Researchers observe two-fold symmetric superconductivity in 2D niobium diselenide

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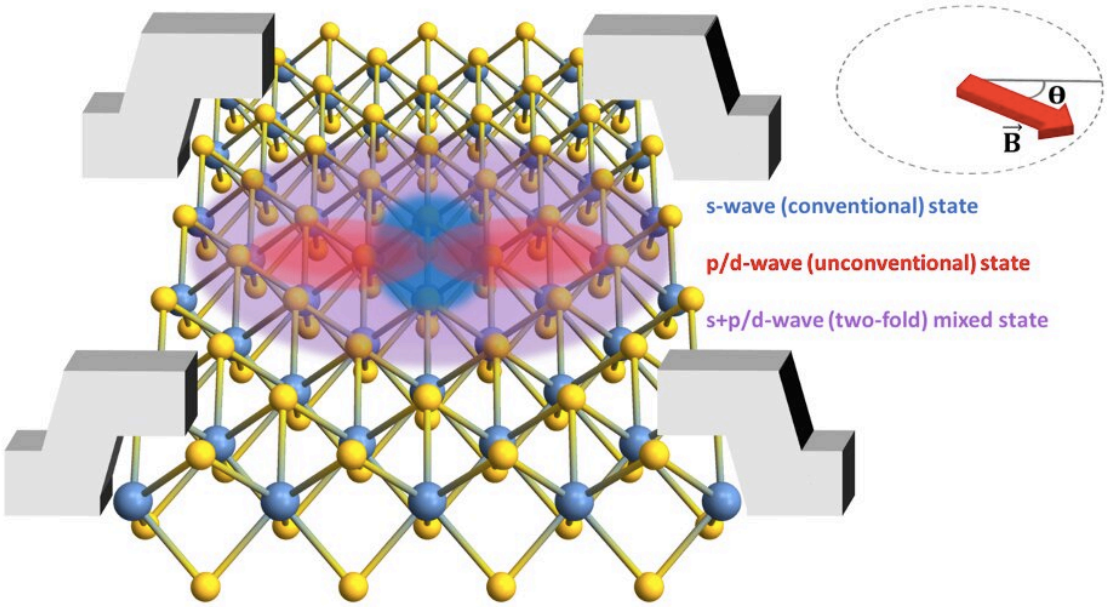

Scientists have detected, through electron transport and tunneling measurements (gray contacts), a mixed conventional/unconventional superconducting state in sheets of NbSe2 a few atoms thick (blue and yellow circles). NbSe2 is a two-dimensional material that has garnered much attention for exploring new superconducting states due to the strong spin-orbit coupling from its heavy transition metal atoms. By applying in-plane magnetic fields (red arrow) up to 35T at various angles θ, a two-fold symmetric (purple ellipse) signal in the resistance and tunneling conductance is found in the superconducting regime. This observed symmetry, which occurs despite the lack of a two-fold structure in the material, suggests nontrivial interactions leading to the measured signals. This

observation is attributed to the mixing of the conventional isotropic (s-wave, blue circle) superconducting gap with an unconventional anisotropic (p- or d-wave, red lobes) superconducting gap. This unexpected finding paves the way for further investigations on how this two-fold behavior may arise, as well as informing future studies on mixed and unconventional superconductivity in two-dimensional materials. Credit: Hamill et al.

In recent years, many material scientists worldwide have been investigating the potential of two-dimensional (2D) materials, which are composed of a single layer or a few ultrathin layers of atoms and have unique physical, electrical and optical properties.

Researchers at University of Minnesota and Cornell University recently carried out a study investigating the superconductivity of few-layer niobium diselenide ($NbSe_2$), a layered transition metal that exhibits a unique intrinsic Ising-type spin-orbit coupling. Their paper, published in *Nature Physics*, shows that the superconducting state of few-layer $NbSe_2$ has a two-fold symmetry, which differs greatly from the structure of its crystals.

