Experiments in twisted, layered quantum materials offer new picture of how electrons behave

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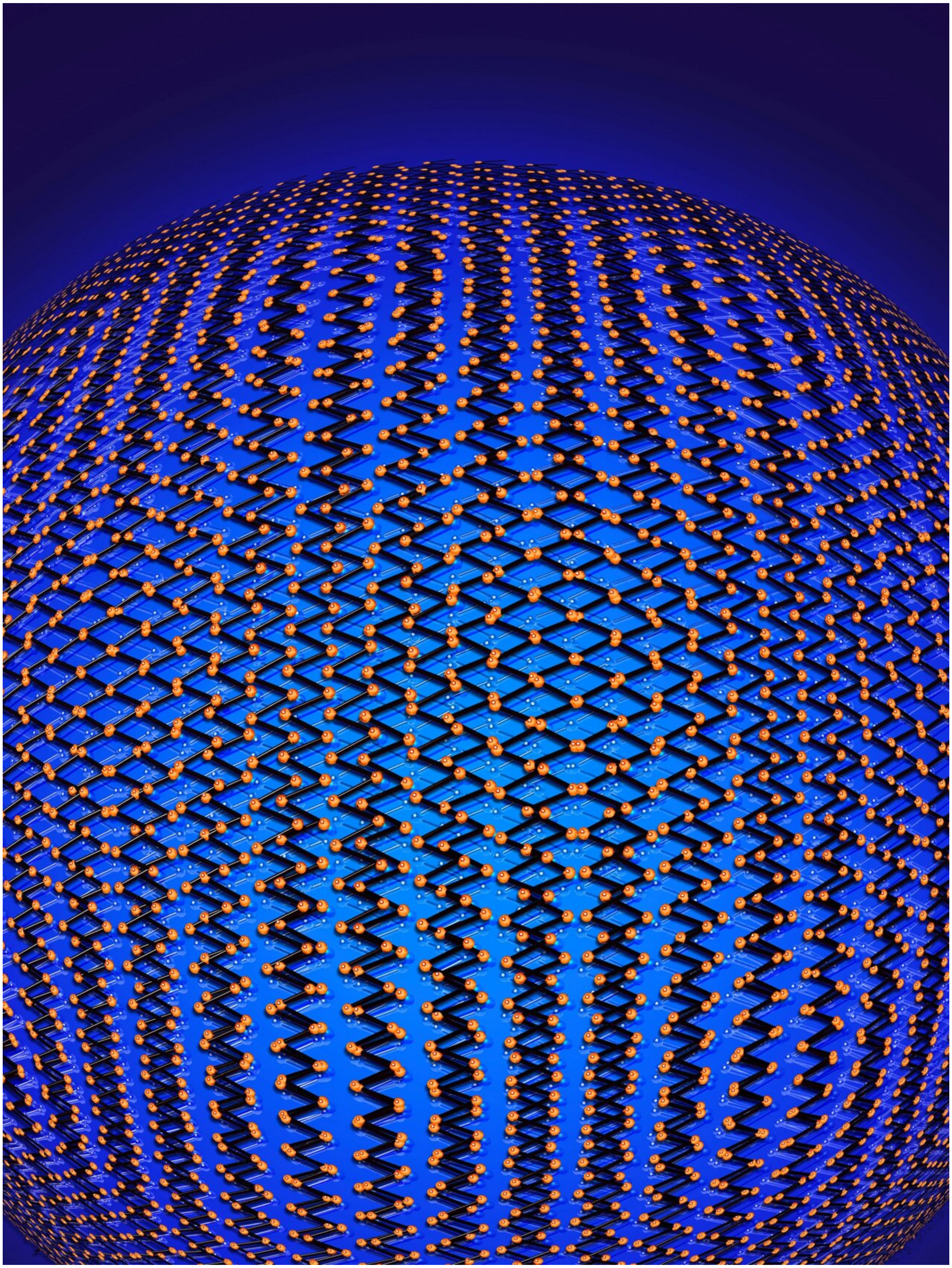


Artist's illustration of the pattern, known as moiré after the French fabric, which develops in the twisted, layered material created by the team. This pattern is key to producing the discovered unusual quantum electron behaviors. Credit: J.F. Podevin for Princeton University Department of Physics.

A recent experiment detailed in the journal *Nature* is challenging our picture of how electrons behave in quantum materials. Using stacked layers of a material called tungsten ditelluride, researchers have observed electrons in two-dimensions behaving as if they were in a single dimension—and in the process have created what the researchers assert is a new electronic state of matter.

