Overcoming magnetic disorder: Toward low-energy topological electronics

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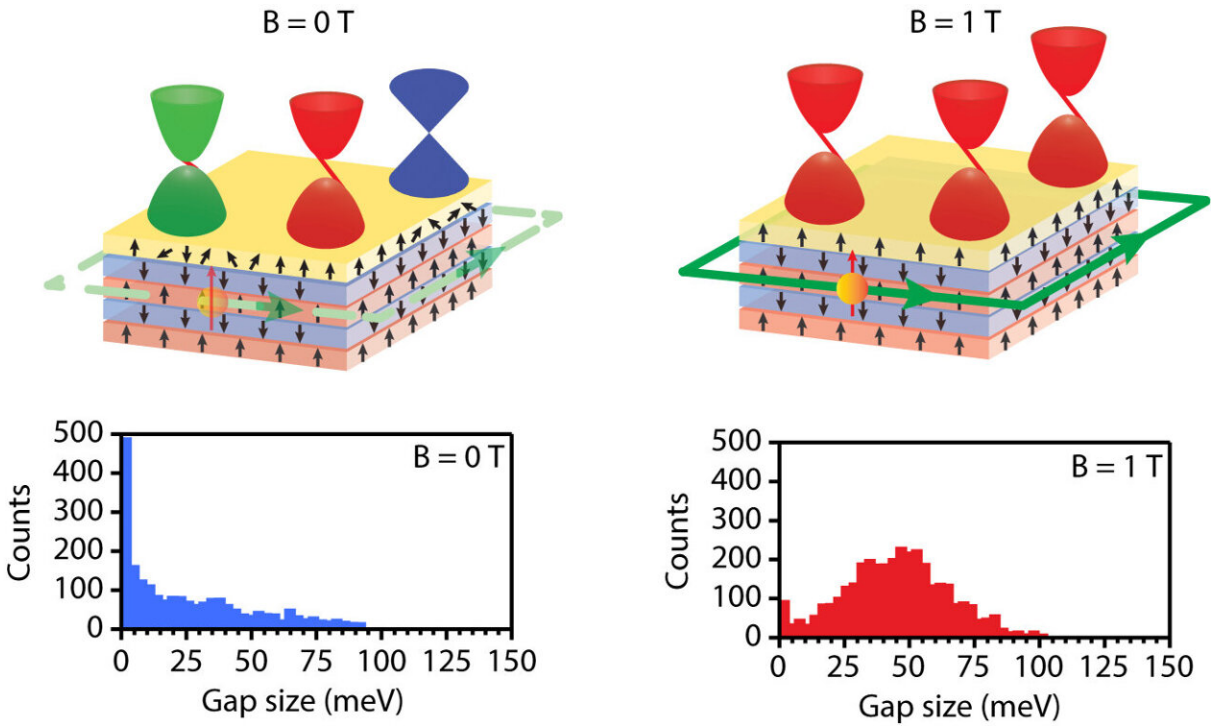


Demonstrating how the exchange gap spatial fluctuation caused by surface magnetic disorder can be reduced significantly by applying a perpendicular magnetic field. Credit: *Advanced Materials* (2024). DOI: 10.1002/adma.202312004

Overcoming magnetic disorder is key to exploiting the unique properties of quantum anomalous Hall (QAH) insulators. A Monash-led team has

demonstrated that the breakdown in topological protection is caused by magnetic disorder, explaining previous observations that topological protection could be restored by application of stabilizing magnetic fields.

The paper, "Imaging the Breakdown and Restoration of Topological Protection in Magnetic Topological Insulator $MnBi_2Te_4$," is published in the journal *Advanced Materials*.

"The study paves a clear research pathway toward the use of MTIs in low-energy topological electronics," says lead author FLEET Ph.D. candidate Qile Li (Monash University).

The challenge

When combined, magnetism and topology can yield the quantum anomalous Hall effect (QAHE), allowing for electrical currents to flow without resistance along one-dimensional edges across macroscopic distances.

