Giant Topological Hall Effect in the Noncollinear Phase of Two-Dimensional Antiferromagnetic Topological Insulator MnBi$_4$Te$_7$

Subhajit Roychowdhury,* Sukriti Singh, Satya N. Guin, Nitesh Kumar, Tirthankar Chakraborty, Walter Schnelle, Horst Borrmann, Chandra Shekhar, and Claudia Felser*

Cite This: Chem. Mater. 2021, 33, 8343–8350

1. INTRODUCTION

Magnetic topological insulators (MTIs) have drawn significant attention owing to the interplay between the magnetic order and nontrivial band topology, which provides an important platform for realizing emergent quantum phenomena such as the axion insulating state and the quantum anomalous Hall effect, owing to the interplay between topology and magnetism. MnBi$_4$Te$_7$ is a two-dimensional $Z_2$ antiferromagnetic (AFM) topological insulator with a Néel temperature of $\sim$13 K. In AFM materials, the topological Hall effect (THE) is observed owing to the existence of nontrivial spin structures. A material with noncollinearity that develops in the AFM phase rather than at the onset of the AFM order is particularly important. In this study, we observed that such an unanticipated THE starts to develop in a MnBi$_4$Te$_7$ single crystal when the magnetic field is rotated away from the easy axis (c-axis) of the system. Furthermore, the THE resistivity reaches a giant value of $\sim$7 $\mu\Omega$-cm at 2 K when the angle between the magnetic field and the c-axis is 75°. This value is significantly higher than the values for previously reported systems with noncoplanar structures. The THE can be ascribed to the noncoplanar spin structure resulting from the cant state during the spin-flip transition in the ground AFM state of MnBi$_4$Te$_7$. The large THE at a relatively low applied field makes the MnBi$_4$Te$_7$ system a potential candidate for spintronic applications.

Received: July 29, 2021
Revised: September 29, 2021
Published: October 19, 2021

© 2021 The Authors. Published by American Chemical Society
https://doi.org/10.1021/acs.chemmater.1c02625
Chem. Mater. 2021, 33, 8343–8350
Figure 1. (a) Crystal structure of MnBi$_4$Te$_7$ (sky blue, dark blue, and white atoms represent Mn, Bi, and Te, respectively). (b) Temperature-dependent field-cooled magnetic susceptibility at $B = 50$ Oe for $B \parallel ab$ and $B \parallel c$. (c) Isothermal magnetization at 2 K for $B \parallel ab$ and $B \parallel c$. The inset shows the virgin line for $B \parallel c$. (d) Variation in resistivity, $\rho_{xy}$, with temperature. (e) Field-dependent resistivity of MnBi$_4$Te$_7$ at various temperatures.

The magnetic septuple layers (SLs), thereby reducing interlayer coupling. Second, the surface termination (magnetic or nonmagnetic) is expected to be different.

Unlike MnBi$_2$Te$_4$, a previous magnetotransport research on MnBi$_2$Te$_4$ showed that it features a direct spin-flip transition from the AFM phase to the FM phase at a low magnetic field ($\sim 0.2$ T), without any canted AFM phase. However, it will be interesting to explore if MnBi$_4$Te$_7$, which also belongs to the homologous family of MnBi$_2$Te$_4$, also exhibits a noncoplanar spin structure under certain conditions. This has not been studied till now. Because of the weak AFM interaction in MnBi$_4$Te$_7$, it is a common intuition to tailor its spin structure from the original one and study the effect by simple magnetic measurement. Here, the noncoplanar spin structure will govern the magnetism of the system. Thus, Hall effect measurements enable the solid-state chemists to get a much deeper insight into the spin structure of 2D materials. Such an understanding might be helpful to design phase diagrams of magnetic ground states in other novel 2D TI families, which was not observed earlier.

In this work, we investigate the angular variation in the Hall effect in a two-dimensional van der Waals AFM topological insulator, i.e., a MnBi$_4$Te$_7$ single crystal. We observed an unexpected THE when the magnetic field was rotated away from the easy axis ($c$-axis) of the system. A large THE resistivity of $\sim 7 \mu\Omega\cdot cm$ was observed at 2 K and $\theta = 75^\circ$ with respect to the $c$-axis. This THE resistivity decreased as temperature increased. In this measurement configuration, the ground AFM state of MnBi$_4$Te$_7$ experienced a canted state from the spin-flip transition. This resulted in a noncoplanar spin structure, which was the origin of the observed THE. The observed value of the THE resistivity was significantly higher than the previously reported values for noncoplanar magnetic structures. Our finding highlights the importance of the
previously unexplored noncoplanar structure in a two-dimensional system to enhance the understanding of the THe.

