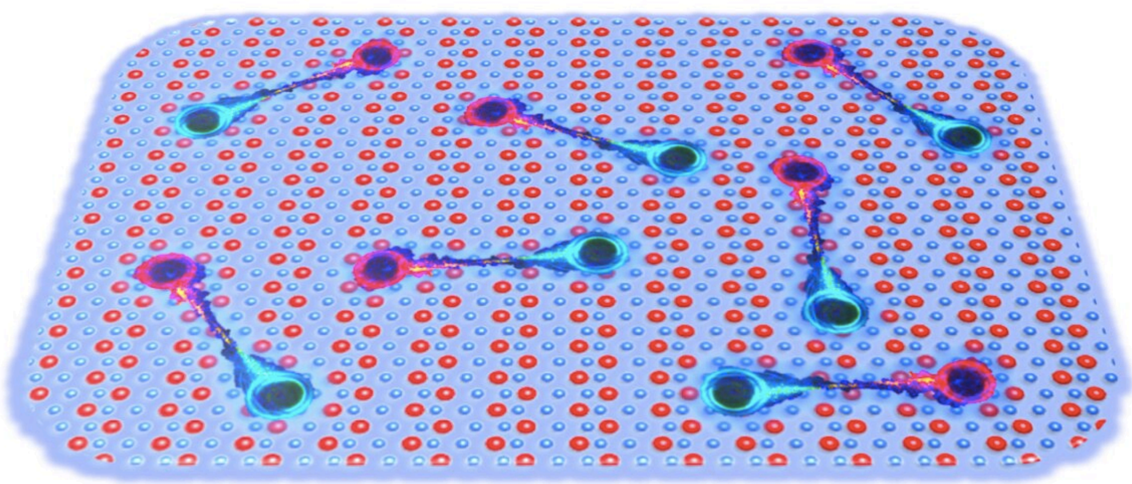
Study shows that monolayer tungsten ditelluride is an excitonic insulator

January 19 2022, by Ingrid Fadelli



Cartoon illustration of the excitonic insulator formed in the single atomic layer of tungsten ditelluride. The excitons are charge neutral composite particles like the hydrogen atoms, hidden in the two-dimensional electrical insulator. Credit: Wu Lab, Princeton University.

Tungsten ditelluride (WTe_2) is a transition metal dichalcogenide with numerous advantageous properties and characteristics, which makes it an ideal material for a wide range of electronic applications. Past studies have established that 2D WTe_2 crystals arranged in a single layer form the first monolayer topological insulator, exhibiting topological properties that survive up to very high temperatures (~100 K).

Over the past few years, physicists have been able to understand the origin of the material's topology fairly well. Nonetheless, the reasons why WTe_2 monolayer behaves as an insulator (i.e., electrons cannot move freely in the material) remain unclear. Theoretical predictions and calculations suggest that the material should in principle be a semimetal, in which electrons and holes coexist and move freely.

Researchers at Princeton University have recently carried out a study investigating the electronic properties of monolayer WTe_2, with the hope of better understanding the reasons why it acts as an insulator. Their paper, published in *Nature Physics*, provides strong evidence that the material is an excitonic insulator, arising from the spontaneous formation of electron-hole bound states known as 'excitons.'

"The initial purpose of our work was to understand the quantum properties of the very novel 2D material monolayer WTe_2," Sanfeng Wu, one of the researchers who carried out the study, told Phys.org. "Over the years, various ways to explain the origin of the insulator state were inconsistently discussed in the literature. Our work performed a systematic study to address this puzzle and found strong evidence that this 2D insulator is an excitonic insulator, a long-sought-after quantum state of electronic matter in solids."

The existence of excitonic insulators was first predicted in 1960s. At the time, physicists suggested that in small-gap semiconductors or semimetals, electrons and holes can sometimes combine to form composite particles (i.e., excitons). This process should in turn lead to a strongly insulating phase, which would differ considerably from standard electrical insulators.

