Direct visualization of edge state in even-layer MnBi₂Te₄ at zero magnetic field

Weiyan Lin

Fudan University

Yang Feng

Fudan University

Yongchao Wang

Tsinghua University <https://orcid.org/0000-0002-1869-2290>

Zichen Lian

Tsinghua University

Hao Li

Tsinghua University

Yang Wu

State Key Laboratory of Low Dimensional Quantum Physics and Department of Physics, Tsinghua University

Chang Liu

Tsinghua University

Yihua Wang

Fudan University

Jinsong Zhang

Tsinghua University <https://orcid.org/0000-0002-3601-4995>

Yayu Wang

Tsinghua University <https://orcid.org/0000-0003-2330-1642>

Chui-Zhen Chen

Soochow University

Xiaodong Zhou (✉ zhouxd@fudan.edu.cn)

Fudan University <https://orcid.org/0000-0002-5602-1084>

Jian Shen

Fudan University <https://orcid.org/0000-0001-5670-1429>

Article

Keywords: MnBi₂Te₄, scanning microwave impedance microscopy, topological axion state

Posted Date: November 30th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-1059799/v1>

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
[Read Full License](#)

Direct visualization of edge state in even-layer MnBi_2Te_4 at zero magnetic field

Weiyan Lin^{1†}, Yang Feng^{2†}, Yongchao Wang^{6†}, Zichen Lian³, Hao Li^{7,8}, Yang Wu^{8,9}, Chang Liu^{3,10}, Yihua Wang^{2,11}, Jinsong Zhang^{3,12}, Yayu Wang^{3,12}, Chui-Zhen Chen^{4,5}, Xiaodong Zhou^{1,14,15*} and Jian Shen^{1,2,13,14,15*}

¹Institute for Nanoelectronic Devices and Quantum Computing, Fudan University, Shanghai, China.

²State Key Laboratory of Surface Physics and Department of Physics, Fudan University, Shanghai, China.

³State Key Laboratory of Low Dimensional Quantum Physics, Department of Physics, Tsinghua University, Beijing, China.

⁴School of Physical Science and Technology, Soochow University, Suzhou, China

⁵Institute for Advanced Study, Soochow University, Suzhou, China

⁶Beijing Innovation Center for Future Chips, Tsinghua University, Beijing, China.

⁷School of Materials Science and Engineering, Tsinghua University, Beijing, China

⁸Tsinghua-Foxconn Nanotechnology Research Center, Department of Physics, Tsinghua University, Beijing, China.

⁹Department of Mechanical Engineering, Tsinghua University, Beijing, China.

¹⁰Beijing Academy of Quantum Information Science, Beijing, China

¹¹Shanghai Research Center for Quantum Sciences, Shanghai, China

¹²Frontier Science Center for Quantum Information, Beijing, China.

¹³Collaborative Innovation Center of Advanced Microstructures, Nanjing, China

¹⁴Zhangjiang Fudan International Innovation Center, Fudan University, Shanghai, China

¹⁵Shanghai Qi Zhi Institute, Shanghai, China

[†]These authors contributed equally to this work

* Emails: zhouxd@fudan.edu.cn, shenj5494@fudan.edu.cn

Being the first intrinsic antiferromagnetic (AFM) topological insulator, MnBi_2Te_4 is argued to be a topological axion state in its even-layer form due to the antiparallel magnetization between the top and bottom layers. Here we combine both transport and scanning microwave impedance microscopy (sMIM) to investigate such axion state in atomically thin MnBi_2Te_4 with even-layer thickness at zero magnetic field. While transport measurements show a zero Hall plateau signaturing the axion state, sMIM uncovers an unexpected edge state raising questions regarding the nature of the “axion state”. Based on our model calculation, we propose that the even-layer MnBi_2Te_4 at zero field is in an AFM

quantum spin Hall (QSH) state hosting a pair of helical edge states. Such novel AFM QSH is originated from the combination of half translation symmetry and time-reversal symmetry in MnBi_2Te_4 . Our finding thus signifies the richness of topological phases in MnBi_2Te_4 that has yet to be fully explored.

