Perspective

In search of Majorana

Ettore Majorana was a brilliant Italian theoretical physicist, who vanished suddenly one day in 1938, leaving no trace, immediately after finishing his most famous work associated with Majorana fermions. Rumour had it that he fell into the sea and drowned or jumped into the water to commit suicide. Or perhaps he had retired to a monastery as a reclusive monk or moved to South America and opened a café in secrecy somewhere. No-one knows what happened. This Perspective discusses Majorana’s profound effect on condensed-matter physics and, in particular, the attempts to observe a version of the particles he predicted in hybrid structures of superconductors and semiconductors.

Majorana postulated that, in principle, there could be real solutions to the Dirac equation associated with a new type of neutral fermion that is its own antiparticle. Such a creation operator, the Majorana operator, is then self-adjoint by definition, because the particle and the antiparticle are the same. Neutrinos may or may not be Majorana fermions — ongoing experiments all over the world are trying to figure out if they are, with huge implications for fundamental physics.

In condensed-matter physics, we cannot create new particles on demand — we only have electrons. However, self-adjoint Majorana operators can arise naturally in two-dimensional (2D) electron systems, creating emergent localized excitations where the particles are their own antiparticles. This is appealing, because these Majorana excitations are neither fermions, but are topological objects called non-Abelian anyons. These excitations have exchange statistics that are neither Fermi nor Bose statistics. This is allowed in 2D, because exchanging particles involves the braid group, rather than the permutation group as in 3D. The most famous examples of such anyons occur in fractional quantum Hall effects where the excitations could be either Abelian (for example, the 1/3 state) or non-Abelian (the 5/2 state). It is predicted that these emergent Majorana excitations can be braided around each other in well-defined manner to carry out fault-tolerant topological quantum computation, providing a huge practical incentive to search for them. As an aside, neutrinos, even if they turn out to be Majorana fermions, are rather pedestrian in that they are neither topological nor antiparticle; they are just neutral Dirac fermions whose creation operators are self-adjoint. One cannot do topological quantum computing with neutrinos.

It was realized some time ago that superconductors are natural hosts for Majorana particles, because the in-gap excitations of superconductors, called Bogoliubov excitations, are created by composite operators consisting of a linear combination of electrons and holes arising from an exact electron–hole symmetry inherent to superconductors. All that is needed is to find the precise neutral excitation that is an equal linear combination of electron and hole operators. By construction, this operator is a self-adjoint Majorana operator that creates midgap neutral excitations that are neither pure electron nor pure hole. In fact, such ‘zero-energy’ excitations (meaning they sit right at the centre of the superconducting gap) are effectively half an electron or half a hole, which must be anyonic. Given that in condensed-matter physics we only have either electrons or holes, an immediate consequence is that such Majorana zero-mode (MZM) excitations can never emerge in isolation by themselves, they must always come in pairs so that two of them together is an electron or a hole or nothing.

Superconductors hosting midgap MZMs are called ‘topological superconductors’, and the simplest example of such a Majorana-hosting topological superconductor is a spinless orbital $p$-wave superconductor. The issue for MZMs and topological quantum computing appears to be straightforward: just find a 2D spinless $p$-wave superconductor, and look for the midgap non-Abelian localized Majorana zero modes, braid them, and create a fault-tolerant topological quantum computer. After all, there are thousands of superconductors of all possible orbital symmetries, so surely some of them must be spinless or can be rendered spinless easily.

Alas, it does not seem that spinless $p$-wave superconductors exist at all in nature, never mind 2D ones. So, an alternative is to try to engineer them in heterostructures. Between 2006 and 2009, theorists worked hard and came up with several suggestions, some reasonable and some less so, to create laboratory systems that work like 2D spinless $p$-wave superconductors under certain conditions. In particular, ref. 14 introduced the physical idea of proximity superconductivity as a tool in this context, and refs. 8–11 emphasized that spin–orbit coupling may help. Some of these suggestions, particularly those involving fractional quantum Hall states, are still worth pursuing.

