A quantum step to a heat switch with no moving parts

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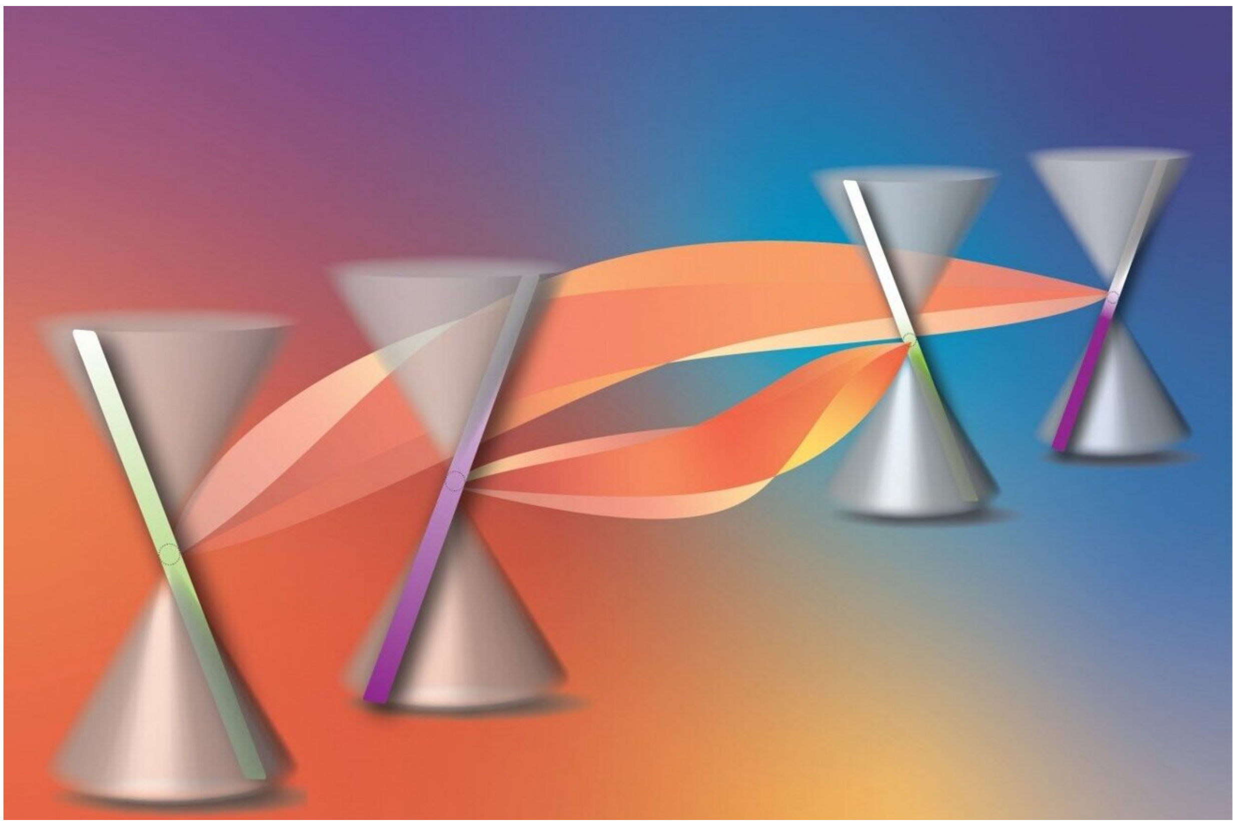

The cones in this image illustrate the equations of motion of electrons when an external magnetic field is applied to the bismuth alloy engineered for the study. Green lines and purple lines represent electrons that generate and absorb energy, respectively. Credit: Renee Ripley

Researchers have discovered a new electronic property at the frontier between the thermal and quantum sciences in a specially engineered metal alloy—and in the process identified a promising material for future devices that could turn heat on and off with the application of a magnetic "switch."

In this material, electrons, which have a mass in vacuum and in most other materials, move like massless photons or light—an unexpected behavior, but a phenomenon theoretically predicted to exist here. The alloy was engineered with the elements bismuth and antimony at precise ranges based on foundational theory.

