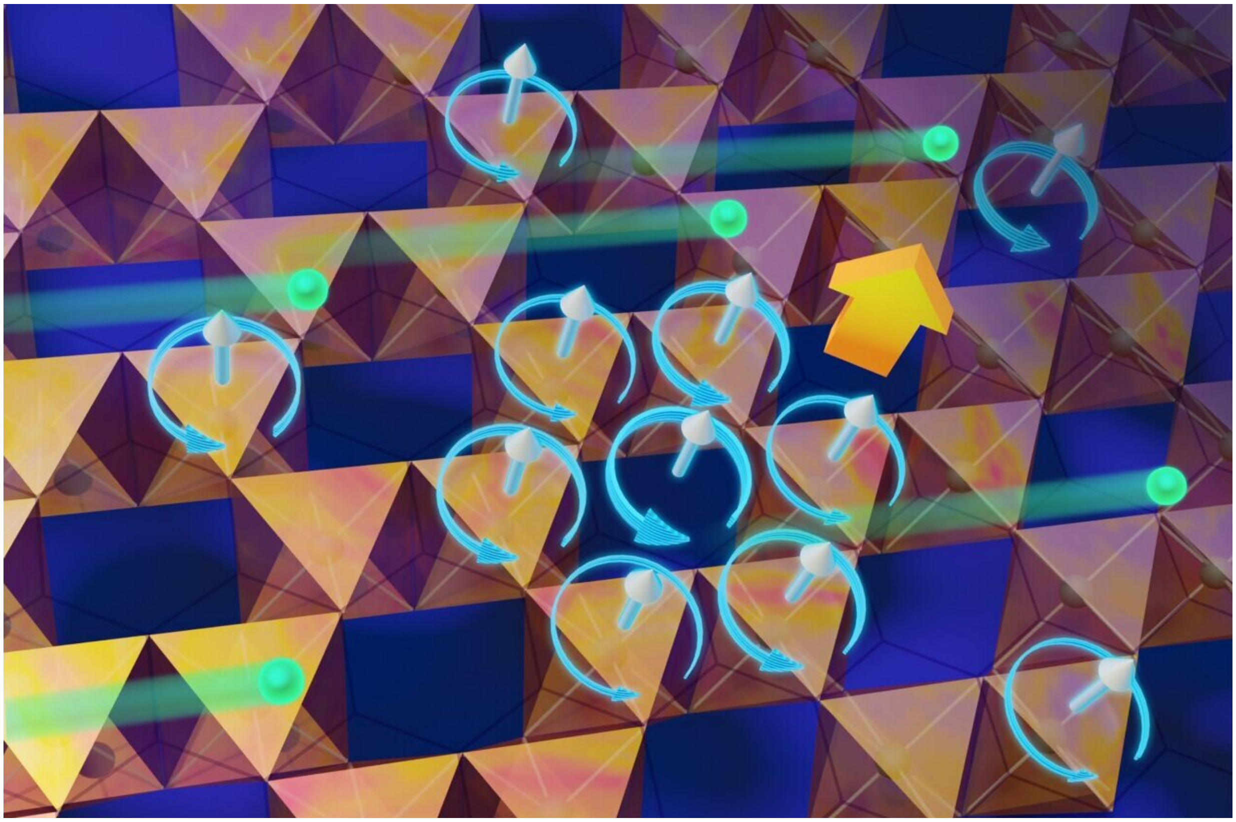
Physicists probe 'astonishing' morphing properties of honeycomb-like material

October 12 2022



By exposing a honeycomb-like material with a specific kind of magnetic field, yellow arrow, researchers can create order among the loop currents, light blue, within that material. Electrons, in green, can then pass through the material much more easily. Credit: Oak Ridge National Laboratory

A series of buzzing, bee-like "loop-currents" could explain a recently discovered, never-before-seen phenomenon in a type of quantum material. The findings from researchers at the University of Colorado Boulder may one day help engineers to develop new kinds of devices, such as quantum sensors or the quantum equivalent of computer memory storage devices.

The quantum material in question is known by the chemical formula $Mn_3Si_2Te_6$. But you could also call it "honeycomb" because its manganese and tellurium atoms form a network of interlocking octahedra that look like the cells in a beehive.