"This is really a whole new horizon," said Sanfeng Wu, assistant professor of physics at Princeton University and the senior author of the paper. "We were able to create a new electronic phase with this experiment—basically, a new type of metallic state."

Our current understanding of the behavior of interacting electrons in metals can be described by a theory that works well with two- and three-dimensional systems, but breaks down when describing the interaction of electrons in a single dimension.

"This theory describes the majority of the metals that we know," said Wu. "It states that electrons in metal, though strongly interacting, should behave like free electrons, except that they may have different values in some characteristic quantities, such as the mass and magnetic moment."

In one-dimensional systems, however, this "Fermi liquid theory" gives way to another theory, "the Luttinger liquid theory," to describe the interaction between electrons.

"Luttinger liquid theory provides a basic starting point to understand interacting electrons in one dimension," said Wu. "Electrons in a one-dimensional lattice are so strongly correlated with one another that, in a sense, they begin not to act like free electrons."

The Fermi liquid theory was first put forward by the Nobel Prize winner L.D. Landau. Luttinger's theory went through a long process of refinement before it became widely accepted by physicists. A theoretical model was first proposed by Japanese Nobel Prize winner Shinichiro Tomonaga in the 1950s, said Wu, and was independently formulated by J.M. Luttinger later in 1963.

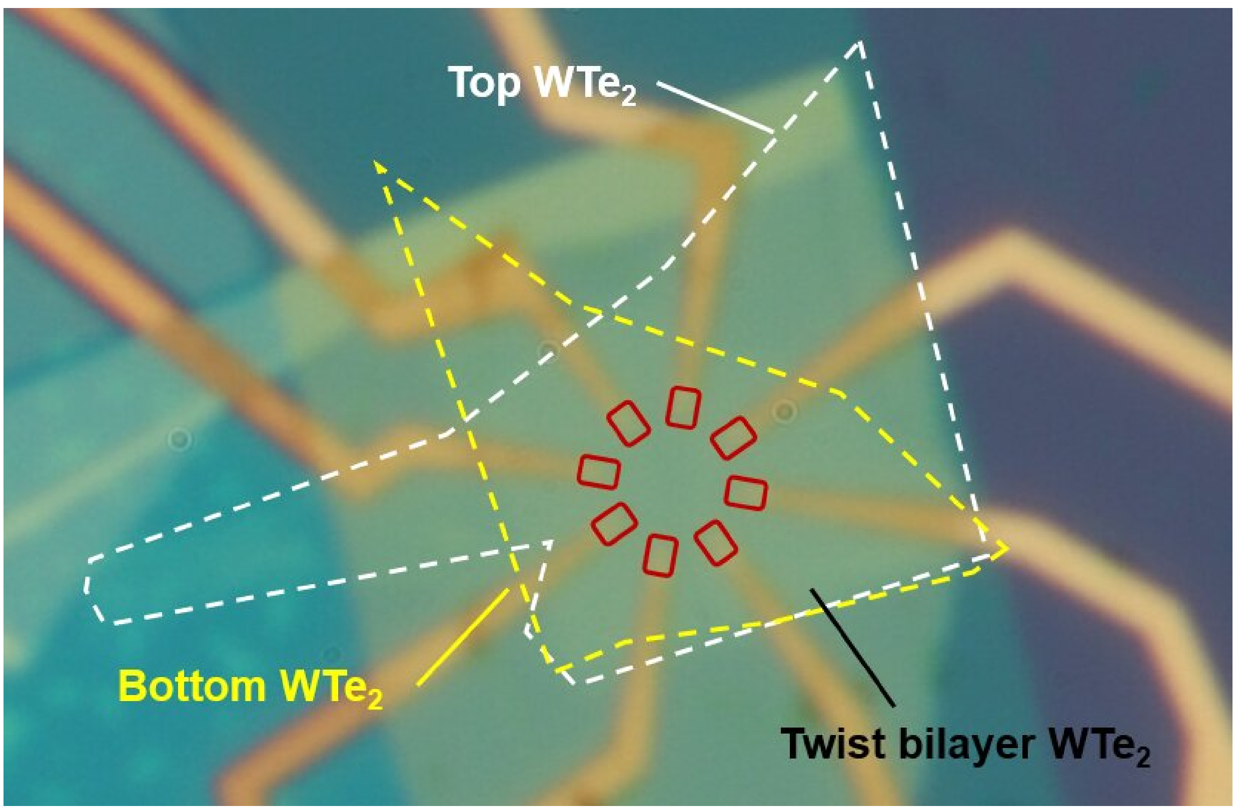
Luttinger, however, provided an inadequate solution and so Princeton mathematician and physicist Elliott Lieb, today the Eugene Higgins Professor of Physics, Emeritus, took up the challenge in 1965, eventually providing a correct solution. Another physicist and Nobel Prize laureate, F. Duncan Haldane, Princeton's Sherman Fairchild University Professor of Physics, then used the model in 1981 to understand the interaction effects of one-dimensional metals. Haldane coined the term "Luttinger liquids" and laid the foundation for the modern theory of Luttinger liquids as a general description for one-dimensional metals.

