Physicists discover topological behavior of electrons in 3-D magnetic material

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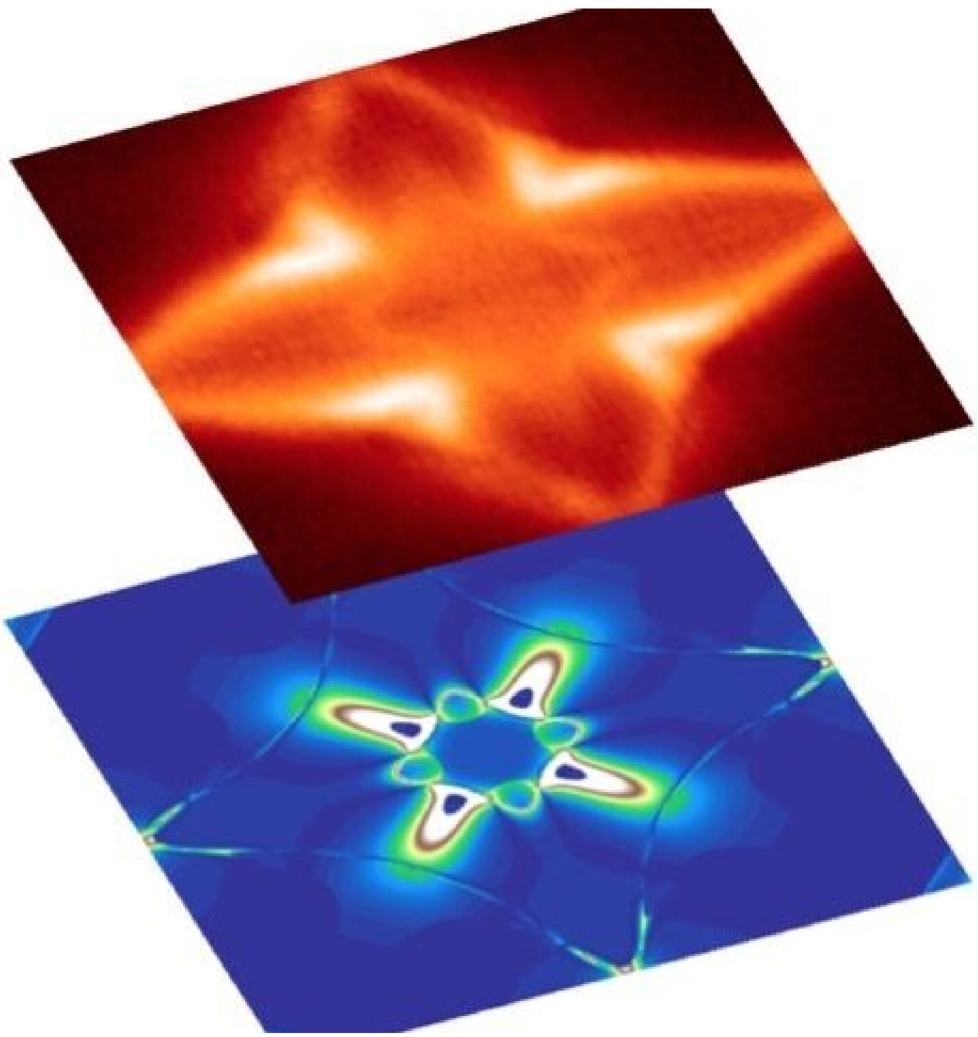


Researchers at Princeton explored electrons in a magnetic material at room temperature and discovered that they engage in collective quantum behaviors called Weyl loops.Top: Photoemission spectroscopy snapshot of the quantum Weyl loops. Middle: A theoretical calculation related to the system's response to applied electromagnetic fields. The correspondence between the top and middle images reflects that the quantum Weyl loops are at the heart of the exotic electromagnetic properties of the topological quantum magnet.Bottom: Distribution of electrons on the surface of the topological quantum magnet. The sharp light-colored features are the quantum Weyl loops. Credit: M. Zahid Hasan research team

An international team of researchers led by scientists at Princeton University has found that a magnetic material at room temperature enables electrons to behave counterintuitively, acting collectively rather than as individuals. Their collective behavior mimics massless particles and anti-particles that coexist in an unexpected way and together form an exotic loop-like structure.

The key to this behavior is topology—a branch of mathematics that is already known to play a powerful role in dictating the behavior of electrons in crystals. Topological materials can contain massless particles in the form of light, or photons. In a topological crystal, the electrons often behave like slowed-down light yet, unlike light, carry electrical charge.

Topology has seldom been observed in magnetic materials, and the finding of a magnetic topological material at room temperature is a step forward that could unlock new approaches to harnessing topological materials for future technological applications.

