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Researchers propose a new method for verifying the existence of Majorana fermions

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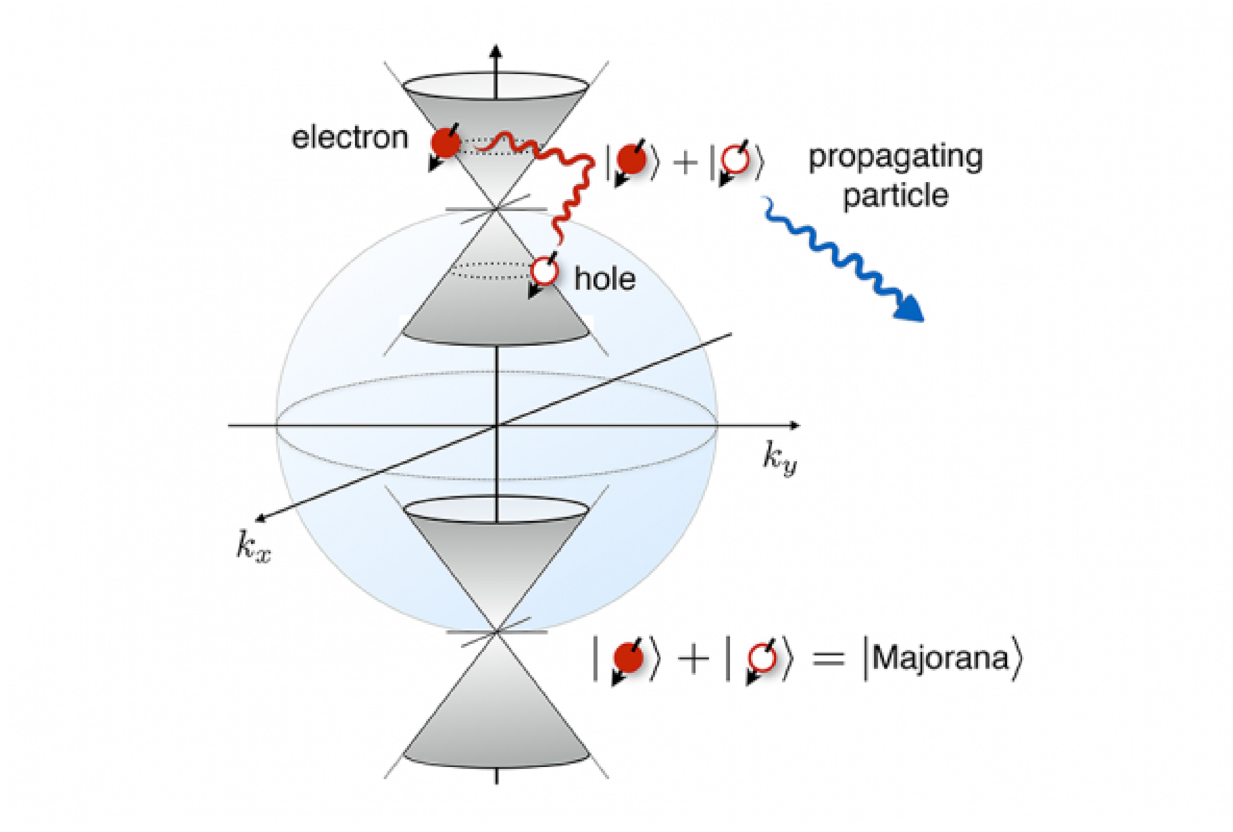

Physicists describe electrons by their energy, momentum, and spin. An electron can occupy a possible energy level, while an unoccupied level is called a hole. Here, a special electronic state called a Majorana fermion is shown as the sum of an electron and a hole that move freely. MIT Assistant Professor Liang Fu predicts this special state should occur near absolute zero temperature in a class of superconducting materials. Both electron and hole have the same spin (indicated by downward pointing arrows), a hallmark of Majorana fermions. Credit: Massachusetts Institute of Technology

A low-temperature material made from the elements praseodymium, osmium, and antimony should be able to host subatomic particles known as Majorana fermions, MIT researchers have shown in a theoretical analysis.

Majorana fermions, first predicted by physicists in 1937, can be thought of as electrons split into two parts, each of which behaves as independent particles. These fermions do not exist as elementary particles in nature but can emerge in certain superconducting materials near absolute zero temperature. In superconducting materials, electrons flow without resistance generating little or no heat.

