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Scientists discover a topological magnet that exhibits exotic quantum effects

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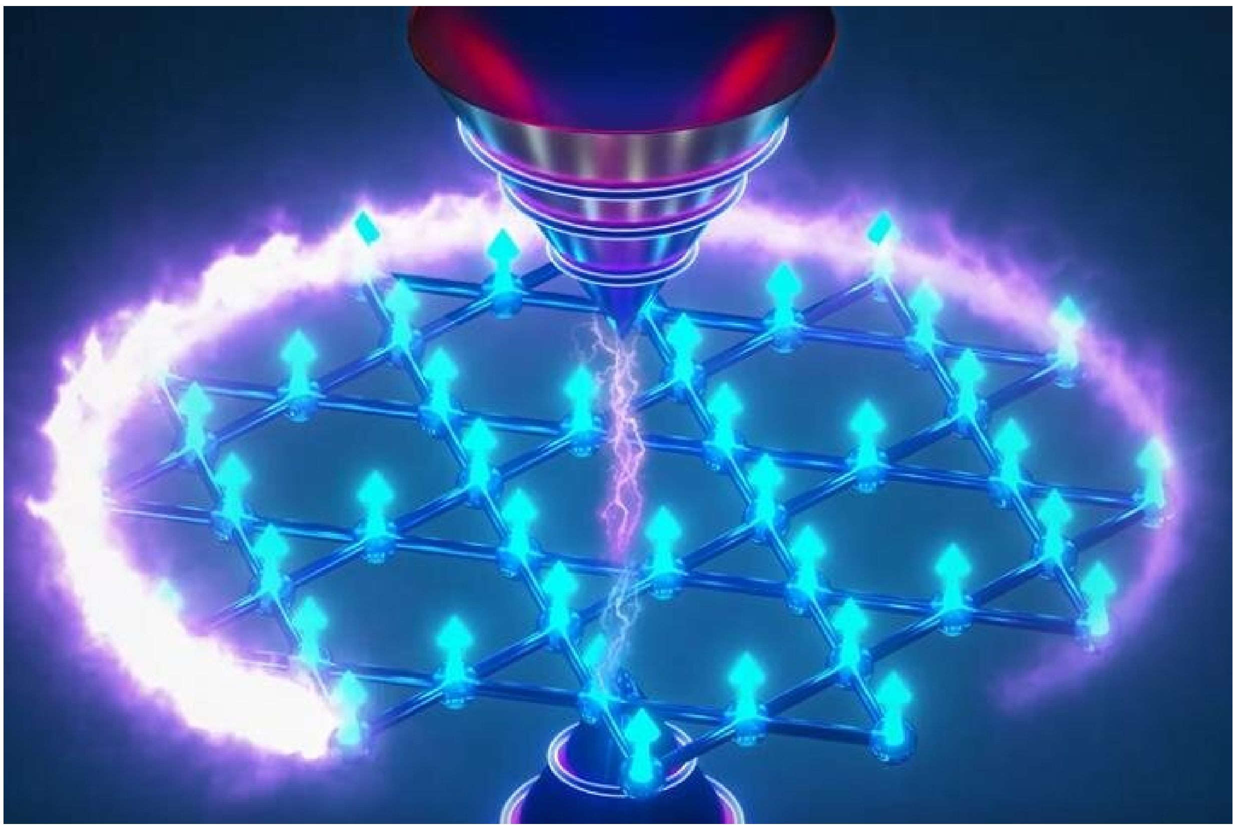

The arrows represent the electron spins pointing up from a kagome lattice. The chirality is represented by the counterclockwise circle of fire, which represents the propagating electrons/current on the edge of the magnet. The two cones demonstrate that the bulk of the magnet contains Dirac fermions (linear or conical dispersion of bands) with an energy gap (Chern gap), making it topological. Credit: M. Zahid Hasan group, Princeton University

An international team led by researchers at Princeton University has uncovered a new class of magnet that exhibits novel quantum effects that extend to room temperature.

The researchers discovered a quantized topological phase in a pristine magnet. Their findings provide insights into a 30-year-old theory of how electrons spontaneously quantize and demonstrate a proof-of-principle method to discover new topological magnets. Quantum magnets are promising platforms for dissipationless current, high storage capacity and future green technologies. The study was published in the journal *Nature* this week.

The discovery's roots lie in the workings of the quantum Hall effect- a form of topological effect which was the subject of the Nobel Prize in Physics in 1985. This was the first time that a branch of theoretical mathematics, called topology, would start to fundamentally change how we describe and classify matter that makes up the world around us. Ever since, topological phases have been intensely studied in science and engineering. Many new classes of quantum materials with topological electronic structures have been found, including topological insulators and Weyl semimetals. However, while some of the most exciting theoretical ideas require magnetism, most materials explored have been nonmagnetic and show no quantization, leaving many tantalizing possibilities unfulfilled.

"The discovery of a magnetic topological material with quantized behavior is a major step forward that could unlock new horizons in harnessing quantum topology for future fundamental physics and next-generation device research" said M. Zahid Hasan, the Eugene Higgins Professor of Physics at Princeton University, who led the research team.

While experimental discoveries were rapidly being made, theoretical physics excelled at developing ideas leading to new measurements.

Important theoretical concepts on 2-D topological insulators were put forward in 1988 by F. Duncan Haldane, the Thomas D. Jones Professor of Mathematical Physics and the Sherman Fairchild University Professor of Physics at Princeton, who in 2016 was awarded the Nobel Prize in Physics for theoretical discoveries of topological phase transitions and topological phases of matter. Subsequent theoretical developments showed that topological insulator-hosting magnetism in a special atomic arrangement known as a kagome lattice can host some of the most bizarre quantum effects.

