Special Topic: Topological Insulators

Creating Majorana fermions in topological insulators

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Having not been verified in experiments yet, the concept of Majorana fermions was originally hypothesized in 1937 to describe the spin-1/2 particles that are their own antiparticles, in contrast to Dirac fermions [1], which differ from their antiparticles and cover most of well-known fermions including quarks, leptons, electrons and their antiparticles. The different properties of these two classes of fermions are the mathematical consequence of modification that Majorana did to Dirac’s equation in depicting the spin-1/2 particles. After the modification, the imaginary numbers indispensable to understand antiparticles in Dirac’s equation can be abandoned and thus only real numbers are involved in Majorana’s equation.

Recently, Majorana fermions have attracted a great deal of interest in condensed matter physics, mainly because of their non-Abelian statistics that can be utilized for fault-tolerant quantum computing [2,3]. Theoretical investigations suggest that some exotic fermionic quasiparticles in a variety of solid state matters, such as the fractional quantum Hall state at filling factor of 5/2, ultra-cold atoms and chiral p-wave superconductors, should be identical to their antiquasiparticles and thus be Majorana fermions. In an Abrikosov vortex core of a superconductor, for example, the electron and hole excitations within the superconducting gap \( \Delta \), i.e. the Andreev bound states, play the role of particle and antiparticle. The Majorana fermion comes out of the equal superposition of an electron (filled state at energy \( E \) above the Fermi level, \( E_F \)) and a hole (empty state at energy \( -E \) below \( E_F \)) excited exactly at the Fermi level, i.e. the Andreev bound state at \( E = 0 \). In a usual s-wave superconductor, where Cooper pairs have orbital angular momentum 0 and the electrons obey a Schrodinger-like, non-relativistic equation, such a zero energy excitation is strictly forbidden and the lowest bound state is at \( E \sim \Delta^2/2E_F \). In contrast, the zero mode Majorana particle is predicted to occur if the Cooper pairs have orbital angular momentum 1 (\( p_x \pm ip_y \)-wave).

Majorana fermions in condensed matters occur always in pair, whose superposition forms a conventional fermion, such as an electron or a hole. What scientists are chasing to discover are Majorana fermions that are spatially separated and thus prevented from overlapping. Such a highly delocalized pair of Majorana fermions form a fermionic state that can be protected from most types of decoherence, since a local perturbation may affect only one Majorana fermion of the pair. This topologically protected fermionic state can be used to store quantum information as a qubit and manipulated by physical exchange of the Majorana fermions based on their non-Abelian statistics. Actually, the object showing non-Abelian statistics, i.e. an Ising anyon referred in the literature on topological quantum computation, is not the Majorana fermion by itself, but a topological defect hosting a Majorana fermion, such as an Abrikosov vortex of a \( p_x \pm ip_y \)-wave superconductor.

Unfortunately, \( p_x \pm ip_y \)-wave superconductors in nature are not easily available, so the boom in searching for Majorana fermions in condensed matters had not come until 2008, when Fu and Kane at University of Pennsylvania theoretically proposed realistic proximity effect induced superconductivity in a strong topological insulator by combining it with an ordinary s-wave superconductor [4]. In this engineered superconductor, Cooper pairs are induced to the topological surface state via proximity effect, so that zero energy Andreev bound states at the vortex cores can occur. This is because the electrons in the normal state obey a Dirac-like equation and have their spin and momentum locked, so that a closed orbit produces a phase shift of \( \pi \) from the 360° rotation of the spin. This additional Berry phase converts destructive interference at \( E = 0 \) into constructive interference and thus results in a Majorana fermion at the Abrikosov vortex core. Here, the necessary underlying physical ingredient is the strong spin–orbit coupling that gives rise to an odd number of bands with momentum-dependent spin crossing \( E_F \). Inspired by this idea, other proximity-induced superconductors were proposed using semiconductor nanowires and/or quantum wells with a strong spin–orbit coupling, in which Kramer’s degeneracy is lifted by Zeeman splitting due to an external magnetic field or a magnetic insulator in proximity [5–7].

Following the rapid theoretical developments, a number of experimental groups have taken up the challenge to create Majorana fermions by constructing the artificial p-wave-like superconductors. Last year, owing to well-developed nanoscale fabrication technology, Kouwenhoven’s group at Delft University of Technology succeeded in
observing a very sharp zero-bias peak in differential conductance spectrum in an InSb nanowire contacted to a NbTiN electrode, and attributed it to the signature of Majorana fermions \[8\]. Soon after that, similar experimental results were reproduced by other groups \[9–11\]. Moreover, an unconventional fractional AC Josephson effect due to the existence of Majorana fermions was observed in an InSb/Nb junction \[12\]. When the quest of Majorana fermions seemed to have seen success, several theoretical studies revealed that inevitable disorder and/or band bending in the nanowires may be also responsible for the reported transport results; therefore, the existence of Majorana fermions in nanowires remains controversial \[13–16\].

At the same time, experimental efforts in creating Majorana fermions with a topological insulator were not in vain either. Proximity-effect-induced superconductivity in topological insulator surfaces has been manifested by several groups including Lu’s at CAS \[17–19\], and an indirect signature of Majorana fermions was obtained in a Josephson current measurement on an Al/Bi\(_2\)Se\(_3\)/Al junction \[20\]. As Majorana fermions reside at Abrikosov vortex cores, it is a promising way to detect the zero-energy bound state at vortex cores of a topological insulator–superconductor heterostructure, so that a single Majorana mode can be explicitly identified. This is very important especially to the potential application of Majorana fermions in quantum computing.

To observe a single Abrikosov vortex and therefore get the chance to detect Majorana fermion, scanning tunneling microscope and spectroscopy are powerful tools as long as the sample has a smooth enough surface. As shown in Fig. 1, Jia’s group at Shanghai Jiao Tong University has recently succeeded in fabricating a high-quality topological insulator films on an s-wave superconductor, NbSe\(_2\), on which the coexistence of topological surface states and superconductivity has been manifested \[21\]. Furthermore, they visualized the Abrikosov vortices and detected Andreev bound states, which is an important prerequisite step towards detecting individual Majorana fermions. As a larger superconducting energy gap enhances the robustness of Majorana fermions bound to vortices to thermal perturbation, Xue’s group at Tsinghua University used a high-\(T_c\) superconductor, Bi\(_2\)Sr\(_2\)CaCu\(_2\)O\(_{8+\delta}\), as the substrate for growing high-quality topological insulators \[22\]. The experimental breakthrough in search of Majorana fermions with the proximity-effect-induced superconducting topological insulators would be to manifestly distinguish the zero-mode Andreev bound state from the other non-zero modes in an Abrikosov vortex core. To realize it, one of the promising ways is to tune the Fermi level to the Dirac point of the topological surface states as closer as possible. Lower temperature is also better for this issue, since the thermo-perturbation is always the main obstacle in the experiment.

Creation and detection of Majorana fermions in laboratories are only the beginning to study these particles for the application in quantum computing. Properties of Majoran fermions will have to be investigated in detail in both experiments and theories, to reach the goal of the controllable manipulation of Majorana fermions in quantum computing.

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