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Approaching the magnetic singularity

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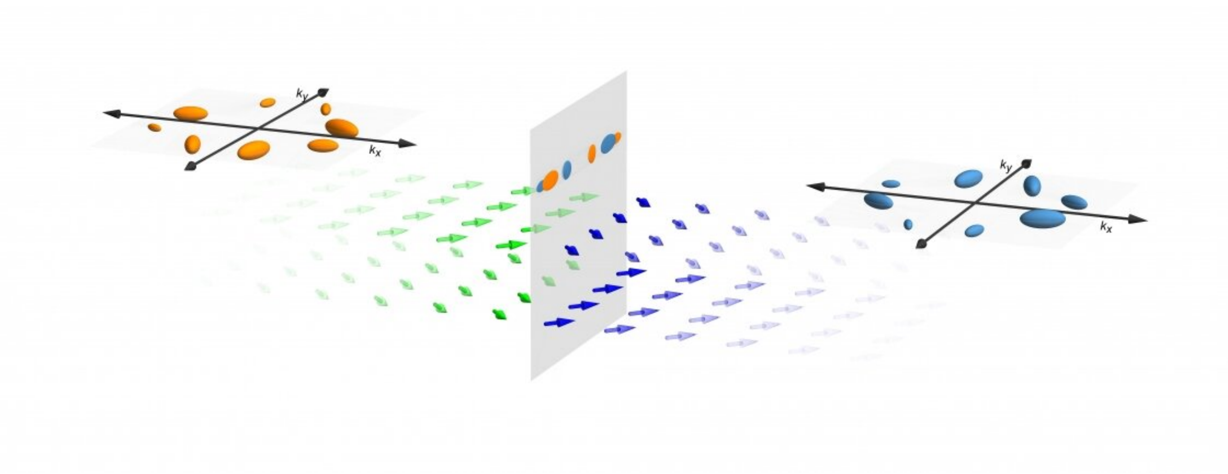

A domain wall (gray panel at center) separates regions with different spin orientations (green and blue arrows). MIT researchers discovered that a magnetic field applied at one particular angle through a single crystal of a new magnetic quantum material makes it harder for electrons to cross this domain wall. Credit: Leon Balents

In many materials, electrical resistance and voltage change in the presence of a magnetic field, usually varying smoothly as the magnetic field rotates. This simple magnetic response underlies many applications including contactless current sensing, motion sensing, and data storage. In a crystal, the way that the charge and spin of its electrons align and interact underlies these effects. Utilizing the nature of the alignment, called symmetry, is a key ingredient in designing a functional material for electronics and the emerging field of spin-based electronics (spintronics).

Recently a team of researchers from MIT, the French National Center for Scientific Research (CNRS) and École Normale Supérieure (ENS) de Lyon, University of California at Santa Barbara (UCSB), the Hong Kong University of Science and Technology (HKUST), and NIST Center for Neutron Research, led by Joseph G. Checkelsky, assistant professor of physics at MIT, has discovered a new type of magnetically driven electrical response in a crystal composed of cerium, aluminum, germanium, and silicon.

At temperatures below 5.6 kelvins (corresponding to -449.6 degrees Fahrenheit), these crystals show a sharp enhancement of electrical resistivity when the magnetic field is precisely aligned within an angle of 1 degree along the high symmetry direction of the crystal. This effect, which the researchers have named "singular angular magnetoresistance," can be attributed to the symmetry—in particular, the ordering of the cerium atoms' magnetic moments. Their results are published today in the journal *Science*.

Novel response and symmetry

Like an old-fashioned clock designed to chime at 12:00 and at no other position of the hands, the newly discovered magnetoresistance only occurs when the direction, or vector, of the magnetic field is pointed straight in line with the high-symmetry axis in the material's crystal structure. Turn the magnetic field more than a degree away from that axis and the resistance drops precipitously.

