Evidence for Majorana fermions in a nanowire

Electrical conductance measurements reveal what may be massless, chargeless, and spinless quasiparticles of zero energy.

No one knows whether Majorana particles—fermions that are their own antiparticles—exist in nature as elementary building blocks. When Italian particle theorist Ettore Majorana rewrote the complex Dirac equation in 1937 as a pair of real wave equations that would admit such exotic objects as solutions, he envisioned the neutrino as a likely suspect.[1] But even today, whether the neutrino is its own antiparticle remains an important open question in particle physics. Experiments looking for telltale neutrinoless double beta decay signatures may resolve the issue (see PHYSICS TODAY, January 2010, page 20).

Even if Majorana fermions don't exist as elementary particles, it's possible to engineer one in a condensed-matter system. In a solid, excitations above the ground state often behave like elementary particles insofar as they can carry quantized amounts of energy, momentum, spin, and electric charge. They can also exhibit exotic properties. Magnetic monopoles that diffuse through a frustrated magnet known as a spin ice are one example (see PHYSICS TODAY, March 2008, page 16); quasiparticles with a third of an electron's charge in the fractional quantum Hall (FQH) effect are another. In both cases, the collective, correlated behavior of electrons leads to the emergence of quasiparticles with a fraction of an electron's spin or charge. (See the article by Philip Anderson in PHYSICS TODAY, October 1997, page 42.) Indeed, recent experiments provide hints that Majoranas may nucleate in the vortices associated with the FQH state at filling factor $\nu = 5/2$ in gallium arsenide.

Two decades ago, theorists realized that superconductors should be ideal breeding grounds for Majoranas. The electron and hole excitations of a superconductor naturally play roles of particle and antiparticle. But the distinction between them is blurred because the charge difference can be absorbed as a Cooper pair in a dense condensate. At the Fermi level—the zero-energy marker in the middle of the superconducting gap—a superconductor's eigenstates are charge-neutral superpositions of electrons and holes. By symmetry, any isolated midgap excitations are Majorana fermions.[2]

In the past few years, researchers have reported a handful of signs of possible Majoranas based, for instance, on a Josephson effect at the surface of topological insulators to which superconducting electrodes have been attached. But none of those signs were readily attributable to a single Majorana.[2] Researchers led by Delft University of Technology's Leo Kouwenhoven have now found what may be the most compelling evidence yet of one—or more specifically, one of a pair of Majoranas predicted to emerge at opposite ends of a nanowire.[3]

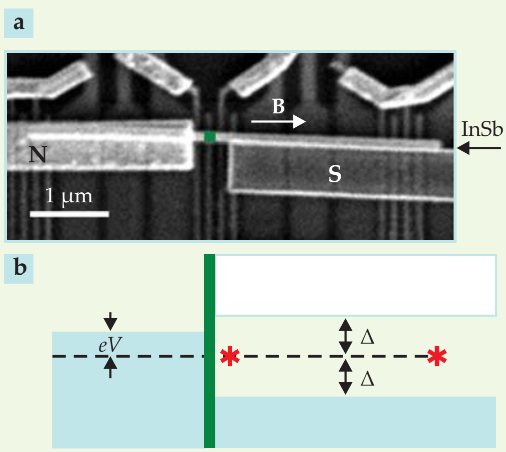

Figure 1. (a) A nanowire of semiconducting indium antimonide bridges normal-metal (N) and superconducting (S) electrodes in this micrograph of a circuit. A gate voltage establishes a tunneling barrier (green) at the interface between the semiconducting part of the wire and the part made superconducting by proximity to S. When a magnetic field **B** is applied parallel to the wire, two Majorana fermions are predicted to emerge as quasiparticles—one at that interface, the other at the end of the wire. **(b)** Normal-metal electrons (blue) can tunnel into the wire when the bias voltage *V* applied across N and S is greater than the superconducting gap Δ. But if a Majorana state (red star) exists at the barrier, electrons can tunnel into the wire's Fermi level (dashed line) at a bias voltage of zero. (Adapted from ref. 3.)

As quasiparticles go, the Majorana is incredibly featureless: It's chargeless, spinless, massless, and without energy. In his blog, Kouwenhoven's colleague Sergey Frolov describes it as being "as close to Nothing as anything can be." (Indeed, purists argue that "mode" or "state" is a better descriptor than composite "particle.") Yet the Delft experiment offers a deceptively simple way to find one: If the nanowire is connected between a gold contact and a superconducting one in a circuit, as outlined in figure 1, the appearance of a peak in the rate at which normal electrons are able to tunnel into a reservoir of Cooper pairs in the wire provides a direct test for the presence of a Majorana. That simplicity, though, belies some subtle physics and sophisticated materials engineering.

