Successive phase transitions and quantum magnetization plateau in the spin-1 triangular-lattice antiferromagnet \( \text{Ba}_2\text{La}_2\text{NiTe}_2\text{O}_{12} \)

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The crystal structure and quantum magnetic properties of the spin-1 triangular-lattice antiferromagnet \( \text{Ba}_2\text{La}_2\text{NiTe}_2\text{O}_{12} \) are reported. Its crystal structure is trigonal \( R3 \), which is the same as that of \( \text{Ba}_2\text{La}_2\text{NiW}_2\text{O}_{12} \) \([\text{Y. Doi et al., J. Phys.: Condens. Matter 29, 365802 (2017)}]\). However, the exchange interaction \( J/k_B \approx 19 \) K is much greater than that observed in the tungsten system. At zero magnetic field, \( \text{Ba}_2\text{La}_2\text{NiTe}_2\text{O}_{12} \) undergoes successive magnetic phase transitions at \( T_{N1} = 9.8 \) K and \( T_{N2} = 8.8 \) K. The results indicate that the ground-state spin structure is a triangular structure in a plane perpendicular to the triangular lattice owing to the small easy-axis-type anisotropy. The magnetization curve exhibits the one-third plateau characteristic of a triangular-lattice quantum antiferromagnet. Exchange constants are also evaluated using density functional theory (DFT). The DFT results demonstrate the large difference in the exchange constants between tellurium and tungsten systems and the good two-dimensionality of the tellurium system.

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I. INTRODUCTION

Owing to the synergy between spin frustration and quantum fluctuation, two-dimensional (2D) triangular-lattice antiferromagnets (TLAFs) with small spin quantum numbers exhibit remarkable quantum many-body effects. It is known that for the isotropic Heisenberg model, the quantum TLAF with the nearest-neighbor exchange interaction has an ordered ground state of the 120° spin structure at zero magnetic field, which is qualitatively the same as the classical spin case \([1,2]\). However, in magnetic fields, nonclassical spin structures that are unstable in the classical spin model are stabilized with the help of the quantum fluctuation \([3,18]\).

For the classical Heisenberg TLAF, the equilibrium condition of the ground state in a magnetic field \( H \) is given by \( S_1 + S_2 + S_3 = H/(3J) \) with three sublattice spins \( S_1, S_2 \), and \( S_3 \). The spin structure of the ground state cannot be uniquely determined because the number of parameters necessary to determine the spin configuration is larger than the number of equations giving the equilibrium condition. Thus, the ground state exhibits a continuous degeneracy in the magnetic field. However, for the quantum Heisenberg TLAF, the classical degeneracy is lifted by the quantum fluctuation, and specific spin configurations are stabilized in magnetic fields. This leads to magnetic-field-induced quantum phase transitions. A noticeable macroscopic quantum phenomenon is the emergence of a magnetization plateau at one-third of the saturation magnetization, which is caused by the stabilization of an up-up-down (UUD) spin state in a finite magnetic field range \([8,13]\). The quantum 1/3 magnetization plateau has actually been observed in \( \text{Cs}_2\text{CuBr}_4 \) \([19,21]\), \( \text{Ba}_3\text{CoSb}_2\text{O}_9 \) \([22,26]\), \( \text{Ba}_3\text{NiSb}_2\text{O}_9 \) \([27]\), and \( \text{Ba}_2\text{CoTeO}_6 \) \([28]\). Although the quantum phases in magnetic fields for the 2D spin-1/2 Heisenberg TLAF are well understood, the instability of the quantum phases arising from the spatial anisotropy \([20,21]\), exchange anisotropy \([15]\), interlayer exchange interaction \([22,26,29]\), spin quantum number and thermal fluctuation has not been sufficiently elucidated.

Recently, magnetic excitations in the spin-1/2 Heisenberg-like TLAF \( \text{Ba}_3\text{CoSb}_2\text{O}_4 \) were investigated by inelastic neutron scattering experiments \([23,30,31]\). Unusual dynamical properties of single-magnon excitations predicted by theory such as the large downward quantum renormalization of excitation energies \([6,32,30]\) and a rotonlike minimum at the M point \([6,36,37]\) were confirmed. A notable feature of the magnetic excitations observed in \( \text{Ba}_3\text{CoSb}_2\text{O}_4 \) is a three-stage energy structure including intense dispersive excitation continua extending to high energy six times the exchange constant \([31]\), which cannot be described by the current theory. These experimental results strongly indicate fractionalized spin excitations because the intense excitation continua cannot be explained in terms of conventional two-magnon excitations \([37]\). For the experimental elucidation of unconventional magnetic excitations, quantum TLAFs with...
different spin quantum numbers such as spin-1 are necessary. In this work, we synthesized Ba$_2$La$_2$NiTe$_2$O$_{12}$ and investigated its crystal structure and magnetic properties. The structure of this compound was found to be the same as that of Ba$_2$La$_2$MWO$_{12}$ ($M =$ Mn, Co, Ni, Zn) [38, 41], which have a uniform triangular lattice composed of transition metal ions $M^{2+}$. Figure 1 shows the crystal structure of Ba$_2$La$_2$NiTe$_2$O$_{12}$. An important feature of the crystal structure is that the magnetic triangular lattices are largely separated by layers of nonmagnetic ions; thus, we can expect good two-dimensionality.

