Discovery of the chiral Majorana fermion

We seem to live in a world of opposites: positive and negative numbers, credits and debits, Yin and Yang, good and evil, angels and demons. In 1928, the great theoretical physicist Paul Dirac predicted that for every particle in the universe, that must exist an exact opposite counterpart: the anti-particle. Soon after, the anti-particle of the electron, the positron was discovered in the cosmic ray, confirming one of the greatest theoretical predictions of all time. The positron is now commonly used in our lives, the medical imaging technique PET scan stands for Positron Emission Tomography. When a particle meets its anti-particle partner, they annihilate each other, turning all their masses into energy, according Einstein's famous formula $E=mc^2$. Dan Brown's popular novel and its cinematic interpretation "Angels and Demons" depict such violent annihilation of particle and anti-particle.

Ever since then, it has become a fundamental law of physics that every particle in the universe (more precisely every fermionic particle) has its anti-particle. But could there exit a particle which does not have an anti-particle counterpart, or a particle which is its own anti-particle? In 1937, exactly 80 years ago, the brilliant and yet elusive Italian theoretical physicist Ettore Majorana proposed the existence of such an enigmatic particle, now called a Majorana fermion, which does not have an anti-particle counterpart. Search for Majorana fermion has become an intense focus across many sub-disciplines of physics. In particle physics, it is conjectured beyond the Standard Model that the neutrino could be a Majorana fermion, which could be experimentally tested in a process called the neutrinoless double beta decay. However, such an experiment is still ten or twenty years away from the required precision. In condensed matter physics, Majorana fermion could appear as a quasi-particle or elementary excitation above some novel ground state. The “most wanted list” of mysterious particles in physics includes the Higgs boson (sometimes also called the God particle, now discovered in accelerator experiments), the gravitational wave-particle, the magnetic monopole, the dark matter particle and the Majorana fermion. The enigmatic Majorana fermion appears even more mysterious than the rest since Majorana himself disappeared without a trace soon after his elusive proposal.

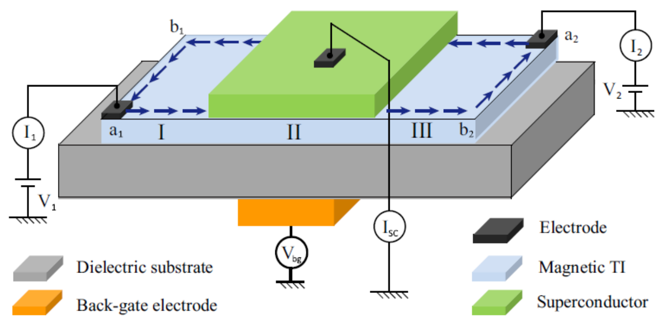
In a series of three papers between 2010 and 2015, Zhang and his team predicted exactly where to find the Majorana fermion and what to look for as its “smoking gun” experimental signature. The team proposed that the chiral Majorana fermion exists in a hybrid device consisting of a quantum anomalous Hall insulator film and a conventional superconductor film on top of it. As the external magnetic field is varied, the conductance of the quantum anomalous Hall insulator film displays quantized plateaus at 1 and 0, in units of the fundamental constants e^2/h, which have already been observed in previous experiments. The proximity with the conventional superconductor film on top gives rise to the chiral Majorana fermion, with additional conductance plateaus at ½ in units of the fundamental constants e^2/h. Since the Majorana fermion has no anti-particle counterpart, it is in some sense half of a conventional particle, therefore the additional half-quantized plateaus provide the “smoking gun” evidence of its existence as a particle propagating in space and time.

Following this theoretical proposal, two teams of experimentalists at UCLA (led by Prof. Kang Wang) and UC Irvine, in close collaboration with Zhang's theory group at Stanford, have now experimentally discovered the chiral Majorana fermion in the proposed device. They prepared samples of quantum anomalous Hall insulator film $(Cr_{0.12}\, Bi_{0.26}\, Sb_{0.62})_2\, Te_3$ grown on $GaAs(111)$ substrate, covered by Nb superconductor. As the magnetic field is swept, they indeed observed the half-quantized plateaus as predicted by Zhang's team, in additional to the usual integer quantized plateaus. Additional experiments were performed at higher magnetic field, and with three terminals, to convincingly rule out possible experimental artifacts or spurious effects. These finding are published in this week's edition of Science Magazine.

