QUANTUM MATERIALS

One compound with two distinct topological states

Two distinct topological states that are closely tied to the spin configurations of a layered compound, here $MnBi_2Te_4$, have been demonstrated. Such control of the topological state should enable new opportunities to realize quantum and spintronic devices.

Peng Wei and Jagadeesh S. Moodera

Topological insulators (TIs) are materials that have an insulating bulk wrapped by an electrically conducting surface. The surface conduction is defined by charge carriers known as massless Dirac fermions. Magnetic TIs are an attractive platform since a finite magnetic moment in a TI provides mass to the massless Dirac fermions — that is, opens up an energy gap in an otherwise gapless Dirac node — thereby leading to several emerging topologically driven quantum states. Two salient examples are the Chern insulator (or quantum anomalous Hall insulator) and axion insulator states. The former state can be realized in a magnetically doped TI compound with uniform magnetization[1]. The latter one, however, requires an unusual magnetic profile — that is, the magnetizations of the top and bottom surfaces of the TI must align oppositely[2]. So far, axion insulator has only been observed in atomically tailored TI heterostructures[3]. Now, writing in *Nature Materials*, Chang Liu and colleagues[4] identify a natural axion insulator in the layered compound $MnBi_2Te_4$, where the necessary magnetic profile is achieved through the intrinsic antiferromagnetic (AFM) coupling of the adjacent atomic layers. Furthermore, by controlling the alignment of the inter-layer spin in $MnBi_2Te_4$ with an applied magnetic field, the Chern insulator and axion insulator states can be interchanged.

The experiment performed by Liu et. al. demonstrates a tunable transition between two distinct topological states — that is, the Chern insulator state and the axion insulator state — in a single compound $MnBi_2Te_4$. The tunability is achieved using a magnetic field applied along the *c* axis of the sample. When the field is larger than a critical value, the Hall resistance of the sample is quantized at h/e^2 (longitudinal resistivity vanishes at the same time), where *h* is Planck's constant and *e* is the elementary charge, and the magnetization of the sample is polarized in one direction — signifying a Chern insulator state in the presence of ferromagnetic (FM) order. A smaller field leads to a vanishing sample magnetization that is accompanied by the Hall resistance switching to zero. The magnetic susceptibility further shows a Néel temperature, indicating AFM order. Although the longitudinal resistivity did not diverge, suggesting a finite longitudinal conductivity likely to be due to material imperfections, the results point to an axion insulator state. The controlled switching in between two topological states as a result of the FM to AFM transition is striking. It can only be observed in $MnBi_2Te_4$ with even number of layers as shown by the authors using a six-septuple-layer (SL) $MnBi_2Te_4$ device, keeping in mind that $MnBi_2Te_4$ is a layered compound. Its magnetic moment is carried by Mn ions, which are arranged in an atomic plane in the middle of each monolayer. When the applied magnetic field (parallel to *c* axis, meaning perpendicular to each layer) is large enough, the spins of all the Mn ions are aligned parallel (Fig. 1a): a finite magnetic moment develops, which leads to the Chern insulator state. When the applied field is smaller, the magnetic ground state depends on the interlayer magnetic coupling. Interestingly, in $MnBi_2Te_4$, the interlayer coupling prefers AFM order at zero or low field. In $MnBi_2Te_4$ with even number of layers, such as six SLs, an AFM coupling between the layers results in oppositely aligned magnetizations at the top and bottom surfaces as required for an axion insulator (Fig. 1b). The work of Liu et al. attains that magnetic state and thus the anticipated axion insulator state.

The single compound material $MnBi_2Te_4$ overcomes the difficulty of synthesizing a TI heterostructure, requiring precise modulation doping, thereby making the axion insulator material more attainable. Although currently there is ongoing debate regarding the surface gap opening in $MnBi_2Te_4$ (ref. [5]), following this new development, the next step would be to

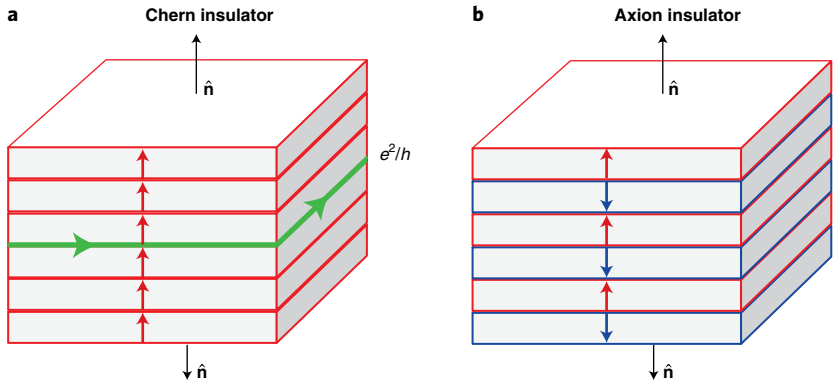

Fig. 1 | The alignment of magnetization (red and blue arrows) in each atomic layer for a six-SL $MnBi_2Te_4$. a,**b**, The even number of layers give rise to both a Chern insulator state (**a**) and an axion insulator state (**b**) based on the overall magnetic configuration. $\hat{\mathbf{n}}$ denotes the direction of the surface normal. The green arrow indicates the chiral gapless edge channel carrying the e^2/h quantized conductance.