Recently, the magnetic properties in the family of triangular-lattice magnets Ba$_2$La$_2$MWO$_{12}$ ($M =$ Mn, Co, Ni) [40, 41] have been investigated by magnetic susceptibility, specific heat and neutron diffraction (ND) measurements. Unfortunately, the exchange interactions were found to be weakly antiferromagnetic [40] or weakly ferromagnetic [41]. It is natural to assume that superexchange interactions between neighboring spins in the same triangular layer occur through $M^{2+} - O^{2-} - O^{2-} - M^{2+}$ and $M^{2+} - O^{2-} - W^{6+} - O^{2-} - M^{2+}$ paths. The superexchange through the former path should be antiferromagnetic, while the latter path leads to a ferromagnetic superexchange interaction because the filled outermost orbitals of nonmagnetic $W^{6+}$ and Nb$^{5+}$ ions are 4$p$ orbitals, as discussed in Refs. [42, 43]. It is considered that the superexchange interactions via these two paths almost cancel in the tungsten compounds, resulting in a weakly antiferromagnetic or ferromagnetic total exchange interaction. Meanwhile, when the nonmagnetic $W^{6+}$ ion is replaced by a Te$^{6+}$ ion, for which the filled outermost orbital is a 4$d$ orbital, the superexchange interaction through the $M^{2+} - O^{2-} - Te^{6+} - O^{2-} - M^{2+}$ path becomes antiferromagnetic and the total exchange interaction should be strongly antiferromagnetic [42, 43].

This is our motivation for studying Ba$_2$La$_2$NiTe$_2$O$_{12}$. The exchange interaction in the triangular layer was found to be antiferromagnetic and strong as expected. We evaluated individual exchange constants using density functional theory (DFT). The DFT results demonstrate that the nearest-neighbor exchange interaction in the triangular layer is antiferromagnetic and predominant. As shown below, the 1/3-magnetization plateau characteristic of the quantum TLAFs was clearly observed in Ba$_2$La$_2$NiTe$_2$O$_{12}$. This compound is magnetically described as a quasi-2D spin-1 Heisenberg TLAF with small easy-axis-type anisotropy.

II. EXPERIMENTAL DETAILS

A powdered sample of Ba$_2$La$_2$NiTe$_2$O$_{12}$ was prepared by a solid-state reaction in accordance with the chemical reaction $2$BaCO$_3$ + La$_2$O$_3$ + NiO + 2TeO$_2$ + O$_2$ → Ba$_2$La$_2$NiTe$_2$O$_{12}$ + 2CO$_2$ in air. BaCO$_3$ (Wako, 99.9%), La$_2$O$_3$ (Wako, 99.99%), NiO (Wako, 99%) and TeO$_2$ (Aldrich, 99.995%) were mixed in stoichiometric quantities and calcined at 1000°C in air for one day. Ba$_2$La$_2$NiTe$_2$O$_{12}$ was sintered at 1000°C for one day after being pressed into a pellet. This sintering process was performed twice. Finally, yellow samples were obtained.

Powder X-ray diffraction (XRD) measurement of Ba$_2$La$_2$NiTe$_2$O$_{12}$ was conducted using a MiniFlex II diffractometer (Rigaku) with Cu Kα radiation at room temperature. Powder ND measurement was also performed to determine both the crystal and magnetic structures using the high-resolution powder diffractometer Echidna installed at the OPAL reactor of the Australian Nuclear Science and Technology Organisation. The diffraction data were collected with a neutron wavelength of 2.4395 Å in the temperature range of 1.6 ≤ $T$ ≤ 14 K. The crystal structure of Ba$_2$La$_2$NiTe$_2$O$_{12}$ was refined by Rietveld analysis of the powder XRD and ND data using the RIETAN-FP program [44].