2. EXPERIMENTAL SECTION

2.1. Single-Crystal Growth of MnBi4Te7 and Characterizations. The Bi3Te4 flux procedure was used to grow the single crystals of MnBi4Te7. As-purchased high-quality elemental manganese (99.9999%, Alfa Aesar), bismuth (99.999%, Alfa Aesar), and tellurium (99.9999%, Alfa Aesar) were mixed in a molar ratio of Mn:Bi:Te of 1:10:16. All of the elements were loaded into an alumina crucible, which was vacuum-sealed in a quartz tube under 10⁻³ Torr. The tube was heated to 1233 K for 12 h, and then submerged for 24 h before being progressively cooled to 855 K for 100 h. After centrifuging at 855 K to remove excess Bi2Te3, the crystals were recovered. The single crystal has a typical dimension of 2 × 2 × 0.3 mm³. A Huber image plate Guinier G670 camera operated with CuKα radiation (λ = 1.54056 Å) was used to measure powder X-ray diffraction (PXRD) at room temperature. Figure S1 shows the powder XRD data for the crushed crystal. White-beam backscattering Laue X-ray diffraction was used to determine the single crystallinity of the as-grown crystal. On a single crystal diffractometer, the quality and orientation of the as-grown crystals were assessed using transmission of thin edges. Unambiguous indexing revealed an expected trigonal unit cell with lattice parameters a = 4.37 Å and c = 23.80 Å. Oscillation images confirmed the determined unit cell and symmetry as well as good crystal quality (Figure S2). Scanning electron microscopy along with an energy-dispersive EDAX analyzer was used to evaluate the composition of the MnBi4Te7 crystal.

2.2. Magnetization Measurements. An MPMS3 instrument was used for the magnetization measurement.

2.3. Electrical Transport Measurements. A physical property measurement system (PPMS9) (ETO option, Quantum Design) was employed to measure the electrical transport. For transport studies, the sample was cut into a standard rectangular shape and a six-probe technique was used to simultaneously measure the normal resistance and Hall resistivity. The final resistivity and (Hall) data were symmetrized (antisymmetrized) to eliminate the misalignment of the electrodes.

3. RESULTS AND DISCUSSION

We have synthesized high-quality single crystals of MnBi4Te7 from the homologous series MnBi2Te4 via a Bi2Te3 flux method (see the Experimental section). MnBi4Te7 crystallizes in a trigonal structure with the P3m1 space group. The structure is characterized by alternate stacking of septuple layers (SL) of MnBi2Te4 (Te-Bi-Te-Mn-Te-Bi-Te) and quintuple layers of Bi2Te3 (Te-Bi-Te-Bi-Te) along the c-axis via van der Waals interaction, making it an ideal two-dimensional material (Figure 1a). The d-orbitals of Mn²⁺ ions, which form long-range FM ordering within the SL, are responsible for the local magnetic moment. In contrast, along the c-axis, the magnetic moments from adjacent SLs are antiferromagnetically ordered, forming an A-type AFM state similar to MnBi2Te4. However, the SLs are separated by a nonmagnetic layer (Bi2Te3), which reduces the interlayer AFM exchange coupling. This results in a lower Néel temperature (TN) of ~13 K for MnBi4Te7 (Figure 1b) compared to MnBi2Te4 (~25 K). Selected oscillation images around the main axes of MnBi4Te7 single crystals are shown in Figure S2, Supporting Information (SI).