Introduction

Combining magnetism with topological order greatly expands the family of topological materials and gives rise to new topological phases such as the Chern insulator, the axion insulator and magnetic Weyl semimetal. While the Chern insulator and the magnetic Weyl semimetal phases have been unambiguously observed in experiments¹⁻⁷, the definite material realization of the axion insulator remains elusive. In the original theoretical framework, such axion state could be realized if the topological surface states of a three-dimensional (3D) topological insulator (TI) are gapped out by ferromagnetic (FM) order on the surface with magnetizations pointing inward or outward⁸. This hedgehog configuration is, however, extremely challenging to be realized in real materials. There was a proposal that one could circumvent this problem by adopting a FM-TI-FM thin film heterostructure with antiparallel magnetizations on the top and bottom surfaces⁹. Experimental efforts along this route followed and reported the transport evidence of axion insulator state by observing a zero Hall plateau (ZHP)¹⁰⁻¹². However, such ZHP is not unique to axion state but has been observed in many other magnetically doped TI systems¹³⁻¹⁵, and thus may not be used as an experimental proof of the existence of the axion state¹⁵. New theoretical schemes other than ZHP are therefore proposed to distinguish an axion insulator from other trivial cases in experiments¹⁶⁻¹⁸.

MnBi_2Te_4 emerges as the first intrinsic antiferromagnetic (AFM) TI¹⁹⁻²⁴. As shown in Fig. 1(a), it is a tetradymite compound consisting of stacked Te-Bi-Te-Mn-Te-Bi-Te septuple layers (SLs) in the vertical direction. The spins of Mn have a FM intralayer exchange coupling and an AFM interlayer coupling forming an A-type AFM with an out-of-plane easy axis. For MnBi_2Te_4 with even-layer thickness, the magnetizations of the top and bottom layers are antiparallel, which is ideal for the realization of the axion state based on a theoretical prediction²³. Although this

prediction gains support from a transport experiment reporting ZHP in a 6-SL MnBi_2Te_4 at zero magnetic field²⁵, it is far from conclusive to determine the axion state based on ZHP. Other factors, such as multi-domain states inside a TI could also generate a zero Hall conductance. It was also pointed out in theory that, to realize an axion state, the thickness of sample should be thick enough to eliminate the finite-size effect but reasonably thin to get rid of side surface conduction²³. It is thus critical to employ spatially resolved imaging techniques to compliment the transport study. Such microscopic characterization is essential to rule out multi-domain states or side surface conduction for the determination of the axion state.

In this article, we combine both transport and scanning microwave impedance microscopy (sMIM) to study the electronic states of the even-layer MnBi_2Te_4 with an emphasis on its characteristics at zero magnetic field. Both transport and sMIM reveal a magnetic field driven quantum phase transition (QPT) with the high field phase to be the previously known Chern insulator phase. The insulating phase at zero field, while featuring a ZHP in transport measurements, exhibits a persistent edge state under sMIM that is unexpected for an axion insulator. Based on our model calculations, we show that the even-layer MnBi_2Te_4 at zero field is not an axion state, but rather an AFM quantum spin Hall (QSH) state hosting helical edge states.

Results

We mechanically exfoliate MnBi_2Te_4 thin flakes whose thickness is determined by optical reflectance (see supplementary information S1). We have fabricated and measured two 6-SL and one 7-SL MnBi_2Te_4 samples (see supplementary information S4 for 7-SL device and S5 for another 6-SL device). Figure 1(b) shows the experimental setup of sMIM used for probing local conductivity²⁶. A 3 GHz microwave is delivered to an atomic force microscope (AFM) tip and its reflected signal is collected and demodulated into two output signals of sMIM-Im and sMIM-Re. The sMIM-Im signal increases monotonically with the local conductivity, and is thus adopted here for nanoscale conductivity imaging. Also shown in Fig. 1(b) is an optical image of our 6-SL MnBi_2Te_4 device with transport electrodes attached. Note that the transport and sMIM

measurements were not conducted simultaneously. Figure 1(c) shows the magnetic field dependent longitudinal resistivity ρ_{xx} and Hall resistivity ρ_{yx} taken with a +25 V gate voltage. ρ_{yx} remains zero from -3.5 T to 3.5 T, forming a ZHP. As the field goes up, ρ_{yx} increases steeply and quickly approaches to a quantized Hall plateau above 6 T, accompanied by a vanishing ρ_{xx} . A complete gate voltage and field dependent transport data is included in the supplement (see supplementary information S2). We conclude from these transport measurements that the Chern insulator phase is realized above 6 T, while the phase with ZHP at low fields will be described as ZHP phase hereafter.