![Figure 1: (Color online) (a) Schematic view of the crystal structure of Ba$_2$La$_2$NiTe$_2$O$_{12}$. The blue-green and ochre single octahedra are NiO$_6$ and TeO$_6$ octahedra with Ni$^{2+}$ and Te$^{6+}$ ions in the center, respectively. Solid lines denote the chemical unit cell. (b) Crystal structure viewed along the c axis. Magnetic Ni$^{2+}$ ions form a uniform triangular lattice in the ab plane.](image)
Magnetic measurements in the temperature range of \(1.8 \leq T \leq 300\) K and the magnetic field range of \(0.1 \leq \mu_0 H \leq 7.0\) T were performed using a Magnetic Property Measurement System (MPMS-XL, Quantum Design). High-field magnetization was measured in a magnetic field of up to \(\mu_0 H = 60\) T at \(T = 1.3\) K using an induction method with a multilayer pulse magnet at the Institute for Solid State Physics (ISSP), The University of Tokyo. Specific heat measurements in the temperature range of \(1.9 \leq T \leq 300\) K at magnetic fields of \(\mu_0 H = 0\) and \(9\) T were performed using a Physical Property Measurement System (PPMS, Quantum Design) by the relaxation method.

III. COMPUTATIONAL DETAILS

We determine the electronic structure of \(\text{Ba}_2\text{La}_2\text{NiTe}_2\text{O}_{12}\) by performing all-electron DFT calculations based on the full potential local orbital (FPLO) code \(\text{[45]}\). We use the generalized gradient approximation (GGA) exchange and correlation functional \(\text{[46]}\). The magnetic exchange interactions are determined by an energy-mapping method \(\text{[47–49]}\). We account for the strong electronic correlations on the Ni 3d orbitals using the GGA+U exchange correlation functional \(\text{[50]}\) with the Hund’s rule coupling strength \(J_H = 0.88\) eV fixed in accordance with the literature \(\text{[51]}\). The on-site interaction \(U\) is determined using the experimental Curie–Weiss temperature as explained below. As the primitive rhombohedral unit cell of \(\text{Ba}_2\text{La}_2\text{NiTe}_2\text{O}_{12}\) in the \(R\bar{3}\) space group contains only a single Ni\(^{2+}\) ion, we create supercells to allow spin configurations with different energies. A supercell containing four Ni\(^{2+}\) ions provides four distinct energies and allows the resolution of nearest- and next-nearest-neighbor coupling in the triangular lattice. A supercell with six Ni\(^{2+}\) ions and eight distinct energies is also required to resolve the shortest interlayer exchange path. As is common for triangular lattice antiferromagnets \(\text{[52]}\), the supercell calculations are computationally demanding, with each formula unit containing one magnetic ion adding more than 100 electrons to the calculation.

IV. RESULTS AND DISCUSSION

A. Crystal structure

The results of the XRD measurement of \(\text{Ba}_2\text{La}_2\text{NiTe}_2\text{O}_{12}\) at room temperature and the Rietveld analysis with RIETAN-FP \(\text{[44]}\) are shown in Fig. 2. First, we chose the structure parameters of \(\text{Ba}_2\text{La}_2\text{NiW}_2\text{O}_{12}\) \(\text{[40, 41]}\) as the initial parameters of the Rietveld analysis, setting the occupancy to 1 for all atoms and the thermal vibration parameter \(B\) to 1.401 Å\(^2\), which was reported for \(\text{Ba}_2\text{La}_2\text{NiW}_2\text{O}_{12}\) \(\text{[40]}\). The analysis was based on two structural models with space groups \(R\bar{3}m\) and \(R\bar{3}\). It is difficult to determine the space group from only the XRD pattern because both structural models successfully reproduce the observed XRD pattern. However, the neutron diffraction pattern obtained at low temperatures above the first ordering temperature \(T_{N1} \approx 10\) K is much better described by space group \(R\bar{3}\) as shown below. The structure parameters refined for space group \(R\bar{3}\) using the XRD data are summarized in Table I.