"There is tremendous interest in two-dimensional materials, such as $NbSe_2$, because when they are prepared to be only a few atomic layers thick, they often have new properties, that are not present in thick samples of the same material," Vlad S. Pribiag, one of the researchers who carried out the study, told Phys.org. "For example, $NbSe_2$ is a superconductor in its bulk form, but when few-layer samples are prepared, the crystal symmetry changes, making the superconductivity much more resilient to applied magnetic fields. This was discovered by some the co-authors a few years ago and served as one impetus for our work."

In the past, researchers predicted that $NbSe_2$ could be a topological superconductor. Topological superconductors are a unique class of superconductors with non-trivial topological properties. These unique superconductors have attracted significant interest, as they may prevent quantum bits from losing the information they store; thus, they could enable the creation of new quantum computers that are topologically protected.

The recent work by Pribiag and his colleagues draws inspiration from previous studies exploring the possibility that $NbSe_2$ is a topological superconductor. In their experiments, the researchers specifically probed the topological superconductivity of $NbSe_2$ that is only a few atomic layers thick.

"We found that the superconducting state of few layer $NbSe_2$ has a two-fold symmetry, which is strikingly distinct from the three-fold symmetry of the crystal (i.e., the crystal looks the same if rotated by 120 degrees, but the superconducting state properties repeat when rotating by 180 degrees)," Pribiag explained. "This two-fold symmetry is consistent with the presence of two competing superconducting states that are very close in energy: one of these could be related to topological superconductivity—and we are now working on follow-up experiments that aim to determine this."

In their experiments, Pribiag and his colleagues found that anisotropy (i.e., a property that allows materials to change its physical characteristics when measured along crystal axes in different directions) appeared as they rotated a magnetic field on their sample's plane. The researchers investigated this observation further using two different types of samples.

In one type of sample, they measured the critical field (i.e., the field at which superconductivity disappears). The second type of sample, studied

by the team at Cornell University, had a thin insulating layer between the $NbSe_2$ and a magnetic material, which allowed them to tunnel into the $NbSe_2$. The two sets of measurements they collected both showed a two-fold anisotropy.

"Atoms in $NbSe_2$ are aligned in a periodical triangular pattern and therefore, the physics properties within are expected to exhibit a three-fold rotational symmetry (i.e, rotating the system or environment around it by 120 degree should result in physical properties indistinguishable to that before the rotation)," Ke Wang, another researcher involved in the study, told Phys.org. "However, we instead observed a two-fold rotational symmetry of the superconducting state in few-layer $NbSe_2$ under in-plane external magnetic fields, in contrast to the three-fold symmetry of the lattice."

According to the Bardeen-Cooper-Schrieffer theory (BCS), a well-established physics theory that explains superconductivity, two electrons can pair with each other to form a so-called Bosonic pair (i.e., Cooper pair). These pairs then contribute to the formation of a dissipation-less electron superfluid, which leads to superconductivity.

In thick-layered, three-dimensional (3D) $NbSe_2$, the pairing mechanisms outlined by BCS theory exhibits a conventional s-wave instability. On the other hand, when $NbSe_2$ approaches 2D limits, an unconventional pairing mechanism involving d- or p-wave electrons can occur in the presence of strong spin-orbit coupling.

"In our few-layer samples which bridge the 2D and 3D limits, the above two pairing instabilities mix and compete with each other, and lead to the 2-fold symmetric superconductivity we observed," Wang explained.

Pribiag, Wang and their colleagues were the first to gather clear evidence of the unconventional pairing mechanism that occurs in 2D

$NbSe_2$ with a few layers of atoms. In addition to broadening the current understanding of 2D $NbSe_2$ and its properties, the findings they collected raise fundamental questions about the origin of the unusual pairing interactions they observed.

"Our future research will focus on answering many fundamental questions about the exotic paring mechanisms that led to our recent discovery," Wang said. "For instance, is the 2-fold anisotropy the result of spontaneous nematic superconductivity, or strong gap-mixing triggered by a small symmetry-breaking field, such as strain? Does topological superconductivity play a role? Guided by our theory collaborators, we will investigate samples with varying thickness and atomic strain that will give us control over the competition between the different order parameters."

More information: Two-fold symmetric superconductivity in few-layer NbSe2. *Nature Physics*(2021). DOI: 10.1038/s41567-021-01219-x.