The excitement over Majorana quasiparticles largely lies in their potential as components of an eventual topological quantum computer. Majoranas bound to either a vortex or the endpoints of a wire obey a peculiar non-abelian quantum statistics that differs from that obeyed by ordinary fermions or bosons. In a superconductivity context, each Majorana is essentially half a fermion, which is why they must emerge as pairs. Together, the pair defines a qubit whose information is encoded not in the individual particles but in the pair's collective degrees of freedom. To the extent that the Majoranas are isolated from each other, the qubit is protected from local perturbations such as temperature and voltage fluctuations. (See PHYSICS TODAY, March 2011, page 20, and the article by Sankar Das Sarma, Michael Freedman, and Chetan Nayak, July 2006, page 32.)

Theoretical prescriptions

If all you needed to do to form a Majorana was mix particle and hole degrees of freedom, any superconductor would do. But in the 1990s Grigori Volovik realized that the zero-energy level required to harbor one exists only in an exotic form of superconductivity in which

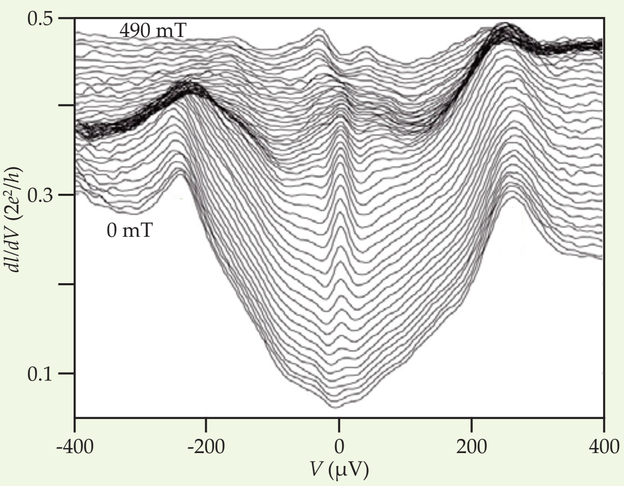

Figure 2. The differential conductance *dI/dV* of an indium antimonide nanowire, measured as a function of bias voltage V applied across normal-metal and superconducting electrodes. Each trace shows the conductance for a different magnetic field **B** parallel to the wire, increased in 10-mT steps. The peaks at ±250 μV reveal electrons spilling into the wire's conduction band above and below its superconducting gap. As **B** increases from 0 mT, a peak at zero voltage signals the emergence of a Majorana fermion inside the gap. At magnetic fields too high to sustain the superconductivity, the peak disappears. (Adapted from ref. 3.)

only electrons with the same spins can pair up. Few such *p*-wave superconductors exist, though, and arguably none are reliable. Strontium ruthenate could be an exception and host a Majorana in so-called half-vortex states (see PHYSICS TODAY, March 2011, page 17), but the status of that proposal remains unresolved. In any case, the trouble with conventional—and much more abundant—*s*-wave superconductors is that because of zero-point motion, their lowest available energy level sits above zero energy.

In 2008 theorists Liang Fu and Charles Kane from the University of Pennsylvania realized that one could engineer an artificial *p*-wave superconductor out of the *s*-wave options commonly available.[4] The trick was to attach the *s*-wave superconductor to a second material with large spin–orbit coupling. Thanks to the proximity of the two materials, Cooper pairs leak through the interface into the second material, which then inherits the superconductivity—at least over a coherence length that could be up to a few hundred nanometers. Crucially, the coupling of spin to orbit introduces a phase shift known as the Berry phase in the wavefunction of a periodic orbit; it shifts the lowest bound state down to zero energy and thus eliminates the usual zero-point energy. A similar Berry phase is responsible for the appearance of a Landau level at zero energy in graphene.

Kane had topological insulators in mind as the material with a large spin–orbit coupling (see the article by Xiao-Liang Qi and Shou-Cheng Zhang in PHYSICS TODAY, January 2010, page 33). Majoranas, he and Fu predicted, should nucleate on vortices formed at the topological insulator's two-dimensional surface. In 2010 the University of Maryland's Sankar Das Sarma and colleagues showed that a conventional semiconductor should work just as well—provided it has a pronounced spin–orbit coupling and a magnetic field is applied to make the band appear spinless.[5] It should also be easier to implement.

Later that year Das Sarma's group and another led by Yuval Oreg of the Weizmann Institute of Science in Israel made roughly the same bold prediction: Given a magnetic field parallel to a 1D wire of indium arsenide or indium antimonide in the proximity of a conventional superconductor, a pair of Majoranas would emerge as localized, midgap states at opposite ends.[6]

Experimental implementation

Kouwenhoven was immediately struck by the theory's simplicity; with few assumptions, it applies to noninteracting electrons. And the theorists' prescription aligned with his expertise. A few years earlier his postdoc Silvano De Franceschi had attached an InAs nanowire atop a superconductor and measured how an electrical supercurrent flowed through the interface.

Kouwenhoven set off to re-create that experiment, but with an InSb wire connected to a normal-metal gold electrode on one side of the circuit and a superconducting niobium titanium nitride electrode on the other (see figure 1). The appeal of NbTiN lay in its ability to superconduct in the presence of a high magnetic field.