![Figure 2: (Color online) XRD pattern of \(\text{Ba}_2\text{La}_2\text{NiTe}_2\text{O}_{12}\) measured at room temperature. Experimental data, the results of Rietveld fitting, their difference and expected reflections are shown by the red symbols, green line, blue line and vertical purple bars, respectively.](image)

**TABLE I: Structure parameters of \(\text{Ba}_2\text{La}_2\text{NiTe}_2\text{O}_{12}\) determined from the XRD measurement at room temperature.**

| Atom | Site | \(x\) | \(y\) | \(z\) |
|------|------|------|------|------|
| Ba   | 6c   | 0    | 0    | 0.13587(7) |
| La   | 6c   | 0    | 0    | 0.28973(6) |
| Ni   | 3a   | 0    | 0    | 0    |
| Te   | 6c   | 0    | 0    | 0.41560(7) |
| O(1) | 18h  | 0.543(5) | 0.514(5) | 0.1186(3) |
| O(2) | 18h  | 0.450(5) | 0.473(5) | 0.2965(4) |

Space group \(R\bar{3}\)

\(a = 5.681(9)\) Å, \(c = 27.60(3)\) Å;

\(R_{wp} = 12.2\%\), \(R_p = 9.4\%\), \(R_c = 6.7\%\).

\(B = 1.401\) Å\(^2\) for all atoms.

Figure 3 shows the ND pattern of \(\text{Ba}_2\text{La}_2\text{NiTe}_2\text{O}_{12}\) measured at low temperatures above the first ordering temperature \(T_{N1} = 9.8\) K, where the diffraction intensity is the average of those measured at \(T = 14.12\) and 10 K. We analyzed the ND data on the basis of two structural models with space groups \(R\bar{3}m\) and \(R\bar{3}\). The values of \(R_{wp}\) and \(R_p\) are obtained from the refinements to be 22.1\% and 15.3\% for \(R\bar{3}m\) and 7.9\% and 5.7\% for \(R\bar{3}\), respectively. The \(R\)-factors for \(R\bar{3}\) are significantly smaller than those for \(R\bar{3}m\). Because no structural phase transition was detected via magnetic susceptibility and specific
heat measurements down to 1.8 K, we can conclude that
the space group of Ba$_2$La$_2$NiTe$_2$O$_{12}$ is R$\overline{3}$, which is
the same as the space group of Ba$_2$La$_2$MWO$_2$O$_{12}$ (M=Mn, Co,
Ni, Zn) [41]. The difference between the crystal
structures for these space groups is in the atomic positions
of oxygen atoms. Because the atomic scattering factor of
oxygen atoms for X-rays is much smaller than those of
other atoms, it is difficult to determine the atomic po-
tures for these space groups is in the atomic positions of
Ni, Zn) [41]. The difference between the crystal struc-
ture of Ba$_2$La$_2$NiTe$_2$O$_{12}$ T > $T_N$ is shown in Fig. 4. The Curie
constant $C = 1.482(2)$ emu K mol$^{-1}$ and the Weiss tem-
perature $\Theta$$_{CW}$ = $-100.7(3)$ K were obtained by fitting
to the Curie–Weiss law $\chi(T) = C/(T - \Theta$$_{CW}$) in the tem-
perature range 100 K $\leq$ $T$ $\leq$ 300 K. This large negative
$\Theta$$_{CW}$ indicates that the dominant exchange interaction
of Ba$_2$La$_2$NiTe$_2$O$_{12}$ is antiferromagnetic and large, as
expected from the superexchange path via the filled outer-
most 4d orbital of Te$^{6+}$. The exchange constant $J$, ef-
fective magnetic moment $\mu$$_{\text{eff}}$ and q-factor are estimated
as $J/k_B = 25$ K, $\mu$$_{\text{eff}}$ = 3.44 $\mu_B$ and $g = 2.4$ on the basis of
molecular field theory.

The magnetic susceptibility of Ba$_2$La$_2$NiTe$_2$O$_{12}$ increases
rapidly near 9 K as the temperature decreases, which is indicative of the antiferromagnetic phase transition. This transition temperature of $T_N \sim 9$ K is lower than $T_N \sim 13$ K for Ba$_3$NiSb$_2$O$_9$ [27–29, 53], which is an $S$ = 1 TLAF with a crystal structure
and exchange interaction $J/k_B \sim 20$ K, similar to those of Ba$_2$La$_2$NiTe$_2$O$_{12}$ [27–29, 53]. Thus, the two-
dimensionality in Ba$_2$La$_2$NiTe$_2$O$_{12}$ is better than that in
Ba$_3$NiSb$_2$O$_9$. Note that the magnetic susceptibility of
Ba$_3$NiSb$_2$O$_9$ powder does not show a rapid upturn below
$T_N$ [53].