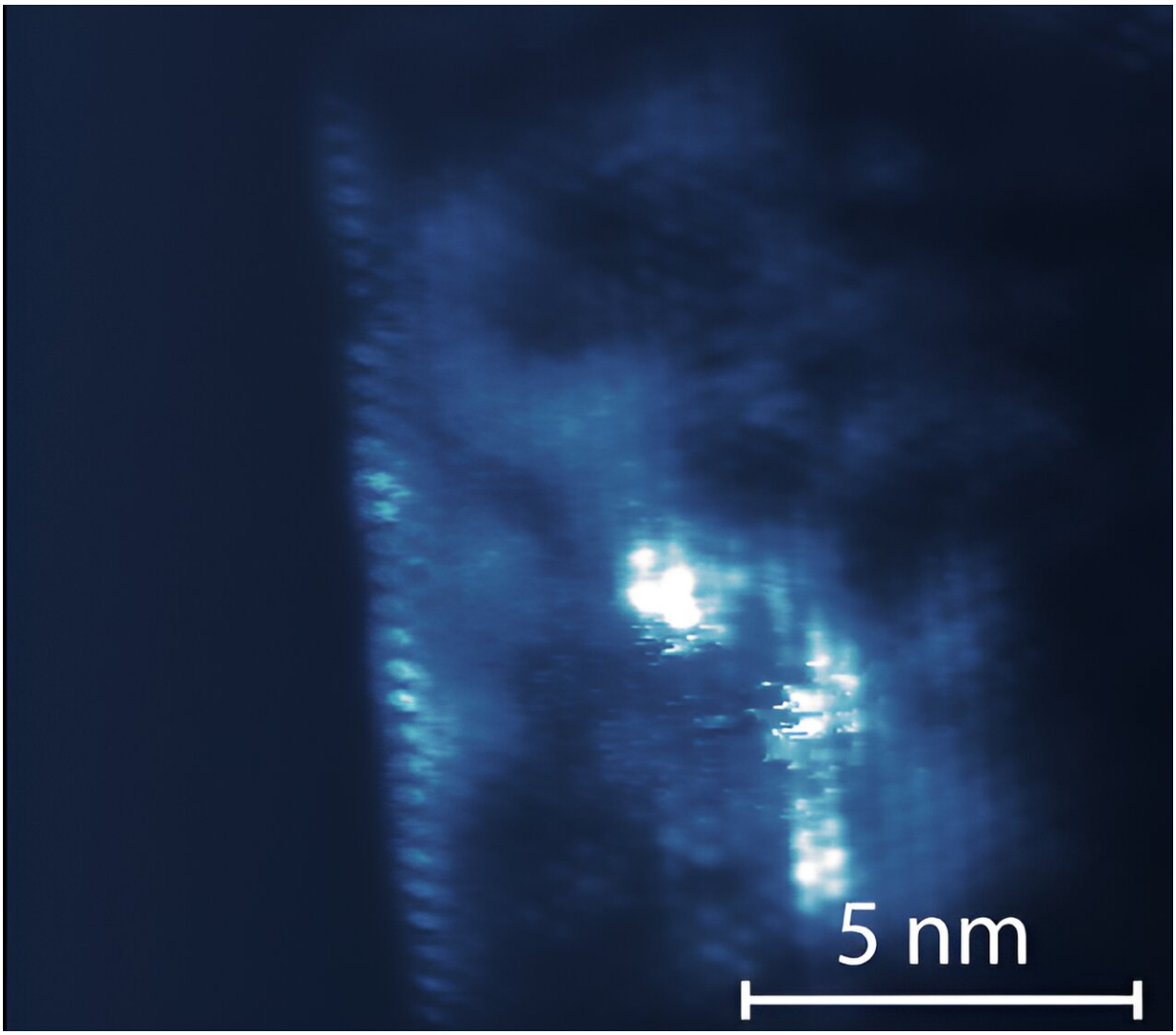
Yet, the current flow along these topologically protected, one-dimensional edges has proven to be far from robust. With the QAHE breaking down in magnetically doped topological insulators at temperatures higher than 1 Kelvin, well below the temperatures predicted by theory.

A new class of materials, known as intrinsic magnetic topological insulators (MTIs), for example $MnBi_2Te_4$, possess both non-trivial topology and intrinsic magnetism and are predicted to offer more robust QAHE at higher temperatures than magnetically doped topological insulators.

In $MnBi_2Te_4$ it has been shown that the QAHE can survive up to 1.4 K, and interestingly, this can rise to 6.5 K with the application of stabilizing

magnetic fields, providing hints at the mechanisms that are driving the breakdown of topological protection.

However, 6.5 K is still well below the 25K that is predicted by theory. To advance these materials toward potential applications, it is necessary to raise that temperature to the hard-line limit set by the magnetic bandgap energy and magnetic transition temperature. And this requires a better understanding of the precise mechanisms involved in the breakdown of topological protection at the material surface.



Conductance map taken with a scanning tunnelling microscope showing the gapless edge state and its coupling to metallic bulk states. Credit: *Advanced Materials* (2024). DOI: 10.1002/adma.202312004

Studying interplay between surface disorder, bandgap fluctuation, and edge state

To fully understand what was happening, the Monash-led team used direct, atomically precise measurement of the interplay between surface disorder, local fluctuations in the bandgap energy, and chiral edge state.

The team used low-temperature scanning tunneling microscopy and spectroscopy (STM/STS) to study five-layer, ultra-thin film $MnBi_2Te_4$.

How the bandgap fluctuates was studied at the location of crystal defects, as well as at the edge and interior of the five-layer film—to understand what might cause the breakdown of QAHE.

The team also applied low magnetic fields, observing the bandgap and QAHE could be restored. The applied magnetic fields are well below the spin-flop transition for $MnBi_2Te_4$.

Results in five-layer $MnBi_2Te_4$ reveal a magnetic villain

The research team found long-range fluctuations in bandgap energy in the interior of the film, ranging between 0 (gapless) and 70 meV, and not correlated to individual surface defects.

Directly observing the breakdown of topological protection shows that

the gapless edge state, the hallmark signature of a QAH insulator, hybridizes with extended gapless regions in the bulk.

These results demonstrate that the gapless edge state in $MnBi_2Te_4$ is directly coupled to extended percolating bulk metallic regions arising from band gap fluctuations caused by magnetic surface disorder.

Band gap fluctuations can be greatly reduced by applying a magnetic field, increasing the average exchange gap to 44 meV, close to predicted values.

"These results provide insight on the mechanism of topological breakdown and how it can be restored in a magnetic field," says corresponding author FLEET Associate Investigator Dr. Mark Edmonds (also at Monash).

More information: Qile Li et al, Imaging the Breakdown and Restoration of Topological Protection in Magnetic Topological Insulator $MnBi_2Te_4$, *Advanced Materials* (2024). DOI: 10.1002/adma.202312004

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