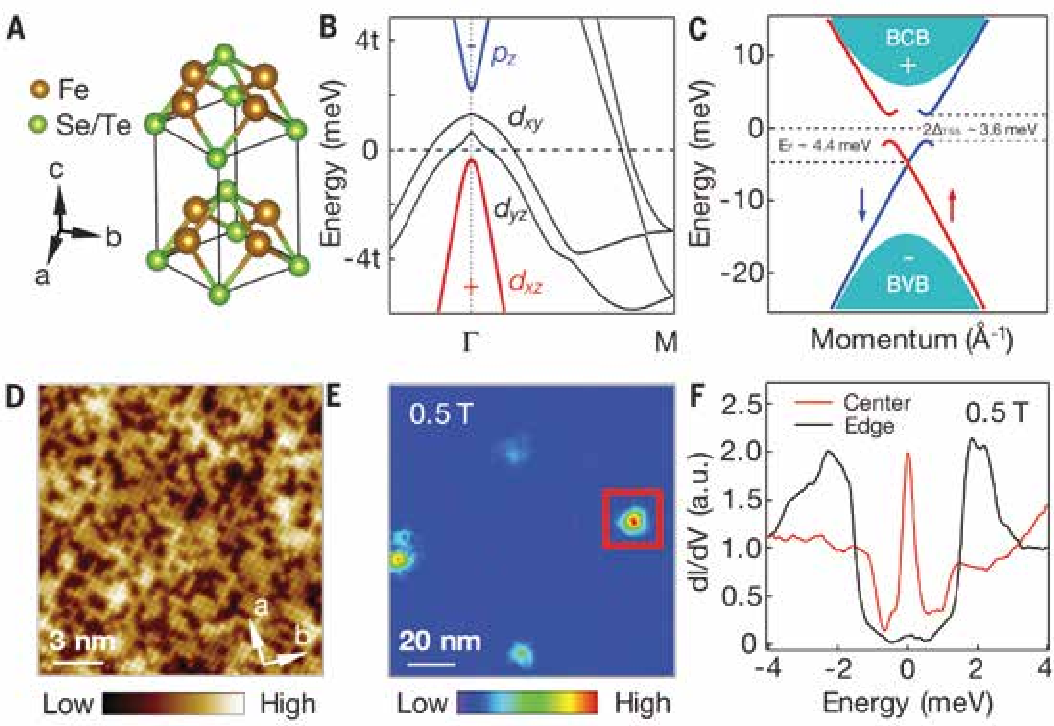
Discovery of Majorana Bound State in Fe-based Superconductor

In 1937, Italian theoretical physicist Ettore Majorana published a paper, in which he made a brilliant discovery by decomposing Dirac equation into the real and imaginary parts. That is the famous equation describing the motion of a Majorana fermion whose antiparticle is itself. Over the past 81 years, the search of Majorana fermion has been one of the most attractive research topics in physics. In high-energy physics, neutrinos have been proposed as Majorana fermions, and a definite experimental evidence will be one of the biggest discoveries since the discovery of Higgs boson.

In the past twenty years, there were plenty of exciting theoretical proposals and experimental discoveries in condensed matter physics. If one can regard the elementary particles as specific excitations of the quantum ground state of the universe, then quasiparticles in a solid material obeying the same motion equation can be regarded as the duality of elementary particle in a high-order field (the space group of crystal). Searching for exotic fermion excitations in solid state has been a focused topic during the last few years. Beside those dualities of elementary particles, *i.e.* Dirac fermion (Na_3Bi), Weyl fermion (TaAs), condensed matter physicists discovered more exotic excitations which are protected by the crystal symmetry that is higher than the symmetry of universe, *i.e.*, hourglass fermion (KHgSb), three-component fermion (MoP). Nowadays, despite extensive knowledge accumulated on the fermionic excitations in solid state, the appearance of Majorana fermion or bound state in topological superconductors