Figure 1(d) displays a sMIM image taken at 9 T and +20 V gate voltage demonstrating the capability of sMIM to visualize the edge state in the Chern insulator phase. The sMIM signal in the sample interior is comparable to the SiO₂ substrate indicating an insulating bulk. A bright line runs along the sample's geometric edge signaling a highly conductive edge. These observations are consistent with the characteristic features of the Chern insulator phase where a conductive edge encloses an insulating bulk. A conductive line is also visible in the upper part of sample interior. We attribute it to an internal crack of this 6-SL device which itself is a physical boundary hosting a topological edge state. Similar behavior has been observed in other topological materials and serves as another evidence of topological nature of edge state²⁷.

We next show the gate voltage dependent sMIM imaging results. For a topological edge mode like a chiral edge state in Chern insulator phase, its energy dispersion goes across the bulk gap. Therefore, while the bulk conductivity can vary with gating as the Fermi level is tuned, the edge should remain highly conductive irrespective of gating. That is what we observed at 9 T in Fig. 2(a). The bulk interior becomes progressively conductive as the gate changes from +20 V to 0 V while the edge signal barely changes with gate. For the ZHP phase, Figure 2(b) shows its gate voltage dependent sMIM images. When the bulk is tuned from a metallic to insulating state as the Fermi level moves into the gap, a conductive edge is resolved, namely, a visible bulk-edge imaging contrast appears at +7 V and +15 V. However, a significant difference exists here compared to the Chern insulator phase. The conductivity contrast between edge and bulk interior is much reduced at ZHP than Chern insulator phase. There is a strong intermixing of edge and

bulk signal over a wider area at ZHP phase which makes the edge state look more diffusive as compared to the Chern insulator phase. Nevertheless, the observation of edge state at zero field raises serious concerns whether the nature of the ZHP phase is an axion state. We leave it to the final discussion.

We then probe the magnetic field driven QPT from ZHP phase to Chern insulator phase when the magnetic order of MnBi_2Te_4 changes from AFM to FM under external fields. Figure 3(a) shows the field dependent sMIM images taken at +14 V to track this transition. This gate voltage is chosen as it corresponds to charge neutral point in both ZHP and Chern insulator phase. Three regimes can be clearly distinguished: 1) For low field regime of $0 \text{ T} \leq \mu_0 H \leq 2.5 \text{ T}$, we again see a bulk-edge imaging contrast demonstrating the existence of edge state in ZHP phase; 2) In intermediate field regime of $3.5 \text{ T} \leq \mu_0 H \leq 5 \text{ T}$, we observe a transition from an insulating to a metallic state for the bulk. The quickly increased bulk conductivity smears out the bulk-edge imaging contrast. There is an area with suppressed conductivity in the upper part of sample interior. That corresponds to the internal crack mentioned above where the underlying insulating substrate contributes to sMIM signal; 3) In high field regime of $6 \text{ T} \leq \mu_0 H \leq 9 \text{ T}$, we restore the bulk-edge imaging contrast as the device enters the Chern insulator phase. The fact that a metallic bulk state exists across the transition suggests that this field-driven QPT is essentially a topological phase transition along which the bulk gap closes and re-opens. The existence of a metallic bulk state during the transition is corroborated by our bulk transport measurement as well (see supplementary information S3). The evolution of bulk conductivity as a function of magnetic field was reported in another work with similar results²⁸.

In Fig. 3(b), we plot the field dependent bulk and edge sMIM signals. For comparison, the bulk conductivity acquired from the bulk transport is laid over the sMIM data after a proper scaling. The good consistency between the sMIM and the transport is observed. For the bulk, there is a four order-of-magnitude conductivity change during the insulator-metal transition, while the edge state remains highly conductive. We also extract the spatial width of the edge state from the sMIM images and plot them as a function of magnetic field as shown in Fig. 3(d). The width of the edge state determined here is around $2 \text{ }\mu\text{m}$, which is not limited by the sMIM spatial resolution

(<100 nm). We note that such a wide edge cannot be taken as a real physical dimension of topological edge state (see Fig. 4 (d)-(f)). Instead it reflects how the local conductivity decreases from the edge to the interior of sample and largely depends on the sMIM technique itself as several sMIM imaging works on similar TI all show edge state width in μm range^{27,29,30}. As shown in Fig. 3(d), such nominal width of edge state barely changes below 4 T, but decreases with increasing magnetic field in the Chern insulator phase. Also plotted in Fig. 3(d) is the energy gap extracted from fitting the Arrhenius plots for the temperature dependent bulk resistance measurements. One sees an anti-correlation between the nominal width and the energy gap. In Fig. 3(c), we show the gate voltage dependence of such nominal width extracted from Fig. 2. Edge state in ZHP phase is wider than that of Chern insulator, and insensitive to gate voltage.

