

ALS

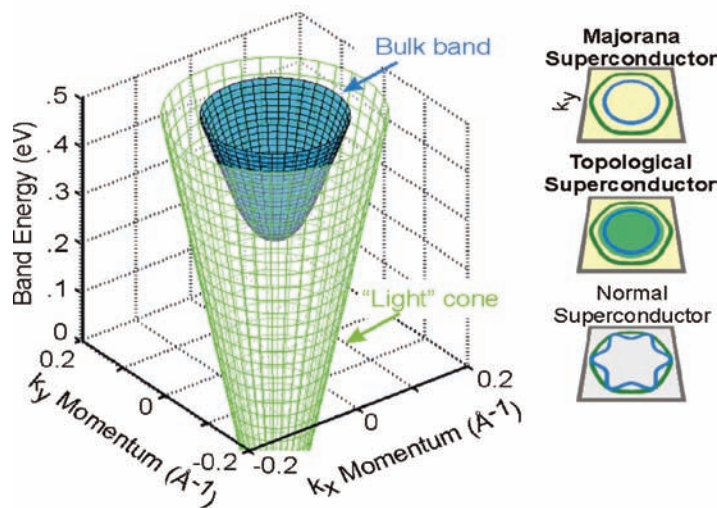
SCIENCE HIGHLIGHT

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# Superconducting Topological Insulators

Three-dimensional topological insulators (TIs), discovered experimentally in 2007–2009 by a Princeton–ALS collaboration, are a promising platform for developing the next generation of electronics. Electrons within one nanometer of a TI's surface move at high speeds in a “light-like” fashion. The quantum interactions that generate these electronic states cause individual electrons to be spin polarized even at room temperature and to strongly resist scattering from defects, naturally achieving some of the most desirable traits for computing components and next-generation “spintronics” technologies. More recent angle-resolved photoemission spectroscopy (ARPES) studies performed at ALS Beamlines 10.0.1 and 12.0.1 by the same collaboration have paved a way for these novel material properties to be taken even further. Their studies showed that by doping the TI, bismuth selenide, with copper, it's possible to make the topologically ordered electrons superconducting, dropping electrical resistance in the surface states all the way to zero.

It's been broadly known that electrons at the surface of a TI move with no mass, in a way that's mathematically equivalent to light (but 1000 times slower). In studies of copper-doped bismuth selenide, the researchers observed that electrons below the surface (in the



**Different laws of motion. Left: The energy vs. momentum relationship for electrons in topological insulators resembles either light (green mesh) or high-energy relativistic particles (blue mesh). Horizontal slices through the cone-shaped bands (right) show more detailed differences between the “topologies” of three types of superconductors. The researchers discovered that electrons deep inside the bulk of bismuth selenide gain mass as their speed increases (like relativistic particles), but electrons at the surface move at a constant speed regardless of their momentum (light-like). Thus, copper-doped bismuth selenide at very low temperatures (3.8 K) enters a state of matter never before seen, becoming either a Majorana superconductor or a topological superconductor.**

bulk) are also “nearly-light-like” and, in a table-top setting, exhibit relativistic effects such as mass dilation that are usually associated with particles approaching the speed of light in a building-sized particle accelerator.

The connection between TI electrons and the physics of special relativity may at first seem like a mere mathematical

oddy, but in fact it's critical to understanding the behavior of superconducting electrons for technological applications. Because of the light-like, spin-locked behavior of the electrons at the surface, it's impossible to describe superconducting behavior there using any standard theory. Based on this property and the number of points of quantum connectivity observed

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Research conducted by L.A. Wray (Princeton University and ALS); S.-Y. Xu, Y. Xia, Y.S. Hor, D. Qian, R.J. Cava, and M.Z. Hasan (Princeton University); A.V. Fedorov (ALS); and H. Lin and A. Bansil (Northeastern University).

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between different types of electrons in the material (a “topological” quantity), the researchers were able to establish that only two classes of theories can reasonably describe the superconducting behavior, each with novel physical properties that have been achieved in no other known material. Distinguishing between these theorized superconducting states of

## A Major(ana) Quantum Leap?

In the history of electronic materials, first there were magnets, then metals, then semiconductors, and eventually, superconductors. Each discovery brought with it new technologies. But because today's electron-based technologies are rapidly approaching the fundamental limits of their design, scientists are looking for ways to exploit quantum-entangled quasiparticles such as the still-theoretical "Majorana fermion" to encode information in more robust, efficient quantum computers.