The measured magnetic susceptibility and resistivity of MnBi4Te7 are shown in Figure 1b–e. The longitudinal resistivity, ρxx, decreases linearly with temperature up to ~20 K. As temperature decreases further, ρxx slightly increases and then decreases because of the increase in scattering caused by the fluctuation of magnetic spins as the Néel temperature is reached. This effect is known to occur in low-dimensional magnetic systems (Figure 1d). The abrupt decrease in ρxx indicates that local Mn moments form a long-range ordered state at T < 13 K; this is consistent with the magnetic susceptibility measurement. We also measured out-of-plane resistance data, and the results are shown in Figure S5b, SI which clearly shows the large transport anisotropy in the system due to the vdW nature of MnBi4Te7. Figure 1b represents the field-cooled magnetic susceptibility curves on B || ab (χab) and B || c (χc) planes at a magnetic field of 50 Oe. Figure 1b shows that χc is two orders of magnitude more than that χab, implying that MnBi4Te7 has significant magnetic anisotropy. The data for the magnetic field applied along the c-axis (χc) show a peak at ~13 K, which has been observed for...
other layered antiferromagnets from the MnBi$_2$Te$_4$ series, such as MnBi$_2$Te$_4$ ($\sim$25 K) and MnBi$_2$Te$_{10}$ ($\sim$11 K).$^{37,38}$

The magnetization isotherm data with on the B $\parallel$ ab and $B \perp$ c at temperatures of 2−30 K are shown in Figures 1c and S4 (SI). It can be clearly seen that MnBi$_2$Te$_7$ undergoes a first-order spin-flip transition with hysteresis at 2 K (Figure 1c). The hysteresis begins at a low field of ~0.15 T, rapidly enters the forced FM state, and becomes saturated at 0.22 T. Thus, the magnetization trend of MnBi$_4$Te$_7$ in a spin-flip transition occurs at 3.5 T and a transition from a canted AFM phase to an FM phase occurs at ~8 T. This confirms the weaker interlayer AFM exchange coupling in MnBi$_2$Te$_4$ compared to MnBi$_2$Te$_4$. However, magnetization along the $B \parallel$ ab-plane requires a high saturation field of ~1 T, indicating that the $c$-axis is the easy magnetic axis. The observed saturation magnetic moment for Mn is 3.74 $\mu_B$ at 7 T, which is lower than the theoretical value for $d^5$ Mn$^{2+}$ (4.6 $\mu_B$).$^{33}$

The discrepancy between the calculated and observed values mainly arises from the Mn disorders in the synthesized samples.$^{35}$

We measured the longitudinal resistivity and Hall resistivity of the MnBi$_2$Te$_7$ single crystal. The AFM–FM spin-flip transitions can be clearly seen from the $\rho_{xx}$-$B$ plot, where the magnetic field is applied along the $c$-axis and $I \parallel$ ab-plane (Figure 1e). From the field dependent measured $\rho_{xx}$ we calculated the transverse magnetoresistance (MR = ($\rho_{xx}(B)$-$\rho_{xx}(0)/\rho_{xx}(0)$)), and the results are shown in Figure 2a. A maximum negative MR of ~8% is observed at 12 K, which is close to the Néel temperature. The negative MR can be attributed to the suppression of spin-flip-related scattering, which is generally observed in magnetic systems.$^{35,34}$

The variation in the Hall resistivity with the magnetic field at various temperatures is presented in Figure 2b–d. Figure 2b,c clearly shows that the AHE is present in the system when $T < T_N$, owing to the AFM–FM spin-flip transition; this is consistent with the isothermal magnetization and magnetoresistance measurements (Figure 1c,e). Thus, the Hall resistivity can be expressed as $\rho_{yx} = R_{xy}H + R_N M$. Typically, the anomalous Hall conductivity (AHC, $\sigma_{xy}$) at 2 K is $\sim$15 $\Omega^{-1}$ cm$^{-1}$, which is consistent with the previous reports.$^{33,34}$

Wu et al. proposed that the AHC in the present system has a dominant contribution from BC.$^{34}$ At a high temperature of $T > 50$ K, the Hall resistivity shows a linear field dependence up to 9 T, suggesting a single carrier band in MnBi$_2$Te$_7$. The electron carrier density of our sample is $\sim$8 $\times$ 10$^{19}$ cm$^{-3}$ at 50 K.