Discussions

Regarding the physical origin of the edge state observed at zero field, the following mechanisms can be firstly ruled out: 1) Trivial edge states exist due to edge contamination or a unidirectional band bending. These trivial edge states are usually resistive and independent of magnetic fields, thus will cause dissipative transport with a sizable ρ_{xx} in the Chern insulator phase³¹. However, the measured longitudinal resistivity ρ_{xx} at 9T in our device is no more than $200\ \Omega$ ($\sim 0.0045\ h/e^2$) indicating negligible contributions from trivial conduction channels. The fact that this edge state has been observed in at least 3 6SL-MnBi₂Te₄ devices (see supplementary information S4 and S5) is unlikely due to an accidental trivial edge state; 2) QAH phase at zero field contributes to a chiral edge state. This cannot be the case because a topological phase transition happens in this device which links topologically distinct phases at two ends; 3) The axion insulator. In axion state, one interprets ZHP as a cancelation of a half-quantized surface Hall effect between its top and bottom surfaces. However, this half-quantized surface Hall cannot support a real one-dimensional (1D) edge state as often misguidedly drawn in theoretical models. This statement is supported by a recent experimental work in which Allen *et al.* uses sMIM to directly visualize an axion insulator and its transition to a Chern insulator³⁰. In their study, a conductive edge state was only observed in the Chern insulator but not in the axion insulator in stark contrast to our observation here.

Having ruled out the aforementioned mechanisms, we now turn to discuss the physical origin of the edge state. The contrasting conductivity profile of edge state between ZHP and Chern insulator phase implies their different underlying mechanisms. As mentioned earlier, sMIM imaging directly probes how the conductivity evolves from the edge to the interior given the existence of a conductive edge state. Such conductivity profile depends on both the actual physical dimension of edge state and its interaction with the bulk. The wider edge state seen in ZHP phase could be due to a smaller bulk gap Δ of this insulating phase as the penetration depth of a topological edge mode r can be generically estimated by $r = 2\hbar v_F / \Delta$ ³². That explains the empirical trend we got from Fig. 3(d). Or it comes from a strong scattering between the edge and bulk states leading to a diffusive rather than localized edge mode. The vulnerability to scattering of edge states in ZHP phase puts one important constrain on possible model that has to consider this dissipative nature.

We perform a model calculation to show that 6-SL MnBi₂Te₄ at zero field is actually an AFM QSH state hosting helical edge states. The intrinsic magnetic TI MnBi₂Te₄ can be described by a 3D 4×4 effective Hamiltonian²³:

$$H = \begin{pmatrix} M_k & A_2 k_z & & A_1 k_- \\ A_2 k_z & -M_k & A_1 k_- & \\ & A_1 k_+ & M_k & -A_2 k_z \\ A_1 k_+ & & -A_2 k_z & -M_k \end{pmatrix} + H_M,$$

in the basis of $(|P1_z^+, \uparrow\rangle, |P2_z^-, \uparrow\rangle, |P1_z^-, \downarrow\rangle, |P2_z^+, \downarrow\rangle)$, where $k_{\pm} = k_x \pm ik_y$, the mass term $M_k = m_0 - B_1(k_x^2 + k_y^2) - B_2 k_z^2$ and the spatial-dependent exchange field $H_M = M_z \sigma_z f_{o,e}$ with σ_z the Pauli matrix acting on spin space and $k_{x,y,z}$ wave vectors in x, y and z directions. $A_{1,2}$, $B_{1,2}$, m_0 and M_z are model parameters. For an AFM phase at zero field, $f_{o,e} = \pm 1$ for even (odd) layers, respectively. The system preserves a combined symmetry $S = \Theta T_{1/2}$, where Θ is time-reversal symmetry (TRS) and $T_{1/2}$ is half translation symmetry. S could lead to a Z_2 topological classification³³. On the other hand, $f_{o,e} = 1$ for a FM phase, and it can generally lead to a QAH phase for MnBi₂Te₄ multilayers. Following the Ref.³⁴, we investigate the crossover behavior from a 3D to two-dimensional (2D) with reducing the layer thickness in z direction (see supplementary information S6) and find that, 6-SL MnBi₂Te₄ is actually an AFM QSH. Figure 4 (a)-(c) show the band structure of a 6-SL MnBi₂Te₄ with different magnetic field B , where the magnetic switching