confirm the topological magnetoelectric effect (TME) expected for an axion insulator. TME is a generic property of a three-dimensional (3D) TI when mass is introduced to the surface massless Dirac fermions. In the theory that describes such massive Dirac fermions, the mass term is contributed directly by the magnetization orthogonal to the surface of a 3D TI. It can be either positive or negative depending on the direction of the magnetization with respect to the surface normal (Fig. 1). Therefore, to introduce a mass term with a fixed sign, the magnetization at the surface of a 3D TI has to be either parallel or antiparallel to the normal directions of all surfaces, requiring the magnetizations of the top and bottom surfaces of the TI slab to point in opposite directions (Fig. 1b). For a 3D TI surface with a fixed sign of mass, a half-quantized Hall conductance ($e^2/2h$) is expected[6,7]. However, because such a surface is closed without an edge, no edge channels are expected. Thus, electric transport will not verify the $e^2/2h$ quantized conductance, and rather would show both vanishing Hall and longitudinal conductivities as observed earlier[3]. This contrasts with the Chern insulator case, in which a chiral gapless edge state carrying e^2/h quantized conduction is formed at the boundary of a 2D TI slab[4]. The chiral edge state can also be considered as a result of a magnetic domain wall due to the opposite mass terms on the top and bottom surfaces of the TI (Fig. 1a). The extra conductance contributed by such a domain wall has been reported before[8,9]. Nevertheless, probing the TME (and polarization), which is a result of the surface half-quantized Hall effect, would be the final proof of the axion insulator.

In addition, due to the intrinsic correlation between the electric and magnetic fields, one can envision the efficient control of the magnetization using electric field by taking advantage of the TME, which has been one of the main goals in spintronics development during the past decade. In particular, if a magnetic dipole can be induced in an axion insulator by an applied electric field, it can be used to magnetize a neighbouring material in a desired multilayer heterostructure. Furthermore, such a magnetic dipolar field could serve to align the magnetization in an adjacent axion insulator $MnBi_2Te_4$ itself to achieve the transition from an axion insulator to a Chern insulator. Therefore, there could be an electric field-induced topological phase transition in $MnBi_2Te_4$ if the TME susceptibility is large enough. On the other hand, the generation of a dipolar electric field in the presence of magnetic field could be a magnetic field sensor. Moreover, other TME effects such as the demonstration of the predicted image magnetic monopole may be expected in the future. ❐

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THERMAL CONDUCTIVITY

Achieving a better heat conductor

Finding a competitor for diamond as a good heat conductor remains challenging. Measurements on crystals of cubic boron nitride demonstrate a thermal conductivity of 1,600 W m^{-1} K^{-1} at room temperature, rivalling diamond.

Ashutosh Giri and Patrick E. Hopkins

Diamond has long stood as the most thermally conductive bulk material, with a room-temperature (RT) thermal conductivity (κ) in excess of 2,000 W m^{-1} K^{-1}.This is a finding that has significantly advanced condensed matter physics and thermal management of various technologies. Thus, the search for bulk crystals with comparable thermal conductivities is an important challenge. In non-metallic crystals, heat is primarily transferred by phonons — quantized lattice vibrations arising from coupled atomic oscillations in crystalline materials. In 1973, Slack identified guidelines to achieve high phonon thermal conductivity based on maximizing phonon velocities and minimizing intrinsic resistive scattering processes; he suggested the crystal must be made up of strongly bonded atoms with low atomic masses arranged in a simple lattice[1]. This leaves little room for new high-thermal-conductivity materials, but the advent of parameter-free first-principles-based calculations in conjunction with rigorous solutions to the Boltzmann transport equation has enabled further atomistic insight. In 2013, it was shown that a large frequency gap between acoustic and optical phonons (accompanying a large mass ratio of atoms in the crystal basis), along with bunching of the acoustic branches, can lead to weak anharmonic phonon–phonon scattering and thus strong thermal conductivity enhancement. In 2018, this enhanced κ prediction for boron arsenide (BAs)[2] was experimentally realized, with measured $\kappa_{RT} \approx 1{,}200$ W m^{-1} K^{-1} for high-quality BAs crystals[3–5]. It was also predicted that if crystalline materials with strong phonon–isotope scattering could be isotopically purified, such as cubic boron nitride (cBN), large enhancements in thermal conductivity of ~150% could be realized[2].

Now, writing in *Science*, Bai Song, David Broido, Gang Chen and colleagues have used these phonon–isotope scattering design rules and performed isotopic enrichment of ^{10}B or ^{11}B to demonstrate ultrahigh κ_{RT} of over 1,600 W m^{-1} K^{-1} in bulk crystals of cBN[6]. The thermal conductivities surpass κ_{RT} of BAs, and are one of the highest reported to date. Following Slack's predictions,