We did not observe any evidence of the existence of a noncoplanar structure from the magnetotransport data in the geometry $B \parallel$ c-axis and $I \parallel$ ab-plane measurements.$^{33,34}$ As the spins (magnetization) in the $ab$-plane and the $c$-plane have completely different behaviors, it is interesting to investigate the effect of spin fluctuations on the magnetotransport for field directions in between these limits. We investigated $\rho_{yx}$ and $\rho_{xx}$ while steadily rotating the magnetic field ($B$) from the $c$-axis to the $ab$-plane. The schematic of our measurement is presented in Figure 3 (inset), where $\theta$ represents the angle between $B$ and the $c$-axis. At $\theta = 0^\circ$, the MR and Hall resistivity (Figure 2) are consistent with the earlier report.$^{35,34}$ Below $T_N$, e.g., at 2 K, $\rho_{yx}$ steadily decreases as $\theta$ increases from 0 to 90$^\circ$. In addition, a hump-like anomaly appears in the low-$B$ region ($<1$ T), which becomes pronounced at $\theta = 75^\circ$, as shown in Figure 3a. We focus on $\theta = 75^\circ$ to investigate the transport properties at different temperatures (below and above the Néel temperature) (Figure 3b).

It should be noted that although we observe a hump-like feature in the low $B$ region of the plot of $\rho_{yx}$, no such anomaly is observed in the $M$ vs $B$ curve (at $\theta = 75^\circ$) (Figure S6, SI). This strongly supports the presence of a Hall effect in addition to the ordinary Hall effect and AHE, namely, the THE, which is different from the $B \parallel$ c-axis measurement (Figure 2). Thus, in this scenario, $\rho_{yx}$ can be expressed as $\rho_{yx} = R_{xy}H + R_N M + \rho_{yx}^T$. After subtracting the first two terms, we obtain the values of $\rho_{yx}^T$ at different temperatures for $\theta = 75^\circ$ (Figure 3c). To clearly observe the variation in the THE, we create a contour plot of the $B$-$T$ phase diagram by extracting $\rho_{yx}^T$ over the measured temperature range (Figure 3d). Surprisingly, a giant topological Hall resistivity ($\rho_{yx}^T$) of $\sim$7 $\mu\Omega$-cm is observed at 2 K, which is significantly higher than any previously reported...
value (Figure 4).\textsuperscript{15,17,19,39–44} This makes the MnBi\textsubscript{4}Te\textsubscript{7} system a potential candidate for spintronic applications.

Figure 4. Comparison of maximum topological Hall resistivity obtained in the present work with previously reported values.\textsuperscript{15,17,19,39–44} We have listed the experimental conditions of each material when they reach their maximum topological Hall resistivity.

We have measured $\rho_{xy}$ as a function of $\theta$ at 3.5 K at various magnetic fields (Figure 5a). At $\theta = 0^\circ$ and $B = 0.2$ T, $\rho_{xy}$ is $\sim 10 \mu\Omega\cdot\text{cm}$. As we rotate the field clockwise from the $c$-axis, $\rho_{xy}$ initially remains flat and then abruptly decreases to almost zero around $\theta = 45^\circ$. Interestingly, hysteresis is observed between the clockwise and anticlockwise rotation of $B$, indicating that this $B$-direction-sensitive phase change is of the first order. With increasing the field, hysteresis slowly decreases. After the application of 0.7 T, hysteresis vanishes (Figure S8, SI). The critical magnetic field for hysteresis is 0.7 T in the present system. A similar observation was previously reported in a frustrated triangular lattice of a Gd$_5$PdSi$_5$ system, in which the skyrmionic lattice was limited to only a two-dimensional space.\textsuperscript{19} Thus, the abovementioned behavior indicates the possibility of realizing a skyrmion lattice in the present system, which is composed of the stacked FM triangular-lattice layers of MnBi$_4$Te$_7$. The amplitude of the topological Hall resistivity abruptly transitions from a finite value to zero, providing a measure of the topological number for the spin texture. Further studies are required to clarify the microscopic origin of the BC in the present system. In contrast, at a higher magnetic field ($B = 3$ T), $\rho_{xy}$ follows a simple $\cos \theta$ relation without any hysteresis. In this case, the AHE simply scales with the out-of-plane component of the magnetic field. However, the components of the AHE are expected to become zero at $\theta = 90$ or 270$^\circ$.