is simulated by $f_e = \tanh\left(\frac{B-B_c}{B_0}\right)$ with $B_c = 4.7\text{T}$ and $B_0 = 0.28\text{T}$. Figure 4 (d)-(f) are the corresponding spatial distribution of wave functions. At zero magnetic field, the system is a $C = 0$ 2D AFM QSH with a pair of helical edge modes. Note that there is a tiny edge gap due to the translation-symmetry breaking in the z direction. Then, the bulk band gap is closed during the magnetic reversal at $B = 4.5\text{T}$, and the system finally turns into a $C = 1$ Chern insulator phase with a chiral edge state at $B = 9\text{T}$. Theory has already discussed the possibility of AFM QSH, a 2D version of 3D AFM TI^{35,36}. Such AFM QSH is usually protected by a combined symmetry of TRS and one other spatial symmetry, which makes it different from non-magnetic QSH protected only by TRS³⁷⁻³⁹. However, no realistic material candidate for AFM QSH has been reported yet. 6SL-MnBi₂Te₄ we reported here could be the first material system to realize such novel AFM QSH protected by the combined symmetry $S = \Theta T_{1/2}$ in the AFM order of MnBi₂Te₄. That explains why the edge state is robust in the low field regime where the Zeeman effect due to external fields is much smaller than the internal field of AFM order in MnBi₂Te₄. It also accounts for the vulnerability to the scatterings of such edge states in ZHP. Previous experiments on QSH already show that such helical edge states can experience certain backscattering process occurred inside helical edges resulting in dissipative transport in contrast to the dissipationless chiral edge states in QAH phase⁴⁰. This is exactly what we observed in Fig. 2. On the other hand, for 3D AFM TI MnBi₂Te₄, there exists 2D gapless topological surface state at side surfaces that preserve S symmetry²². Such metallic 2D surface state will evolve into a 1D quantum well state when the system is reduced from 3D to 2D as revealed by our model calculations. The observation of 1D conducting edge state in 6-SL MnBi₂Te₄ implies that its side surface is not gapped out, thus rules out axion state. Our model calculations also show that the edge state exponentially decays from the edge to the bulk within a few tens of nm (see Fig.4 (d) and (f)), much smaller than the apparent width measured in sMIM. One need to consider the strong edge-bulk scattering mechanisms to account for the large measured width. A recent first-principles calculation provides insights into it⁴¹. It predicted that even-number-layer MnBi₂Te₄ have gapped helical edge states which becomes gapless due to the existence of disorder. Such gapless helical state is dissipative consistent with our sMIM imaging. In particular, as seen from Fig. 3(a), the edge state in 1 T is more localized than zero field case presumably due to the suppressed magnetic disorder under a finite magnetic field. The validity of our model

calculation is also evidenced by the 7-SL MnBi_2Te_4 case. We predict an oscillatory behavior of bulk energy gap as the thickness of MnBi_2Te_4 is reduced (see supplementary information S6). The bulk gap of 7-SL MnBi_2Te_4 is much smaller than that of 6-SL. Our sMIM imaging of 7-SL MnBi_2Te_4 indeed shows an enhanced bulk conductivity of 7-SL as compared to 6-SL (see supplementary information S4).

In summary, we study the even-layer MnBi_2Te_4 at zero field combining transport and sMIM measurements. The observation of edge state challenges the existence of the axion state in the 6-SL MnBi_2Te_4 . Instead, we propose an AFM QSH state as the origin of the edge state. Our discovery of the AFM QSH can stimulate further works to explore novel topological phases that are protected by the combination of TRS and crystalline symmetries in the MnBi_2Te_4 family materials.

Note added: During the preparation of this manuscript, we became aware of a recent nonlocal transport study of 6-SL MnBi_2Te_4 reporting the existence of edge state in its axion insulator state⁴².

Methods

Crystal growth. The MnBi_2Te_4 single crystal were grown by direct reaction of a 1:1 mixture of Bi_2Te_3 and MnTe in a sealed silica ampoule under a dynamic vacuum. The mixture was first heated to 973 K then slowly cooled down to 864 K. The crystallization occurred during the prolonged annealing at this temperature.