A notable feature of the magnetic susceptibility in
Ba$_2$La$_2$NiTe$_2$O$_{12}$ is the rapid increase below $T_N$. This

TABLE II: Structure parameters of Ba$_2$La$_2$NiTe$_2$O$_{12}$ determined from the ND measurements at several temperatures above $T_N \approx 10$ K.

| Atom | Site | $x$ | $y$ | $z$ | $B$ [Å$^2$] |
|------|------|-----|-----|-----|-----------|
| Ba   | 6c   | 0   | 0   | 0.1370(2) | 0.354 |
| La   | 6c   | 0   | 0   | 0.2890(1) | 0.354 |
| Ni   | 3a   | 0   | 0   | 0   | 0.437 |
| Te   | 6c   | 0   | 0   | 0.4150(1) | 0.377 |
| O(1) | 18h  | 0.4631(4) | 0.4675(5) | 0.1168(1) | 0.877 |
| O(2) | 18h  | 0.4339(4) | 0.4603(5) | 0.2947(1) | 0.877 |

Space group R$\overline{3}$

$a = 5.6682(7)$ Å, $c = 27.472(2)$ Å;

$R_{wp} = 7.9\%$, $R_p = 5.7\%$, $R_e = 1.5\%$. 

FIG. 3: (Color online) ND pattern of Ba$_2$La$_2$NiTe$_2$O$_{12}$ measured at low temperatures above the first ordering temperature $T_N = 9.8$ K. Experimental data, the results of Rietveld fitting, their difference and expected reflections are shown by the red symbols, green line, blue line and vertical purple bars, respectively. The experimental data is the average of measurements at $T = 14, 12$ and 10 K.

FIG. 4: (Color online) Temperature dependence of the magnetic susceptibility of Ba$_2$La$_2$NiTe$_2$O$_{12}$ powder measured in an external magnetic field of $\mu_0H = 0.1$ T. The blue solid line shows the result of a Curie–Weiss fit in the temperature range of 100 $\leq$ $T$ $\leq$ 300 K. The inset is an enlarged view around 10 K.
behavior can be understood in terms of a small easy-axis-type anisotropy and a ferromagnetic interlayer exchange interaction. When the magnetic anisotropy is of the easy-axis type and small, the spin configuration in the ground state is a triangular structure in a plane including the crystallographic c axis, as shown in Fig. 5(a). The triangular structure is slightly distorted from a perfect 120° structure. The angle $\theta$ between canted sublattice spins and the c axis is smaller than 60°. Therefore, the sum of the magnetic moments of three sublattice spins is nonzero; thus, a resultant magnetic moment along the c axis appears in a triangular layer. When the interlayer exchange interaction is antiferromagnetic, the resultant magnetic moments appearing in the neighboring triangular layers are canceled out. On the other hand, when the interlayer exchange interaction is ferromagnetic, all the resultant magnetic moments appearing in the triangular layers align in the same direction, giving the system a net magnetic moment along the c axis. The small easy-axis-type anisotropy of Ba$_2$La$_2$NiTe$_2$O$_{12}$ is also consistent with the successive magnetic phase transitions observed by the specific heat measurements shown later.

The magnetic field dependence of the magnetization of Ba$_2$La$_2$NiTe$_2$O$_{12}$ powder is shown in Fig. 6. It is clearly observed that there is a finite magnetization even in zero field. The magnetic moment per spin $\Delta M$ in the ground state at zero magnetic field is given by

$$\Delta M = \frac{1}{3} (2\cos\theta - 1) g \mu_B S,$$

where $S = 1$ and $\theta$ is the canting angle shown in Fig. 5(a). The powder average of the weak moment $\Delta M$ is given by $\Delta M = \Delta M / 2$. By using the value $\Delta M = 0.015 \mu_B / \text{Ni}^{2+}$, which is obtained by extrapolating the magnetization curve to zero magnetic field, and $g = 2.4$ estimated from the Curie constant, we obtain the angle $\theta = 58.75^\circ$.

The origin of the small easy-axis-type anisotropy is considered to be the single-ion anisotropy expressed as

$$D \left( S_z^2 \right)^2 + D < 0.$$
magnetic field is shown in Fig. 7. There is no anomaly indicative of a structural phase transition below 300 K. The hump anomaly around room temperature is an extrinsic anomaly that originates from the instability of the temperature. The low-temperature specific heat measured at \( \mu_0 H = 0 \) and 9 T is shown in Fig. 8. Double peaks indicative of successive magnetic phase transitions are observed at \( T_{N1} = 9.8 \) K, \( T_{N2} = 8.9 \) K for \( \mu_0 H = 0 \) T and at \( T_{N1} = 10.5 \) K, \( T_{N2} = 9.2 \) K for \( \mu_0 H = 9 \) T. Each transition temperature shifts to the high-temperature side with increasing magnetic field, and the shift for \( T_{N1} \) is larger than that for \( T_{N2} \).