An AFM state with a noncollinear spin structure is likely to have a large THE.\textsuperscript{45} In such materials, symmetry breaking combined with significant spin–orbit coupling can lift spin degeneracy, producing a net Berry curvature in momentum space and an intrinsic AHE effect. Earlier Wu et al. proposed that the AHC in MnBi$_4$Te$_7$ has a dominant contribution from the Berry curvature.\textsuperscript{34} The observed THE can be attributed to the relative strength of interlayer exchange coupling ($J$) and uniaxial anisotropy ($K$), which plays a crucial role in controlling the transition from the A-type AFM state to the FM state.\textsuperscript{36} In MnBi$_4$Te$_7$, there exists a competition between AFM and FM couplings owing to the separation of the two magnetic SLs of MnBi$_4$Te$_7$ by a nonmagnetic layer (Bi$_4$Te$_3$), which reduces the interlayer AFM exchange coupling. Tan et al. recently reported that a metamagnetic phase exists in MnBi$_4$Te$_7$, which is controlled by uniaxial anisotropy at a low temperature.\textsuperscript{46} When a magnetic field is applied along the $c$-axis, either a parallel or an antiparallel alignment of sublattice magnetizations occurs. This results in two spin-flip transitions in MnBi$_4$Te$_7$ accompanied by hysteresis. Depending on the relative strength of $K$ and $J$ ($K/J$ ratio), the spin-flip transition might change to either a canted state or an FM-like alignment under a finite magnetic field. According to a recent theoretical model, the AFM state of MnBi$_4$Te$_7$ experiences a canted state from the spin-flip transition at $K/2J < 1/3$.\textsuperscript{46} Therefore, the spins of Mn$^{2+}$ become noncoplanar during the spin-flip process, resulting in the THE. Thus, we observe the THE owing to the existence of the canted spin structure in MnBi$_4$Te$_7$, at $\theta = 75^\circ$ (Figure 5b). As the magnetic field is increased further, the THE is suppressed because the spins become parallel. The noncollinear spin structure can be ascribed to the significant TH value obtained here in the CAFM phase of MnBi$_4$Te$_7$. This finding means that the electronic structure of MnBi$_4$Te$_7$ is strictly related to its magnetism, allowing for the observation of several topological states modulated by a magnetic field. Similarly, strong coupling between electronic and magnetic properties has been observed in the canted AFM state of MnBi$_4$Te$_4$ as a result of the net Berry curvature in the momentum space induced by the noncollinear spin structure.\textsuperscript{37} Compared with MnBi$_2$Te$_4$, the weaker interlayer exchange interactions in MnBi$_4$Te$_7$ have...
significant influences on the TH value. We observed the maximum TH value at a much lower field (∼0.5 T) for MnBi$_4$Te$_7$ compared to that of MnBi$_4$Te$_6$ (∼5 T), which has significant advantages for spintronic applications. However, the magnetic structure of MnBi$_4$Te$_7$ at angles around θ = 75° should be investigated further.

4. CONCLUSIONS

In summary, we synthesized a MnBi$_4$Te$_7$ single crystal and studied its magnetic topological properties. The crystal exhibits large magnetocrystalline anisotropy owing to its two-dimensional layered structure; this is supported by magnetization measurements. We systematically investigated the angle-dependent electrical transport properties and revealed an unanticipated THE in the MnBi$_4$Te$_7$ single crystal. A large TH value at a much lower field (∼0.5 T) for MnBi$_4$Te$_7$ compared to that of MnBi$_4$Te$_6$ (∼5 T), which has significant advantages for spintronic applications. However, the magnetic structure of MnBi$_4$Te$_7$ at angles around θ = 75° should be investigated further.

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.chemmater.1c02625

Funding

Open access funded by Max Planck Society.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work was financially supported by the European Union’s Horizon 2020 Research and Innovation Programme (grant No. 766566). This work was financially supported by the Deutsche Forschungsgemeinschaft (DFG) under SFB1143 (Project No. 247310070), the European Research Council (ERC) Advanced Grant No. 742068 (“TOPMAT”), and the Würzburg-Dresden Cluster of Excellence on Complexity and Topology in Quantum Matter—ct.qmat (EXC 2147, project no. 39085490). S.R. thanks the Alexander von Humboldt Foundation for a fellowship.

