Iron-based superconductors went topological ?

1. **Observation of topological superconductivity on the surface of iron-based superconductor**

   Authors: Peng Zhang, Koichiro Yaji, Takahiro Hashimoto, Yuichi Ota, Takeshi Kondo, Kozo Okazaki, Zhijun Wang, Jinsheng Wen, G. D. Gu, Hong Ding, and Shik Shin

   arXiv:1706.05163

2. **Observation of pristine Majorana bound state in iron-based superconductor**

   Authors: Dongfei Wang, Lingyuan Kong, Peng Fan, Hui Chen, Yujie Sun, Shixuan Du, John Schneeloch, Ruidan Zhong, Genda Gu, Liang Fu, Hong Ding, and Hongjun Gao

   arXiv:1706.06074

Recommended with a Commentary by Fa Wang, Peking University, Beijing

The first iron-based superconductor was discovered in 2006, and the first two-dimensional topological insulator was reported one year later. These two topics soon became major research directions in condensed matter physics. After more than a decade of development, these two directions show evidence of possible intersection. Two preprints posted on arXiv last summer reported angle-resolved photoemission spectroscopy (ARPES) evidence of topological surface states [1] and scanning tunneling spectroscopy (STS) evidence of zero-energy Majorana bound states [2] in an iron-based superconductor $FeTe_{1-x}Se_x$ (x=0.45).

The smoking-gun signature of topological insulators is their robust gapless surface states [3][4]. These surface states usually have the “spin-momentum locking” feature [3]. Several theory groups have predicted the existence of such “topological surface states” in $FeTe_{1-x}Se_x$ by density functional theory and model calculations [5][6][7]. The main ingredient of these theories is the “band inversion” at the Γ point, where the (Se,Te) p_z-orbital band energy becomes lower than some of the Fe d-orbital bands. Together with strong spin-orbit coupling this would produce a “strong topological insulator” if the bulk was a band insulator. Although the normal state of

$FeTe_{1-x}Se_x$ is a metal, the 2D Dirac cone of topological surface states can still exist inside the direct band gap near the Γ point.

In Ref. [1] Dirac-cone-like bands were indeed observed in $FeTe_{1-x}Se_x$ around the Γ point by high-resolution laser ARPES (see Fig. 1), and momentum-dependent spin polarizations of these states were observed by spin-resolved ARPES. All these observations seem to be consistent with that of the predicted topological surface states.

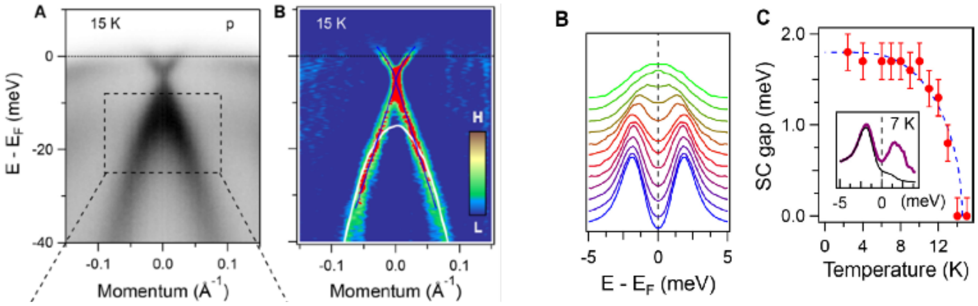

Figure 1: The ARPES band structure around the Γ point, and the temperature dependence of the symmetrized EDC and gap value on the Dirac-cone-like bands, taken from Ref. [1].

$FeTe_{1-x}Se_x$ is a superconductor with T_c=14.5K. In Ref. [1] a uniform gap of about 1.8meV was observed on the Dirac-cone-like bands at Fermi level at low temperatures (see Fig. 1). The authors interpreted this small gap as the proximity effect induced pairing gap on the topological surface states. Then this material would be a natural realization of the Fu-Kane proposal of topological-insulator/superconductor heterostructures [8], which support one zero-energy Majorana bound state at the core of a superconducting vortex.

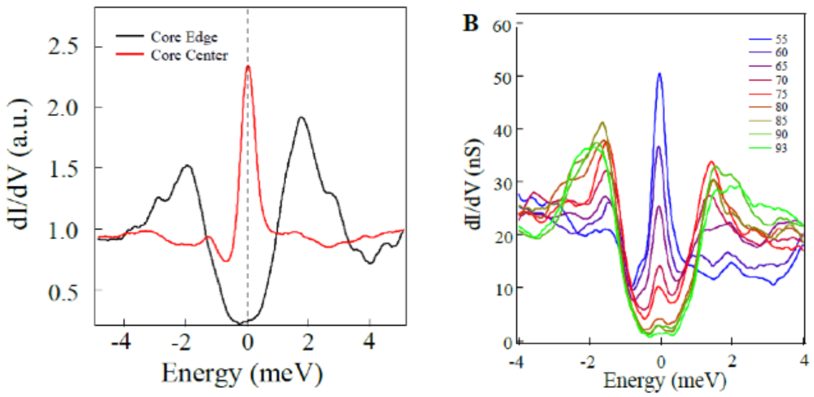

Figure 2: The zero-energy STS peak in a vortex core, and the spectra taken at different positions near a vortex core, taken from Ref. [2].