Then, in 2009, the Maryland group wrote a paper that proposed an experimentally tractable alternative for an artificially engineered effective spinless $p$-wave superconductor in semiconductor/superconductor (SM/SC) hybrid structures. The precise proposal that got the attention of experimentalists is a 1D adaptation of previous...
of opposite spins. When the Zeeman splitting is strong enough (Box 1), one of the spin types becomes effectively inactive, lifting the spin degeneracy, and the nanowire will host a spinless $p$-wave topological superconducting state (Fig. 2).

One substantial advantage of this engineered 1D Majorana construction using SM/SC hybrid structures is its tunability by varying either the applied magnetic field (to change the Zeeman splitting) or the voltages applied on various gates (to change the chemical potential). This can tune the device in and out of the topological regime. If the wire is long (much longer than the coherence length), the two end MZMs that exist in the topological phase are effectively isolated, and act as non-Abelian anyons that are immune to all local perturbations that preserve fermion parity and are protected by the topological gap itself. For short wires (shorter than the effective SC coherence length), however, the end MZMs may overlap (Fig. 1d), producing oscillations, which would be detrimental to topological quantum computing.

Although the existence of the critical Zeeman splitting where the nanowire superconducting gap opens or closes is a necessary condition for the topological quantum phase transition to occur, it is not sufficient on its own. The existence of a critical magnetic field (or Zeeman splitting) is necessary but not sufficient. Additional conditions are required to ensure that the system remains in the topological phase. These conditions include the presence of a strong magnetic field and the need for the Zeeman splitting to be large enough to lift the degeneracy of the spin states. The specific criteria for these conditions can be found in the literature on topological quantum computing using Majorana fermions.

Fig. 1 | Theoretical predictions for experimental signatures of MZMs. a, Sketch of a typical SM/SC nanowire. Electrical current enters and leaves via the two metallic contacts, and the tunnel gate regulates its flow into the region under the superconducting shell, allowing for spectroscopic measurements. The in-plane magnetic field (red arrow) provides the Zeeman splitting $V_z$ and can drive the topological phase transition. There are more gates (not shown) in the experimental set up controlling the chemical potential in the SM wire. b, The calculated induced gap closing and reopening as a function of $V_z$. The topological quantum phase transition occurs when the induced gap closes at the critical value (TQPT) when $V_z = V_c = 0.5$ meV. c, Calculated tunnel conductance spectra as a function of bias voltage for different values of $V_z$ (with $V_c = 0.5$ meV), showing MZM-induced ZBCPs for $V > V_c$. d, Calculated ZBCP strength for $V > V_c (= 0.5$ meV) as a function of wire length $a$, showing Majorana oscillation becoming more prominent with increasing Majorana overlap from the two ends for shorter wires. Panels adapted with permission from: a, c, d, ref. 15, American Physical Society. Panel b reproduced with permission from ref. 15, American Physical Society.
SM/SC hybrids for topological superconductivity

The key idea is that if spinless $p$-wave superconductors do not exist in nature, then we must engineer one in the laboratory by combining well-known and easily available components that, when appropriately combined in a hybrid structure, will manifest this state under well-defined conditions of parameter tuning. The necessary components are superconductivity and spinlessness. Gaining a spinless superconductor sounds easy—just apply a magnetic field that polarizes it—but this does not work because spin splitting would simply suppress the superconducting gap to zero when the spin splitting equals the gap. This is the well-known Pauli limit or Clogston effect, where spin polarization suppresses the gap in an $s$-wave superconductor, making all superconductivity vanish. Instead, what is necessary is to create a spin texture at the Fermi surface along with a spin splitting so that, with increasing spin splitting, the system can retain its superconductivity. This can be done via spin–orbit coupling (see figure).

