWO_9 ; the green and purple lines constitute triangles connecting Gd ions in an adjacent kagome plane (3.880 Å) and within a kagome plane (4.825 Å). (c), (d) Isothermal magnetization $M(H)$ and the derivative $[dM(H)/dH]$ curves for selected temperatures of 1, 1.8, 3, 5, and 10 K along the c and a axes. The solid red lines show the Brillouin function fits. (e), (f) $M(H)$ and $dM(H)/dH$ curves along c and a axes at 0.4 K. The dotted lines represent the features.

profile analysis are $a = 8.564(1)$ Å and $c = 5.402(1)$ Å, consistent with previous reports [17,25]. The distances between Gd and Gd in the kagome plane are 4.212 Å and 4.825 Å [Fig. 1(a)], while those in adjacent kagome planes are 3.880 Å and 4.311 Å [Fig. 1(b)]. The four comparable distances highlight the three-dimensional characteristics of the magnetic interaction. The complete crystal data are provided in the Supplemental Material [27].

Moreover, we have grown large-size single crystals by flux method, with typical crystals shown in the left inset of Fig. 1(d). The XRD patterns of the bc plane [Fig. 1(d)] display dominant ($H00$) reflections. Rocking curve analysis of the Bragg peak (200) [right inset of Fig. 1(d)] demonstrates a narrow full width at half maximum (FWHM) of 0.11° , indicating high quality of the single crystal. As illustrated in Figs. 1(e) and 1(f), the sixfold symmetry of the Laue pattern agrees well with the experimental simulation data, based on the crystal structure presented in Figs. 1(a) and 1(b).

B. Magnetic susceptibility and magnetization

Figure 2(a) presents the temperature dependence of magnetic susceptibility $\chi(T)$ and inverse susceptibility $1/\chi(T)$ for $\mathbf{H} \parallel a$ and $\mathbf{H} \parallel c$, measured from 0.4 K to 300 K under 0.05 T. For a low-temperature region (4–15 K) in Fig. 2(b), the Curie-Weiss temperature is determined to be -0.6 K for $\mathbf{H} \parallel a$ and -0.4 K for $\mathbf{H} \parallel c$, revealing the competition between predominant antiferromagnetic (AFM) interaction in adjacent layers and relatively weak intralayer ferromagnetic (FM) interaction within the triangular framework of Gd_3BWO_9

[inset of Fig. 2(b)]. For a high-temperature region (200–300 K), the effective moment is calculated to be $7.82 \mu_B$ for both field orientations, close to the expected value of $7.94 \mu_B$.

The low-temperature $\chi(T)$ [Fig. 2(b)] shows an obvious peak centered at $T_N = 1.08$ K, signaling long-range AFM ordering. Above T_N , isotropic susceptibility behavior reflects the absent orbital component of Gd^{3+} moments. Below T_N , the $\chi(T)$ increases with the temperature decreasing under $\mathbf{H} \parallel a$, whereas it decreases under $\mathbf{H} \parallel c$. This anisotropic behavior demonstrates characteristic AFM ordering along the c axis. As mentioned above, the nearest interlayer distance between Gd^{3+} ions significantly enhances the AFM interaction along the c axis, serving as the primary reason for magnetic ground state properties. Our experimental results provide direct evidence supporting the magnetic structure [inset of Fig. 2(b)] predicted by density functional theory (DFT) [24]. Similar phenomena have been observed in Eu^{2+} containing EuMnBi_2 [28] and EuMnSb_2 [29]. In EuMnBi_2 , the Eu moments order ferromagnetically in the ab plane and align along the c axis in the sequence of up-up-down-down below $T_N \sim 22$ K, where the $\chi(T)$ parallel to the c axis steeply decreases while it slightly increases vertical to the c axis [28].

Figures 2(c) and 2(d) depict the isothermal magnetization curves $M(H)$ at various temperatures and the magnetic moment is derived to be $6.85 \mu_B$ for $\mathbf{H} \parallel a$ and $6.78 \mu_B$ for $\mathbf{H} \parallel c$ at 0.4 K under 7 T, slightly smaller than the theoretical value $7 \mu_B$. The $M(H)$ data can be well fitted to Brillouin function above $T = 5$ K, which reveals the paramagnetic coupled nature between Heisenberg-like spins of Gd^{3+} ions. Below 5 K, the deviation of the fitted curve at 3 K

