Basic Research

Observation of Nearly Quantized Majorana Conductance Plateau in an Iron-based Superconductor

In 1937, Ettore Majorana, an Italian physicist, predicted an elementary particle called the Majorana Fermion, for which the particle is its own anti-particle. The Majorana Fermion in condensed matter physics is also known as the Majorana zero mode. Because Majorana zero modes obey non-Abel statistics, it holds a great promise for the realization of topological quantum computing, which has attracted widespread interest.

Since 2014, studies into non-trivial topological band structures in iron-based superconductors have been pursued by researchers at the Institute of Physics (IOP), Chinese Academy of Sciences (CAS) as well as the University of the Chinese Academy of Sciences (UCAS), from both experimental perspective (P. Zhang *et al*., *Appl. Phys. Lett*. 105, 172601 (2014); P. Zhang *et al*., *Science* 360, 182 (2018)) and with theoretical efforts (Z.-J. Wang *et al*., *Phys. Rev*. B 92, 115119 (2015)). Starting from 2017, the joint group led by Prof. GAO Hongjun and Prof. DING Hong investigated the vortices in an iron-based superconductor using the scanning tunneling microscope/spectroscopy (STM/STS). For the first time, they reported the observation of evidence for Majorana zero modes in an iron-based superconductor Fe(Te,Se) (D. Wang *et al*., *Science* 362, 333 (2018)). These results were later verified by independent research groups from Fudan University, the Japan Institute of Physics and Chemistry (RIKEN), and other institutions (Q. Liu *et al*., *Phys. Rev*. X 8, 041056 (2018); T. Machida *et al*., *Nat. Mater*. 18, 811 (2019)). Moreover, the joint research group further performed a detailed study of Majorana zero modes in

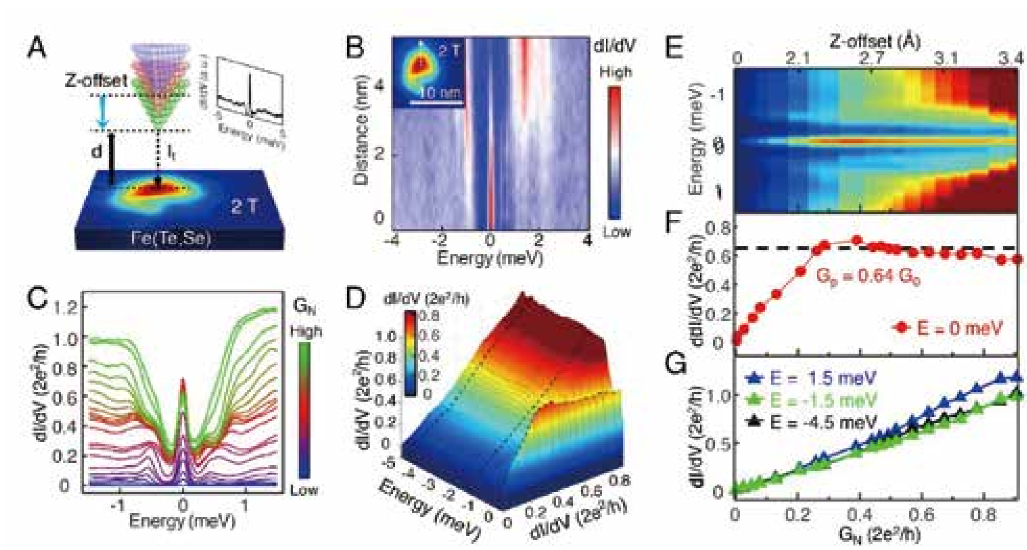

Figure 1: Zero-bias conductance plateau observed on Fe(Te,Se). (Image by IOP)

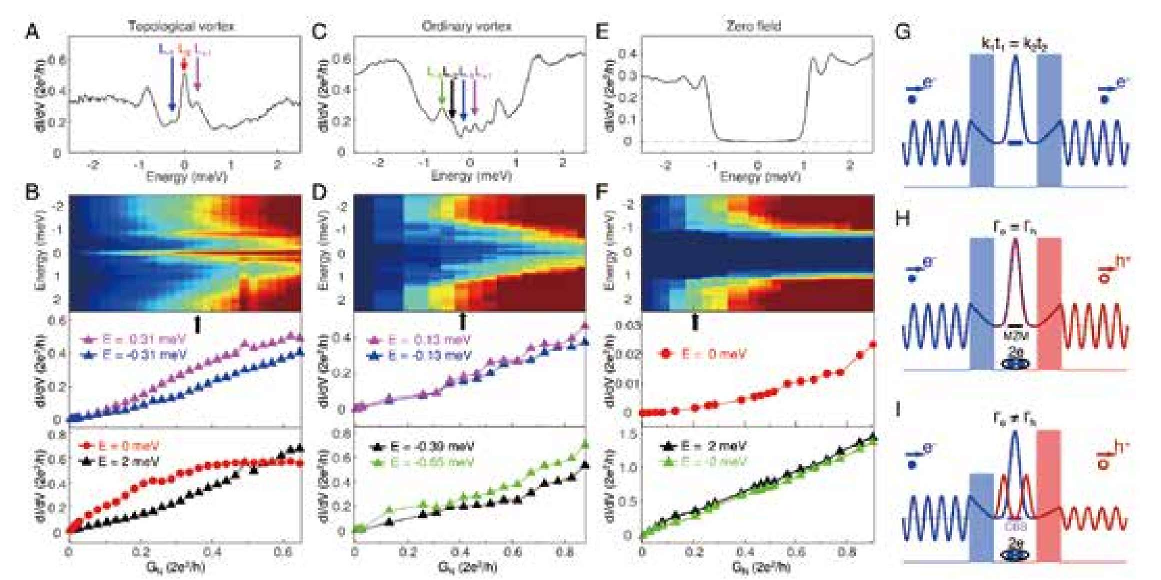

Figure 2: Majorana induced resonant Andreev reflection. (Image by IOP)

iron-based superconductors and found that there are two distinct types of vortices on the surface of Fe(Te,Se) single crystal when applying a magnetic field. They differ by a half-integer shift of vortex bound states energy levels, which is directly tied to the presence/absence of a zero-bias conductance peak. These results have helped deepen the understanding of vortex bound states and the topological nature of the Majorana zero mode (L.Y. Kong *et al*., *Nat. Phys*. 15,1181 (2019)).