It is theoretically known that successive magnetic phase transitions occur in a TLAF with easy-axis-type anisotropy \[55\]. With decreasing temperature, the \( z \) components of spins order first at \( T = T_{N1} \), and the \( xy \) components of spins order next at \( T = T_{N2} \), as shown in Fig. 3b. Similar successive magnetic phase transitions arising from the small easy-axis-type anisotropy were reported for \( \text{Ba}_3\text{NiSb}_2\text{O}_9 \) \[27\], which has an exchange constant similar to that of \( \text{Ba}_2\text{La}_2\text{NiTe}_2\text{O}_{12} \) \[27,54\]. The phase transition temperatures of \( \text{Ba}_3\text{NiSb}_2\text{O}_9 \) are \( T_{N1} = 13.5 \) K and \( T_{N2} = 13.0 \) K, both of which are higher than those of \( \text{Ba}_2\text{La}_2\text{NiTe}_2\text{O}_{12} \). This suggests that the two-dimensionality in \( \text{Ba}_2\text{La}_2\text{NiTe}_2\text{O}_{12} \) is better than that in \( \text{Ba}_3\text{NiSb}_2\text{O}_9 \).

### High-field magnetization

The result of the high-field magnetization measurement of \( \text{Ba}_2\text{La}_2\text{NiTe}_2\text{O}_{12} \) powder up to 60 T is shown in Fig. 9. The absolute value of the magnetization is calibrated by using the result of the magnetization measurement up to 7 T with a SQUID magnetometer. A magnetization plateau is clearly observed at \( M \approx 0.8 \mu_0 \text{B}/\text{Ni}^{2+} \) for \( 32 < \mu_0 H < 47 \) T. The lower and higher edge fields of the plateau were assigned to the magnetic fields at which \( dM/dH \) has inflection points. Because the \( g \)-factor estimated from the magnetic susceptibility is \( g = 2.4 \), the plateau corresponds to the 1/3-magnetization plateau characteristic of the quantum TLAF. The edge fields of the plateau are rather smeared and the plateau is not completely flat. It is expected that this arises from the distribution of the edge fields in the powdered sample owing to the anisotropy of the \( g \)-factors and the magnetic anisotropy and not from the exchange randomness \[55,57\]. When the anisotropy of the \( g \) factor is \( \Delta g \), the edge fields \( H_{\alpha\alpha} \) with \( \alpha = 1 \) and 2 are distributed in the range of \( (\Delta g/\bar{g})H_{\alpha\alpha} \), where \( \bar{g} \) is the average of the \( g \) factor. When the magnetic anisotropy is of the easy-axis type, the field range of the 1/3-plateau becomes wider for \( H \parallel c \) and narrower for \( H \perp c \) than those for the Heisenberg model.

We fit the theoretical magnetization curves of an \( S = 1 \) Heisenberg TLAF calculated by the coupled cluster method (CCM) and the exact diagonalization (ED) \[54\] to our experimental result, as shown in Fig. 10. From this fit, we obtain the saturation magnetization \( M_s/\mu_B = 2.31(2) \), which leads to \( g = 2.31(2) \). The magnetic field range of the experimental 1/3-plateau \( 32 < \mu_0 H < 47 \) T is somewhat larger than the calculated field range \( 35 < \mu_0 H < 46 \) T.

The saturation magnetic field \( H_s \) of the \( S = 1 \) Heisenberg TLAF is given by \( g\mu_B H_s = 9JS \). Using \( g \approx 2.3 \) and...
$H_s \simeq 110$ T, which are estimated from the theoretical magnetization curve fitted to the magnetization data, the exchange interaction is estimated as $J/k_B \simeq 19$ K. This $J$ value is somewhat smaller than $J/k_B = 25$ K estimated from the Weiss constant $\Theta_{CW} = -100.7$ K of the high-temperature magnetic susceptibility. Because the saturation field given by $g\mu_B H_s = 9JS$ is exact, the exchange constant $J/k_B \simeq 19$ K estimated from the saturation field is considered to be more precise.