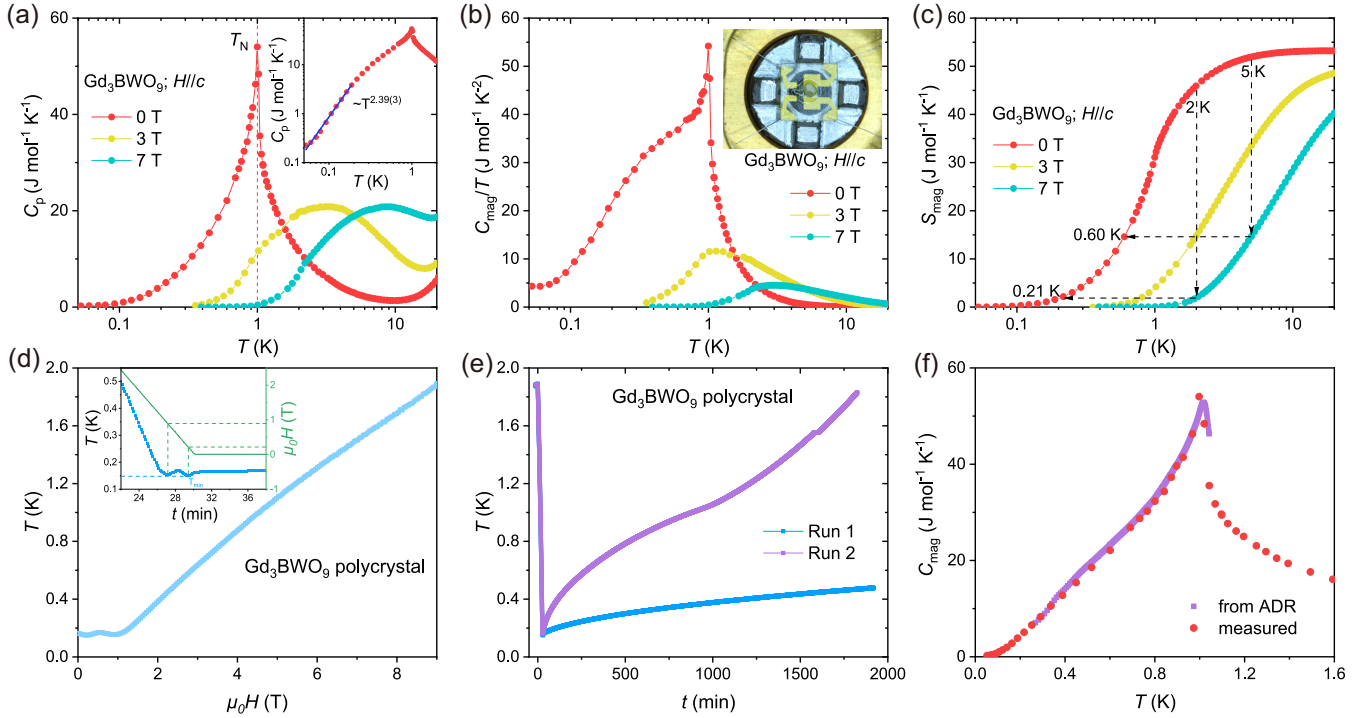


FIG. 3. Specific heat result of Gd₃BWO₉ along $\mathbf{H} \parallel c$ and ADR of Gd₃BWO₉ polycrystal. (a) Total specific heat $C_p(T)$ measured down to 0.05 K in zero field and 0.39 K in applied fields 3 T and 7 T along $\mathbf{H} \parallel c$. The inset shows a power law fit from 0.05 to 0.2 K in zero field. (b) Magnetic specific heat as $C_{\text{mag}}(T)/T$ in a logarithmic presentation at 0, 3, and 7 T. The inset shows a photo of the sample on the platform of the specific-heat puck. (c) Temperature variation of the magnetic entropy S_{mag} computed from the heat capacity data of Gd₃BWO₉ for $\mathbf{H} \parallel c$. The arrows designate the adiabatic demagnetization process starting from initial temperatures of 2 K and 5 K under 7 T. (d) The cooling curve of Gd₃BWO₉ polycrystal in the ADR process starting from 9 T and 2 K (slightly shifted due to the neglect of the magnetoresistance of the thermometer). The inset shows the process around T_{min} . (e) The temperature evolution was measured over a period exceeding 30 h, with Run 1 conducted in the absence of a resistance heater. (f) The heat capacity calculated from the warming curve of the ADR experiment and directly measured in the PPMS.

and 1.8 K indicates the appearance of short-range spin correlations.

To further analyze the magnetic properties of Gd₃BWO₉, Figs. 2(e) and 2(f) display the field derivative of magnetization dM/dH curves at 0.4 K. For the dM/dH curve under $\mathbf{H} \parallel a$ in Fig. 2(f), a pronounced peak is observed at 0.58 T, where the magnetization reaches $3.50 \mu_B$, close to 1/2 of the saturated value (M_s^a). Additionally, a shoulder feature is present at 0.96 T, with the M value of $5.10 \mu_B$ roughly $3/4 M_s^a$. In the case of $\mathbf{H} \parallel c$ [Fig. 2(e)], a sharp peak appears at 0.40 T, followed by a shoulder at 0.82 T. The respective M values are $2.17 \mu_B$ and $4.60 \mu_B$, corresponding to approximately 1/3 and 2/3 of the saturated value (M_s^c), respectively. It would be valuable to investigate which variations in magnetic order states are associated with these anomalies in the dM/dH curves. Remarkably, the magnetization curve of Nd₃BWO₉ exhibits a 1/3 fractional plateau for $\mathbf{H} \parallel c$ in the AFM order state, where the dM/dH curve approaches zero in the vicinity of the plateau region [20–22].

C. Specific heat, magnetic entropy, and magnetocaloric effect

To study thermodynamic properties of Gd₃BWO₉, the specific heat $C_p(T)$ measurements are performed down to 0.05 K in zero field and 0.39 K in applied fields of 3 T and 7 T, as

depicted in Fig. 3(a). The zero-field specific heat data displays a λ -shaped anomaly at T_N , consistent with the magnetic result above. The peak shape in $C_p(T)$ changes to a Schottky-type anomaly in an applied field of 3 T and 7 T.

Below T_N , the specific heat mainly comes from the magnetic contribution. As shown in the inset of Fig. 3(a), the zero-field $C_{\text{mag}}(T)$ from 0.05 K to 0.2 K is fitted to a power law expression: $C_{\text{mag}}(T) \sim T^\gamma$, yielding $\gamma = 2.39(3)$, lower than the value of 3 typically observed in conventional gapless antiferromagnets [30]. In the triangular antiferromagnet KBaGd(BO₃)₂, the power law relationship with an exponent $\gamma = 2.0$ reflects the two-dimensional (2D) magnetic interaction intrinsic to the system [31–33]. In the pyrochlore Heisenberg antiferromagnet Gd₂Sn₂O₇, specific heat and inelastic neutron scattering (INS) measurements reveal the presence of magnon excitations with a gap ~ 1.5 K [34–36]. According to INS, the spin-spin correlations begin to develop around 20 K and eventually form a gapped long-range ordered “Palmer Chalker” state below $T_C = 1$ K. Below 0.3 K, the $C_{\text{mag}}(T)$ drops exponentially and its value drops to $0.02 \text{ J mol}_{\text{Gd}}^{-1} \text{ K}^{-1}$ near 0.1 K [35]. In contrast, the $C_{\text{mag}}(T)$ of Gd₃BWO₉ displays a value around $0.2 \text{ J mol}_{\text{Gd}}^{-1} \text{ K}^{-1}$ at 0.1 K, an order of magnitude larger than that of Gd₂Sn₂O₇. Furthermore, the $C_{\text{mag}}(T)/T$ approaches a constant value of

4.3 J mol⁻¹K⁻² below 0.07 K [Fig. 3(b)], indicating the unconventional gapless low-energy excitations in Gd₃BWO₉.

The lattice contribution arising from thermal vibration dominates the high temperature region. As shown in Fig. S1, an analysis is performed by fitting the zero-field specific heat data using a polynomial expression $C_{ph} = \beta_1 T^3 + \beta_2 T^5 + \beta_3 T^7 + \dots$ [24], between 20 K and 50 K. The magnetic specific heat is obtained by subtracting the lattice contributions $C_{mag} = C_p - C_{ph}$. As temperature decreases, the zero-field $C_{mag}(T)/T$ curve of Gd₃BWO₉ begins to increase below 5 K and reaches its maximum value at T_N [Fig. 3(b)]. The magnetic entropy $S_{mag}(T)$ is obtained by integrating $C_{mag}(T)/T$ data [Fig. 3(b)] and the value of $S_{mag}(T)$ is slightly larger than $3R\ln 8$ at 20 K in zero field [Fig. 3(c)].

