Discovery of quantum behavior in insulators suggests possible new particle

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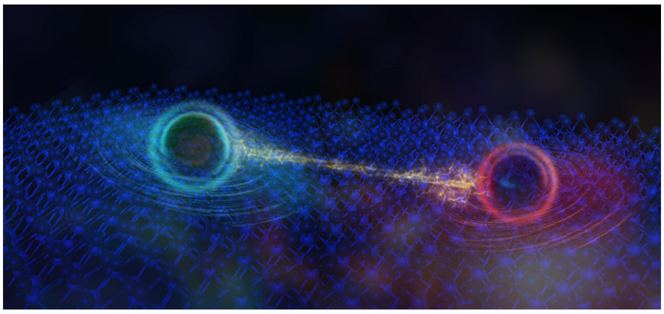

A team led by Princeton physicists discovered a surprising quantum phenomenon in an atomically thin insulator made of tungsten ditelluride. The results suggest the formation of completely new types of quantum phases previously hidden in insulators. Credit: Kai Fu for the Wu Lab, Princeton University

In a surprising discovery, Princeton physicists have observed an unexpected quantum behavior in an insulator made from a material called tungsten ditelluride. This phenomenon, known as quantum oscillation, is typically observed in metals rather than insulators, and its discovery offers new insights into our understanding of the quantum world. The findings also hint at the existence of an entirely new type of quantum particle.

The discovery challenges a long-held distinction between metals and insulators, because in the established quantum theory of materials, insulators were not thought to be able to experience quantum oscillations.

"If our interpretations are correct, we are seeing a fundamentally new form of quantum matter," said Sanfeng Wu, assistant professor of physics at Princeton University and the senior author of a recent paper in *Nature* detailing this new discovery. "We are now imagining a wholly new quantum world hidden in insulators. It's possible that we simply missed identifying them over the last several decades."

The observation of quantum oscillations has long been considered a hallmark of the difference between metals and insulators. In metals, electrons are highly mobile, and resistivity—the resistance to electrical conduction—is weak. Nearly a century ago, researchers observed that a magnetic field, coupled with very low temperatures, can cause electrons to shift from a "classical" state to a quantum state, causing oscillations in the metal's resistivity. In insulators, by contrast, electrons cannot move and the materials have very high resistivity, so quantum oscillations of this sort are not expected to occur, no matter the strength of magnetic field applied.

The discovery was made when the researchers were studying a material called tungsten ditelluride, which they made into a two-dimensional material. They prepared the material by using standard scotch tape to increasingly exfoliate, or "shave," the layers down to what is called a monolayer—a single atom-thin layer. Thick tungsten ditelluride behaves like a metal. But once it is converted to a monolayer, it becomes a very strong insulator.

"This material has a lot of special quantum properties," Wu said.

The researchers then set about measuring the resistivity of the monolayer tungsten ditelluride under magnetic fields. To their surprise, the resistivity of the insulator, despite being quite large, began to oscillate as the magnetic field was increased, indicating the shift into a quantum state. In effect, the material—a very strong insulator—was exhibiting the most remarkable quantum property of a metal.

"This came as a complete surprise," Wu said. "We asked ourselves, 'What's going on here?' We don't fully understand it yet."

Wu noted that there are no current theories to explain this phenomenon.

Nonetheless, Wu and his colleagues have put forward a provocative hypothesis—a form of quantum matter that is neutrally charged. "Because of very strong interactions, the electrons are organizing themselves to produce this new kind of quantum matter," Wu said.

But it is ultimately no longer the electrons that are oscillating, said Wu. Instead, the researchers believe that new particles, which they have dubbed "neutral fermions," are born out of these strongly interacting electrons and are responsible for creating this highly remarkable quantum effect.

Fermions are a category of quantum particles that include electrons. In quantum materials, charged fermions can be negatively charged electrons or positively charged "holes" that are responsible for the electrical conduction. Namely, if the material is an electrical insulator, these charged fermions can't move freely. However, particles that are neutral—that is, neither negatively nor positively charged—are theoretically possible to be present and mobile in an insulator.

"Our experimental results conflict with all existing theories based on charged fermions," said Pengjie Wang, co-first author on the paper and postdoctoral research associate, "but could be explained in the presence of charge-neutral fermions."

The Princeton team plans further investigation into the quantum properties of tungsten ditelluride. They are particularly interested in discovering whether their hypothesis—about the existence of a new quantum particle—is valid.

"This is only the starting point," Wu said. "If we're correct, future researchers will find other insulators with this surprising quantum property."

Despite the newness of the research and the tentative interpretation of the results, Wu speculated about how this phenomenon could be put to practical use.

"It's possible that neutral fermions could be used in the future for encoding information that would be useful in quantum computing," he said. "In the meantime, though, we're still in the very early stages of understanding quantum phenomena like this, so fundamental discoveries have to be made."

More information: Pengjie Wang et al, Landau quantization and highly mobile fermions in an insulator, *Nature* (2021). DOI: 10.1038/s41586-020-03084-9

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