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Observing Axion Dynamics in $MnBi_2Te_4$

Observation of the Axion quasiparticle in 2D $MnBi_2Te_4$
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Recommended with a Commentary by Taige Wang and Dung-Hai Lee, University of California, Berkeley

The axion was first invoked to resolve the strong–CP puzzle of quantum chromodynamics: promoting the CP-violating vacuum angle to a dynamical field allows it to relax to zero and restores the observed symmetry. Condensed-matter systems revive this idea in a new guise. When one integrates out the electrons of a three-dimensional insulator, symmetry allows an additional pseudoscalar term in the electromagnetic action

$$\mathcal{L}_\theta = \frac{\theta e^2}{4\pi^2 \hbar c}\, \mathbf{E}\cdot\mathbf{B}, \tag{1}$$

where the angle θ is defined modulo 2π. Qi, Hughes, and Zhang showed that in a time-reversal-symmetric three-dimensional topological insulator (TI) this angle is *quantized* to the universal value $\theta = \pi$ [1]. Equation (1) then yields a *topological magneto-electric effect*: an electric field induces a parallel magnetization, and *vice versa*, with a strength fixed entirely by the fine-structure constant $e^2/\hbar c$ (Fig. 1).

The most direct probe of Eq. (1) is optical. Linearly polarised light transmitted through a TI acquires a quantised Faraday rotation, while the reflected beam acquires a quantised Kerr rotation. In the long-wavelength limit each rotation equals an integer multiple of $e^2/\hbar c$, independent of microscopic details. Plateaus in such rotation angle were resolved in terahertz polarimetry on low-carrier-density Bi_2Se_3, providing the first optical confirmation of a static $\theta = \pi$ in a solid [3].

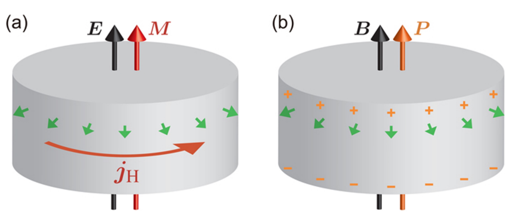

Figure 1: Topological magnetoelectric effect. (a) External electric field **E** produces a magnetization **M** parallel to **E**. (b) The reciprocal response: an external magnetic field **B** generates an electric polarization **P** along **B** (adapted from Ref. [2]).

Quantization is only the beginning. The angle θ is pinned to π *only while* the protecting symmetries—time-reversal $\mathcal{T}$, spatial inversion $\mathcal{P}$, or their product $\mathcal{PT}$—remain intact. If any of them is broken, θ may vary in space and time, becoming a dynamical field: the *condensed-matter axion quasiparticle.* Li, Wang, Qi, and Zhang first analysed this dynamical regime, showing that $\theta(\mathbf{r}, t)$ couples to spin-wave excitations in magnetic TIs and predicted hybrid axion quasiparticle–photon excitations (axion-polaritons) together with nonlinear magneto-optical phenomena [4]. More concretely, in an intrinsic antiferromagnetic TI such as $MnBi_2Te_4$ the four-band Dirac model gives [2],

$$\theta = \frac{\pi}{2}\left[1 - \mathrm{sgn}\left(m_0\right)\right] - \tan^{-1}\left(\frac{m_a}{m_0}\right), \tag{2}$$

where m_0 is the bulk gap and $m_a \propto M_z$ the exchange gap set by the out-of-plane magnetization, locking magnon and axion quasiparticle dynamics.