"Excitons are charge neutral particles, like hydrogen atoms," Wu explained. "The concept of excitons is not new in semiconductor physics, for instance, excitons play key roles in optical excitations and emissions of semiconductors. However, the optically excited excitons in a semiconductor are very short lived as they must decay, say by emitting light, within nanoseconds. In contrast, in an excitonic insulator, the excitons do not emit light and do not decay."

In excitonic insulators, excitons are hidden in the insulator state, which makes them difficult to detect experimentally. As a result, conclusively demonstrating the existence of excitonic insulator states has so far proved to be incredibly challenging.

To show that WTe_2 monolayer is an excitonic insulator, Wu and his colleagues first tried to rule out all other known possible explanations for its insulating behavior. This included the possibility of a disorder-induced insulating phase and a trivial insulator with a band gap resembling that of typical semiconductors.

"This is a very important step but typically very difficult to do for 3D candidate materials," Wu said. "We examined the role of disorders by comparing samples with different impurity levels and found that cleaner samples host stronger insulating states, uncovering that the insulating state is an intrinsic property of the monolayer in the clean limit, rather than induced by disorders."

In their experiments, the researchers also ruled out the possibility that monolayer WTe_2 is a band insulator. To do this, they examined a 2D WTe_2 crystal using electron tunneling spectroscopy, a renowned and powerful technique for distinguishing correlated insulating states from trivial band insulators.

"We concluded that the monolayer insulating state develops due to intrinsic electronic correlations," Wu said. "Combining this with the fact that the state appears exactly at charge neutrality, meaning that the number of electrons and holes are exactly equal, it became obvious that the monolayer insulator is an excitonic insulator."

Interestingly, Wu and his colleagues also found that the monolayer WTe_2 sample they examined exhibited unusual transport behaviors that are consistent with those that would be expected in an excitonic insulator. Subsequently, they developed a theoretical model that considers electron-hole correlations, further supporting the formation of an excitonic insulator phase.

"We gathered two notable findings that may have broad implications," Wu said. "Firstly, our study adds a significant new aspect to the understanding of a 2D topological material that shows many other unusual quantum properties as well. This finding revises our understanding of quantum physics, where topology and electron correlations are both important. It could eventually lead to new discoveries, especially in this novel class of materials."

The recent study conducted by this team of researchers shows that monolayer WTe_2 is a very promising 2D excitonic insulator candidate. In the future, it could inform further studies examining monolayer WTe_2 or other materials with similar structures, to explore the possibility of uncovering more excitonic insulating materials.

"Our work provides valuable opportunities to experimentally tackle the 6-decade old problem of excitonic insulators," Wu said. "Our findings are already inspiring new ideas to directly detect the hidden excitons using approaches that are impossible for previous candidate materials."

The results gathered by Wu and his colleagues open new fascinating opportunities for the development of new experimental techniques for detecting neutral quantum phases hidden in insulators. This could improve the current understanding of electrical insulators, and more importantly, lead to the discovery of new types of electrical insulators beyond the standard ones.

"Our work identifies monolayer WTe_2 as a unique and unprecedented platform for the future studies of not only excitonic insulating state but also other possible new quantum phases such as excitonic superconductivity, especially since monolayer WTe_2 can be electrostatically tuned from the excitonic insulator state to a superconductor state," Yanyu Jia, a graduate student and lead author of the paper, told Phys.org. "Revealing the underlying relations between the two phases will be interesting and for sure deepen our understanding of quantum phenomena in materials."

In their next studies, Wu, Jia and their colleagues will try to devise alternative experimental procedures that would allow them to detect ground-state excitons directly and even more conclusively. In addition, they would like to conduct further research focusing on any possible new quantum phases that could characterize excitonic insulators.

"One key factor here is that we are not dealing with single excitons; instead, the exciton density here is ~ 10^{12} cm^{-2}," Wu added. "Just like with many atoms together, we can have different phases of matter, we expect these many excitons to form interesting new electronic phases of various kinds. So, there should be a rich quantum world hidden in such electrical insulators and we hope to uncover them."

More information: Yanyu Jia et al, Evidence for a monolayer excitonic insulator, *Nature Physics* (2021). DOI: 10.1038/s41567-021-01422-w