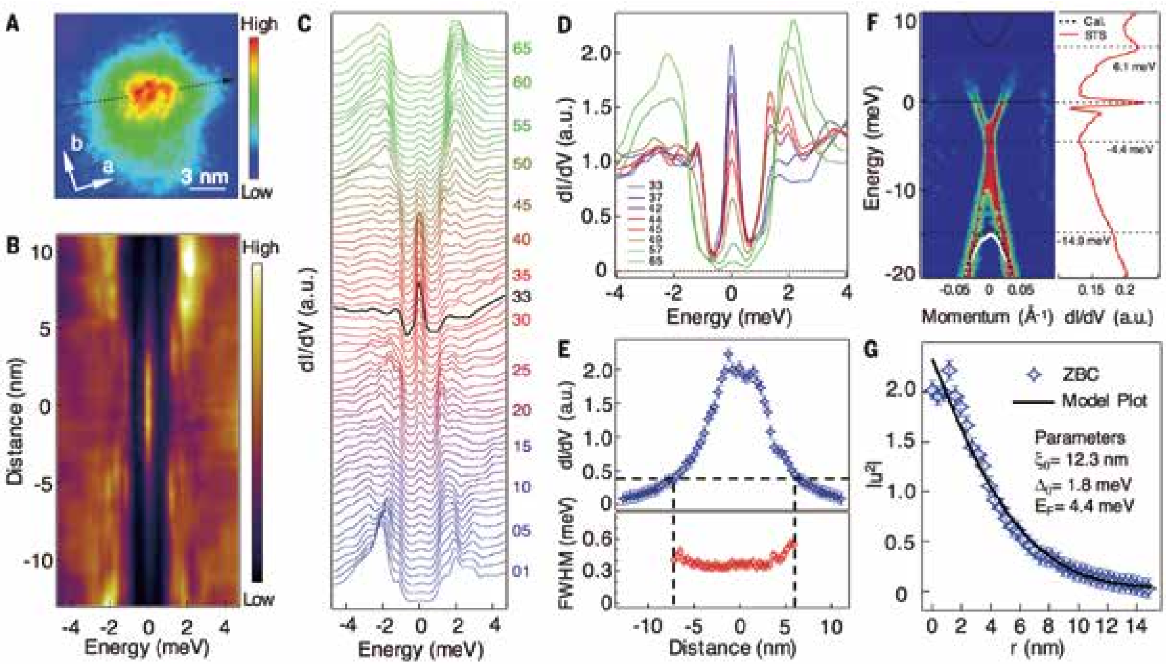
Band structure and vortex cores of $FeTe_{0.55}Se_{0.45}$ (Image by courtesy of GAO Hongjun & DING Hong's groups) has not been settled conclusively.

A Majorana fermion is charge neutrality due to the self-conjugation of Majorana operator. It inspired condensed matter physicist to compose Majorana quasiparticles in a topological superconductor, as the Bogoliubov excitation is a mixture of particle and hole components. In the early 2000s, theorists made an initial prediction, that the chiral p-wave superconductor without time-reversal symmetry can harbor Majorana excitations, both the Majorana bound states (0D) inside the half-flux vortex core and the Majorana chiral modes (1D) propagating along the edges of a superconductor. What is more interesting is that Majorana bound states obey the non-Abelian statistics. It has been proved that Majorana bound states can stay at different degenerate ground states by braiding operations. This is the building block of topological quantum qubit and a promising method realizing topological quantum computing.

However, a p-wave superconductor is rare and extremely sensitive to disorders. It leads to huge difficulties in experimental realization of Majorana fermion. A breakthrough occurred in 2008 when theoretical physicist Liang Fu and Charles L. Kane from University of Pennsylvania proposed a new mechanism based on superconductivity of topological surface state induced by the proximity effect of an ordinary s-wave superconductor. They found Majorana bound state should exist inside the vortex core. This proposal eliminates the difficulties of a p-wave superconductor and creates huge enthusiasm of condensed matter community to study related routes of creating detectable Majorana fermions. Later on, several evidences on Majorana quasiparticles were published on different platforms, *i.e.*, semiconducting nanowire based heterostructure (Delft/Copenhagen), magnetic atomic chain based heterostructure (Princeton), and topological insulator thin films based heterostructure (Shanghai Jiao Tong). However, all those platforms suffer the problem of complex interface.

Moreover, their ultra-low critical temperature and very small superconducting gap led to more troubles. The signals of the zero-bias peak (evidence of a Majorana bound state) were always mixed by trivial states that located very near the zero energy as well. It weakens the reliability of experimental evidences and limits potential applications in the future. If one can make a combination of band topological property, intrinsic high temperature superconductivity and strong electron correlations into a single material, the next breakthrough may occur in this field.

In 2015, an ARPES group at the Institute of Physics (IOP), led by Prof. DING Hong, obtained initial evidence of a Dirac-cone-like surface state in a highly correlated Fe-based superconductor $FeTe_{0.55}Se_{0.45}$ (P. Zhang *et al.*,