The Delft researchers' experimental

geometry allowed them to spectroscopically probe the wire's density of states in the gap. Fortunately, the InSb wire abutting the edge of the NbTiN retained enough semiconducting character that a series of capacitively coupled gates could be attached to it. One gate voltage created a barrier through which normal gold electrons could tunnel into the wire; others acted as knobs to tune the wire's Fermi energy. The team then applied a bias voltage between the normal metal and superconductor and looked for a peak in the supercurrent conductance through the wire.

Usually, a normal electron cannot tunnel into a superconducting gap. But if a Majorana resides there, the electron can tunnel into that state, adding to the circuit's conductance. As shown in figure 2, the expected conductance peak appeared only when the bias voltage was tuned to zero, and it began to do so at a critical value of the magnetic field consistent with theory. What's more, the peak remained stubbornly pinned at zero bias voltage over a broad range of magnetic field intensities and gate voltages.

Must this be evidence for a Majorana? Kouwenhoven acknowledges that other physics, including the Kondo effect, antilocalization, and reflectionless tunneling, could give zero-bias features. His team systematically considered those in an effort to rule them out. Not everyone is convinced. But as Harvard University's Charles Marcus points out, "Showing that an idea is right is difficult, if not impossible, to do with a single experiment—much harder than showing that an idea is wrong—so the natural response to this important result will be a series of further refinements of both theory and subsequent experiments. This is just the start of the experimental program. Stand by for a lot more."

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Carbon dioxide drove the ending of the last glacial epoch

A worldwide assemby of proxy paleothermometers has addressed the disputed role of greenhouse gases in periodic deglaciations.

Antarctic ice-core records covering the past million years show temperature rising and falling with a principal periodicity of about 100 000 years, closely tracked by corresponding rise and fall of the atmospheric concentration of carbon dioxide. The Antarctic temperature troughs and peaks roughly mark the maxima and minima of successive epochal advances and retreats of ice sheets and glaciers in both hemispheres.

In common parlance, the intervals of extensive ice coverage are called ice ages. But geologists classify the entire Quaternary Period—from 2.6 Myr ago to the present—as an ice age because, unlike most of Earth's history, it has had year-round polar ice caps. It's thought that the timing of the Quaternary's 100-kyr cycle of glaciation and deglaciation is set by cycles of Earth's orbital and axial parameters due to gravitational nudges from other planets.

But the Antarctic ice-core data made it clear that CO_2 was somehow also intimately involved. Was the increasing CO_2 an important driving mechanism of the glacial retreats, or was it mostly just a consequence of those retreats? The question has obvious resonance for our time.

The Antarctic data, in isolation, seem to show CO_2 increase generally lagging temperature rise by a few centuries, thus suggesting that CO_2 may have been more a passenger than a driver. Indeed, that lag is often cited by critics of the argument that greenhouse gases contribute importantly to global warming. Retreating ice can, in fact, trigger events that lead to increased atmospheric CO_2, the most important of which are thought to involve warming of the carbon-rich depths of the Southern Ocean around Antarctica.

Now Jeremy Shakun and coworkers have put together a temperature record of unprecedented global scope and temporal resolution for the most recent deglaciation, which began about 20 kyr ago and leveled off 10 kyr later to initiate the present "interglacial" Holocene Epoch. They report that the newly constructed global record shows global mean temperature, unlike local Antarctic temperature, clearly trailing CO_2 increase during most of the last deglaciation.[1] (See figure 1.)

The team also used the global data to distinguish between warming in the Northern and Southern Hemispheres and thus reveal a plausible mechanism for why Antarctic temperature rise tends to precede the mean global rise. Then, attempting to fit various simula-

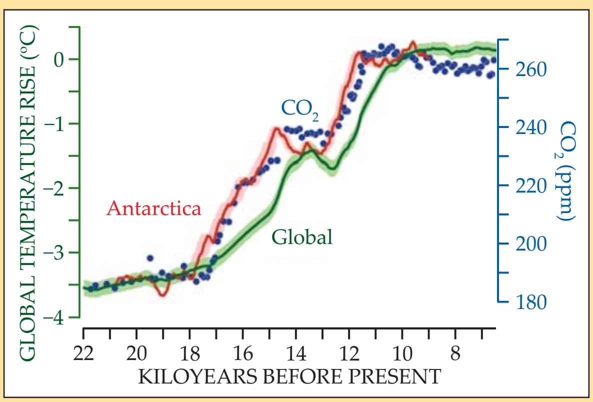

Figure 1. Global mean temperature, Antarctic temperature, and atmospheric CO_2 all rose dramatically during the great deglaciation that ushered in the present Holocene Epoch 10 000 years ago. Global temperature, as measured by proxy data from 80 core sites worldwide, is plotted as differences from the early-Holocene mean. The Antarctic temperature rise is scaled for comparison. During the periods of steepest warming, the CO_2 rise precedes the global temperature by several centuries, but it lags the Antarctic temperature. (Adapted from ref. 1.)