Under the influence of an external magnetic field, the researchers found, these oddly behaving electrons manipulate heat in ways not seen under normal conditions. On both the hot and cold sides of the material, some of the electrons generate heat, or energy, while others absorb energy, effectively turning the material into an energy pump. The result: A 300% increase in its thermal conductivity.

Take the magnet away, and the mechanism is turned off.

"The generation and absorption form the anomaly," said study senior author Joseph Heremans, professor of mechanical and aerospace engineering and Ohio Eminent Scholar in Nanotechnology at The Ohio State University. "The heat disappears and reappears elsewhere—it is like teleportation. It only happens under very specific circumstances predicted by quantum theory."

This property, and the simplicity of controlling it with a magnet, makes the material a desirable candidate as a heat switch with no moving parts, similar to a transistor that switches electrical currents or a faucet that switches water, that could cool computers or increase the efficiency of solar-thermal power plants.

"Solid-state heat switches without moving parts are extremely desirable, but they don't exist," Heremans said. "This is one of the possible mechanisms that would lead to one."

The research is published today (June 7, 2021) in the journal *Nature Materials*.

The bismuth-antimony alloy is among a class of quantum materials called Weyl semimetals, whose electrons don't behave as expected. They are characterized by properties that include negatively and positively charged particles, electrons and holes, respectively, that behave as "massless" particles. Also part of a group called topological materials, their electrons react as if the material contains internal magnetic fields that enable the establishment of new pathways along which those particles move.

In physics, an anomaly—the electrons' generation and absorption of heat discovered in this study—refers to certain symmetries that are present in the classical world but are broken in the quantum world, said study co-author Nandini Trivedi, professor of physics at Ohio State.

Bismuth alloys and other similar materials also feature classical conduction like most metals, by which vibrating atoms in a crystal lattice and the movement of electrons carry heat. Trivedi described the new pathway along which light-like electrons manipulate heat among themselves as a highway that seems to appear out of nowhere.

"Imagine if you were living in a small town that had tiny roads, and suddenly there's a highway that opens up," she said. "This particular pathway only opens up if you apply a thermal gradient in one direction and a magnetic field in the same direction. So you can easily close the highway by putting the magnetic field in a perpendicular direction.

"No such highways exist in ordinary metals."

When a metal like copper is heated and electrons flow from the hot end to the cold end, both the heat and the charge move together. Because of the way this highway opens in the experimental Weyl semimetal material, there's no net charge motion—only energy movement. The absorption of heat by certain electrons represents a break in chirality, or directionality, meaning that it's possible to pump energy between two particles that wouldn't be expected to interact—another characteristic of Weyl semimetals.

The theoretical physicists and engineers collaborating on this study predicted that these properties existed in specific bismuth alloys and other topological materials. For these experiments, the scientists constructed the specialized alloy to test their predictions.

"We worked hard to synthesize the correct material, which was designed from the ground up by us to show this effect. It was important to purify it way below the levels of impurities that you find in nature," Heremans said. As composed, the alloy minimized background conduction so the researchers could detect the behavior of the massless electrons, known as Weyl Fermions.

"In ordinary materials, electrons drag around with them a small magnet. However, the peculiar electronic structure of these bismuth alloys means the electrons drag around a magnet almost 50 times bigger than normal," said Michael Flatté, professor of physics and astronomy at the University of Iowa and a study co-author. "These huge subatomic magnets allowed the novel electronic state to be formed using laboratory magnetic fields.

"These results show that theories developed for high-energy physics and subatomic particle theories can often be realized in specially designed electronic materials."

Like everything quantum, Heremans said, "what we observed looks a little like magic, but that is what our equations say it should do and that is what we proved experimentally that it does."

One catch: The mechanism in this material works only at a low temperature, below minus 100 degrees Fahrenheit. With the fundamentals now understood, the researchers have lots of options as they work toward potential applications.

"Now we know what materials to look for and what purity we need," Heremans said. "That is how we get from discovery of a physical phenomenon to an engineering material."

More information: Dung Vu et al, Thermal chiral anomaly in the magnetic-field-induced ideal Weyl phase of $Bi_{1-x}Sb_x$, *Nature Materials* (2021). [DOI: 10.1038/s41563-021-00983-8](https://dx.doi.org/10.1038/s41563-021-00983-8)

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