Search for Majoranas: a new piece of the puzzle

Exponential Protection of Zero Modes in Majorana Islands

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Recommended with a commentary by Anton Akhmerov, Delft University of Technology.

I am going to discuss the recent advances in the search for Majorana bound states. The main motivation in this search is the prospect of engineering particles that store quantum degrees of freedom protected from noise by their nonlocal nature, and Majoranas are the simplest particles having such a property. When achieved, this would be a truly impressive advance of condensed matter and quantum physics, and I can hardly advertise the overall topic better than Wilczek [1]. I would like to argue that the paper deserves much more attention than a finished story of an accomplishment, but rather that we are witnessing how the story still unfolds. A necessary disclaimer: Majoranas are my field of work, and I am personally acquainted with most of the authors of the papers I mention. Of course, this also means that my point of view is by no means guaranteed to be neutral despite I try my best.

Let me begin from a brief history of the field [2]. Majoranas were proposed to exist in exotic systems like half-vortices in chiral p-wave superconductors and $5/2$ fractional quantum Hall effect. Then Kitaev realized their potential for quantum computation and proposed a simple one-dimensional system supporting them, but it still took about a decade after his publication for experimentally realizable proposals to be designed. There are now several known systems likely to support Majoranas; the most popular ones are based on a hybrid between a conventional superconductor and a low dimensional system such as the surface of a 3D topological insulator, a quantum spin Hall edge, a chain of magnetic atoms, or a semiconducting nanowire. All of these platforms provide a different combination of the necessary ingredients for creation of Majoranas: superconductivity, broken time-reversal symmetry, broken spin-rotation symmetry, control over the number of electron states at the Fermi level. In a way, Majoranas are at a summit of non-interacting condensed matter physics: creating them requires precision control over all of electron degrees of freedom.

The article by Albrecht *et al.* uses a relatively new technology for creating a clean interface between a semiconducting InAs nanowire and a superconductor by growing the superconductor epitaxially [3]. While it sounds like a technical detail, this recipe proved to perform much better than the previous generations of devices relying on evaporated or sputtered superconductors; for instance Josephson junctions made using such samples make superconducting transmon qubits comparable to traditional ones even without optimization. The authors now report verifying that Majoranas in these systems are localized at the ends of a nanowire. They measure transport through a Coulomb-blockaded island made out of a proximitized nanowire and observe that when the magnetic field increases above a threshold value, two almost degenerate transmission peaks appear. Further, the splitting between these peaks shrinks rapidly with the length of the nanowire. This is a significant improvement over a local probe of existence of a single zero bias peak at an end of the nanowire because it agrees with the theoretical expectation of exponential localization of the Majoranas localized at the nanowire ends.

Without paying attention to details, this paper is a milestone towards Majorana-based quantum computation improving on mere creation of Majoranas and preceding measurement of their non-Abelian properties. To me the main interesting aspect of this discovery is not its role in a roadmap, but rather its relation to other bits of experimental and theoretical knowledge.

The first related work I would like to mention is a preprint [4] from the group of Kouwenhoven in Delft reporting a similar fabrication recipe applied to an InSb nanowire and a much stronger superconductor—NbTiN—with critical temperature an order of magnitude above that of Al. The authors see that the nanowire quality is improved compared to the previous generations of devices, and they demonstrate that electron transport in new systems becomes ballistic. On the other hand, the induced superconducting gap they observe is strongly suppressed compared to the bulk value (although it is still larger than the bulk gap of Al), and the density of states significantly deviates from the ideal BCS behavior observed in Copenhagen devices. Comparing the two experiments, we can conclude that atomically clean, lattice-matched interfaces are much better. However what about the drastic difference between two systems; which superconductor is better: the one with a larger induced gap, or the one with the density of states profile better fitting the simple expectations?

Comparing with the theory is also not straightforward. The most directly related work by van Heck, Lutchyn, and Glazman [5] theoretically analyses transport in an identical setup assuming ideal conditions. Overall their model predicts a region in magnetic field without visible resonant peaks, just like observed experimentally. However their theory also predicts that the conductance peaks in a regime without Majoranas should always be lower than the Majorana resonances, unlike what is seen in the experimental data (in the conclusions van Heck *et al.* argue that a more general model may reverse this trend).

Finally, already answering why Majoranas would appear in these wires is an open question by itself. In two works [6, 7], researchers from the University of Maryland and West Virginia University analyse Majoranas in the strong coupling regime. They argue that firstly the effective g-factor must be suppressed, while the sensitivity of the spectral gap to disorder should be strongly increased. The experiments are guaranteed to be in a strong coupling regime since the observed superconducting gap is very close to the bulk gap of Al. Additionally, while the interface between the nanowire and the superconductor is clean, the outer surface of the superconductor is likely disordered (it is even visible in some micrographs of the device). So the experimental systems should be in a similar regime as analysed in these papers, but the Majoranas still seem to appear.

In summary, the measurements by Albrecht *et al.* are a leap forward in making Majoranas, but we seem to be missing important insight into why they work. Exploring this further is interesting from the fundamental as well as practical points of view: it is hard to make Majoranas reliably if we do not know why and how they appear.

[1] F. Wilczek, Nature Physics **5**, 614 (2009)

[2] For reviews see e.g.: M. Leijnse, K. Flensberg, Semicond. Sci. Tech. **27**, 12 (2012), J. Alicea, Rep. Prog. Phys. **75**, 7 (2012), C.W.J. Beenakker, Ann. Rev. Cond. Mat. Phys. **4**, 113 (2013).

[3] W. Chang, S. M. Albrecht, *et al.*, Nat. Nano. **10**, 232 (2015).

[4] H. Zhang, O. Gul, *et al.*, arXiv:1603.04069 (2016).

[5] B. van Heck, R.M. Lutchyn, L.I. Glazman, arXiv:1603.08258 (2016).

[6] W. S. Cole, S. Das Sarma, T. D. Stanescu, Phys. Rev. B **92**, 174511 (2015).

[7] W. S. Cole, J. D. Sau, S. Das Sarma, arXiv:1603.03780 (2016).