Semiconductor demonstrates elusive quantum physics model

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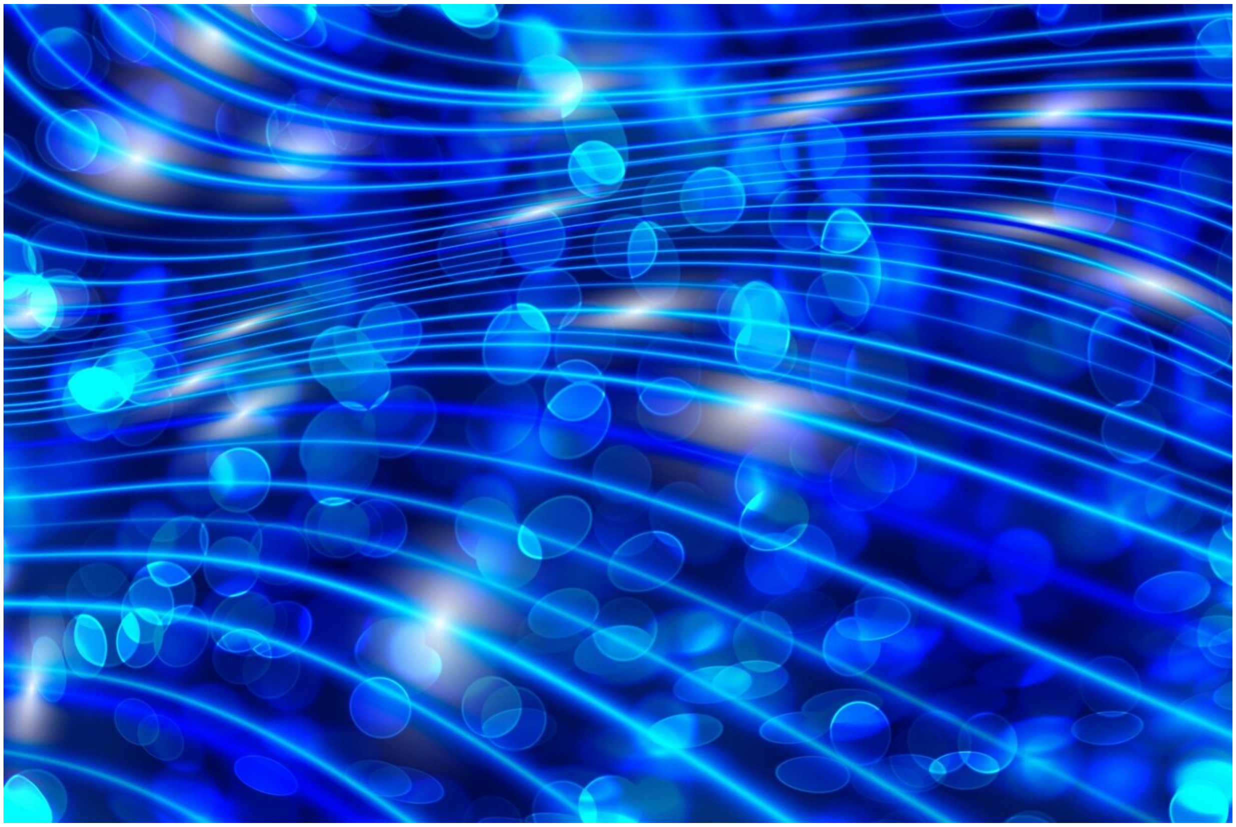

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With a little twist and the turn of a voltage knob, Cornell researchers have shown that a single material system can toggle between two of the wildest states in condensed matter physics: The quantum anomalous Hall insulator and the two-dimensional topological insulator.

By doing so, they realized an elusive model that was first proposed more than a decade ago, but which scientists have never been able to demonstrate because a suitable material didn't seem to exist. Now that the researchers have created the right platform, their breakthrough could lead to advances in quantum devices.