Hasan and his team has been on a decade-long search for a topological magnetic quantum state that may also operate at room temperature since their discovery of the first examples of three dimensional topological insulators. Recently, they found a materials solution to Haldane's conjecture in a kagome lattice magnet that is capable of operating at room temperature, which also exhibits the much desired quantization. "The kagome lattice can be designed to possess relativistic band crossings and strong electron-electron interactions. Both are essential for novel magnetism. Therefore, we realized that kagome magnets are a promising system in which to search for topological magnet phases as they are like the topological insulators that we studied before," said Hasan.

For so long, direct material and experimental visualization of this phenomenon has remained elusive. The team found that most of the kagome magnets were too difficult to synthesize, the magnetism was not sufficiently well understood, no decisive experimental signatures of the topology or quantization could be observed, or they operate only at very low temperatures.

"A suitable atomic chemistry and magnetic structure design coupled to first-principles theory is the crucial step to make Duncan Haldane's speculative prediction realistic in a high-temperature setting," said

Hasan. "There are hundreds of kagome magnets, and we need both intuition, experience, materials-specific calculations, and intense experimental efforts to eventually find the right material for in-depth exploration. And that took us on a decade-long journey."

Through several years of intense research on several families of topological magnets (Nature 562, 91 (2018); Nature Phys 15, 443 (2019), Phys. Rev. Lett. 123, 196604 (2019), Nature Commun. 11, 559 (2020), Phys. Rev. Lett. 125, 046401 (2020)), the team gradually realized that a material made of the elements terbium, manganese and tin (TbMn6Sn6) has the ideal crystal structure with chemically pristine, quantum mechanical properties and spatially segregated kagome lattice layers. Moreover, it uniquely features a strong out-of-plane magnetization. With this ideal kagome magnet successfully synthesized at the large single crystal level by collaborators from Shuang Jia's group at Peking University, Hasan's group began systematic state-of-the-art measurements to check whether the crystals are topological and, more important, feature the desired exotic quantum magnetic state.

The Princeton team of researchers used an advanced technique known as scanning tunneling microscopy, which is capable of probing the electronic and spin wavefunctions of a material at the sub-atomic scale with sub-millivolt energy resolution. Under these fine-tuned conditions, the researchers identified the magnetic kagome lattice atoms in the crystal, findings that were further confirmed by state-of-the-art angle-resolved photoemission spectroscopy with momentum resolution.

"The first surprise was that the magnetic kagome lattice in this material is super clean in our scanning tunneling microscopy," said Songtian Sonia Zhang, a co-author of the study who earned her Ph.D. at Princeton earlier this year. "The experimental visualization of such a defect-free magnetic kagome lattice offers an unprecedented opportunity to explore its intrinsic topological quantum properties."

The real magical moment was when the researchers turned on a magnetic field. They found that the electronic states of the kagome lattice modulate dramatically, forming quantized energy levels in a way that is consistent with Dirac topology. By gradually raising the magnetic field to 9 Tesla, which is hundreds of thousands of times higher than the earth's magnetic field, they systematically mapped out the complete quantization of this magnet. "It is extremely rare—there has not been one found yet—to find a topological magnetic system featuring the quantized diagram. It requires a nearly defect-free magnetic material design, fine-tuned theory and cutting-edge spectroscopic measurements" said Nana Shumiya, a graduate student and co-author of the study.

The quantized diagram that the team measured provides precise information revealing that the electronic phase matches a variant of the Haldane model. It confirms that the crystal features a spin-polarized Dirac dispersion with a large Chern gap, as expected by the theory for topological magnets. However, one piece of the puzzle was still missing. "If this is truly a Chern gap, then based on the fundamental topological bulk-boundary principle, we should observe chiral (one-way traffic) states at the edge of the crystal," Hasan said.

The final piece fell into place when the researchers scanned the boundary or the edge of the magnet. They found a clear signature of an edge state only within the Chern energy gap. Propagating along the side of the crystal without apparent scattering (which reveals its dissipationless character), the state was confirmed to be the chiral topological edge state. Imaging of this state was unprecedented in any previous study of topological magnets.

The researchers further used other tools to check and reconfirm their findings of the Chern gapped Dirac fermions, including electrical transport measurements of anomalous Hall scaling, angle-resolved photoemission spectroscopy of the Dirac dispersion in momentum space, and first-principles calculations of the topological order in the material family. The data provided a complete spectrum of inter-linked evidence all pointing to the realization of a quantum-limit Chern phase in this kagome magnet. "All the pieces fit together into a textbook demonstration of the physics of Chern-gapped magnetic Dirac fermions," said Tyler A. Cochran, a graduate student and co-first author of the study.

Now the theoretical and experimental focus of the group is shifting to the dozens of compounds with similar structures to TbMn6Sn6 that host kagome lattices with a variety of magnetic structures, each with its individual quantum topology. "Our experimental visualization of the quantum limit Chern phase demonstrates a proof-of-principle methodology to discover new topological magnets," said Jia-Xin Yin, a senior postdoctoral researcher and another co-first author of the study.

"This is like discovering water in an exoplanet—it opens up a new frontier of topological quantum matter research our laboratory at Princeton has been optimized for," Hasan said.

More information: Jia-Xin Yin et al, Quantum-limit Chern topological magnetism in TbMn6Sn6, *Nature* (2020). DOI: 10.1038/s41586-020-2482-7

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