An unusual superconductor

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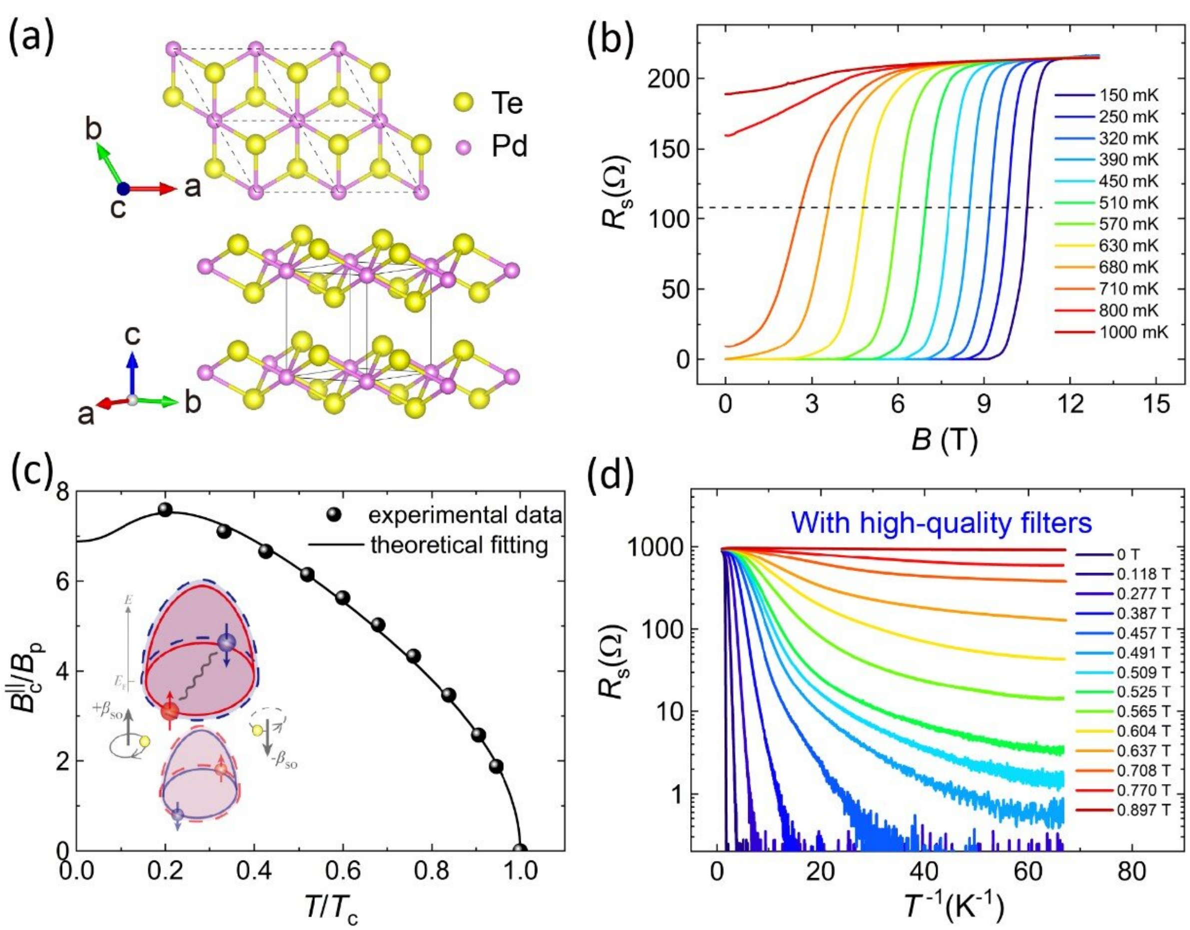

(a) The lattice structure of $PdTe_2$, indicating that it is a centrosymmetric system. (b) The in-plane magnetic field dependent sheet resistance at different temperatures for 6-ML $PdTe_2$ film. (c) The temperature dependence of in-plane critical fields (the black spheres) of 6-ML $PdTe_2$ film, which is consistent with the theoretical formula of Ising superconductivity (the solid black lines). Inset: the schematic of type-II Ising pairing. (d) The lgRS-1/T curves of 4-ML PdTe2 film at different magnetic fields. The resistance drops and then saturates with decreasing temperature, which is the hallmark of anomalous metallic states. High quality filters are used in the measurements to well exclude the influence of high-frequency noise. Credit: This figure is adapted from: https://doi.org/10.1021/acs.nanolett.0c01356

