Novel gate may enhance power of Majorana-based quantum computers

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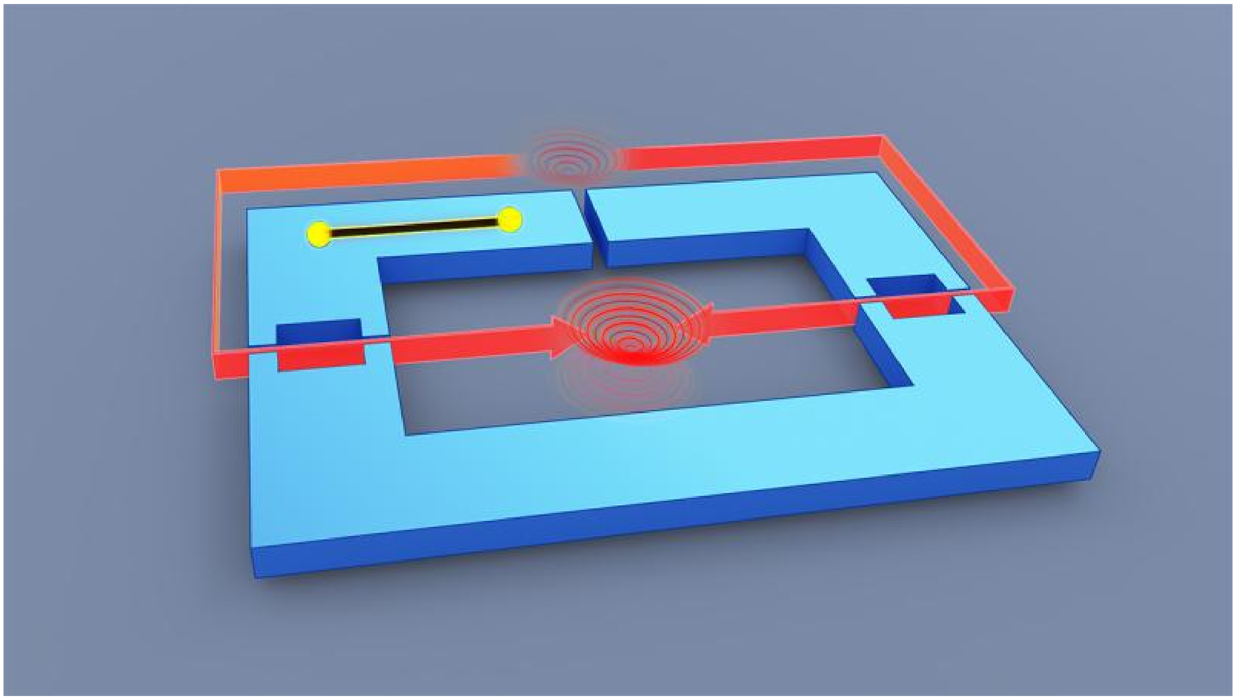