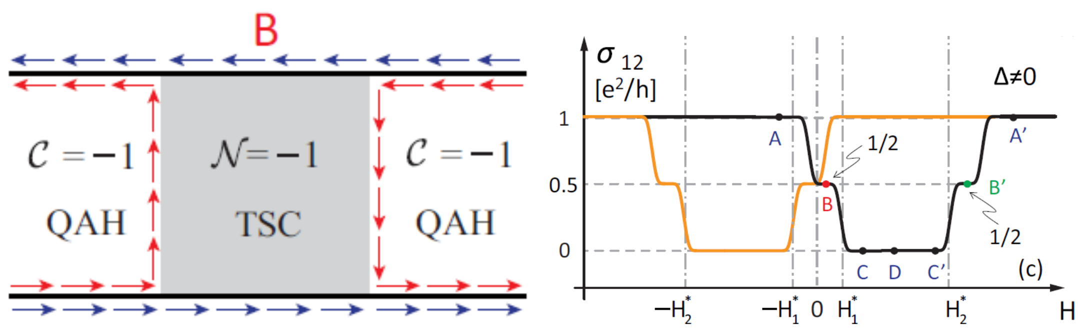
So the discovery the chiral Majorana fermion concludes one of the most intensive searches in fundamental physics which spanned exactly 80 years. Playing on the theme of Dan Brown's novel "Angels and Demons" depicting the violent annihilation of particle and antiparticle, Zhang proposes to call the newly discovered chiral Majorana fermion the "Angel particle": "we discovered a perfect world, with only angels, no demons!".

Majorana fermion could be used to construct robust topological quantum computers. Quantum world is intrinsically parallel, a quantum particle could go through two slits at the same time. Therefore, quantum computers could perform massively parallel quantum computation with much greater efficiency compared with classical computers. However, a quantum bit of information (sometime called a qubit) is notoriously difficult to store: any environmental noise could lead to decoherence which destroys its quantum character. Since the Majorana fermion has no anti-particle partner, it is in some sense half of a conventional particle, leading to the intriguing possibility of storing one qubit in two far separated Majorana fermions. It would be extremely difficult for the classical noise to conspire in exactly the same way as to destroy the two far separated Majorana fermions at the same time. Therefore, the topological qubit stored in two far separated Majorana fermions could be intrinsically more robust and protected compared to other conventional storage mechanism using electron spin, superconducting flux or photonic polarizations. Zhang's proposed device is also intrinsically two dimensional, allowing for the braiding of Majorana fermions and performing efficient quantum computation. Taking a fundamental discovery to its practical applications usually takes many years, however, Zhang is exuberant about the "quantum paradise roamed by Angel particles": "topological quantum computer could solve some of the greatest problems facing humanity today, advancing to a more perfect world".

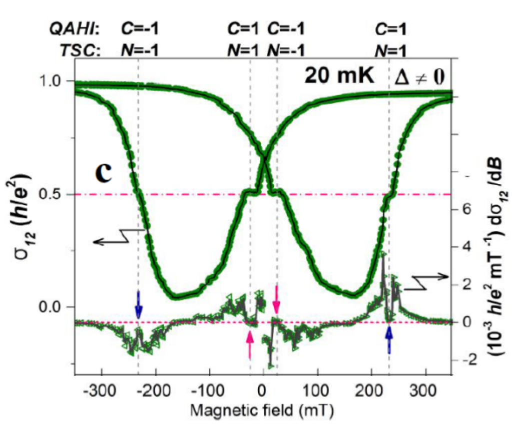
Addtional materials:



Zhang’s team proposed where to find the chiral Majorana fermion: in a hybrid device consisting of a quantum anomalous Hall insulator film and a conventional superconductor film on top of it.



Zhang’s team also proposed what to look for as “smoking gun” experimental signature: half-quantized conductance plateau as magnetic field in swept.



Experimental teams at UCLA and UC Irvine, in close collaboration with Zhang’s theory team at Stanford, observed the predicted half-quantized plateaus, providing direct experimental evidence for the discovery of the chiral Majorana fermion.

Video of public lecture:
https://www.youtube.com/watch?v=sbJSAOngiGI

References:

Xiao-Liang Qi, Taylor L. Hughes, Shou-Cheng Zhang, “Chiral Topological Superconductor From the Quantum Hall State", Phys. Rev. B82, 184516 (2010).

Suk Bum Chung, Xiao-Liang Qi, Joseph Maciejko, Shou-Cheng Zhang, ``Conductance and noise signatures of Majorana backscattering", Phys. Rev. B83, 100512(R) (2011).

Jing Wang, Quan Zhou, Biao Lian and Shou-Cheng Zhang, ``Chiral topological superconductor and half-integer conductance plateau from quantum anomalous Hall plateau transition", Physical Review B, 92, 064520 (2015).

Qing. Lin He, Lei Pan, Alexander. L Stern, Edward Burks, Xiaoyu Che, Gen Yin, Jing Wang, Biao Lian, Quan Zhou and Eun. Sang Choi, Koichi Murata, Xufeng Kou, Tianxiao Nie, Qiming Shao, Yabin Fan, Shou-Cheng Zhang, Kai Liu, Jing Xia and Kang L. Wang, ``Chiral Majorana edge state in a quantum anomalous Hall insulator-superconductor structure", arXiv:1606.05712, Science Magazine, in press.