Device fabrication. Most of the device's fabrication processes were carried out in argon-filled glove box with the O_2 and H_2O levels below 0.1 ppm. Before device fabrication, marker array was first prepared on 285 nm-thick SiO_2/Si substrates for precise alignment between selected area and patterns. Before exfoliation, the 285 nm-thick SiO_2/Si substrates were pre-cleaned in air plasma for 5 min at 125 Pa. The thin MnBi_2Te_4 flakes were exfoliated by using the Scotch tape method onto the 285 nm-thick SiO_2/Si substrates. Before spin coating PMMA, the surrounding thick

flakes were scratched by a sharp needle. By using electron-beam lithography, metal electrodes (Cr/Au, 5/50 nm) were deposited in a thermal evaporator connected to the glove box. When transferred between glove box, electron-beam lithography and the cryostat, the devices were covered by a layer of PMMA to mitigate air contamination and sample degradation.

Transport measurement. Electrical measurements of magneto transport properties were performed in a commercial cryostat Attodry 2100 with a base temperature ~ 1.7 K and magnetic field up to 9T. The AC current of 200 nA was generated by the AC voltage of 2V applied on a $10\text{M}\Omega$ resistor. The longitudinal and Hall voltages drops were detected simultaneously by using lock-in amplifiers with AC current. The bottom-gate voltage with SiO_2 dielectric were applied by a Keithley 2400 multimeter.

sMIM measurement. The sMIM in this work is based on a commercial LT ScanWave system from PrimeNano Inc. All the sMIM measurements were performed at 1.7 K. The technique utilizes a cantilever-based AFM combined with a 3 GHz microwave signal delivered through a customized shielded cantilever probes also commercially available from PrimeNano Inc.

Data Availability

All raw and derived data used to support the findings of this work are available from the authors on request.

Acknowledgements

The work at Fudan University is supported by National Natural Science Foundation of China (Grant Nos. 12074080, 11904053 and 11827805), National Postdoctoral Program for Innovative Talents (Grant No. BX20180079), Shanghai Science and Technology Committee Rising-Star Program (19QA1401000), Major Project (Grant No. 2019SHZDZX01) and Ministry of Science and Technology of China (Grant Nos. 2016YFA0301002 and 2017YFA0303000). The work at Tsinghua University is supported by National Natural Science Foundation of China (Grant Nos. 21975140, 51991313), the Basic Science Center Project of National Natural Science Foundation

of China (Grand No. 51788104) and the National Key R&D Program of China (Grand No. 2018YFA0307100). The work at Soochow University is funded by the National Natural Science Foundation of China (Grant No. 11974256), the Priority Academic Program Development (PAPD) of Jiangsu Higher Education Institutions and the Natural Science Foundation of Jiangsu Province (Grant No. BK20190813).

Author contributions

J. S. and X. D. Z. supervised the research. H. L. and Y. W. grew the MnBi_2Te_4 crystals. Y. C. W. and Z. C. L. fabricated the devices. W. L. and Y. F. performed the sMIM and transport measurements. C. Z. C. performed an effective model calculation. W. L., Y. F. and X. D. Z. prepared the manuscript with comments from all authors.

References

- 1 Chang, C. Z. *et al.* Experimental Observation of the Quantum Anomalous Hall Effect in a Magnetic Topological Insulator. *Science* **340**, 167-170, (2013).
- 2 Checkelsky, J. G. *et al.* Trajectory of the anomalous Hall effect towards the quantized state in a ferromagnetic topological insulator. *Nat. Phys.* **10**, 731-736, (2014).
- 3 Kou, X. F. *et al.* Scale-Invariant Quantum Anomalous Hall Effect in Magnetic Topological Insulators beyond the Two-Dimensional Limit. *Phys. Rev. Lett.* **113**, 137201, (2014).
- 4 Chang, C. Z. *et al.* High-precision realization of robust quantum anomalous Hall state in a hard ferromagnetic topological insulator. *Nat. Mater.* **14**, 473-477, (2015).
- 5 Belopolski, I. *et al.* Discovery of topological Weyl fermion lines and drumhead surface states in a room temperature magnet. *Science* **365**, 1278-1281, (2019).
- 6 Liu, D. F. *et al.* Magnetic Weyl semimetal phase in a Kagome crystal. *Science* **365**, 1282-1285, (2019).
- 7 Morali, N. *et al.* Fermi-arc diversity on surface terminations of the magnetic Weyl semimetal $\text{Co}_3\text{Sn}_2\text{S}_2$. *Science* **365**, 1286-1291, (2019).
- 8 Qi, X. L., Hughes, T. L. & Zhang, S. C. Topological field theory of time-reversal invariant insulators. *Phys. Rev. B* **78**, 195424, (2008).
- 9 Wang, J., Lian, B., Qi, X. L. & Zhang, S. C. Quantized topological magnetoelectric effect of the zero-plateau quantum anomalous Hall state. *Phys. Rev. B* **92**, 081107, (2015).
- 10 Mogi, M. *et al.* A magnetic heterostructure of topological insulators as a candidate for an axion insulator. *Nat Mater* **16**, 516-521, (2017).
- 11 Mogi, M. *et al.* Tailoring tricolor structure of magnetic topological insulator for robust axion insulator. *Sci. Adv.* **3**, (2017).