Because a spinless superconductor must have the spin part of its wavefunction be symmetrical, its orbital part must be antisymmetric to ensure that the overall wavefunction is antisymmetric. This implies that the orbital wavefunction must be $p$-wave (meaning it has an angular momentum of 1) or $f$-wave (angular momentum of 3). We know how to create this spin texture using the spin–orbit coupling that is native to many semiconducting materials, and inducing superconductivity via the proximity effect.

The theory provides a crisp prediction for the development of an effectively spinless $p$-wave topological superconductivity in the nanowire:

$$V_Z > V_c = \sqrt{\Delta^2 + \mu^2},$$

where $V_Z$ is the field-induced Zeeman spin splitting in the nanowire, $\Delta$ is the zero-field proximity-induced superconducting gap in the nanowire, and $\mu$ is the chemical potential in the semiconductor. The field $V_c$ defines the TQPT separating trivial from topological. When $V_Z < V_c$, the system is in the trivial (meaning non-topological) phase, and for $V_Z > V_c$, it is in the topological phase with Majorana zero modes at the wire ends (Fig. 1). At the critical field $V_c$, the induced effective gap in the nanowire vanishes (this is the same as the Pauli limit described above), characterizing a TQPT from an ordinary spinful (s-wave) trivial superconductor ($V_z < V_c$) to a topological effectively spinless $p$-wave superconductor ($V_z > V_c$), with a topological gap opening for $V_z > V_c$, accompanied by the appearance of midgap MZMs as defect states localized at the two wire ends (Fig. 2). The topological gap is proportional to the spin–orbit coupling strength, which does not affect $V_c$ itself.

**Engineering a 1D spinless $p$-wave superconductor in SM/SC nanowires.** a. The spin-degenerate bandstructure of a 1D electronic system. b. Spin–orbit coupling shifts the spin-up (blue) and spin-down (red) bands in momentum space. c. An in-plane magnetic field adds a Zeeman coupling $V_Z$ that mixes and splits the bands near $k = 0$. d. When the Zeeman field is strong enough, it shifts the Fermi energy into the gap at $k = 0$, and the system becomes topological. Adding superconductivity in this situation leads to a spinless $p$-wave order parameter.

for the topological quantum phase transition (TQPT) and the associated MZMs, no published experiment has as yet definitively reported this feature in a robust manner. The experimental focus has been on the predicted midgap tunnelling transport through the MZMs, which should produce a zero-bias conductance peak (ZBCP), meaning a finite differential conductance at zero voltage, in local tunnelling spectroscopy data from both ends of the wire. In 2012, interest and excitement in the subject grew enormously as several experimental groups reported observations of ZBCPs in InSb or InAs nanowires in the presence of Al or Nb as the parent superconductor under an applied magnetic field of ~1 T. In solid-state physics involving complex materials, it is very rare for five different well-known experimental groups to apparently verify the same theoretical predictions more or less simultaneously, as happened here. There was euphoria over the physics, and the strange mystery of the disappearance of Ettore Majorana served as a romantic background in spite of these localized MZMs really having little to do with Majorana’s old work.

There was also an additional experimental report in 2012 of the observation of the theoretically predicted fractional Josephson effect in an InSb/Nb system. Theoretically, this arises from the qualitative fact that the MZM is effectively half an electron, leading to an effective $h/e$ fractional Josephson effect, compared with the standard $h/2e$ effect, thus doubling the flux periodicity. This experiment has never been reproduced, in contrast to the ZBCP observations in tunnelling, which have been reproduced many times by many groups. With so many groups reporting MZMs in SM/SC structures under an applied magnetic field, the community started to believe that MZMs had been seen, and that MZM-based topological quantum computing would soon follow. There were many exaggerated popular articles and many immodest press releases declaring Majorana victory far too soon.