Although there is already a lot of experimental evidence for the existence of Majorana zero mode in iron-based superconductors, more efforts are still needed to exclude other possibilities contributing to zero-energy conductance signals. In real materials, the Majorana intrinsic particle-antiparticle symmetry protects the equivalence of electrons and holes components, resulting in a unique quantized conductance plateau feature in the transport measurement, which is a hallmark for Majorana zero modes. For example, in nanowire systems, the zero-bias peaks have been observed since 2012, but many topological trivial explanations have not been excluded until Kouwenhoven's research group observed the quantized conductance plateau (Hao Zhang *et al*., *Nature* 556, 74 (2018)).

Recently, Prof. GAO Hongjun and Prof. DING Hong's team took a step further in the research of Majorana physics. Using the home-upgraded ultra-low-temperature and strong-magnetic-field STM/STS system, they observed conductance plateaus as a function of tunnel coupling for the zero-energy vortex bound states (Majorana zero modes) with values close to or even reaching the $2e^2/h$ quantum conductance by continuously tuning the tunnel-coupling between STM tip and Fe(Te,Se) single crystal (Figure 1). In contrast, no plateau was observed on neither finite energy vortex bound states nor in the continuum of electronic states outside the superconducting gap (Figure 2). The statistical analysis of 31 Majorana zero modes show the value of Majorana plateau concentrated near the quantized conductance $2e^2/h$. They also investigated how the instrumental broadening and the quasiparticle poisoning effect affect the conductance plateau value from the theoretical quantized value $2e^2/h$ (Figure 3).

The observation of a zero-bias conductance plateau in the two-dimensional vortex case, which approaches the quantized conductance of $2e^2/h$, provides spatially-resolved spectroscopic evidence for Majorana-induced resonant electron transmission into a bulk superconductor, moving one step further towards the braiding operation applicable to topological quantum computation.

This study entitled "Nearly quantized conductance plateau of vortex zero mode in an iron-based superconductor" was published in *Science* on December 12, 2019. Prof. GU Genda at the Brookhaven National

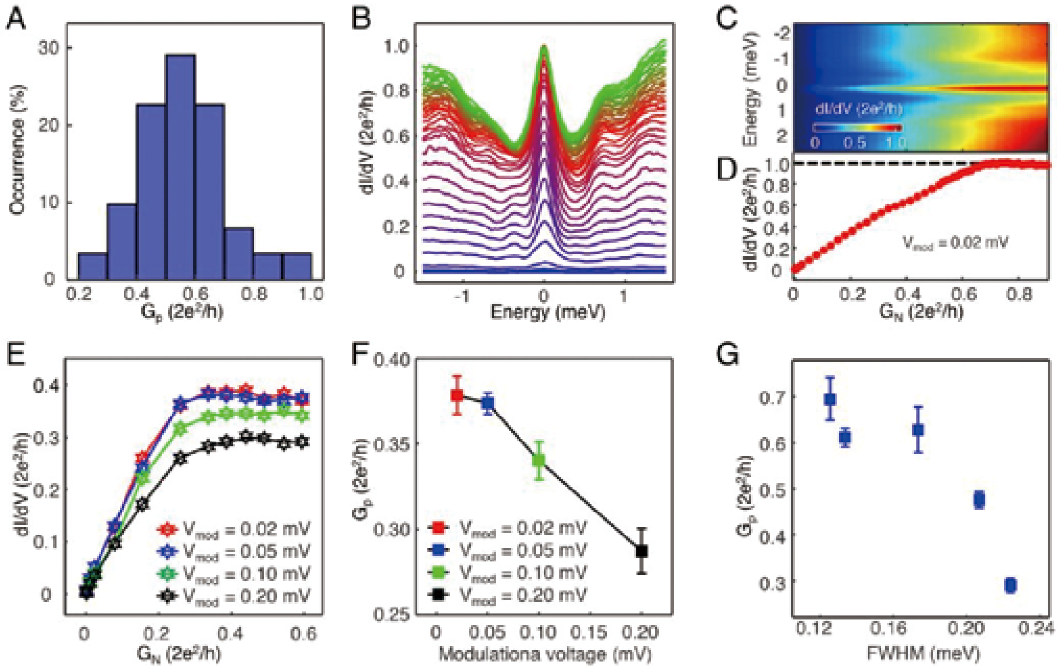

Figure 3: The conductance variation of Majorana plateau. (Image by IOP)

Laboratory provided high-quality samples, and Prof. FU Liang at MIT provided theoretical modeling. The work at IOP is supported by grants from the Ministry of Science and Technology of China (2015CB921000, 2015CB921300, 2016YFA0202300), the National Natural Science Foundation of China (11234014, 61888102), and CAS (XDB28000000, XDB07000000, 112111KYSB20160061).

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