REFERENCES

(1) Tokura, Y.; Yasuda, K.; Tsukazaki, A. Magnetic topological insulators. Nat. Rev. Phys. 2019, 1, 126.
(2) Mong, R. S. K.; Essin, A. M.; Moore, J. E. Antiferromagnetic topological insulators. Phys. Rev. B 2010, 81, No. 245209.
(3) Nenno, D. M.; Garcia, C. A. C.; Gooth, J.; Felser, C.; Narang, P. Axion physics in condensed-matter systems. Nat. Rev. Phys. 2020, 2, 682.
(4) Liu, E.; Sun, Y.; Kumar, N.; Muechler, L.; Sun, A.; Jiao, L.; Yang, S. Y.; Liu, D.; Liang, A.; Su, Q.; Kroder, J.; Siüß, V.; Bormann, H.; Shekhar, C.; Wang, Z.; Xi, C.; Wang, W.; Schnelle, W.; Wirth, S.; Chen, Y.; Goennenwein, S. T. B.; Felser, C. Giant anomalous Hall effect in a ferromagnetic kagome-lattice semimetal. Nat. Phys. 2018, 14, 1125.
(5) Kumar, N.; Guin, S. N.; Manna, K.; Shekhar, C.; Felser, C. Topological Quantum Materials from the Viewpoint of Chemistry. Chem. Rev. 2021, 121, 2780.
(6) Hall, E. H. XVIII. On the Rotational Coefficient in nickel and cobalt. London, Edinburgh Dublin Philos. Mag. J. Sci. 1881, 12, 157.
(7) Nagaosa, N.; Sinova, J.; Onoda, S.; MacDonald, A. H.; Ong, N. P. Anomalous Hall effect. Rev. Mod. Phys. 2010, 82, 1539.
(8) Hall, E. H. On a New Action of the Magnet on Electric Currents. Am. J. Math. 1879, 2, 287.
(9) Thakur, G. S.; Vir, P.; Guin, S. N.; Shekhar, C.; Wehrich, R.; Sun, Y.; Kumar, N.; Felser, C. Intrinsic Anomalous Hall Effect in Ni-Substituted Magnetic Weyl Semimetal Co$_x$Sn$_2$. Chem. Mater. 2020, 32, 1612.
(10) Onoda, S.; Sugimoto, N.; Nagaosa, N. Intrinsic Versus Extrinsic Anomalous Hall Effect in Ferromagnets. Phys. Rev. Lett. 2006, 97, No. 126602.
(11) Xiao, D.; Chang, M. C.; Niu, Q. Berry phase effects on electronic properties. Rev. Mod. Phys. 2010, 82, 1959.
(12) Guin, S. N.; Xu, Q.; Kumar, N.; Kung, H. H.; Dufresne, S.; Le, C.; Vir, P.; Michiardi, M.; Pedersen, T.; Gorovikov, S.; Zhdanovich, S.; Manna, K.; Auffermann, G.; Schnelle, W.; Gooth, J.; Shekhar, C.;
unconventional anomalous Hall effect in the metallic triangular antiferromagnet Mn$_{1.4}$PtSn.

© 2020, No. 1086602.

Chiral skyrmions in thin magnetic films: new objects for magnetic storage technologies? J. Phys. D: Appl. Phys. 2014, 47, No. 204001.

Large topological Hall effect near room temperature in noncollinear order in MnBi$_2$Te$_3$ and MnBi$_2$Te$_5$ single crystals. Phys. Rev. Mater. 2020, 4, No. 054402.

Large topological Hall effect in the uniaxial field of the Waals ferromagnet Fe$_x$Ge$_{1-x}$Te$_2$. Phys. Rev. B 2019, 100, No. 134441.

Large topological Hall effect near room temperature in noncollinear ferromagnet LaMn$_2$Ge$_2$ single crystal. Phys. Rev. B 2019, 110, No. 054409.

Large topological Hall effect in noncollinear magnetic Mn$_2$Ge$_2$ single crystal. Phys. Rev. B 2021, 103, No. 041408.

Large topological Hall effect in MnBi$_2$Te$_3$: A Bi$_2$Te$_3$ Derivative with a Perpendicular Sublattice. Phys. Rev. X 2019, 9, No. 041065.

Large topological Hall effect near room temperature in noncollinear ferromagnet Mn$_2$Ge$_2$. Phys. Rev. Lett. 2020, 124, No. 237201.

Large topological Hall effect in the metallic triangular antiferromagnet Mn$_{1.4}$PtSn. Phys. Rev. B 2020, 101, No. 180404(R).

Large topological Hall effect in MnBi$_2$Te$_3$:AB $i_2$Te$_3$ Derivative with a c-axis component in the metallic kagome antiferromagnetic field. J. Phys. D: Appl. Phys. 2019, 52, No. 095002.

Large topological Hall effect in the non-collinear phase of an antiferromagnet. Nat. Commun. 2014, 5, No. 3400.

