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The first-time direct observation of exotic charge-neutral quasiparticles in twisted tungsten diselenide

Researchers at UC Santa Barbara have for the first time observed Goldstone modes — elusive, charge-neutral quasiparticles — in a twisted tungsten diselenide superlattice. Using an ultrafast imaging technique, the researchers were able to directly capture these collective excitation, which are associated with quantum phenomena such as superconductivity and other collective quantum behaviors.

"We go beyond traditional measurement with optics, which allows us to really take a movie and get more information," said Richen Xiong, a researcher in the lab of UCSB condensed matter physicist Chenhao Jin, and lead author of a paper that appears in the journal Nature Physics.

The research is supported largely by the U.S. Department of Energy and the National Science Foundation.

Moiré magic

The field of condensed matter physics — a branch that studies the liquid and solid states of matter — took a great step forward when it was found that atom-thick sheets of material could be probed for their interesting properties. These 2D lattices could then be layered atop other 2D lattices, their atoms’ electrons interacting with each other for even more interesting behaviors. These stacked lattices can be layered slightly offset from one another in a moiré pattern, which leads to new interactions as well.

For this study the researchers used a superlattice of tungsten diselenide (WSe_2), a material from the family of transition metal dichalcogenides known for their electronic properties, twisted at intermediate (3.5° - 4°) and large (5°) angles from each other.

“Among the most intriguing consequences of interacting electrons are the emergence of new collective excitations that are qualitatively different free electrons, which lead to exotic material properties beyond simple metal,” Jin said. “However, the often charge-neutral nature of these quasiparticles makes them more challenging to investigate than charge-carrying particles, as their motion does not lead to a charge current – the primary observable for many conventional methods such as scanning tunnelling microscopy and electrical measurements.”

As a result, the team turned to light.

“What we’re doing is using optics to probe the space-and-time-resolved properties of the material,” Xiong said, explaining that they pumped light into the system first to excite it and create the quasiparticles, and then capture their space-time evolution using a separate probe light, in a process akin to shooting a movie with very fast camera. “Our method is different from the traditional method in that we want to approach these things from a dynamical view,” he added.

What they were able to capture were phenomena that had yet to be directly observed in condensed matter systems. They tracked down an intervalley coherent state (IVC), a state in which the electrons in different low-energy pockets (“valleys”) in the material superimpose and act in sync. A Goldstone mode corresponds to a change in the phase of such coherence, which does not involve charge motion but can support fast and dissipationless transport of valley polarization. That is, according to Jin, the imbalance between different energy pockets can flow without resistance.

The researchers record a movie of such spin-valley transport, which is analogous to the supercurrent in a spin-valley superfluid. Interestingly, the system can be a charge insulator at the same time, where electrons themselves cannot move at all.

The researchers' method sets the stage for more dynamical studies of exotic collective modes in condensed matter.

"Our idea is to use this dynamic view to directly study excitations in these exotic phases," Xiong said. Because excitations govern the responses of a quantum system to perturbations, this knowledge would help the researchers understand the atoms' collective behaviors, which would in turn help the scientists control the material better and with less energy.

Research in this paper was also conducted by Yi Guo, Chenxin Qin, Fanzhao Yin, Samuel L. Brantley, Youngjoon Choi, Junhang Qi, Jinfei Zhou, Zihan Zhang and Andrea F. Young at UCSB; Taige Wang at UC Berkeley; Melike Erdi and Seth Ariel Tongay at Arizona State University; Liang Fu at MIT; Kenji Watanabe and Takashi Taniguchi at the National Institute for Materials Science in Japan; and Shu Zhang at the Okinawa Institute of Science and Technology Graduate University in Japan.

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