Alas, these early claims (and subsequent published experimental claims of Majorana sighting in nanowires) turned out to be hasty and incorrect. However, the silver lining to that cloud was that these experiments represented considerable scientific progress, advancing...
our understanding of the subtle and complex physics of SM/SC hybrid systems. One important accomplishment of MZM research during 2012–2016 is the achievement of the hard proximity superconducting gap in a semiconductor nanowire by using epitaxial SM/SC systems following specific theoretical predictions, in contrast to the soft proximity gap, with substantial subgap fermionic states in the early (2012–2013) experiments.

With the benefit of hindsight, among the many problems that should have been obvious in the 2012–2013 experiments was that the wires they were performed on were not in the long-wire limit, the induced superconducting gap was very soft with obvious subgap states, and there was a complete absence of any gap closing and reopening, which is essential for a TQPT. There was also an absence of any end-to-end nonlocal correlations between tunnelling carried out from the two ends, as there must be for nonlocal MZMs, an absence of any stability against parameter changes, an absence of any Majorana oscillations with increasing field because of the overlap of the MZM wave functions, and very poor statistics for the occurrence of ZBCPs.

So, why were the Majoranas not there? We know now that disorder was playing a dominant role, and what were observed are signatures of disorder-induced non-topological subgap fermionic Andreev bound states (ABSs) rather than anyonic topological MZMs. A disorder-induced ABS could once in a while be rather close to zero energy, thus accidentally simulating some features (for example, the ZBCPs of MZMs).

My opinion is that ABSs were mimicking some, but not all, of MZM properties, and so we can understand the experimentalists could always find a small fraction of their data in a small fraction of their samples that looked misleadingly like ‘MZM signatures’: most particularly, ZBCPs that are almost at zero energy may arise naturally from disorder-induced ABSs in a finite magnetic field. Essentially, the claims of MZM signatures (or MZM observations) were, in my view, all results of honest and unwitting confirmation bias, arising from the fact that the theoretical predictions are so precise that it was easy to be misled that they have been experimentally verified. An unfortunate exclusive focus on ZBCP observations in the local tunnelling spectroscopy (rather than, for example, nonlocal signals or gap reopening or Majorana oscillatory features) had led the experimentalists down the wrong track.

The fact that disorder may be playing a role was already being pointed out in some early cautionary theoretical papers during 2012–2013, but their key importance became manifestly clear with detailed analyses of two important experimental papers in 2016. One, by Albrecht and colleagues, claimed the observation of the predicted topological protection arising from the MZM separation being larger than the coherence length so that the MZM wavefunction overlap from the two ends is exponentially small. The other, by Deng and colleagues, claimed to observe the merging of two ABSs into the MZM, leading to the ZBCP. Although no theory can definitively prove that MZMs were not seen in these (or any other) measurements, it nonetheless established compellingly that in the presence of disorder, experimental signatures involving ZBCPs are a necessary but not sufficient condition to claim the existence of MZMs.

More recently, the Maryland group carried out a detailed theoretical analysis of all SM/SC tunnelling experiments, arguing that there can be three different types of ZBCP: good (actual MZMs), bad (ABSs, sometimes called quasi-MZMs, produced by accidental quantum dots in the nanowire) and ugly (produced by random disorder-induced ZBCPs). The conclusion is that, most likely, all SM/SC structures have so far observed only disorder-induced ugly ZBCPs, although, occasionally, good ZBCPs may also have manifested, but good ZBCPs arising from MZMs have not been seen.

In particular, the good/bad/ugly analysis specifically addressed the experimental claims of the observation of ‘Majorana quantization’, meaning that the ZBCPs have a precise value of $2e^2/h$, as is appropriate for perfect MZMs at $T = 0$ (refs. 31–33). Occasionally, disorder-induced ZBCPs could manifest approximate $2e^2/h$ apparent ‘quantization’, and experiments most probably reported these ugly ZBCPs through fine-tuned post-selection (Fig. 3). Our ‘ugly’ simulations generically seem to produce fine-tuned and post-selected ZBCPs that are indistinguishable from the experimental data.