To estimate the minimum temperature in ADR, the adiabatic demagnetization process is roughly depicted by arrows in Fig. 3(c) [31,32]. The $S_{mag}(T)$ is reduced by 44.02 J mol⁻¹K⁻¹ when applying a field of $\mu_0 H = 7$ T from an initial temperature $T_0 = 2$ K (isothermal). Driving the field back to 0 T adiabatically is supposed to cool the material to 0.21 K. When initiating from $T_0 = 5$ K under 7 T, the material could cool down to 0.60 K with the $S_{mag}(T)$ reduction of 37.33 J mol⁻¹K⁻¹. Similarly, the commercial magnetic coolant Gd₃Ga₅O₁₂ (GGG) achieves a minimum temperature of 0.32 K with an initial condition of $T_0 = 2$ K and $\mu_0 H = 6$ T [33,37] and another spin chain containing antiferromagnet NaGdP₂O₇ achieves a minimum temperature of 0.22 K with $T_0 = 2$ K and $\mu_0 H = 5$ T [38].

We continue to directly test the refrigeration performance of Gd₃BWO₉ polycrystal using the modified ADR cooling setup reported in Refs. [32,38,39]. Starting from an initial condition 2 K and 9 T, the sample temperature instantaneously decreases as soon as the field begins to decrease. Upon ramping the field down to zero at a sweep rate of 5 mT/s, a local minimum $T_{min2} = 0.156$ K is achieved at $\mu_0 H = 0.90$ T and another minimum $T_{min1} = 0.151$ K is achieved at $\mu_0 H = 0.22$ T in Run 1 [Fig. 3(d)], consistent with the estimated value 0.21 K under 2 K and 7 T condition. We will discuss the temperature minimum and phase boundary later. The temperature starts to increase from $T_0 = 0.164$ K as the magnetic field drops to zero [inset of Fig. 3(d)]. As depicted in Fig. 3(e), the warm-up time from T_0 up to 0.48 K exceeded 24 h in Run 1, indicating exceptional holding time.

To calculate the specific heat of the Gd₃BWO₉ sample from ADR, we conduct a second run with a resistance heater on the pellet. As shown in Fig. 3(e), there seems to be a slope change in the warming curve around $T_N = 1.08$ K, due to the AFM ordering of Gd₃BWO₉. As the external resistive heat input was accurately measured and found to be nearly constant as $\dot{Q} = 1.4 \mu W$, much larger than the natural heat leakage into the system, which is below 100 nW, the slope of the warming curve is closely associated with the sample's heat capacity. According to $\dot{Q} = C_{ADR} \dot{T}$, C_{ADR} obtained in Run 2 is in good agreement with the "directly" measured heat capacity [Fig. 3(f)].

In order to gain deeper insights into the MCE of Gd₃BWO₉, the magnetic entropy change $-\Delta S_{mag}$ is calculated based on the $M(H)$ curves in Fig. S2, through Maxwell's thermodynamic relation $-\Delta S_{mag} = -\int_0^H (\frac{\partial M}{\partial T})_{P,H} dH$ [24].

For each curve, we have used two sets of $M(H)$ data at temperatures $T - \Delta T$ and $T + \Delta T$. Through $\partial M / \partial T \approx \Delta M / \Delta T = [M(T + \Delta T, H) - M(T - \Delta T, H)] / 2\Delta T$ [Figs. 4(a) and 4(b)], the field dependence of the entropy $-\Delta S_{mag}(H)$ could be obtained by integrating $\Delta M / \Delta T$ over the field range [38,40]. For instance, the $-\Delta S_{mag}(H)$ of 0.7 K is calculated from the $M(H)$ of 0.4 K and 1 K.

The field variation of $-\Delta S_{mag}$ is shown in Fig. 4(c) for $H \parallel a$ and Fig. 4(d) for $H \parallel c$, respectively. The contour plots of $-\Delta S_{mag}$ for $H \parallel c$ [Fig. 4(e)] are similar to the polycrystalline data [24,25]. According to the $-\Delta S_{mag}$ for $H \parallel c$, the temperature dependence of $-\Delta S_{mag}$ is depicted under different fields in Fig. 4(f) and the $-\Delta S_{mag}(T)$ derived from $C_{mag}(T, H)$ data closely matches the $-\Delta S_{mag}(T)$ curves calculated from $M(H, T)$ data. Given the high spin state and high density of Gd³⁺ ions, the theoretically calculated $-\Delta S_{mag}$ reaches 51.87 J mol⁻¹K⁻¹ (63.99 J kg⁻¹K⁻¹) for Gd₃BWO₉ and the volumetric entropy density reaches 483 mJ K⁻¹cm⁻³, surpassing most Gd-oxide magnets, including GGG (363 mJ K⁻¹cm⁻³), GdPO₄ (401 mJ K⁻¹cm⁻³), and KBaGd(BO₃)₂ (192 mJ K⁻¹cm⁻³), while remaining comparable to Gd_{9.33}[SiO₄]₆O₂ (509 mJ K⁻¹cm⁻³) [41]. During our experiment, the $-\Delta S_{mag}$ achieves the maximum value 43.32 J mol⁻¹K⁻¹ (53.45 J kg⁻¹K⁻¹) and 42.82 J mol⁻¹K⁻¹ (52.83 J kg⁻¹K⁻¹) at 2.1 K under fields up to 7 T along a and c axes, accounting for 83.5% and 82.6% of the theoretical value, respectively. These values exceed the maximum value of GGG (38.4 J kg⁻¹K⁻¹) at 2 K under a 7 T field [42,43]. The large volumetric entropy density, magnetic entropy change, and low temperature in ADR suggest that Gd₃BWO₉ holds significant potential for refrigeration applications.

D. Phase diagram and magnetic critical behavior under $H \parallel c$

More interestingly, at $T = 0.7$ K < T_N , the value of $-\Delta S_{mag}$ is negative when the magnetic field is less than 1 T for $H \parallel c$, while it is always positive for $H \parallel a$ [Figs. 4(c) and 4(d)]. This anisotropic response can be attributed to the dominant AFM coupling along the c axis between Gd³⁺ ions. The emergence of two anomalies in the dM/dH curve under $\mu_0 H = 0.40$ T and 0.82 T at $T = 0.4$ K may be associated with critical behavior in thermodynamic properties. Below, we map the phase diagram for $H \parallel c$ with more detailed magnetic and thermodynamic data.

