Observation of Majorana fermions in ferromagnetic atomic chains on a superconductor.

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Recommendation and commentary by Patrick Lee.

Majorana fermions are "real" fermions which are their own anti-particles.[1] In the past several years, the Majorana state has attracted the attention of the condensed matter physics community. The article by Nadj-Perge et al reports significant progress in creating the Majorana state in the laboratory. The quasi-particles in a superconductor are natural candidates for Majorana physics, because they are quantum mechanical admixture of particles and holes. If the admixture has equal amplitude, the anti-particle and particle becomes the same. It was pointed out by Kitaev[2] that Majorana bound states (MBS) form at the ends of a p-wave superconductor chain. The MBS wavefunctions are zero energy modes localized at each end of the chain. They hybridize to form a conventional quasi-particle (complex fermion) with energy $E_0 \approx \exp(-L/\xi)$ where L is the length of the chain and ξ is the coherence length of the superconductor. In the limit $L \gg \xi$, $E_0 \rightarrow 0$ and the addition or removal of the quasi-particle costs no energy, i.e. they become part of the ground state manifold. It is as if each complex fermion has been split into two real MBS's which are spatially far apart. More generally, the presence of 2N MBS's far apart implies the existence of N low energy quasi-particles, each of which can either be empty or occupied, leading to a ground state degeneracy of 2^N. The MBS's obey what is referred to as non-abelian statistics. Apart from being a fascinating example of quantum weirdness, the ability to spatially decompose quasi-particle states has been proposed to be the basis of fault tolerant quantum computer and memory.[2] Superconductors with p wave pairing are rare in nature, let alone forming a one-dimensional chain out of them. Fortunately, it may be possible to create structures with the desired properties using proximity coupling to conventional s wave superconductors. Starting with the proposal of Fu and Kane[3] to couple the newly discovered surface state of topological insulator to conventional superconductors by the proximity effect, many schemes have been proposed to build structures using a variety of more or less conventional materials and the race to create MBS in the Laboratory is on.

Up to now the most convincing sighting of MBS was reported a couple of years ago by the Delft group using a scheme that places a semiconducting nanowire on top of a superconductor.[4] A zero bias peak was observed in the tunneling conductance under conditions consistent with theoretical predictions. However, the energy scale of the spin orbit coupling, a key parameter responsible for the formation of the MBS, is very small in the semiconductor nanowire and is of order 0.05 meV. This raises the question of whether disorder or other conventional effects may give alternative explanations of the zero bias peak.[5,6] Additional experiments are clearly desirable.

Nadj-Perge et al report the observation of Majorana fermions in a new system. They fabricated a chain of iron (Fe) atoms on the surface of superconductivity lead (Pb).

Remarkably, the Fe chains grow out of a central island along the atomic rows in the Pb (110) crystalline surface. Extensive modeling using LDA suggests that the Fe atoms form a buckled chain partly buried under the Pb surface. If the chain of Fe is ferromagnetic, theory predicts that the strong spin orbit coupling in Pb will lead to an effective p wave component in the induced superconductivity in the Fe chain and hence a realization of the Kitaev model. Indeed, using a scanning tunneling microscope (STM), the group discovered zero bias peaks at the end of the chains, but not in the middle. The wavefunction of the state is localized near the chain end to a surprising degree, so that the zero bias peaks disappears over a distance of 10 Å, or 4 spacing between Fe atoms. These are signatures consistent with MBS's.

The Fe chain system has an advantage over the semiconductor nanowire in that since we are dealing with atomic scale devices, all the energy scales are several orders of magnitude higher. For example, the spin orbit coupling is estimated to be 100 meV vs. 0.05 meV, and the spin splitting due to exchange is 900 meV vs. a few meV from the magnetic field in the nanowire system. Thus there are reasons to believe that the MBS's are more robust, once the conditions needed for its stability are achieved.

The experiment is clearly a tour-de-force combining the fabrication of structures on an atomic scale and the ability to probe the electronic structure with high energy and spatial resolution. Unlike the earlier experiment [4] the spatial location of the zero bias state is clearly identified. However, there are still a number of loose ends to contend with. The energy gap of the induced superconductivity on the Fe chain is very small and estimated to be 0.2 meV, 20% of the Pb bulk gap. This corresponds to about 2K, not much higher than the temperature where the experiment is carried out, 1.5K. As a result, no clear gap structure is seen and the tunneling conductance only shows a modest reduction of no more than 50% at low energies. The zero bias peak is a small structure on top of this large background. The peak height is about 10^{-4} times $2e^2/h$, the value expected in the ideal case. This by itself is not an issue of concern, because the height is expected to be reduced when the tunneling rate is much less than the temperature scale. Unfortunately there is no T dependent data to test the expected 1/T dependence in the high temperature limit. In addition, just like the Delft data from two years ago, the large tunneling background suggests that the decay of MBS into quasi-particles (called quasi-particle poisoning) may be reducing the peak height as well. [7] On the other hand, we should keep in mind that all the interesting phenomena associated with MBS's require the state to be well isolated from the quasi-particle excitations, a condition which is far from being satisfied in this experiment.

A second problem is that the chain length is quite short, about 300 Å whereas, the superconductivity coherence length is expected to be much longer, due to the small energy gap. Thus we are in the opposite limit where $L \ll \xi$ and the MBS's are expected to strongly hybridize to form convention fermions with a finite energy splitting E_0. This expectation seems at variance with the experimental observation of a rapid decay of the end state wavefunction. While the authors offer numerical calculations to explain this rapid decay, the energy gap they used is far too large to be realistic. We believe this short distance physics is not yet fully understood, but the long distance behavior must still be controlled by the coherence length. To make further progress, it is important to go to the lower temperature to resolve the energy splitting. Currently the upper bound on the splitting is estimated to be 0.15 meV which is comparable to the estimated induced superconductivity gap of 0.2 meV. Again, for the MBS to be useful, the splitting must be much less than the gap. The temperature limitation may be a technical issue, which will be overcome by future experiments, but the limitation of chain length may be more difficult to overcome. This could mean that the most fascinating phenomena associated with “real” Majorana bound states such as nonabelian statistics and the so called 4π Josephson effect which require the limit $L \gg \xi$ may be beyond the reach of the atomic chain system. On the other hand, there are other interesting phenomena, such as the cross Andreev effect[8] and noise correlation between leads attached to opposite ends or a chain, [9] which require a voltage and temperature smaller than the energy splitting. It will be exciting to see whether the next generation of experiments capable of reaching much lower temperature will reveal these and other features of Majorana bound states. Meanwhile, other schemes which may be more scalable to long lengths are being pursued. Notable among them is a return to the original Fu-Kane scheme using a new type of two dimension topological insulators fabricated out of semiconductor hetero-structures. [10,11] The story of the search for real Majorana is far from over.

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