**E. Magnetic structure**

Next, we discuss the magnetic structure in the ordered phases in Ba$_2$La$_2$NiTe$_2$O$_{12}$. The neutron diffraction intensities averaged over $T = 14, 12, 10$ K ($> T_{N_1} = 9.8$ K) and $T = 6, 4, 1.6$ K ($< T_{N_2} = 8.9$ K) are shown in Fig. 11. There is a small but obvious difference between these ND intensities. Figure 12 shows powder ND spectra obtained at various temperatures, where the average of the diffraction spectra obtained at $T = 6, 4, 1.6$ K was subtracted as the background. No magnetic peak is observed for $T \geq 10$ K. However, new peaks appear below 8 K, which is just below $T_{N_2} = 8.9$ K. Thus, these new peaks can be attributed to magnetic Bragg peaks. Diffraction angles for some possible magnetic Bragg reflections, which are estimated from the lattice constants, are also indicated by arrows in Fig. 11. The diffraction angles calculated for $q = (1/3, 1/3, 0)$ and its equivalent points coincide with the experimental results. This indicates that Ba$_2$La$_2$NiTe$_2$O$_{12}$ has a triangular spin structure characterized by the propagation vector $q = (1/3, 1/3, 0)$ in the low temperature phase $T_{N_2}$. This propagation vector is in contrast to $q = (1/3, 1/3, 1)$ observed for Ba$_2$La$_2$CoTe$_2$O$_{12}$. The propagation vector $q = (1/3, 1/3, 0)$ observed for Ba$_2$La$_2$NiTe$_2$O$_{12}$ implies that the Y-like triangular structures shown in Fig. 5(a) are ferromagnetically stacked along the c axis; thus, the weak resultant magnetic moments induced in the triangular layers are summed to produce the net moment along the c axis. This spin structure is consistent with the weak magnetic moment observed by magnetization measurement (see Figs. 4 and 6). In addition, we attempted
to refine the size of the ordered magnetic moment of Ni$^{2+}$ by the magnetic structure analysis of the ND data but failed owing to the weakness of the magnetic peaks.

F. Density functional theory calculations

The band structure of Ba$_2$La$_2$NiTe$_2$O$_{12}$ is shown in Fig. 13. There are five bands with dominant Ni 3d character from the one Ni$^{2+}$ ion in the unit cell. High-symmetry points in the Brillouin zone for the rhombohedral space group are explained in the text. The errors shown are only the statistical errors arising from the energy mapping.

![Fig. 13](color online) Band structure of Ba$_2$La$_2$NiTe$_2$O$_{12}$ obtained from GGA calculations. Orbital weights for Ni 3d orbitals are marked. The high-symmetry points for the rhombohedral space group are explained in the text.

![Table III: Exchange couplings of Ba$_2$La$_2$NiTe$_2$O$_{12}$, calculated within GGA+U at $J_H = 0.88$ eV using a $6 \times 6 \times 6$ k mesh in a supercell containing four Ni$^{2+}$ sites. The last row contains the Ni–Ni distances, which identify the exchange paths. The errors shown are only the statistical errors arising from the energy mapping.](table)

| $U$ [eV] | $J_i$ / $k_B$ [K] | $J_{ij}$ / $k_B$ [K] | $J_{ij}$ / $k_B$ [K] | $\Theta_{CW}$ [K] |
|----------|-----------------|-----------------|-----------------|-------------|
| 3        | 28.3(1)         | -0.09(1)        |                | -113        |
| 3.5      | 25.2(1)         | -0.07(1)        |                | -101        |
| 3.52     | 25.1(1)         | 0.07(1)         |                | -100.7      |
| 4        | 22.6(1)         | 0.06(1)         |                | -91         |
| 4.5      | 20.3(1)         | 0.05(1)         |                | -81         |
| 5        | 18.2(1)         | 0.04(1)         |                | -73         |
| 5.5      | 16.5(1)         | 0.03(1)         |                | -66         |
| 6        | 14.9(1)         | 0.03(1)         |                | -60         |
| 6.5      | 13.5(1)         | 0.02(1)         |                | -54         |
| 7        | 12.2(1)         | 0.02(1)         |                | -49         |
| 7.5      | 11.0(1)         | 0.02(1)         |                | -44         |
| 8        | 10.0(1)         | 0.01(1)         |                | -40         |

$\bar{d}_{Ni-Ni}$ [Å] 5.66827 9.72442 9.81773

We find that the total moments in all our calculations are exact multiples of $2\mu_B$ as all the nickel moments are exactly $S = 1$, and all the fits are very good, resulting in very low statistical errors. We first use a supercell with four Ni$^{2+}$ ions to determine the two in-plane exchange couplings $J_1$ and $J_3$, where we index the couplings with increasing Ni–Ni distance. The geometry of the Ni$^{2+}$ ions in Ba$_2$La$_2$NiTe$_2$O$_{12}$ is shown as an inset in Fig. 14.