As shown in Fig. 5(a), the low temperature $\chi(T)$ curves of Gd₃BWO₉ are measured under several small fields along the c axis, whose peak shifts to lower temperature as field increases. In addition, we conducted the $M(H)$ measurements with more data points below 3 T at 0.4 K, 0.6 K, 0.8 K, 1.0 K, and 1.2 K, respectively (Fig. S3) [27]. Correspondingly, Figs. 5(c) and 5(d) and Fig. S4 show low field variation of ΔS_{mag} curves at various temperatures, calculated based on the $M(H)$ curves in Fig. S3 [27]. Since $\Delta S_{mag}(H) = S_{mag}(H) - S_{mag}(0 T)$, the $S_{mag}(H)$ curve at a constant temperature can be obtained through vertically shifting the $\Delta S_{mag}(H)$ curve by the zero-field entropy value, as shown in Fig. 5(b). It is worth noting that a shoulder around $\mu_0 H_{c1} = 0.42$ T and a peak at $\mu_0 H_{c2} = 0.84$ T are observed for the $S_{mag}(H)$ curve at 0.5 K, which gradually evolve into one single peak as temperature

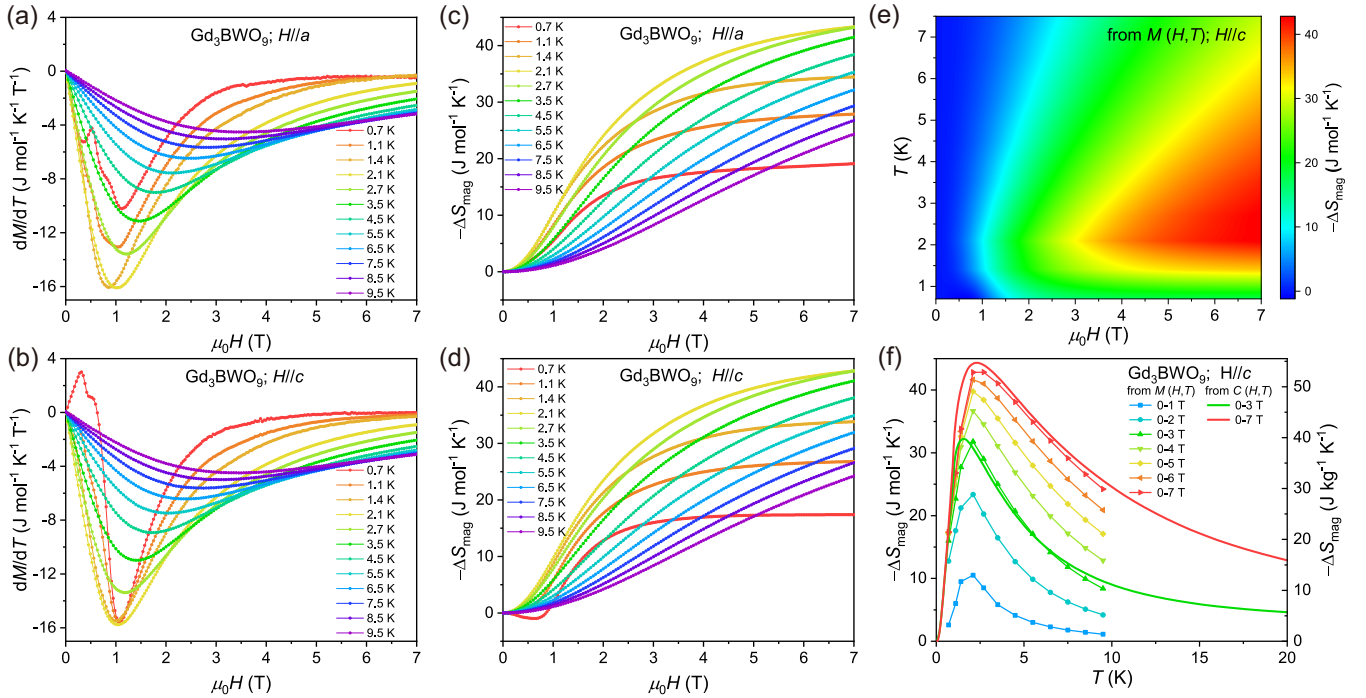


FIG. 4. Magnetic entropy and magnetocaloric effect analysis of Gd_3BWO_9 . (a), (b) Derivative of the magnetization with respect to temperature as a function of the applied magnetic field for $\mathbf{H} \parallel a$ and $\mathbf{H} \parallel c$. (c), (d) Field variation of the magnetic entropy change $-\Delta S_{\text{mag}}$ calculated from isothermal magnetization curves for different temperatures of Gd_3BWO_9 for $\mathbf{H} \parallel a$ and $\mathbf{H} \parallel c$, respectively. (e) Contour plots for $-\Delta S_{\text{mag}}$ as a variation of applied field and temperature. (f) Temperature variation of $-\Delta S_{\text{mag}}$ obtained from isothermal magnetization curves and heat capacity data, with vertical axes representing units in volumetric $\text{J mol}^{-1} \text{K}^{-1}$ (left) and $\text{J kg}^{-1} \text{K}^{-1}$ (right).

increases. Taking the features mentioned above, Fig. 5(e) displays an H - T phase diagram of Gd_3BWO_9 under $\mathbf{H} \parallel c$, with the color coding representing $S_{\text{mag}}(H, T)$ in Fig. 5(b).

The isothermal field scans on $C_{\text{mag}}(H)$ are measured under $\mathbf{H} \parallel c$ at 0.9 K and 0.4 K, respectively. As shown in the top panel of Figs. 5(c) and 5(d), a peak is identified on the $C_{\text{mag}}(H)$ curve at $\mu_0 H = 0.5$ T at 0.9 K, while upon cooling to 0.4 K, a shoulder is observed around $\mu_0 H = 0.85$ T in addition to the peak at $\mu_0 H = 0.55$ T. The magnetic Grüneisen parameter is calculated through $\Gamma_{\text{mag}} \equiv \frac{1}{T} \left(\frac{dT}{d\mu_0 H} \right)_S = -\frac{1}{\mu_0 C} \frac{dS}{dH} \approx -\frac{1}{\mu_0 C_{\text{mag}}} \frac{dS_{\text{mag}}}{dH}$, in which the nonmagnetic specific heat is much smaller than the magnetic component below T_N . Combined with Maxwell's thermodynamic relation $\left(\frac{\partial S}{\partial H} \right)_{P,T} = \left(\frac{\partial M}{\partial T} \right)_{P,H}$, the $\Gamma_{\text{mag}}(H)$ curves are shown in Figs. 5(c) and 5(d).