"Before this work, evidence for the topological properties of magnets in three dimensions was inconclusive. These new results give us direct and decisive evidence for this phenomenon at the microscopic level," said M. Zahid Hasan, the Eugene Higgins Professor of Physics at Princeton, who led the research. "This work opens up a new continent for exploration in topological magnets."

Hasan and his team spent more than a decade studying candidate materials in the search for a topological magnetic quantum state.

"The physics of bulk magnets has been understood for many decades. A natural question for us is: Can magnetic and topological properties together produce something new in three dimensions?" Hasan said.

Thousands of magnetic materials exist, but most did not have the correct properties, the researchers found. The magnets were too difficult to synthesize, the magnetism was not sufficiently well understood, the magnetic structure was too complicated to model theoretically, or no decisive experimental signatures of the topology could be observed.

Then came a lucky turning point.

"After studying many magnetic materials, we performed a measurement on a class of room-temperature magnets and unexpectedly saw signatures of massless electrons," said Ilya Belopolski, a postdoctoral researcher in Hasan's laboratory and co-first author of the study. "That set us on the path to the discovery of the first three-dimensional topological magnetic phase."

The exotic magnetic crystal consists of cobalt, manganese and gallium, arranged in an orderly, repeating three-dimensional pattern. To explore the material's topological state, the researchers used a technique called angle-resolved photoemission spectroscopy. In this experiment, high-intensity light shines on the sample, forcing electrons to emit from the surface. These emitted electrons can then be measured, providing information about the way the electrons behaved when they were inside the crystal.

"It's an extremely powerful experimental technique, which in this case allowed us to directly observe that the electrons in this magnet behave as if they are massless. These massless electrons are known as Weyl fermions," said Daniel Sanchez, a Princeton visiting researcher and Ph.D. student at the University of Copenhagen, and another co-first author of the study.

A key insight came when the researchers studied the Weyl fermions more closely and realized that the magnet hosted an infinite series of distinct massless electrons that takes the form of a loop, with some electrons mimicking properties of particles and some of anti-particles. This collective quantum behavior of the electrons has been termed a magnetic topological Weyl fermion loop.

"It truly is an exotic and novel system," said Guoqing Chang, a postdoctoral researcher in Hasan's group and co-first author of the study. "The collective electron behavior in these particles is unlike anything familiar to us in our everyday experience—or even in the experience of particle physicists studying subatomic particles. Here we are dealing with emergent particles obeying different laws of nature."

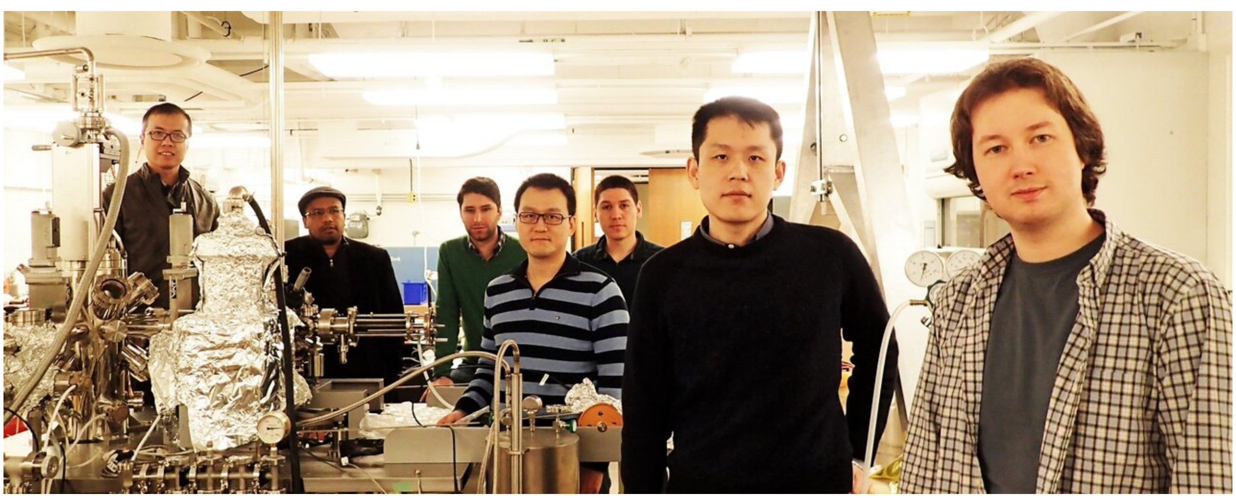
It turns out that a key driver of these properties is a mathematical quantity that describes the infinite series of massless electrons. The researchers were able to pin down the role of topology by observing subtle changes in the difference of the behavior of electrons living on the surface of the sample and deeper in its interior. The technique to demonstrate topological quantities through the contrasts of surface and bulk properties was pioneered by Hasan's group and used to detect Weyl fermions, a finding published in 2015. The team recently used an analogous approach to discover a topological chiral crystal, work published in the journal *Nature* earlier this year that was also led by Hasan's group at Princeton and included Daniel Sanchez, Guoqing Chang and Ilya Belopolski as leading authors.