- 12 Xiao, D. *et al.* Realization of the Axion Insulator State in Quantum Anomalous Hall Sandwich Heterostructures. *Phys. Rev. Lett.* **120**, 056801, (2018).
- 13 Feng, Y. *et al.* Observation of the Zero Hall Plateau in a Quantum Anomalous Hall Insulator. *Phys. Rev. Lett.* **115**, 126801, (2015).
- 14 Kou, X. F. *et al.* Metal-to-insulator switching in quantum anomalous Hall states. *Nat. Commun.* **6**, (2015).
- 15 Fijalkowski, K. M. *et al.* Any axion insulator must be a bulk three-dimensional topological insulator. *Phys. Rev. B* **103**, 235111, (2021).
- 16 Gu, M. *et al.* Spectral signatures of the surface anomalous Hall effect in magnetic axion insulators. *Nat. Commun.* **12**, 3524, (2021).
- 17 Chen, R. *et al.* Using nonlocal surface transport to identify the axion insulator. *Phys. Rev. B* **103**, L241409, (2021).
- 18 Li, H. L., Jiang, H., Chen, C. Z. & Xie, X. C. Critical Behavior and Universal Signature of an Axion Insulator State. *Phys. Rev. Lett.* **126**, 156601, (2021).
- 19 Otrokov, M. M. *et al.* Highly-ordered wide bandgap materials for quantized anomalous Hall and magnetoelectric effects. *2D Mater.* **4**, 025082, (2017).
- 20 Otrokov, M. M. *et al.* Prediction and observation of an antiferromagnetic topological insulator. *Nature (London)* **576**, 416-422, (2019).
- 21 Gong, Y. *et al.* Experimental Realization of an Intrinsic Magnetic Topological Insulator. *Chin. Phys. Lett.* **36**, (2019).
- 22 Li, J. H. *et al.* Intrinsic magnetic topological insulators in van der Waals layered MnBi₂Te₄-family materials. *Sci. Adv.* **5**, (2019).
- 23 Zhang, D. Q. *et al.* Topological Axion States in the Magnetic Insulator MnBi₂Te₄ with the Quantized Magnetoelectric Effect. *Phys. Rev. Lett.* **122**, 206401, (2019).
- 24 Otrokov, M. M. *et al.* Unique Thickness-Dependent Properties of the van der Waals Interlayer Antiferromagnet MnBi₂Te₄ Films. *Phys. Rev. Lett.* **122**, 107202, (2019).
- 25 Liu, C. *et al.* Robust axion insulator and Chern insulator phases in a two-dimensional antiferromagnetic topological insulator. *Nat. Mater.* **19**, 522-527, (2020).
- 26 Chu, Z., Zheng, L. & Lai, K. Microwave Microscopy and Its Applications. *Annu. Rev. Mater. Res.* **50**, 105-130, (2020).
- 27 Shi, Y. M. *et al.* Imaging quantum spin Hall edges in monolayer WTe₂. *Sci. Adv.* **5**, (2019).
- 28 Ovchinnikov, D. *et al.* Intertwined Topological and Magnetic Orders in Atomically Thin Chern Insulator MnBi₂Te₄. *Nano Lett.* **21**, 2544-2550, (2021).
- 29 Ma, E. Y. *et al.* Unexpected edge conduction in mercury telluride quantum wells under broken time-reversal symmetry. *Nat. Commun.* **6**, (2015).
- 30 Allen, M. *et al.* Visualization of an axion insulating state at the transition between 2 chiral quantum anomalous Hall states. *Proc. Natl. Acad. Sci. U.S.A* **116**, 14511-14515, (2019).
- 31 Wang, J., Lian, B., Zhang, H. J. & Zhang, S. C. Anomalous Edge Transport in the Quantum Anomalous Hall State. *Phys. Rev. Lett.* **111**, 086803, (2013).
- 32 Zhang, F., Kane, C. L. & Mele, E. J. Surface states of topological insulators. *Phys. Rev. B* **86**, 081303, (2012).
- 33 Mong, R. S. K., Essin, A. M. & Moore, J. E. Antiferromagnetic topological insulators. *Phys. Rev. B* **81**, 245209, (2010).