At 0.9 K, the sign of the $\Gamma_{\text{mag}}(H)$ curve changes from negative to positive at $\mu_0 H_c = 0.5$ T, indicating a local maximum in entropy $S_{\text{mag}}(H)$ at this field, as well as a respective minimum in the adiabatic temperature trace $T(H)_S$, arising at the phase boundary. At $T = 0.4$ K, there is a local maximum in $\Gamma_{\text{mag}}(H)$ curve at $\mu_0 H_{c1} = 0.42$ T, with its value approaching zero. As the magnetic field increases beyond $\mu_0 H_{c2} = 0.85$ T, the $\Gamma_{\text{mag}}(H)$ curve changes its sign from negative to positive, reaching a constant value up to 1.5 T. The lower critical field $\mu_0 H_{c1} = 0.42$ T may indicate a metamagnetic transition within the AFM regime and the system subsequently reaches a fully polarized state above the upper critical field $\mu_0 H_{c2} = 0.85$ T. This behavior is similar to that in Nd_3BWO_9 , in which a proximate quantum bicritical point (BCP) is observed along

the c axis. In the magnetocaloric effect results of Nd_3BWO_9 , a temperature diplike feature appears near the critical fields $B_{\text{BCP}} \sim 0.61$ T, where magnetic entropy change $\Delta S_{\text{mag}}(H)$ accumulates its maximum value [21].

As detailed in Fig. 4 of Ref. [44], when the quantum critical point (QCP) serves as the endpoint of a line of classical second order transitions, the isentropes ($dS = 0$), i.e., the contour lines in $S_{\text{mag}}(H, T)$, would exhibit minima values close to the phase boundary. Intriguingly, the contour lines in $S_{\text{mag}}(H, T)$ in Fig. 5(e) explicitly illustrate the evolution of temperature during an adiabatic sweep of the field along the c axis at $T > 0.4$ K. This observation aligns precisely with the light blue contour line depicted in Fig. 5(e). It also includes the adiabatic temperature traces of field sweep $T(H)_S$ of Gd_3BWO_9 polycrystal. These sweeps were measured by ramping the magnetic field from 9 T to 1.5 T, as in the ADR runs. Subsequently, the field was swept repeatedly at a substantially reduced rate of 1.5 mT/s from 1.5 T to 0 T and back to 1.5 T. Though the critical field might be slightly different from the polycrystal compared with the single crystal under $\mathbf{H} \parallel c$ axis, the temperature traces $T(H)_S$ fit quite nicely into the phase diagram based on $S_{\text{mag}}(H, T)$. By drawing boundary lines through local minima of the temperature traces, the phase boundaries could be extended to lower temperatures.

For a quantum-critical point (QCP), there shall be the sign change at the critical field B_c and also a divergence $\Gamma_{\text{mag}} \sim |B - B_c|^{-1}$ at very low temperature. Thus the quantum critical phenomena in Gd_3BWO_9 at $T < 0.1$ K, including the

