Researchers demonstrate three-dimensional quantum Hall effect for the first time

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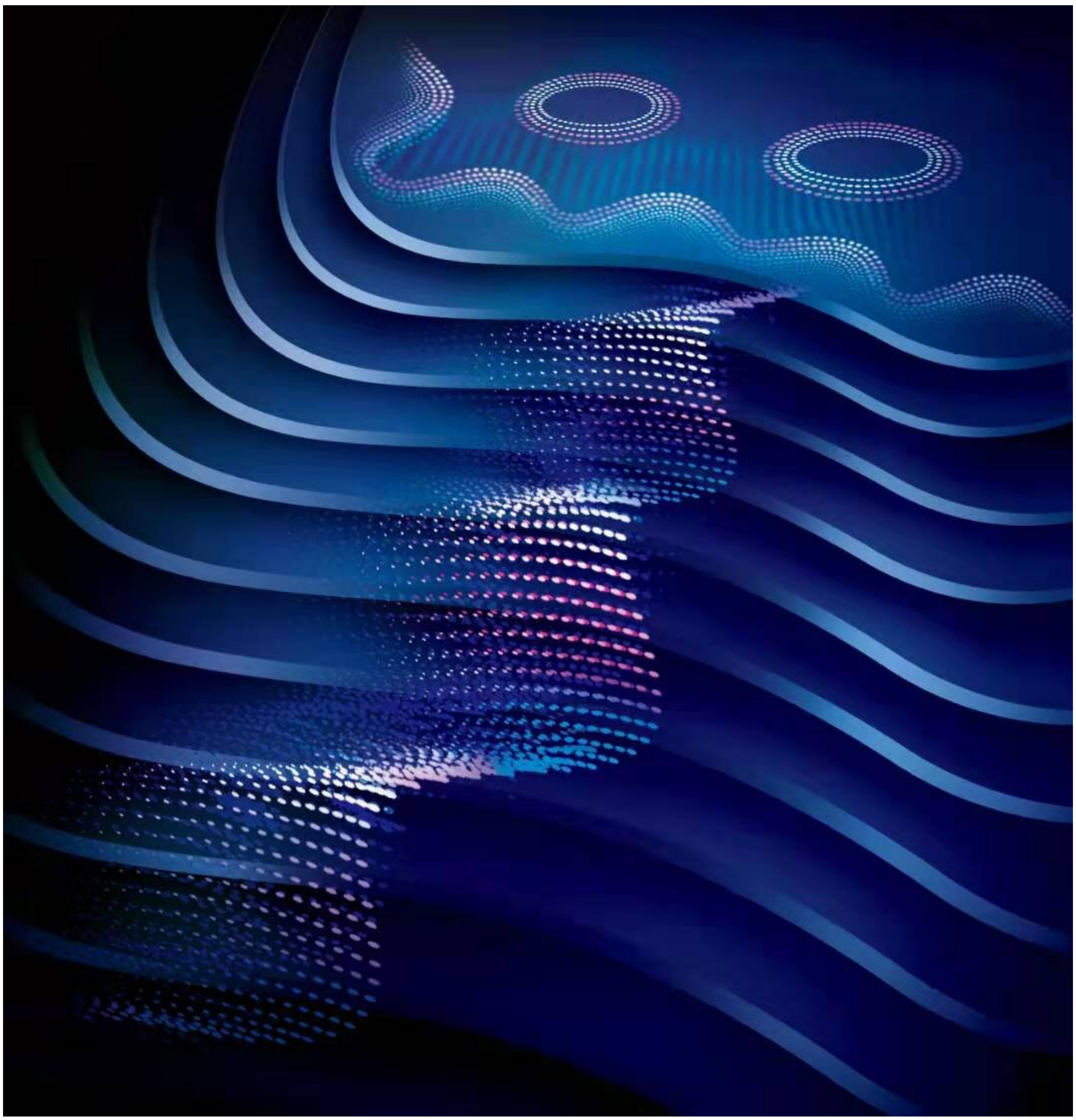

An illustration of the 3D quantum Hall effect. Under enhanced interaction effects, the electrons form a special charge density wave along the applied magnetic field. The interior becomes insulating, while the conduction is through the surface of the material. Credit: Wang Guoyan & He Cong

The quantum Hall effect (QHE), which was previously known for two-dimensional (2-D) systems, was predicted to be possible for three-dimensional (3-D) systems by Bertrand Halperin in 1987, but the theory was not proven until recently by researchers from the Singapore University of Technology and Design (SUTD) and their research collaborators from around the globe.

The Hall effect, a fundamental technique for material characterization, occurs when a magnetic field deflects the flow of electrons sideways and leads to a voltage drop across the transverse direction. In 1980, researchers made a surprising observation when measuring the Hall effect for a two-dimensional (2-D) electron gas trapped in a semiconductor structure—the measured Hall resistivity showed a series of completely flat plateau, quantized to values with a remarkable accuracy of one part in 10 billion. This became known as the QHE.

QHE has since revolutionized the fundamental understanding of condensed matter physics, generating a vast field of physics research. Many new emerging topics, such as topological materials, can also be traced back to it.

Soon after its discovery, researchers pursued the possibility of generalizing QHE from 2-D systems to three dimensions (3-D). Bertrand Halperin predicted that such a generalized effect, called the 3-D QHE, is indeed possible in a seminal paper published in 1987. From theoretical analysis, he gave signatures for 3-D QHE and pointed out that enhanced interactions between the electrons under a magnetic field can be the key to drive a metal material into the 3-D QHE state.

30 years have passed since Halperin's prediction, and while there have been continuing efforts in to realize 3-D QHE in experiment, clear evidence has been elusive due to the stringent conditions required for 3-D QHE—the material needs to be very pure, have high mobility, and low carrier density.

SUTD's experimental collaborator, the Southern University of Science and Technology (SUSTech) in China, has been working on a unique material known as $ZrTe_5$ since 2014. This material is able to satisfy the required conditions and exhibit the signatures of 3-D QHE.

In the research paper published in *Nature*, the researchers show that when the material is cooled to very low temperature while under a moderate magnetic field, its longitudinal resistivity drops to zero, indicating that the material transforms from a metal to an insulator. This is due to the electronic interactions where the electrons redistribute themselves and form a periodic density wave along the magnetic field direction (as illustrated in the image) called the charge density wave.

"This change would usually freeze the electron motion and the material becomes insulating, disallowing the electron to flow through the interior of the material. However, using this unique material, the electrons can move through the surfaces, giving a Hall resistivity quantized by the wavelength of the charge density wave," explained co-author Professor Zhang Liyuan from SUSTech. This in turn proves the first demonstration of the long speculating 3-D QHE, pushing the celebrated QHE from 2-D to 3-D.

"We can expect that the discovery of 3-D QHE will lead to new breakthroughs in our knowledge of physics and provide a cornucopia of new physical effects. This new knowledge, in one way or another, will also provide us new opportunities for practical technological development," said co-author, Assistant Professor Yang Shengyuan from SUTD.

More information: Fangdong Tang et al, Three-dimensional quantum Hall effect and metal-insulator transition in $ZrTe_5$, *Nature* (2019). DOI: 10.1038/s41586-019-1180-9

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