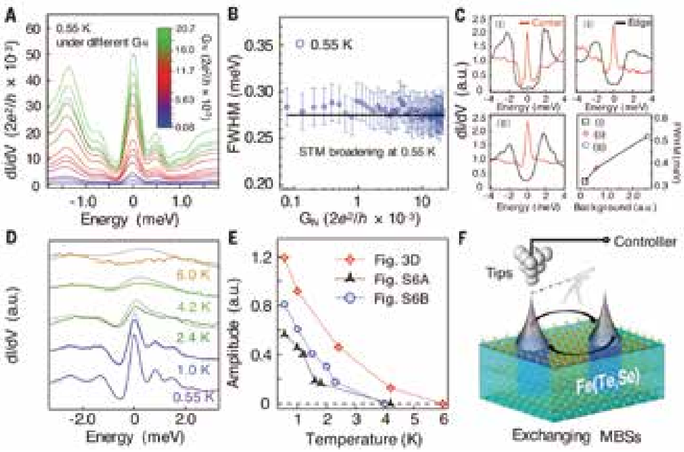


Energetic and spatial profile of ZBPs (Image by courtesy of GAO Hongjun & DING Hong's groups)

APL 105, 172601 (2014)) They then collaborated with a first-principle group at IOP, led by Profs. FANG Zhong and DAI Xi, and proved theoretically and experimentally that there is a topological nontrivial band inversion in this material upon Te substitution (Z.-J. Wang *et al*., *Phys. Rev. B* 92, 115119 (2015)). At the same time, another theoretical group of IOP, led by Prof. HU Jiangping, found that Fe(Te,Se) monolayer film may also have the similar topological band inversion by Te substitution (X.-X. Wu *et al*., *Phys. Rev. B* 93, 115129 (2016)). This prediction was later verified by DING Hong's group (X. Shi *et al., Sci. Bull*. 62, 503 (2017)). In 2016 a theoretical group at Stanford University, led by Prof. Shoucheng Zhang, made a theoretical prediction that a Majorana bound state (MBS) may exist inside a vortex core of $FeTe_{0.5}Se_{0.5}$ under a suitable condition. In 2017, DING Hong's group collaborated with Prof. Shik Shin's group in Tokyo University, and performed ultra-high resolution ARPES experiments on $FeTe_{0.55}Se_{0.45}$, and for the first time they clearly observed a superconducting topological surface state (P. Zhang *et al*., *Science* 360, 182 (2018)). It was found the Fermi energy (EF) is comparable to the superconducting gap (Δ) of the surface state. That proved the combination mentioned above does occur in $FeTe_{0.55}Se_{0.45}$, and one would naturally expect an MBS inside a vortex core of $FeTe_{0.55}Se_{0.45}$ can be free from contamination of other trivial bound states.

Since April 2017, Prof. DING Hong has made a close collaboration with Prof. GAO Hongjun at IOP. They guided PhD students WANG Dongfei, KONG Lingyuan, FAN Peng, ZHU Shiyu and other students at IOP to perform measurements of vortex core of $FeTe_{0.55}Se_{0.45}$ single crystals. During the last year, they measured many samples and carried out He-3 low temperature measurements for more than 100 times using two low-temperature STMs developed at GAO's lab. They successfully obtained repeatable observations of a strong zero-bias peak inside a vortex core of $FeTe_{0.55}Se_{0.45}$, regarded as a hallmark of an MBS.

The experiments were benefitted very much by the excellent facilities and rich experiences of measurement of GAO's group. Team members dedicate themselves to the experiments. In the first 6 months of the experiment, the team worked nearly 24 hours a day and 7 days a week. Some major members of the team even worked continuously for over 30 hours. ZHU Shiyu, WANG Dongfei, FAN Peng, and others even sacrificed their Chinese New Year holidays to continue the experiments.



Temperature and tunneling barrier evolution of ZBPs. (Image by courtesy of GAO Hongjun & DING Hong's groups)

It would not have been possible without all of these to get a large amount of data in a short time.

There are several advantages in the new discovery as comparing with previous observations. They clearly observed the spatial non-split feature of an MBS with its width being nearly energy resolution limited. The MBS is robust against changing tunneling barriers, and it can be observed across a large range of magnetic fields. Comparing to theoretical models, they concluded that the MBS observed come from the quasiparticles of the superconducting topological surface state, while the temperature behavior indicates the bulk thermal quasiparticles could poison the MBS.

All the evidence has led to the conclusion that the observed MBS is largely pure and free of mixing with other trivial bound states. This marks the first clear observation of a pure Majorana bound state. The relatively high temperature indicates that the Majorana bound states can be realized under the He-4 temperature.

This work is published in *Science* on August 16, 2018. The co-first authors are WANG Dongfei, KONG Lingyuan and FAN Pen. The co-corresponding authors are Profs. GAO Hongjun and DING Hong. Prof. Genda Gu at Brookhaven National laboratory provided high-quality samples, and Prof. Liang Fu at MIT provided theoretical modeling.

The work at IOP is supported by grants from the Ministry of Science and Technology of China (2013CBA01600, 2015CB921000, 2015CB921300, 2016YFA0202300), the National Natural Science Foundation of China (11234014, 11574371, 61390501), and CAS (XDPB08-1, XDB07000000, XDPB0601).