- 34 Liu, C. X. *et al.* Oscillatory crossover from two-dimensional to three-dimensional
topological insulators. *Phys. Rev. B* **81**, 041307, (2010).
- 35 C. Niu *et al.* Quantum spin Hall effect and topological phase transitions in honeycomb
antiferromagnets. *arXiv:1705.07035*, (2017).
- 36 Niu, C. W. *et al.* Antiferromagnetic Topological Insulator with Nonsymmorphic
Protection in Two Dimensions. *Phys. Rev. Lett.* **124**, 066401, (2020).
- 37 Konig, M. *et al.* Quantum spin hall insulator state in HgTe quantum wells. *Science* **318**,
766–770, (2007).
- 38 Knez, I., Du, R. R. & Sullivan, G. Evidence for Helical Edge Modes in Inverted InAs/GaSb
Quantum Wells. *Phys. Rev. Lett.* **107**, 136603, (2011).
- 39 Wu, S. F. *et al.* Observation of the quantum spin Hall effect up to 100 kelvin in a
monolayer crystal. *Science* **359**, 76–79, (2018).
- 40 Spanton, E. M. *et al.* Images of Edge Current in InAs/GaSb Quantum Wells. *Phys. Rev.*
Lett. **113**, 026804, (2014).
- 41 Zhaochen Liu, Dongheng Qian, Yadong Jiang & Wang, J. Dissipative Edge Transport in
Disordered Axion Insulator Films. *arXiv:2109.06178*, (2021).
- 42 Yaoxin Li *et al.* Nonlocal Transport in Axion Insulator State of MnBi₂Te₄.
arXiv:2105.10390, (2021).

Fig. 1 Experimental set-up and transport characterization of the 6-SL MnBi₂Te₄ device. **a**, Crystal and magnetic structure of MnBi₂Te₄. **b**, Schematic diagram of sMIM. **c**, Magnetic field dependent ρ_{xx} and ρ_{yx} at +25 V gate voltage. **d**, sMIM image taken at 9 T and +20 V gate voltage. The scale bar is 4 μm .

Fig. 2. Gate voltage dependent sMIM imaging. **a**, Gate voltage dependent sMIM images at 9 T. The scale bar is $4\text{ }\mu\text{m}$. **b**, Gate voltage dependent sMIM images at 0 T. The scale bar is $4\text{ }\mu\text{m}$.

Fig. 3. Magnetic field dependent sMIM imaging. **a**, Magnetic field dependent sMIM images at +14 V gate voltage. The scale bar is 4 μm . **b**, Field dependent sMIM bulk and edge signal extracted from Fig. 3(a). The signal is averaged over green and blue boxes denoted in Fig. 3(a). Also plotted is the measured bulk conductivity from transport. **c**, Gate voltage dependent edge state spatial width determined from Fig. 2. **d**, Field dependent edge state spatial width determined from Fig. 3(a). Also plotted is the fitted energy gap from bulk transport measurement.

Fig. 4. Effective model calculations. **a-c**, Evolution of band structures of 6-SL MnBi_2Te_4 by sweeping the magnetic field B . The blue and red lines indicate the helical (or chiral) edge modes. The system employs a periodic boundary condition in the x direction and an open boundary conditions in the y direction. **d-f**, Spatial distributions of the typical wave functions along y direction at $E = 0.006 \text{ eV}$ for different B . The model parameters are $M_z = 0.04 \text{ eV}$, $A_2 = 2 \text{ eV} \cdot \text{\AA}$, $B_2 = 24 \text{ eV} \cdot \text{\AA}^2$, $m_0 = 0.116 \text{ eV}$, $A_1 = 3.1964 \text{ eV} \cdot \text{\AA}$, and $B_1 = 9.4048 \text{ eV} \cdot \text{\AA}^2$.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [MBTsupplementraymaterials20211108.docx](#)