The values of the exchange constants are given in Table III. The values of $J_i$ are given with respect to spin operators of length $S = 1$. Note that if the Hamiltonian is written as $\sum_{ij}$, counting every bond twice, then the values of $J_i$ need to be divided by two. The Curie–Weiss temperatures are estimated from

$$\Theta_{CW} = -\frac{2}{3}S(S+1)(3J_1 + 3J_2 + 3J_3), \quad (4)$$

where $S = 1$.

The calculated exchange couplings are shown graphically in Fig. 14. The statistical errors are smaller than the symbols. The inset shows the nickel sublattice of the defect perovskite Ba$_2$La$_2$NiTe$_2$O$_{12}$ with bonds indicating the first three exchange pathways. The nearest- and next-nearest-neighbor couplings of the triangular lattice are $J_1$ (purple) and $J_3$ (red), respectively. $J_2$ (turquoise) is the first-interlayer coupling. $U = 3.52$ eV was determined to be the value at which the couplings exactly yield the experimental Curie–Weiss temperature $\Theta_{CW} = -100.7$ K.

A larger supercell containing six inequivalent Ni$^{2+}$ sites also allows the determination of the interlayer coupling $J_2$. The result of this calculation is shown in Table IV. The interlayer coupling turns out to be even smaller than the next-nearest-neighbor coupling $J_3$ in the triangular lattice. However, consistent with the fact that the calcula-
We have reported on the crystal structure and magnetic properties of the $S=1$ TLAF $\text{Ba}_2\text{La}_2\text{NiTe}_2\text{O}_{12}$ composed of a uniform triangular lattice of Ni$^{2+}$ ions. We refined the crystal structure parameters by Rietveld analysis using XRD and ND data obtained from a powdered sample. The space group was determined to be $\bar{R}3$. The large negative Weiss constant $\Theta_{\text{CW}} \simeq -100$ K for the magnetic susceptibility shows that predominant exchange interaction is antiferromagnetic and strong, in contrast to $\text{Ba}_2\text{La}_2\text{NiW}_2\text{O}_{12}$ [40, 41]. Specific heat measurement demonstrated that $\text{Ba}_2\text{La}_2\text{NiTe}_2\text{O}_{12}$ undergoes successive magnetic phase transitions at $T_{N1} = 9.8$ K and at $T_{N2} = 8.9$ K, which arise from the competition between the antiferromagnetic exchange interaction and the single-ion anisotropy of the easy-axis type. From the weak net magnetic moment of $\Delta M = 0.015 \mu_B/\text{Ni}^{2+}$ observed at $T = 1.8$ K ($\ll T_{N2}$), the ratio of single-ion anisotropy to the exchange interaction was estimated as $|D|/J \simeq 0.108$. It was found from high-magnetic-field magnetization measurement up to 60 T that the magnetization curve exhibits a wide plateau at one-third of the saturation magnetization, which is characteristic of quantum TLAFs. We estimated the exchange interaction $J$ and the $g$ factor as $J/k_B \simeq 19$ and $g \simeq 2.3$, respectively, by fitting the theoretical magnetization curve to the experimental data. From the ND measurements at zero magnetic field, the propagation vector in the low-temperature phase for $T < T_{N2}$ was found to be $q = (1/3, 1/3, 0)$. This result, together with the magnetization and specific heat results, indicates that below $T_{N2}$, spins form a triangular structure in a plane including the $c$ axis in each triangular layer and these triangular spin structures are ferromagnetically stacked along the $c$ axis. The DFT calculations demonstrated that the nearest-neighbor exchange interaction is predominant and that the next-nearest-neighbor exchange interaction in the triangular layer and the interlayer exchange interactions are negligible.

V. CONCLUSION

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FIG. 15: (Color online) Band structure of Ba$_2$La$_2$NiW$_2$O$_{12}$ obtained from GGA calculations. Orbital weights for Ni 3$d$ orbitals are marked.

Appendix A: Electronic structure of Ba$_2$La$_2$NiW$_2$O$_{12}$

For comparison with the new material Ba$_2$La$_2$NiTe$_2$O$_{12}$, we have determined the electronic structure of Ba$_2$La$_2$NiW$_2$O$_{12}$ using the crystal structure provided in Ref. 10. Figure 15 shows the bands calculated with the GGA exchange correlation functional. The path through the Brillouin zone is explained in the main text. As in isostructural Ba$_2$La$_2$NiTe$_2$O$_{12}$, two Ni 3$d$ bands of $e_g$ character cross the Fermi level. However, the band width is only 0.2 eV, indicating rather small effective hopping parameters between Ni $e_g$ orbitals compared to Ba$_2$La$_2$NiTe$_2$O$_{12}$.

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