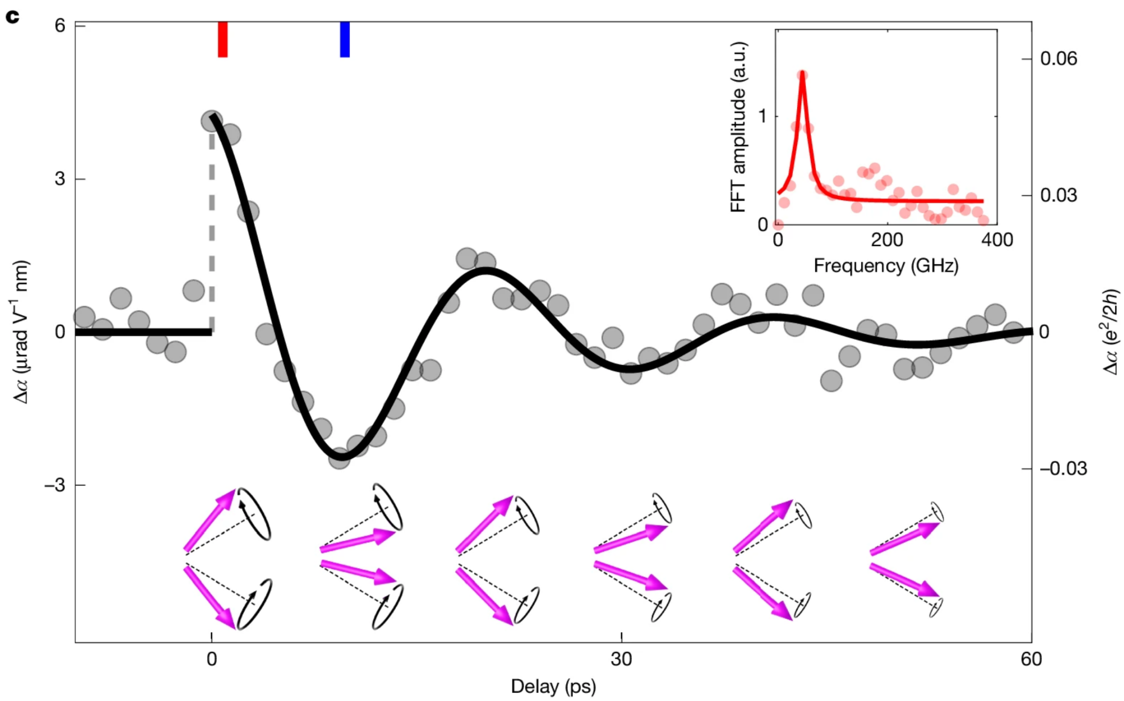

Figure 2: Time-resolved Kerr rotation $\Delta\alpha(t)$ in a $MnBi_2Te_4$ thin film (adapted from Ref. [5]).

Direct access to a *dynamical* axion quasiparticle (DAQ) has long been deemed challenging: the GHz–THz oscillations of θ couple only weakly to standard probes and are easily masked by backgrounds [6]. The pump–probe experiment of Qiu *et al.* represents the first tangible progress [5]. Working with a six-layer $MnBi_2Te_4$ film, the authors use an ultrafast laser pulse to launch antiferromagnetic magnons at frequency ~ 44 GHz, in which the two sublattices precess out of phase. A static electric field applied perpendicular to the layers converts the instantaneous magneto-electric coefficient $\alpha(t) = (e^2/\hbar c)\,\theta(t)/\pi$ into a time-resolved Kerr rotation which is measured with sub-picosecond time resolution. Fig. 2 plots the resulting $\Delta\alpha(t)$: a clean, long-lived oscillation corresponding to a swing of $\simeq 0.2\pi$ in θ. Control experiments rule out thermal artefacts, and tight-binding calculations reproduce both the frequency and amplitude, leaving little doubt that the observed mode is the long-sought *dynamical* $\theta(t)$. The study thus provides the first real-time window onto ultrafast magneto-electric physics in a topological quantum material.

While Qiu *et al.* measure how θ responds *after* a magnon is injected, the broader goal is reciprocity: to *create* magnons by driving the θ field with photons and to detect the two-photon burst emitted when a magnon (axion quasiparticle) decays [7]. Realizing such bidirectional conversion would complete the condensed-matter analogy to the particle-physics axion and would furnish a powerful platform for coherent microwave control at the quantum limit. With the present experiment establishing the essential dynamical coupling, this milestone now comes clearly into view.

Detecting ultralight axion dark matter via photons produced during its decay is especially compelling, yet single-photon counting technology is still in its infancy. Conventional photomultipliers, avalanche photodiodes, and SNSPDs excel at optical energies but cannot reach the microwave band, while Rydberg-atom and superconducting-qubit sensors that do operate at gigahertz frequencies struggle in high magnetic fields and exhibit non-negligible dark counts [8]. Qiu *et al.* conclude by proposing that $MnBi_2Te_4$ could serve as a detector for millielectron-volt photons to reveal cosmic axions. They emphasize that *"a unique advantage is that the detection frequency can be continuously tuned over a wide range by $B_\parallel$"* and that *"there is no axion detector for the millielectron-volt regime."* Their idea is to replace the pump photons in their pump–probe experiment with photons produced by axion decay in a parallel magnetic field $B_\parallel$, and they outline two read-out schemes.

Scheme I – Photon re-emission. Analogous to the "BRASS" proposal, a static in-plane field $B_\parallel$ converts axions into THz photons whose energy resonates with the dynamical-axion quasiparticle (DAQ) mode of $MnBi_2Te_4$. Each photon excites the DAQ, which then relaxes *radiatively*; the secondary photons are counted to register an axion event. Sweeping $B_\parallel$ tunes the DAQ across the entire meV window.

Scheme II – Kerr rotation. Echoing the "BREAD" concept, the axion-generated photon again excites the DAQ, but read-out is optical: in the presence of an external electric field E_z, the oscillatory magneto-electric response $M_z(t) = \alpha(t)E_z$ rotates the polarization of a probe beam, and the Kerr angle serves as the signal. As in Scheme I, $B_\parallel$ affords *in situ* frequency control.

However, pushing the sensitivity of the current experiment to a *single* photon is exceptionally demanding. Several practical issues must be addressed before $MnBi_2Te_4$ can serve as a competitive platform for cosmic-axion detection:

1. *Volume and quality factor.* The exfoliated $MnBi_2Te_4$ flakes used so far have tiny volumes $V \sim 10^{-12}\,\mathrm{m}^3$ and modest electromagnetic Q factors, which limit signal power.
2. *Single-photon effect.* The pump–probe measurement reported in the current paper injects roughly 10^{11} photons per laser pulse. In contrast, because cosmic axions convert to photons only extremely weakly, an effective axion detector should operate at the

single-photon level. This eleven-order-of-magnitude disparity highlights the need to estimate the signal strength expected from a single photon for both the DAQ's radiative emission or its Kerr-rotation response.

3. *The effectiveness in exciting the DAQ mode.* For a single incident photon, it is crucial to determine the branching ratio between exciting the DAQ mode and being absorbed incoherently.

Overcoming these challenges is essential before an axion-insulator platform can complement or surpass existing cavity-based and quantum-sensor technologies in the quest for cosmic axion dark matter.

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