This work pre-dated the unpleasant controversy around the reproducibility of MZMs that led to the retraction of the Zhang Nature article in 2018 (Zhang, H. et al., Nature 556, 74 (2018)). In fact, the updated version of that paper following the retraction concedes that the observed approximate $2e^2/h$ ZBCPs are most likely the disorder-induced ugly peaks discussed in ref. 31, settling the technical aspects of this controversy. The decisive role of confirmation bias in the retracted Nature paper has been emphasized by a report from a group of independent experts appended to the retraction note. The good/bad/ugly paper also showed that the claim of the MZM observation based on temperature scaling is consistent with disorder-induced ugly ZBCPs.
InAs nanowires on Al substrates. Once the nanowires are clean enough, true MZMs will emerge in long wires, and the condensed-matter version of the search for Majorana will end.

So, materials improvement would lead to MZMs, and this appears to be the current emphasis of the community working on MZMs in SM/SC structures. What matters is the dimensionless ratio of the disorder strength to the pristine topological superconducting gap, which cannot be much larger than unity for MZMs to emerge. Currently, this ratio is of the order of 10 or 100. Therefore, future progress must involve reducing disorder in the currently used InAs/Al samples, or finding new materials where the induced superconducting gap in the semiconductor is much larger, so that the need for reducing disorder is less stringent. The future is bright, because we know what the problems are and how to solve them. The problems are difficult, but by no means insurmountable.

I will be convinced once experiments in ultra-pure SM/SC systems observe simultaneous stable correlated ZBCPs generically from both ends in local tunnelling (without extreme fine-tuning), in nanowires that are longer than the coherence length, along with the controlled closing and opening of a gap in nonlocal tunnelling, indicating the TQPT. A very recent experiment from Microsoft might indicate such results, but the situation is unclear, because the sample still has considerable disorder, and the reported topological gap is tiny. More work is obviously necessary in less disordered samples to decisively resolve the situation. Once MZMs are seen, braiding experiments would show that ‘our’ condensed-matter Majorana is much more interesting than anything even the genius of Ettore Majorana could ever have imagined.

Our realistic numerical modelling and theoretical analysis of the experimental samples convince me that the current SM/SC samples are -10–100 times dirtier than what would be necessary to realize pristine ‘good’ ZBCPs arising from topological MZMs. But what is this disorder and where is it located?

The main disorder is in the semiconducting nanowire itself and at the SM/SC interface, and arises from the parent semiconducting material and the SM/SC interface not being clean enough. We also know from numerical simulations, compared with both transport and tunnelling data, that the disorder essentially arises from unintentional random charged impurities in the semiconductor. This materials problem should be solvable by improving semiconductor growth techniques—it is not cheap to do so, but developing a new technology and observing completely new types of ‘particle’ cannot be either easy or inexpensive.

The mechanism by which the disorder compromises the topological superconductivity is also known. Remember that two completely overlapping MZMs are basically fermions, and two nearby MZMs are equivalent to an ABS. Only MZMs very far from each other with little overlap are non-Abelian anyons. Although a topological superconductor is immune to weak disorder, very strong disorder necessarily mixes MZMs, generically producing ABSs that can occasionally mimic some MZM properties. Also, in short wires, there are no MZMs, because their overlap is strong. Current published experiments are all in short-wire and strong-disorder regimes, and therefore cannot manifest topological MZMs.

I fully expect topological MZMs to be observed in the near future in SM/SC nanowires, once the samples are made purer. The underlying theory is a free fermion bandstructure theory, which should essentially be exact for experimentally studied SM/SC systems, except for the problems of disorder and short wires. Just as our current Si-based complementary metal–oxide semiconductor electronics industry depends crucially on highly purified Si wafers through extremely complex engineering, the eventual Majorana technology will depend on ultra-pure...
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The author declares no competing interests.

Additional information

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