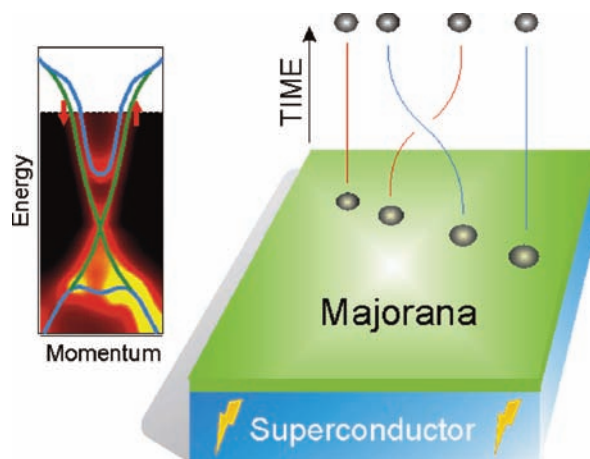
Topological insulators are the ideal nurseries for creating and manipulating Majorana fermions. In the last few years, experiments have verified the existence of this new state of matter. Building on those developments, Wray et al. have now shown that adding copper to a particular topological insulator makes it superconducting—a "topological superconductor" that could transform the way information is stored and processed, in low-power-consumption devices that are not only "green," but also immune to the overheating problems that befall current silicon-based electronics.

matter ("non-Abelian Majorana superconductor" and "topological superconductor") will require future nano-engineering and quantum measurements.

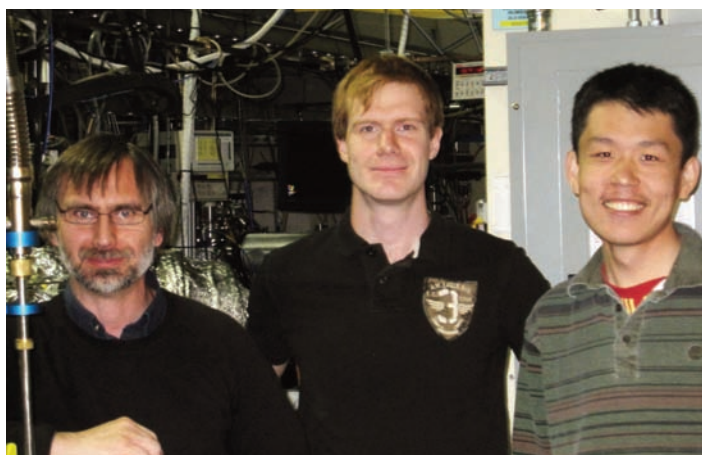
In addition to providing an incremental advance in material capabilities for technological applications, the unusual forms of superconductivity in TIs may in the future provide the basis for a whole new type of computer. If copper-doped bismuth selenide is the world's first non-Abelian Majorana superconductor, as seems most likely from current research, electrons on its surface will readily form stable vortices (whirlpools) with an intrinsic quantum memory of their positions relative to other vortices. By manipulating the relative positions of vortices, it's thought that the basic operations of quantum computing may be performed in a perturbation-resistant and fault-tolerant way. This property of quantum memory comes from the unusual laws of motion for topological electrons and is related

to a type of fundamental particle called a Majorana fermion that has been theoretically postulated but does not appear to exist naturally in the universe. By creating new laws of electronic motion different from those that exist anywhere else in normal matter, TI superconductors can cause electronic vortices on their surface to become Majorana fermions.

The successful introduction of superconductivity into a TI is a long-anticipated achievement, and the resulting novel properties, such as relativistic electrons and quantum memory, will undoubtedly provide the basis for ongoing device-development projects. In a larger context, these results begin to give a richer perspective on the broad range of new physical phenomena that can be achieved with TIs and are only a first step in exploring their applications under a wide range of physical environments including magnetic fields, electric fields, nanoscale interfaces, and various quantum-interacting systems.



**Quantum memory.** The quantum connectivity between surface (green) and bulk (blue) electronic states (left inset) in copper-doped bismuth selenide causes stable whirlpools of electrons on the surface to behave as exotic particles called Majorana fermions (gray circles). Majorana fermion vortices can intrinsically store quantum information and are a promising building-block for constructing a quantum computer.



Alexei Fedorov, Andrew Wray, and Suyang Xu at ALS Beamline 12.0.1.