Physicist Gang Cao and his colleagues at CU Boulder synthesized this molecular beehive in their lab in 2020, and they were in for a surprise: Under most circumstances, the material behaved a lot like an insulator. In other words, it didn't allow electric currents to pass through it easily. When they exposed the honeycomb to magnetic fields in a certain way, however, it suddenly became millions of times less resistant to currents. It was almost as if the material had morphed from rubber into metal.

"It was both astonishing and puzzling," said Cao, professor in the Department of Physics and corresponding author of the new study. "Our follow-up effort in pursuing a better understanding of the phenomena led us to even more surprising discoveries."

Now, he and his colleagues think they can explain that astonishing behavior. The group, including several graduate students at CU Boulder, published its most recent results on Nov. 17 in the journal *Nature*.

Drawing on experiments in Cao's lab, the group reports that, under certain conditions, the honeycomb is abuzz with tiny, internal currents known as chiral orbital currents, or loop currents. Electrons zip around in loops within each of the octahedra in this quantum material. Since the 1990s, physicists have theorized that loop currents could exist in a handful of known materials, such as high-temperature superconductors, but they have yet to directly observe them.

Cao said they could be capable of driving startling transformations in quantum materials like the one he and his team stumbled on.

"We've discovered a new quantum state of matter," Cao said. "Its quantum transition is almost like ice melting into water."

Colossal changes

The study homes in on a strange property in physics called colossal magnetoresistance (CMR).

In the 1950s, physicists realized that if they exposed certain types of materials to magnets that generate a magnetic polarization, they could make those materials undergo a shift—causing them to switch from insulators to more wire-like conductors. Today, this technology shows up in computer disk drives and many other electronic devices where it helps to control and shuttle electric currents along distinct paths.

The honeycomb in question, however, is vastly different from those materials—the CMR occurs only when conditions avoid that same kind of magnetic polalrization. The shift in electrical properties is also much more extreme than what you can see in any other known CMR material, Cao added.

"You have to violate all the conventional conditions to achieve this change," Cao said.

Melting ice

He and his colleagues, including CU Boulder graduate students Yu Zhang, Yifei Ni and Hengdi Zhao, wanted to find out why.

They, along with co-author Itamar Kimchi of Georgia Institute of Technology, hit on the idea of loop currents. According to the team's theory, countless electrons circulate around inside their honeycombs at all times, tracing the edges of each octahedron. In the absence of a magnetic field, those loop currents tend to stay disorderly, or flow in both clockwise and counterclockwise patterns. It's a bit like cars driving through a roundabout in both directions at once.

That disorder can cause "traffic jams" for electrons traveling in the material, Cao said, increasing the resistance and making the honeycomb an insulator.

As Cao put it: "Electrons like order."

The physicist added, however, that if you pass an electric current into the quantum material in the presence of a specific kind of magnetic field, the loop currents will begin to circulate only in one direction. Put differently, the traffic jams disappear. Once that happens, electrons can speed through the quantum material, almost as if it was a metal wire.

"The internal loop currents circulating along the edges of the octahedra are extraordinarily susceptible to external currents," Cao said. "When an external electric current exceeds a critical threshold, it disrupts and eventually 'melts' the loop currents, leading to a different electronic state."

He noted that in most materials, the switch from one electronic state to another happens almost instantaneously, or in the span of trillionths of a second. But in his honeycomb, that transformation can take seconds or even longer to occur.

Cao suspects the entire structure of the honeycomb begins to morph, with the bonds between atoms breaking and reforming in new patterns. That kind of reordering takes an unusually long time, he noted—a bit like what happens when ice melts into water.

Cao said the work provides a new paradigm for quantum technologies. For now, you probably won't see this honeycomb in any new electronic devices. That's because the switching behavior only takes place at cold temperatures. He and his colleagues, however, are searching for similar materials that will do the same thing under much more hospitable conditions.

"If we want to use this in future devices, we need to have materials that show the same type of behavior at room temperature," Cao said.

Now, that sort of invention could be buzz-worthy.

More information: Gang Cao, Control of chiral orbital currents in a colossal magnetoresistance material, *Nature* (2022). DOI: 10.1038/s41586-022-05262-3.
www.nature.com/articles/s41586-022-05262-3

Provided by University of Colorado at Boulder

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