Experimental realization and detection of zero-energy Majorana bound states have been a very active research direction in the last few years (see previous commentaries [9][10][11]). A commonly used necessary criterion for zero-energy Majorana bound states is the zero-bias conductance peak (ZBCP) in tunneling or STS experiments [12]. This ZBCP was indeed observed by STS near some of the vortex cores in $FeTe_{1-x}Se_x$ in Ref. [2], and the authors reported no shift of this peak energy when the STM tip moved away from the vortex core (see Fig. 2). This suggests that the observed conductance peak is not from the Caroli-de Gennes-Matricon bound states in the vortex cores. These "trivial" bound state energies are proportional to Δ_{sc}^2/E_F and usually very low, because of the typical smallness of the ratio Δ_{sc}/E_F between the superconducting gap and the Fermi energy. But for this $FeTe_{1-x}Se_x$ system Δ_{sc}/E_F is quite large, about 0.4 (see previous commentary [13]). In this regard $FeTe_{1-x}Se_x$ is a very promising platform for the realization and manipulation of zero-energy Majorana bound states.

There are still a lot of questions to be answered about the results of Ref. [1,2], and more experiments to verify the reported observations should probably be performed on $FeTe_{1-x}Se_x$.

- It would be more convincing to distinguish the Dirac-cone-like bands from the bulk states by varying photon energies in ARPES experiments [14].
- It would be more convincing to have some other evidences of the complete spin-momentum locking in the Dirac-cone-like bands, for example, circular dichroism [15].
- The spin polarization [16] and quantized conductance [12] of the ZBCP would be further evidences of zero-energy Majorana bound states.
- It is important to explain why only about 20% of the vortex cores showed this ZBCP [17].
- The same type of Fe(Se,Te) superconductors have been studied by STS before[18][19][20]. Robust zero-bias conductance peaks were observed on Fe impurities in Ref.[19], and very low energy conductance peaks were observed in vortex cores in Ref.[20]. It is important to check whether the new results in Ref. [1,2] are related to the old ones.
- Testing the non-Abelian statistics of these Majorana bound states is very challenging. Braiding these vortex core bound states on surface may cause real braiding of the vortex lines in the bulk superconductor. Interferometry experiments would require making complicated heterostructures to suppress superconductivity in some surface region [21], and the bulk superconductor may still cause trouble. Better ideas are certainly called for here.

In any case the current results reported by Ref. [1,2] are definitely encouraging and might start a new phase of researches in iron-based superconductors.

References

1. Peng Zhang, *et al*, arXiv:1706.05163.
2. Dongfei Wang, *et al*, arXiv:1706.06074.
3. M. Z. Hasan, and C. L. Kane, Rev. Mod. Phys. 82, 3045 (2010).
4. Xiao-Liang Qi, and Shou-Cheng Zhang, Rev. Mod. Phys. 83, 1057 (2011).
5. Xianxin Wu, *et al*, Phys. Rev. B 93, 115129 (2016).
6. Zhijun Wang, *et al*, Phys. Rev. B 92, 115119 (2015).
7. Gang Xu, *et al*, Phys. Rev. Lett. 117, 047001 (2016).
8. Liang Fu, and C. L. Kane, Phys. Rev. Lett. 100, 096407 (2008).
9. Carlo Beenakker, "Majorana fermions debut", *Journal Club for Condensed Matter Physics*, May, 2012. Available at https://www.condmatjclub.org/?p=1744.
10. Patrick Lee, "Observation of Majorana fermions in ferromagnetic atomic chains on a superconductor", *Journal Club for Condensed Matter Physics*, October, 2014. Available at https://www.condmatjclub.org/?p=2488.
11. Anton Akhmerov, "Search for Majoranas: a new piece of the puzzle", *Journal Club for Condensed Matter Physics*, May, 2016. Available at https://www.condmatjclub.org/?p=2840.
12. K.T.Law, *et al*, Phys. Rev. Lett. 103, 237001 (2009).
13. Dung-Hai Lee, "Is FeSe a superconductor in the Bose-Einstein condensation limit?", *Journal Club for Condensed Matter Physics*, November, 2017. Available at https://www.condmatjclub.org/?p=3264.
14. see *e.g.* D. Hsieh, *et al*, Nature 452, 970 (2008).
15. Y. H. Wang, *et al*, Phys. Rev. Lett. 107, 207602 (2011).
16. J. J. He, *et al*, Phys. Rev. Lett. 112, 037001 (2014).
17. according to a talk given by Hong Ding at Peking University, December, 2017.
18. T. Hanaguri, *et al*, Science 328, 474 (2010).
19. J.-X. Yin, *et al*, Nat. Phys. 11, 543 (2015).
20. Freek Massee, *et al*, Science Advances 1, e1500033 (2015).
21. see *e.g.* J. Alicea, Rep. Prog. Phys. 75, 076501 (2012).