Large topological Hall effect and double-fan spin structure with a c-axis component in the metallic kagome antiferromagnetic field. J. Phys. D: Appl. Phys. 2019, 52, No. 095020.

Large topological Hall effect in the metallic kagome antiferromagnetic compound YMn$_2$Sn$_2$. Phys. Rev. B 2021, 103, No. 044416.

Large topological Hall effect in the metallic kagome antiferromagnetic compound YMn$_2$Sn$_2$. Phys. Rev. B 2021, 103, No. 014416.

Large topological Hall effect in the noncollinear phase of an antiferromagnet. Nat. Commun. 2014, 5, No. 3400.

Large topological Hall effect in the metallic kagome antiferromagnetic field. J. Phys. D: Appl. Phys. 2019, 52, No. 095002.

Large topological Hall effect in the metallic kagome antiferromagnetic field. J. Phys. D: Appl. Phys. 2019, 52, No. 095020.

Large topological Hall effect in the noncollinear phase of an antiferromagnet. Nat. Commun. 2014, 5, No. 3400.

Large topological Hall effect and double-fan spin structure with a c-axis component in the metallic kagome antiferromagnetic field. J. Phys. D: Appl. Phys. 2019, 52, No. 095020.

Large topological Hall effect in the metallic kagome antiferromagnetic compound YMn$_2$Sn$_2$. Phys. Rev. B 2021, 103, No. 044416.

Large topological Hall effect and double-fan spin structure with a c-axis component in the metallic kagome antiferromagnetic field. J. Phys. D: Appl. Phys. 2019, 52, No. 095002.

Large topological Hall effect in the metallic kagome antiferromagnetic compound YMn$_2$Sn$_2$. Phys. Rev. B 2021, 103, No. 014416.

Large topological Hall effect in the metallic kagome antiferromagnetic compound YMn$_2$Sn$_2$. Phys. Rev. B 2021, 103, No. 044416.

Large topological Hall effect and double-fan spin structure with a c-axis component in the metallic kagome antiferromagnetic field. J. Phys. D: Appl. Phys. 2019, 52, No. 095002.

Large topological Hall effect in the metallic kagome antiferromagnetic compound YMn$_2$Sn$_2$. Phys. Rev. B 2021, 103, No. 014416.

Large topological Hall effect and double-fan spin structure with a c-axis component in the metallic kagome antiferromagnetic field. J. Phys. D: Appl. Phys. 2019, 52, No. 095002.

Large topological Hall effect in the metallic kagome antiferromagnetic compound YMn$_2$Sn$_2$. Phys. Rev. B 2021, 103, No. 014416.

Large topological Hall effect and double-fan spin structure with a c-axis component in the metallic kagome antiferromagnetic field. J. Phys. D: Appl. Phys. 2019, 52, No. 095002.

Large topological Hall effect in the metallic kagome antiferromagnetic compound YMn$_2$Sn$_2$. Phys. Rev. B 2021, 103, No. 014416.

Large topological Hall effect and double-fan spin structure with a c-axis component in the metallic kagome antiferromagnetic field. J. Phys. D: Appl. Phys. 2019, 52, No. 095002.

Large topological Hall effect in the metallic kagome antiferromagnetic compound YMn$_2$Sn$_2$. Phys. Rev. B 2021, 103, No. 014416.

Large topological Hall effect and double-fan spin structure with a c-axis component in the metallic kagome antiferromagnetic field. J. Phys. D: Appl. Phys. 2019, 52, No. 095002.

Large topological Hall effect in the metallic kagome antiferromagnetic compound YMn$_2$Sn$_2$. Phys. Rev. B 2021, 103, No. 014416.

Large topological Hall effect and double-fan spin structure with a c-axis component in the metallic kagome antiferromagnetic field. J. Phys. D: Appl. Phys. 2019, 52, No. 095002.

Large topological Hall effect in the metallic kagome antiferromagnetic compound YMn$_2$Sn$_2$. Phys. Rev. B 2021, 103, No. 014416.

Large topological Hall effect and double-fan spin structure with a c-axis component in the metallic kagome antiferromagnetic field. J. Phys. D: Appl. Phys. 2019, 52, No. 095002.

Large topological Hall effect in the metallic kagome antiferromagnetic compound YMn$_2$Sn$_2$. Phys. Rev. B 2021, 103, No. 014416.