The new analysis by graduate student Vladyslav Kozii, postdoc Jörn Venderbos, and Lawrence C. (1944) and Sarah W. Biedenharn Career Development Assistant Professor Liang Fu predicts this special state should occur in a praseodymium, osmium and antimony compound, $PrOs_4Sb_{12}$, and similar materials made of heavy metals.

Physicists describe electrons by their energy, momentum, and spin. An electron can occupy a possible energy level, and an unoccupied level is called a hole. In the new analysis, Majorana fermions emerge as a quantum superposition of an electron and a hole that move freely, with each having the same direction, or spin. This Majorana fermion spin can interact with the spin of atomic nuclei in the material, so it ought to be seen using nuclear magnetic resonance techniques, they predict.

"We address a certain class of superconductors, show that they have Majorana fermions as freely propagating quasiparticles in the bulk, and then look at how they can be detected and what other properties these materials have that one could use in the future for interesting functionality," says Venderbos. "I think it very nicely bridges the gap between experiment and theory and it can be used by experimentalists right now." Their paper was published this month in the journal *Science Advances*.

A key physics concept in this work is that of time-reversal symmetry. Such symmetry means that equations of motions governing an object or particle stay the same if one could reverse the direction of time—with time flowing backward rather forward. If the equation of motion of electrons in a material is different when time flows backwards—as is true in magnets, for instance—then time-reversal symmetry is said to be broken. This gives physicists an important way to distinguish different materials. In the proposed antimony-compound based superconductor, analysis shows that the Majorana fermions can only exist when time reversal symmetry is broken. Upon reversing the motion in time, the spin of the Majorana fermions is reversed—for example, from clockwise to counterclockwise—and this implies a different equation of motion for Majorana fermions going backward in time. "Regarding the material that we proposed, actually there is one recent experiment that confirms that time-reversal symmetry is broken in the superconducting state of this material. This reinforces our conclusion that it is indeed a very promising candidate for our theory to apply," Kozii explains.

Majorana fermions were first proposed by Italian physicist Ettore Majorana as a special mathematical solution for quantum behavior of electrons. Princeton University researchers reported detection of a zero-dimensional realization of these particles at the end of an atom chain in October 2014. The MIT theorists now show that the three-dimensional propagating Majorana fermions they predict are governed by Majorana's original equation. "The extensive study we have performed shows that this peculiar particle may now find its realization in solid state physics in a real material," Venderbos says.

Electrons in materials such as metals and semiconductors can fill only certain energy levels, or bands, with excluded, or forbidden, energy levels referred to as a bandgap. In a superconductor, this is also called the superconducting gap. Ordinarily, it takes outside energy in order to lift a lower energy electron to a higher energy level, especially when it has to cross a bandgap. The Fu groups' analysis of praseodymium, osmium, and antimony reveals that there are some special points in its electronic excitation spectrum where the bandgap vanishes in its superconducting state, which means that low energy excitations are possible. "However low energy you take, there will be always excitation at this energy. These excitations are exactly these Majorana fermions we were talking about," Kozii explains. Venderbos adds, "There are some excitations for which you don't have to put in any energy or just an infinitesimally tiny amount and you can still create the excitation."

Noting that Fu has made "some fantastic predictions in the past," Princeton University professor of chemistry Robert J. Cava, who was not involved in this research, suggests: "Experimentalists should listen to what he has to say. ... I am very happy to see that he and his coworkers have presented an analysis of real materials in which their ideas might be embodied."

Kozii, Venderbos, and Fu analyzed these unconventional superconductors for a year. For Kozii, the work will become part of his doctoral thesis.

The researchers hope their work will inspire experimentalists to look again at some previously studied materials to identify ones that host superconducting states with Majorana fermions. "I think the first step would be just to find a material in which everyone can agree that it has these Majorana fermions. That would be really exciting and constitute the discovery of a new type of superconductor in experiment," Venderbos says. "The next step would be to think about functionalization of these materials, what could be the specific applications." Trying to make quantum devices out of these materials is one possible direction. "We hope this research ultimately brings closer efforts from the quantum material and quantum device community in finding out the many facets of Majorana fermions," Fu adds.

More information: V. Kozii et al. Three-dimensional Majorana fermions in chiral superconductors, *Science Advances* (2016). DOI: 10.1126/sciadv.1601835

S. Nadj-Perge et al. Observation of Majorana fermions in ferromagnetic atomic chains on a superconductor, *Science* (2014). DOI: 10.1126/science.1259327

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