The team's paper, "Quantum Anomalous Hall Effect from Intertwined Moiré Bands," published Dec. 22 in *Nature*. The co-lead authors are former postdoctoral researchers Tingxin Li and Shengwei Jiang, doctoral student Bowen Shen and Massachusetts Institute of Technology researcher Yang Zhang.

The project is the latest discovery from the shared lab of Kin Fai Mak, associate professor of physics in the College of Arts and Sciences, and Jie Shan, professor of applied and engineering physics in the College of Engineering, the paper's co-senior authors. Both researchers are members of the Kavli Institute at Cornell for Nanoscale Science; they came to Cornell through the provost's Nanoscale Science and Microsystems Engineering (NEXT Nano) initiative.

Their lab specializes in exploring the electronic properties of 2D quantum materials, often by stacking ultrathin monolayers of semiconductors so their slightly mismatched overlap creates a moiré lattice pattern. There, electrons can be deposited and interact with each other to exhibit a range of quantum behavior.

For the new project, the researchers paired molybdenum ditelluride ($MoTe_2$) with tungsten diselenide (WSe_2), twisting them at a 180-degree angle for a configuration that is known as an AB stack.

After applying a voltage, they observed what's known as a quantum anomalous Hall effect. This has its roots in a phenomenon called the Hall effect, first observed in the late 19th century, in which electrical current is flowed through a sample and then bent by a magnetic field that is applied at a perpendicular angle.

The quantum Hall effect, discovered in 1980, is the supersized version, in which a far greater magnetic field is applied, triggering even stranger phenomena: The interior of the bulk sample becomes an insulator, while an electrical current moves in a single direction along the outer edge, with resistances quantized to a value defined by the fundamental constants in the universe, regardless of the details of the material.

The quantum anomalous Hall insulator, first discovered in 2013, achieves the same effect but without the intervention of any magnetic field, the electrons speeding along the edge as if on a highway, without dissipating energy, somewhat like a superconductor.

"For a long time people thought that a magnetic field is needed for the quantum Hall effect, but you actually don't need one," Mak said. "So what replaces the role of a magnetic field? It turns out that it is magnetism. You have to make the material magnetic."

The $MoTe_2/WSe_2$ stack now joins the ranks of only handful of materials that are known to be quantum anomalous Hall insulators. But that is only half of its appeal.

The researchers found that by simply tweaking the voltage, they could turn their semiconductor stack into a 2D topological insulator, which is a cousin of sorts to the quantum anomalous Hall insulator, except that it exists in duplicate. In one "copy," the electron highway flows clockwise around the edge, and in the other, it flows counterclockwise.

The two states of matter have never before been demonstrated in the same system.

After consulting with collaborators led by co-author Liang Fu at MIT, the Cornell team learned its experiment had realized a toy model for graphene first proposed by physics professors Charles Kane and Eugene Mele at the University of Pennsylvania in 2005. The Kane-Mele model was the first theoretical model for 2D topological insulators.

"That was a surprise to us," Mak said. "We just made this material and did the measurements. We saw the quantum anomalous Hall effect and the 2D topological insulator and said 'Oh, wow. That's great.' Then we talked to our theory friend, Liang Fu, at MIT. They did the calculations and figured out the material actually realized a long sought-after model in condensed matter. We never expected this."

Like graphene moiré materials, $MoTe_2/WSe_2$ can switch between a range of quantum states, including a transition from a metal to a Mott insulator, a discovery the team reported in *Nature* in September.

Now Mak and Shan's lab is investigating the full potential of the material by coupling it with superconductors and using it to build quantum anomalous Hall interferometers, both of which in turn could generate qubits, the basic element for quantum computing. Mak is also hopeful they may find a way to significantly raise the temperature at which the quantum anomalous Hall effect occurs—which is at about 2 kelvin—resulting in a high-temperature dissipationless conductor.

Co-authors include doctoral students Lizhong Li and Zui Tao; and researchers from MIT and the National Institute for Materials Science in Tsukuba, Japan.

More information: Tingxin Li et al, Quantum anomalous Hall effect from intertwined moiré bands, *Nature* (2021). DOI:

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