For a long time, these two theories—the Fermi liquid theory and the Luttinger liquid theory —have been central to our understanding of the behavior of electrons in condensed matter physics, according to their dimensionality.

But there have been hints that the interactions of electrons are much more complex than this simple classification. Philip Anderson, another Nobel Prize winner and Princeton physicist, proposed in the 1990s that there might be certain "exotic" cases in which the behavior of electrons in two-dimensional systems, on rare occasions, could also follow the predictions of Luttinger liquid theory. In other words, although the electrons in two-dimensional systems are typically explained by the Fermi liquid theory, Anderson wondered if those electrons counterintuitively could behave as a Luttinger liquid, as if they were in a one-dimensional system.

This was largely hypothetical. There were no experiments that could be connected to these exotic cases, Wu said.

Until now.



Researchers created a device made of tungsten (W) and telluride (Te) in two crystalline layers stacked on top one another and twisted in relation to each other by just a few degrees. The resulting twisted bilayer tungsten ditelluride exhibited strange and unexpected properties. Credit: Pengjie Wang

Through experimentation, Wu and his team discovered that electrons in a specially created two-dimensional material structure, when cooled to very low temperatures, suddenly began to behave as predicted by Luttinger liquid theory. In other words, they were acting like correlated electrons in a one-dimensional state.

The researchers carried out their experiment using a material called tungsten ditelluride (WTe_2), a layered semimetal. A semimetal is a compound that has intermediate properties that place it between metals and insulators. Princeton researchers Leslie Schoop, assistant professor of chemistry, and Robert Cava, the Russell Wellman Moore Professor of Chemistry, and their teams created tungsten ditelluride crystals of the highest quality. Wu's team then created single atomic layers of this material, and stacked two of them together vertically for the study.

"We stacked monolayers of tungsten ditelluride on top of one another and used an angle twist of either 5 or 6 degrees," said Pengjie Wang, co-first author of the paper and a postdoctoral research associate. This created a large rectangular lattice called a moiré pattern, which resembles a common French textile design.

The team had originally intended to observe how the twist angle would affect the other types of quantum phenomena in the tungsten ditelluride. But what they found astonished them.

"At first, we were confused by the results," Wang said. "But it turned out to be right."

The researchers observed that the electrons, instead of acting freely, began to congregate strongly into a linear array indicative of electrons in a one-dimensional system.

"What you have here is really a two-dimensional metallic state that is not described by the standard Fermi liquid theory," said Wu. "For the first time, we find a completely new electronic phase of matter in two dimensions described by the Luttinger liquid theory."

Guo Yu, co-first author on the paper and a graduate student in electrical and computer engineering, described the properties of the material as remarkably switchable between either uniform in all directions (isotropic) or varying strongly in physical properties when measured in different directions (anisotropic).

"What is unique for our twisted bilayer tungsten ditelluride system is that, unlike most of the other monolayer materials and their moiré superlattices which are isotropic, the moiré pattern in our sample is highly anisotropic, crucial to hosting the one-dimensional physics," Yu said.

A new metallic phase might sound like it would have numerous practical applications, but Wu cautioned that this is preliminary research. Before such applications can be realized, he said, additional work needs to be carried out.

Nonetheless Wu is optimistic about the future. "This might help open up a whole new window to look at novel quantum phases of matter," he said. "In the coming years, we will see a lot of new findings coming out of this research."

More information: Pengjie Wang et al, One-dimensional Luttinger liquids in a two-dimensional moiré lattice, *Nature* (2022). DOI: 10.1038/s41586-022-04514-6

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