"Rather than responding to the individual components of the magnetic field like a traditional material, here the material responds to the absolute vector direction," says Takehito Suzuki, a research scientist in the Checkelsky group who synthesized these materials and discovered the effect. "The observed sharp enhancement, which we call singular angular magnetoresistance, implies a distinct state realized only under those conditions."

Magnetoresistance is a change in the electrical resistance of a material in response to an applied magnetic field. A related effect known as giant magnetoresistance is the basis for modern computer hard drives and its discoverers were awarded the Nobel Prize in 2007.

"The observed enhancement is so highly confined with the magnetic field along the crystalline axis in this material that it strongly suggests symmetry plays a critical role," Lucile Savary, permanent CNRS researcher at ENS de Lyon, adds. Savary was a Betty and Gordon Moore Postdoctoral Fellow at MIT from 2014-17, when the team started collaborating.

To elucidate the role of the symmetry, it is crucial to see the alignment of the magnetic moments, for which Suzuki and Jeffrey Lynn, NIST fellow, performed powder neutron diffraction studies on the BT-7 triple axis spectrometer at the NIST Center for Neutron Research (NCNR). The research team used the NCNR's neutron diffraction capabilities to determine the material's magnetic structure, which plays an essential role in understanding its topological properties and nature of the magnetic domains. A "topological state" is one that is protected from ordinary disorder. This was a key factor in unraveling the mechanism of the singular response.

Based on the observed ordering pattern, Savary and Leon Balents, professor and permanent member of Kavli Institute of Theoretical Physics at UCSB, constructed a theoretical model where the spontaneous symmetry-breaking caused by the magnetic-moment ordering couples to the magnetic field and the topological electronic structure. As a consequence of the coupling, switching between the uniformly ordered low- and high-resistivity states can be manipulated by the precise control of the magnetic field direction.

"The agreement of the model with the experimental results is outstanding and was the key to understanding what was a mysterious experimental observation," says Checkelsky, the paper's senior author.

Universality of the phenomenon

"The interesting question here is whether or not the singular angular magnetoresistance can be widely observed in magnetic materials and, if this feature can be ubiquitously observed, what is the key ingredient for engineering the materials with this effect," Suzuki says.

The theoretical model indicates that the singular response may indeed be found in other materials and predicts material properties beneficial for realizing this feature. One of the important ingredients is an electronic structure with a small number of free charges, which occurs in a point-like electronic structure referred to as nodal. The material in this study has so-called Weyl points that achieve this. In such materials, the allowed electron momenta depends on the configuration of the magnetic order. Such control of the momenta of these charges by the magnetic degree of freedom allows the system to support switchable interface regions where the momenta are mismatched between domains of different magnetic order. This mismatch also leads to the large increase in resistance observed in this study.

This analysis is further supported by the first-principles electronic structure calculation performed by Jianpeng Liu, research assistant professor at the HKUST, and Balents. Using more traditional magnetic elements such as iron or cobalt, rather than rare-earth cerium, may offer a potential path to higher temperature observation of the singular angular magnetoresistance effect. The study also ruled out a change in the arrangement of the atoms, called a structural phase transition, as a cause of the change in resistivity of the cerium-based material.

Kenneth Burch, graduate program director and associate professor of physics at Boston College, whose lab investigates Weyl materials, notes: "The discovery of remarkable sensitivity to magnetic angle is a completely unexpected phenomena in this new class of materials. This result suggests not only new applications of Weyl semimetals in magnetic sensing, but the unique coupling of electronic transport, chirality and magnetism." Chirality is an aspect of electrons related to their spin that gives them either a left-handed or right-handed orientation.

The discovery of this sharp but narrowly confined resistance peak could eventually be used by engineers as a new paradigm for magnetic sensors. Notes Checkelsky, "One of the exciting things about fundamental discoveries in magnetism is the potential for rapid adoptions for new technologies. With the design principles now in hand, we are casting a wide net to find this phenomena in more robust systems to unlock this potential."

More information: T. Suzuki et al. Singular angular magnetoresistance in a magnetic nodal semimetal, *Science* (2019). DOI: 10.1126/science.aat0348

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