Theoretical predictions

The relationship between the topology and magnetic quantum loop particles was explored in the Hasan group's theoretical predictions published in October 2017 in *Physical Review Letters*. However, the group's theoretical interest in topological magnets dates back much earlier to theoretical predictions published in *Nature Materials* in 2010. These theoretical works by Hasan's group were funded by U.S. Department of Energy's office of Basic Energy Sciences.

"This work represents the culmination of about a decade of seeking to realize a topological magnetic quantum phase in three dimensions," Hasan said.

In 2016, Duncan Haldane, Princeton's Sherman Fairchild University Professor of Physics, won the Nobel Prize in Physics for his theories predicting the properties of one- and two-dimensional topological materials.



Researchers led by M. Zahid Hassan (second from left) at Princeton University
Credit: Denise Applewhite, Princeton University

An important aspect of the result is that the material retains its magnetism up to 400 degrees Celsius—well above room temperature—satisfying a key requirement for real-world technological applications.

"Before our work, topological magnetic properties were typically observed when the thin films of materials were extremely cold—a fraction of a degree above absolute zero—requiring specialized equipment simply to achieve the necessary temperatures. Even a small amount of heat would thermally destabilize the topological magnetic state," Hasan said. "The quantum magnet studied here exhibits topological properties at room temperature."

A topological magnet in three dimensions reveals its most exotic signatures only on its surface—electron wavefunctions take the shape of drumheads. This is unprecedented in previously known magnets and constitute the telltale signature of a topological magnet. The researchers observed such drumhead-shaped electronic states in their data, providing the crucial decisive evidence that it is a novel state of matter.

Patrick Lee, the William & Emma Rogers Professor of Physics at the Massachusetts Institute of Technology, who was not involved in the study, commented on the importance of the finding. "The Princeton group has long been at the forefront of discovering new materials with topological properties," Lee said. "By extending this work to a room temperature ferromagnetic and demonstrating the existence of a new kind of drumhead surface states, this work opens up a new domain for further discoveries."

To understand their findings, the researchers studied the arrangement of atoms on the surface of the material using several techniques, such as checking for the right kind of symmetry using the scanning tunneling microscope in Hasan's Laboratory for Topological Quantum Matter and

Advanced Spectroscopy located in the basement of Princeton's Jadwin Hall.

An important contributor to the finding was the cutting-edge spectroscopy equipment used to carry out the experiment. The researchers used a dedicated photoemission spectroscopy beamline recently built at the Stanford Synchrotron Radiation Lightsource, part of the SLAC National Accelerator Laboratory in Menlo Park, California.

"The light used in the SLAC photoemission experiment is extremely bright and focused down to a tiny spot only several tens of micrometers in diameter," said Belopolski. "This was important for the study."

The work was carried out in close collaboration with the group of Professor Hsin Lin at the Institute of Physics, Academia Sinica in Taiwan, and Professor Claudia Felser at the Max Planck Institute for the Chemical Physics of Solids in Dresden, Germany, including postdoctoral researcher Kaustuv Manna as co-first author.

Driven by the tantalizing possibility of applications, the researchers went one step further and applied electromagnetic fields to the topological magnet to see how it would respond. They observed an exotic electromagnetic response up to room temperature, which could be directly traced back to the quantum loop electrons.

"We have many topological materials, but among them it has been difficult to show a clear electromagnetic response arising from the topology," Hasan added. "Here we have been able to do that. It sets up a whole new research field for topological magnets."

The study, "Discovery of topological Weyl fermion lines and drumhead surface states in a room temperature magnet," by Ilya Belopolski, Kaustuv Manna, Daniel S. Sanchez, Guoqing Chang, Benedikt Ernst, Jiaxin Yin, Songtian S. Zhang, Tyler Cochran, Nana Shumiya, Hao Zheng, Bahadur Singh, Guang Bian, Daniel Multer, Maksim Litskevich, Xiaoting Zhou, Shin-Ming Huang, Baokai Wang, Tay-Rong Chang, Su-Yang Xu, Arun Bansil, Claudia Felser, Hsin Lin and Zahid Hasan appears in the Sept. 19 issue of *Science*.

More information: "Discovery of topological Weyl lines and drumhead surface states in a room temperature magnet" *Science* (2019). science.sciencemag.org/cgi/doi … 1126/science.aav2327

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