Large topological Hall effect and double-fan spin structure with a c-axis component in the metallic kagome antiferromagnetic field. J. Phys. D: Appl. Phys. 2019, 52, No. 095002.

Large topological Hall effect in the metallic kagome antiferromagnetic compound YMn$_2$Sn$_2$. Phys. Rev. B 2021, 103, No. 014416.

Large topological Hall effect and double-fan spin structure with a c-axis component in the metallic kagome antiferromagnetic field. J. Phys. D: Appl. Phys. 2019, 52, No. 095002.

Large topological Hall effect in the metallic kagome antiferromagnetic compound YMn$_2$Sn$_2$. Phys. Rev. B 2021, 103, No. 014416.

Large topological Hall effect and double-fan spin structure with a c-axis component in the metallic kagome antiferromagnetic field. J. Phys. D: Appl. Phys. 2019, 52, No. 095002.

Large topological Hall effect in the metallic kagome antiferromagnetic compound YMn$_2$Sn$_2$. Phys. Rev. B 2021, 103, No. 014416.

Large topological Hall effect and double-fan spin structure with a c-axis component in the metallic kagome antiferromagnetic field. J. Phys. D: Appl. Phys. 2019, 52, No. 095002.

Large topological Hall effect in the metallic kagome antiferromagnetic compound YMn$_2$Sn$_2$. Phys. Rev. B 2021, 103, No. 014416.

Large topological Hall effect and double-fan spin structure with a c-axis component in the metallic kagome antiferromagnetic field. J. Phys. D: Appl. Phys. 2019, 52, No. 095002.

Large topological Hall effect in the metallic kagome antiferromagnetic compound YMn$_2$Sn$_2$. Phys. Rev. B 2021, 103, No. 014416.

Large topological Hall effect and double-fan spin structure with a c-axis component in the metallic kagome antiferromagnetic field. J. Phys. D: Appl. Phys. 2019, 52, No. 095002.

Large topological Hall effect in the metallic kagome antiferromagnetic compound YMn$_2$Sn$_2$. Phys. Rev. B 2021, 103, No. 014416.

Large topological Hall effect and double-fan spin structure with a c-axis component in the metallic kagome antiferromagnetic field. J. Phys. D: Appl. Phys. 2019, 52, No. 095002.

Large topological Hall effect in the metallic kagome antiferromagnetic compound YMn$_2$Sn$_2$. Phys. Rev. B 2021, 103, No. 014416.

Large topological Hall effect and double-fan spin structure with a c-axis component in the metallic kagome antiferromagnetic field. J. Phys. D: Appl. Phys. 2019, 52, No. 095002.

Large topological Hall effect in the metallic kagome antiferromagnetic compound YMn$_2$Sn$_2$. Phys. Rev. B 2021, 103, No. 014416.
(44) Li, X.; Collignon, C.; Xu, L.; Zuo, H.; Cavanna, A.; Gennser, U.; Mailly, D.; Fauqué, B.; Balents, L.; Zhu, Z.; Behnia, K. Chiral domain walls of Mn$_3$Sn and their memory. *Nat. Commun.* 2019, 10, No. 3021.
(45) Chen, H.; Niu, Q.; MacDonald, A. H. Anomalous Hall Effect Arising from Noncollinear Antiferromagnetism. *Phys. Rev. Lett.* 2014, 112, No. 017205.
(46) Tan, A.; Labracherie, V.; Kunchur, N.; Wolter, A. U. B.; Cornejo, J.; Dufouleur, J.; Büchner, B.; Isaeva, A.; Giraud, R. Metamagnetism of Weakly Coupled Antiferromagnetic Topological Insulators. *Phys. Rev. Lett.* 2020, 124, No. 197201.
(47) Lee, S. H.; Zhu, Y.; Wang, Y.; Miao, L.; Pillsbury, T.; Yi, H.; Kempinger, S.; Hu, J.; Heikes, C. A.; Quarterman, P.; Ratcliff, W.; Borchers, J. A.; Zhang, H.; Ke, X.; Graf, D.; Alem, N.; Chang, C.-Z.; Samarth, N.; Mao, Z. Spin scattering and noncollinear spin structure-induced intrinsic anomalous Hall effect in antiferromagnetic topological insulator MnBi$_2$Te$_4$. *Phys. Rev. Res.* 2019, 1, No. 012011(R).