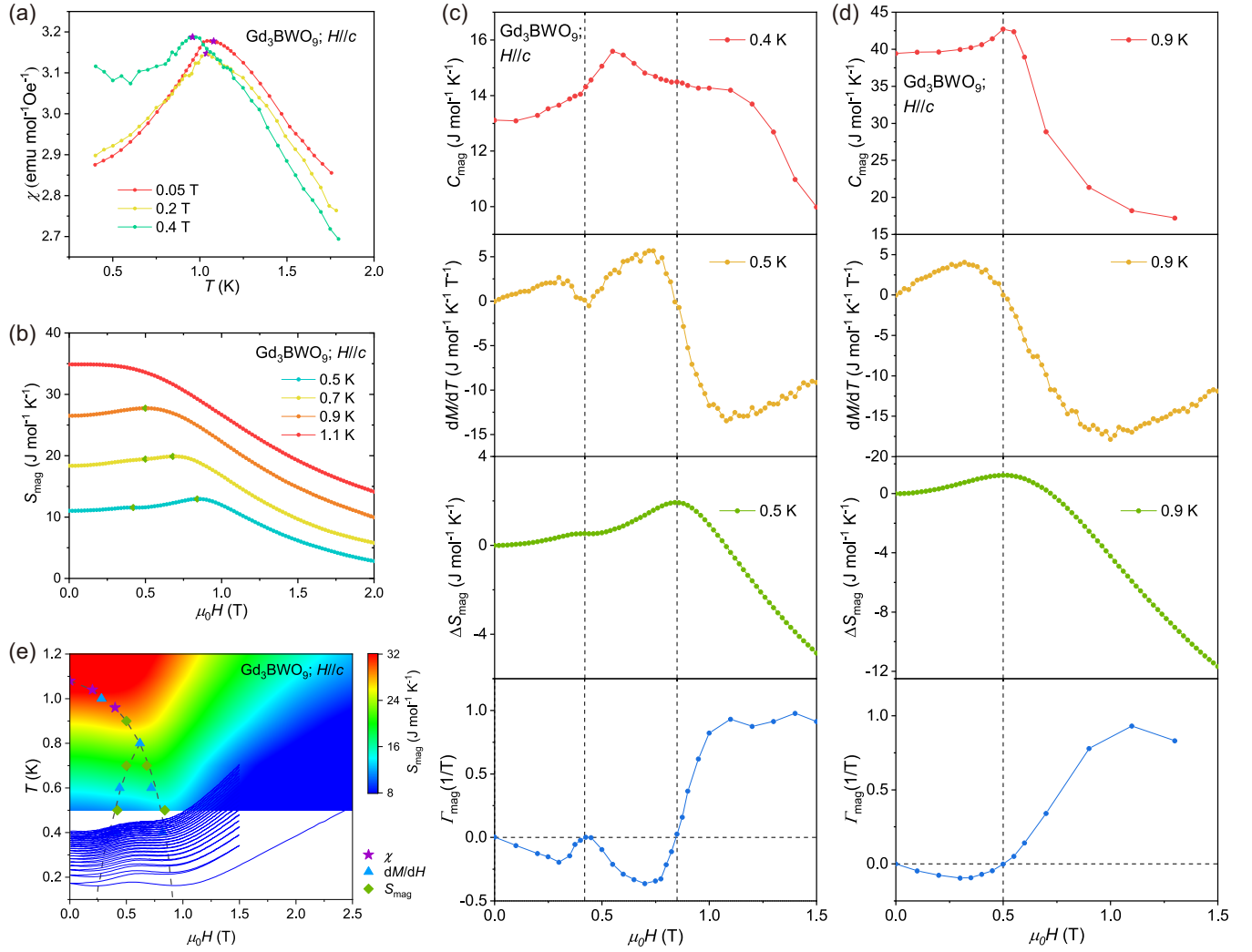


FIG. 5. Phase diagram of Gd₃BWO₉ single crystal under $H \parallel c$. (a) The low-temperature susceptibility $\chi(T)$ curves under 0.05, 0.2, and 0.4 T for $H \parallel c$; the purple stars indicate the positions of peaks. (b) The low field variation of magnetic entropy $S_{\text{mag}}(H)$ for $H \parallel c$ at 0.5, 0.7, 0.9, and 1.1 K, respectively; the green rhombuses denote the positions of local peaks. The magnetic specific heat C_{mag} , the derivative of magnetization with respect to temperature dM/dT , magnetic entropy change ΔS_{mag} , and magnetic Grüneisen parameter Γ_{mag} at 0.4 K (the C_{mag} and Γ_{mag} of 0.4 K would be similar with that of 0.5 K) (c) and 0.9 K (d) under $H \parallel c$. (e) The H - T phase diagram of Gd₃BWO₉ as derived from $\chi(T)$ (purple stars), dM/dH (blue triangles), $S_{\text{mag}}(H)$ (green rhombuses), and $T(H)_s$ (blue lines), with the dashed lines guiding the eyes and the color coding representing $S_{\text{mag}}(H)$.

enhanced MCE approaching the putative QCPs, warrant further investigation in the future [40,44–47].

IV. SUMMARY

In summary, we have performed magnetic and thermodynamic characterization of a distorted kagome lattice Gd₃BWO₉ single crystal. Below $T_N = 1.08$ K, the Gd³⁺ moments exhibit AFM alignment between layers and FM alignment within layers, resulting in alternating AFM-FM stripes along the c axis, as confirmed by magnetic susceptibility measurements. Compared to the GGG case, the maximum $-\Delta S_{\text{mag}}$ of Gd₃BWO₉ shows larger values of 53.45 J kg⁻¹ K⁻¹ for $H \parallel a$ and 52.83 J kg⁻¹ K⁻¹ for $H \parallel c$ under 7 T, presenting the giant MCE related to its AFM order. Given the long-range order at $T_N = 1.08$ K, the strong magnetic frustration of Gd₃BWO₉ suppresses the release of

magnetic entropy down to low temperature, resulting in a $T_{\text{min}} = 0.151$ K far below T_N in the ADR measurement. Furthermore, the constructed H - T phase diagram of Gd₃BWO₉ under $H \parallel c$ reveals evidence of magnetic critical behavior, as indicated by the sign change of $\Gamma_{\text{mag}}(H)$ near the metamagnetic transitions.

ACKNOWLEDGMENTS

The authors would like to thank Peijie Sun, Zhaoming Tian, Junsen Xiang, Jie Shen, Huifen Ren, and Shaokui Su for helpful discussions and experimental support. The work was supported by the National Key R&D Program of China (Grant No. 2023YFA1406003), the National Natural Science Foundation of China (Grant No. 12274015), the Beijing Natural Science Foundation (Grant No. JQ24012), and the Fundamental Research Funds for the Central Universities. The work

in Augsburg was supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation), Grants No. 514162746 (GE 1640/11–1) and No. TRR 360–492547816. We are grateful to the extreme condition characterization platform of the Analysis & Testing Center of Beihang University for the facilities, and the scientific and technical assistance. A portion of this work was carried out at the Synergetic Extreme Condition User Facility (SECUF).

DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

- [1] L. Balents, Spin liquids in frustrated magnets, *Nature (London)* **464**, 199 (2010).
- [2] S. T. Bramwell and M. J. P. Gingras, Spin ice state in frustrated magnetic pyrochlore materials, *Science* **294**, 1495 (2001).
- [3] C. Broholm, R. J. Cava, S. A. Kivelson, D. G. Nocera, M. R. Norman, and T. Senthil, Quantum spin liquids, *Science* **367**, eaay0668 (2020).
- [4] T.-H. Han, J. S. Helton, S. Y. Chu, D. G. Nocera, J. A. Rodriguez-Rivera, C. Broholm, and Y. S. Lee, Fractionalized excitations in the spin-liquid state of a kagome-lattice antiferromagnet, *Nature (London)* **492**, 406 (2012).
- [5] A. Zorko, F. Bert, A. Ozarowski, J. van Tol, D. Boldrin, A. S. Wills, and P. Mendels, Dzyaloshinsky-Moriya interaction in vesignieite: A route to freezing in a quantum kagome antiferromagnet, *Phys. Rev. B* **88**, 144419 (2013).
- [6] Z. L. Dun, J. Trinh, K. Li, M. Lee, K. W. Chen, R. Baumbach, Y. F. Hu, Y. X. Wang, E. S. Choi, B. S. Shastry *et al.*, Magnetic ground states of the rare-earth tripod kagome lattice $\text{Mg}_2\text{RE}_3\text{Sb}_3\text{O}_{14}$ (RE = Gd, Dy, Er), *Phys. Rev. Lett.* **116**, 157201 (2016).
- [7] J. A. M. Paddison, H. S. Ong, J. O. Hamp, P. Mukherjee, X. J. Bai, M. G. Tucker, N. P. Butch, C. Castelnovo, M. Mourigal, and S. E. Dutton, Emergent order in the kagome Ising magnet $\text{Dy}_3\text{Mg}_2\text{Sb}_3\text{O}_{14}$, *Nat. Commun.* **7**, 13842 (2016).
- [8] V. Fritsch, N. Bagrets, G. Goll, W. Kitzler, M. J. Wolf, K. Grube, C.-L. Huang, and H. v. Löhneysen, Approaching quantum criticality in a partially geometrically frustrated heavy-fermion metal, *Phys. Rev. B* **89**, 054416 (2014).
- [9] A. Sakai, S. Lucas, P. Gegenwart, O. Stockert, H. v. Löhneysen, and V. Fritsch, Signature of frustrated moments in quantum critical $\text{CePd}_{1-x}\text{Ni}_x\text{Al}$, *Phys. Rev. B* **94**, 220405(R) (2016).
- [10] S. Lucas, K. Grube, C.-L. Huang, A. Sakai, S. Wunderlich, E. L. Green, J. Wosnitza, V. Fritsch, P. Gegenwart, O. Stockert, and H. v. Löhneysen, Entropy evolution in the magnetic phases of partially frustrated CePdAl , *Phys. Rev. Lett.* **118**, 107204 (2017).
- [11] H. C. Zhao, J. H. Zhang, M. Lyu, S. Bachus, Y. Tokiwa, P. Gegenwart, S. Zhang, J. G. Cheng, Y.-F. Yang, G. F. Chen *et al.*, Quantum-critical phase from frustrated magnetism in a strongly correlated metal, *Nat. Phys.* **15**, 1261 (2019).
- [12] K. Zhao, H. Deng, H. Chen, K. A. Ross, V. Petříček, G. Günther, M. Russina, V. Hutanu, and P. Gegenwart, Realization of the kagome spin ice state in a frustrated intermetallic compound, *Science* **367**, 1218 (2020).
- [13] K. Zhao, Y. Tokiwa, H. Chen, and P. Gegenwart, Discrete degeneracies distinguished by the anomalous Hall effect in a metallic kagome ice compound, *Nat. Phys.* **20**, 442 (2024).
- [14] K. Zhao, H. Deng, H. Chen, N. Ma, N. S. Oefele, J. S. Guo, X. L. Cui, C. Tang, M. J. Gutmann, T. Mueller, Y. X. Su, V. Hutanu, C. Q. Jin, and P. Gegenwart, Nonlinear time-reversal symmetry breaking in kagome spin ice HoAgGe , *arXiv:2505.22544*.
- [15] S. Chillal, Y. Iqbal, H. O. Jeschke, J. A. Rodriguez-Rivera, R. Bewley, P. Manuel, D. Khalyavin, P. Steffens, R. Thomale, A. T. M. Nazmul Islam, J. Reuther, and B. Lake, Evidence for a three-dimensional quantum spin liquid in $\text{PbCuTe}_2\text{O}_6$, *Nat. Commun.* **11**, 2348 (2020).
- [16] X. Hong, M. Gillig, A. R. N. Hanna, S. Chillal, A. T. M. Nazmul Islam, B. Lake, B. Büchner, and C. Hess, Spinon heat transport in the three-dimensional quantum magnet $\text{PbCuTe}_2\text{O}_6$, *Phys. Rev. Lett.* **131**, 256701 (2023).
- [17] M. Ashtar, J. J. Guo, Z. T. Wan, Y. Q. Wang, G. S. Gong, Y. Liu, Y. L. Su, and Z. M. Tian, A new family of disorder-free rare-earth-based kagome lattice magnets: Structure and magnetic characterizations of RE_3BWO_9 (RE = Pr, Nd, Gd-Ho) boratotungstates, *Inorg. Chem.* **59**, 5368 (2020).
- [18] K. Y. Zeng, F. Y. Song, Z. M. Tian, Q. Chen, S. Wang, B. Liu, S. L. Li, L. S. Ling, W. Tong, L. Ma, and L. Pi, Local evidence for collective spin excitations in the distorted kagome antiferromagnet Pr_3BWO_9 , *Phys. Rev. B* **104**, 155150 (2021).
- [19] J. Nagl, D. Flavián, S. Hayashida, K. Y. Povarov, M. Yan, N. Murai, S. Ohira-Kawamura, G. Simutis, T. J. Hicken, H. Luetkens *et al.*, Excitation spectrum and spin Hamiltonian of the frustrated quantum Ising magnet Pr_3BWO_9 , *Phys. Rev. Res.* **6**, 023267 (2024).
- [20] D. Flavián, J. Nagl, S. Hayashida, M. Yan, O. Zaharko, T. Fennell, D. Khalyavin, Z. Yan, S. Gvasaliya, and A. Zheludev, Magnetic phase diagram of the breathing-kagome antiferromagnet Nd_3BWO_9 , *Phys. Rev. B* **107**, 174406 (2023).
- [21] F. Y. Song, H. Ge, A. D. Liu, Y. Q. Qin, Y. Y. Han, L. S. Ling, S. L. Yuan, Z. W. Ouyang, J. M. Sheng, L. S. Wu, and Z. M. Tian, Magnetic field tuned anisotropic quantum phase transition in the distorted kagome antiferromagnet Nd_3BWO_9 , *Phys. Rev. B* **108**, 214410 (2023).
- [22] J. Nagl, D. Flavián, B. Duncan, S. Hayashida, O. Zaharko, E. Ressouche, J. Ollivier, Z. Yan, S. Gvasaliya, and A. Zheludev, Braided Ising spin-tube physics in a purported kagome magnet, *Phys. Rev. B* **111**, L180406 (2025).
- [23] K. Y. Zeng, F. Y. Song, L. S. Ling, W. Tong, S. L. Li, Z. M. Tian, L. Ma, and L. Pi, Incommensurate magnetic order in Sm_3BWO_9 with distorted kagome lattice, *Chin. Phys. Lett.* **39**, 107501 (2022).
- [24] Z. Y. Yang, H. H. Zhang, M. J. Bai, W. Li, S. L. Huang, S. C. Ruan, and Y. J. Zeng, Large magnetocaloric effect in gadolinium borotungstate Gd_3BWO_9 , *J. Mater. Chem. C* **8**, 11866 (2020).
- [25] L.-L. Li, X.-Y. Yue, W.-J. Zhang, H. Bao, D.-D. Wu, H. Liang, Y.-Y. Wang, Y. Sun, Q.-J. Li, and X.-F. Sun, Magnetism