Professor Wang Jian at Peking University and collaborators investigated the superconducting properties of two-dimensional crystalline superconducting $PdTe_2$ films grown by molecular beam epitaxy. They observed the experimental evidence of anomalous metallic state and detected type-II Ising superconductivity existing in centrosymmetric systems. Moreover, the superconductivity of $PdTe_2$ films remains almost the same for more than 20 months without any protection layer. This macro-size ambient-stable superconducting system with strong spin-orbit coupling shows great potentials in superconducting electronic and spintronic applications. The paper was published online in *Nano Letters* and selected for the Editors' Choice of *Science* with a title of "An unusual superconductor" (*Science* 369, 388 2020).

The magnetic field is normally believed to hinder the formation of superconductivity. For most superconducting systems, strong magnetic field can break the superconducting Cooper pairs and destroy the superconductivity. Recently, a new kind of two-dimensional (2-D) superconducting system survives under a large in-plane magnetic field, called Ising superconductors. Previous works suggest that the Ising superconductor requires in-plane inversion symmetry breaking. The broken in-plane inversion symmetry gives rise to Zeeman-type spin-orbit coupling (SOC), which polarizes the electron spins to the out-of-plane direction and leads to a huge in-plane critical magnetic field up to several times of the Pauli limit, normally corresponding to dozens of Tesla. The Pauli limit is defined as the magnetic field required to destroy the Cooper pairs via the spin pair breaking effect in conventional superconductors. Professor Wang Jian and collaborators ever reported the observation of Ising superconductivity in macro-size monolayer $NbSe_2$ films grown by molecular beam epitaxy (MBE) and the interface induced Ising superconductivity in ultrathin crystalline Pb films for the first time.

Recently, Professor Wang Jian and Professor Lin Xi at Peking University, in collaboration with Professor Xue Qikun, Professor Wang Lili, Professor Xu Yong, Professor Yao Hong at Tsinghua University, Professor Liu Haiwen at Beijing Normal University detected a new kind of Ising superconductivity in 2-D crystalline $PdTe_2$ films grown by MBE. The 6-monolayer (ML) (around 3 nm) $PdTe_2$ film exhibits a large in-plane critical field more than 7 times of the Pauli limit, which is the characteristic of Ising superconductivity. Different from the previously reported Ising superconductors, the $PdTe_2$ film keeps the in-plane inversion symmetry, which indicates that there exists a new mechanism of Ising superconductivity (named type-II Ising superconductivity by Professor Wang Jian in discussion with Professor Xu Yong).

Band structure calculation and theoretical analysis reveal that the 3-fold rotational symmetry in the $PdTe_2$ films makes the effective field of SOC along the out-of-plane direction and leads to the out-of-plane spin polarization. The superconducting Cooper pairs formed by the electrons with out-of-plane spin polarization can survive under very large magnetic field parallel to the 2-D system, which gives rise to the type-II Ising superconductivity with large in-plane critical field. Theoretical calculations indicate that for 2-D superconducting systems with in-plane inversion symmetry, 4 and 6-fold rotational symmetry can also make the orientation of the effective SOC field along out-of-plane direction. Thus, the type-II Ising superconductivity can be generalized to various 2-D systems with 3, 4 and 6-fold rotational symmetry. Therefore, the discovery of type-II Ising superconductivity is promising to stimulate a new research direction in condensed matter physics.

Interestingly, under perpendicular magnetic field, the sheet resistance of $PdTe_2$ films drops and then saturates to a temperature-independent constant with decreasing temperature via ultralow temperature transport measurements with high-quality filters. It is the first solid experimental evidence of anomalous metallic states in high-quality 2-D crystalline films grown by MBE, which further reveals that besides superconducting and insulating ground states, anomalous metallic state is another quantum ground state for 2-D Bosonic systems.

Moreover, most 2-D superconducting systems are very sensitive to the atmosphere and easy to lose superconductivity. The superconductivity of $PdTe_2$ films remains almost the same for more than 20 months without any protection layer. This macro-size ambient-stable superconducting system with strong SOC shows great potentials in superconducting electronic and spintronic applications.

More information: Yi Liu et al, Type-II Ising Superconductivity and Anomalous Metallic State in Macro-Size Ambient-Stable Ultrathin Crystalline Films, *Nano Letters* (2020). DOI: 10.1021/acs.nanolett.0c01356

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