- and giant magnetocaloric effect in rare-earth-based compounds R_3BWO_9 ($R = \text{Gd}, \text{Dy}, \text{Ho}$), *Chin. Phys. B* **30**, 077501 (2021).
- [26] A. Majchrowski, E. Michalski, and A. Brenier, Growth and spectroscopic characterization of Nd_3BWO_9 single crystal, *J. Cryst. Growth* **247**, 467 (2003).
- [27] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/7l6y-hdw5> for additional details about x-ray diffraction, magnetization, and heat capacity results.
- [28] H. Masuda, H. Sakai, M. Tokunaga, Y. Yamasaki, A. Miyake, J. Shiogai, S. Nakamura, S. Awaji, A. Tsukazaki, H. Nakao *et al.*, Quantum Hall effect in a bulk antiferromagnet EuMnBi_2 with magnetically confined two-dimensional Dirac fermions, *Sci. Adv.* **2**, e1501117 (2016).
- [29] K. Zhao, X. J. Chen, Z. S. Wang, J. Y. Liu, J. T. Wu, C. Y. Xi, X. D. Lv, L. Li, Z. C. Zhong, and P. Gegenwart, Magnetic tuning of band topology evidenced by exotic quantum oscillations in the Dirac semimetal EuMnSb_2 , *Phys. Rev. B* **107**, L081112 (2023).
- [30] Z. W. Yang, J. Zhang, B. Liu, X. X. Zhang, D. B. Lu, H. T. Zhao, M. C. Pi, H. Z. Cui, Y.-J. Zeng, Z. Pan *et al.*, Exceptional magnetocaloric responses in a gadolinium silicate with strongly correlated spin disorder for sub-Kelvin magnetic cooling, *Adv. Sci.* **11**, 2306842 (2024).
- [31] Z. M. Song, N. Zhao, H. Ge, T. T. Li, J. Yang, L. Wang, Y. Fu, Y. Z. Zhang, S. M. Wang, J. W. Mei *et al.*, Magnetic phase diagrams and large magnetocaloric effects of the two-dimensional antiferromagnetic triangular lattice of Gd^{3+} ions in $\text{KBaGd}(\text{BO}_3)_2$, *Phys. Rev. B* **107**, 125126 (2023).
- [32] A. Jesche, N. Winterhalter-Stocker, F. Hirschberger, A. Bellon, S. Bachus, Y. Tokiwa, A. A. Tsirlin, and P. Gegenwart, Adiabatic demagnetization cooling well below the magnetic ordering temperature in the triangular antiferromagnet $\text{KBaGd}(\text{BO}_3)_2$, *Phys. Rev. B* **107**, 104402 (2023).
- [33] J. S. Xiang, C. Su, N. Xi, Z. D. Fu, Z. Chen, H. Jin, Z. Y. Chen, Z.-J. Mo, Y. Qi, J. Shen, L. Zhang, W. Jin, W. Li, P. J. Sun, and G. Su, Dipolar spin liquid ending with quantum critical point in a Gd-based triangular magnet, [arXiv:2301.03571](https://arxiv.org/abs/2301.03571).
- [34] A. G. Del Maestro and M. J. P. Gingras, Low-temperature specific heat and possible gap to magnetic excitations in the Heisenberg pyrochlore antiferromagnet $\text{Gd}_2\text{Sn}_2\text{O}_7$, *Phys. Rev. B* **76**, 064418 (2007).
- [35] J. A. Quilliam, K. A. Ross, A. G. Del Maestro, M. J. P. Gingras, L. R. Corruccini, and J. B. Kycia, Evidence for gapped spin-wave excitations in the frustrated $\text{Gd}_2\text{Sn}_2\text{O}_7$ pyrochlore antiferromagnet from low-temperature specific heat measurements, *Phys. Rev. Lett.* **99**, 097201 (2007).
- [36] J. R. Stewart, J. S. Gardner, Y. Qiu, and G. Ehlers, Collective dynamics in the Heisenberg pyrochlore antiferromagnet $\text{Gd}_2\text{Sn}_2\text{O}_7$, *Phys. Rev. B* **78**, 132410 (2008).
- [37] M. Kleinhans, K. Eibensteiner, J. C. Leiner, C. Resch, L. Worch, M. A. Wilde, J. Spallek, A. Regnat, and C. Pfleiderer, Magnetocaloric properties of $R_3\text{Ga}_5\text{O}_{12}$ ($R = \text{Tb}, \text{Gd}, \text{Nd}, \text{Dy}$), *Phys. Rev. Appl.* **19**, 014038 (2023).
- [38] P. Telang, T. Treu, M. Klinger, A. A. Tsirlin, P. Gegenwart, and A. Jesche, Adiabatic demagnetization refrigeration with antiferromagnetically ordered NaGdP_2O_7 , *Phys. Rev. B* **111**, 064431 (2025).
- [39] Y. Tokiwa, S. Bachus, K. Kavita, A. Jesche, A. A. Tsirlin, and P. Gegenwart, Frustrated magnet for adiabatic demagnetization cooling to milli-Kelvin temperatures, *Commun. Mater.* **2**, 42 (2021).
- [40] Y. Tokiwa, T. Radu, C. Geibel, F. Steglich, and P. Gegenwart, Divergence of the magnetic grüneisen ratio at the field-induced quantum critical point in YbRh_2Si_2 , *Phys. Rev. Lett.* **102**, 066401 (2009).
- [41] T. Treu, M. Klinger, N. Oefele, P. Telang, A. Jesche, and P. Gegenwart, Utilizing frustration in Gd- and Yb-based oxides for milli-Kelvin adiabatic demagnetization refrigeration, *J. Phys.: Condens. Matter* **37**, 013001 (2025).
- [42] B. Daudin, R. Lagnier, and B. Salce, Thermodynamic properties of the gadolinium gallium garnet, $\text{Gd}_3\text{Ga}_5\text{O}_{12}$, between 0.05 and 25 K, *J. Magn. Magn. Mater.* **27**, 315 (1982).
- [43] J. A. Barclay and W. A. Steyert, Materials for magnetic refrigeration between 2 K and 20 K, *Cryogenics* **22**, 73 (1982).
- [44] M. Garst and A. Rosch, Sign change of the Grüneisen parameter and magnetocaloric effect near quantum critical points, *Phys. Rev. B* **72**, 205129 (2005).
- [45] J. S. Xiang, C. D. Zhang, Y. Gao, W. Schmidt, K. Schmalzl, C.-W. Wang, B. Li, N. Xi, X.-Y. Liu, H. Jin *et al.*, Giant magnetocaloric effect in spin supersolid candidate $\text{Na}_2\text{BaCo}(\text{PO}_4)_2$, *Nature (London)* **625**, 270 (2024).
- [46] C. D. Zhang, J. S. Xiang, Q. L. Zhu, L. F. Wu, S. F. Zhang, J. P. Xu, W. Yin, P. J. Sun, W. Li, G. Su, and W. T. Jin, Structural, magnetic, and magnetocaloric properties of triangular-lattice transition-metal phosphates, *Phys. Rev. Mater.* **8**, 044409 (2024).
- [47] T. Liu, X.-Y. Liu, Y. Gao, H. Jin, J. He, X.-L. Sheng, W. Jin, Z. Chen, and W. Li, Significant inverse magnetocaloric effect induced by quantum criticality, *Phys. Rev. Res.* **3**, 033094 (2021).