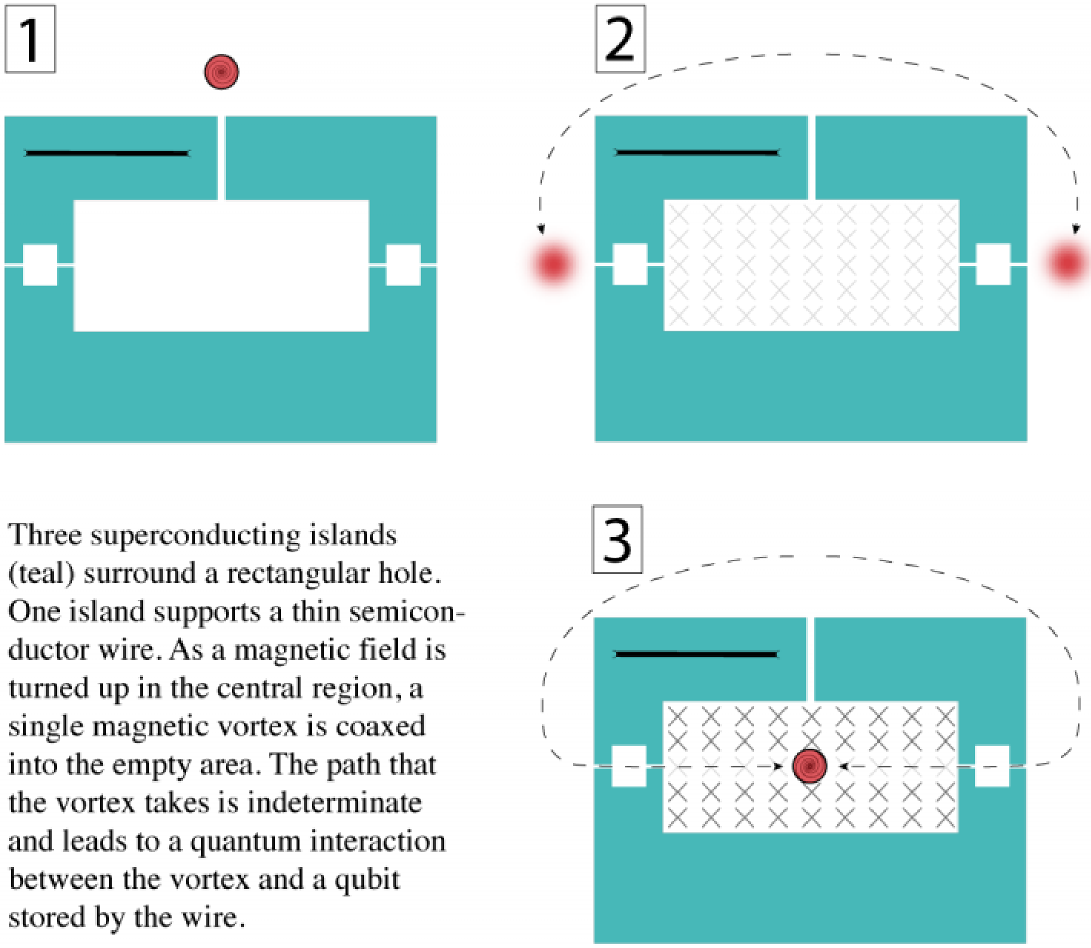
Credit: S. Kelley/NIST

Quantum computers hold great potential, but they remain hard to build because their basic components—individual quantum systems like atoms, electrons or photons—are fragile. A relentless and noisy background constantly bombards the computer's data.

One promising theoretical approach, known as topological quantum computing, uses groups of special particles confined to a plane to combat this environmental onslaught. The particles, which arise only in carefully crafted materials, are held apart from each other so that the information they store is spread out in space. In this way, information is hidden from its noisy environment, which tends to disrupt small regions at a time. Such a computer would perform calculations by moving the particles around one another in a plane, creating intricate braids with the paths they trace in space and time.

Although evidence for these particles has been found in experiments, the most useful variety found so far appear only at the ends of tiny wires and cannot easily be braided around one another. Perhaps worse for the prospect of quantum computing is that these particles don't support the full power of a general quantum computer—even in theory.

Now, researchers at JQI and the Condensed Matter Theory Center (CMTC) at the University of Maryland, including JQI Fellows Sankar Das Sarma and Jay Deep Sau, have proposed a way to dispense with both of these problems. By adding an extra process beyond ordinary braiding, they discovered a way to give a certain breed of topological particles all the tools needed to run any quantum calculation, all while circumventing the need for actual braiding. The team described their proposal last month in Physical Review X (link is external).



Three superconducting islands (teal) surround a rectangular hole. One island supports a thin semiconductor wire. As a magnetic field is turned up in the central region, a single magnetic vortex is coaxed into the empty area. The path that the vortex takes is indeterminate and leads to a quantum interaction between the vortex and a qubit stored by the wire.

The new proposal continues a line of research that began at JQI and CMTC in 2010. Two papers that year, co-authored by Das Sarma and Sau, were among the first to consider how to use Majorana fermions—exotic particles first theorized in 1937—as the foundation for a topological quantum computer. Those papers proposed both a platform for quantum computation using the particles and an experiment in which they might be found. Experimenters have since spotted signatures of the particles at the interfaces of certain materials—systems similar to those proposed by the JQI group.

Those interfaces are called upon again in the new work, which relies on the physics of a thin semiconductor wire placed atop a superconductor—a material that allows electrical currents to flow unhindered. The presence of the wire can change the quantum behavior of the superconductor in interesting ways.

"Normally, in superconductors, there is a barrier to having an odd number of electrons," says David Clarke, a postdoctoral researcher at CMTC and the first author of the paper. That's because in superconductors electrons are bound together in pairs. But, Clarke explains, adding a thin wire on top of a superconductor can create a refuge for single electrons. When a single electron occupies the wire, Majorana fermions are present at its two ends. And the presence or absence of the Majorana fermions stores one qubit—the fundamental memory unit of a quantum computer.

However, even if the Majorana fermions at the ends of wires were easy to braid around one another, they still would not support a universal quantum computer—a device capable of performing any quantum computation or simulating another quantum computer.

To get around this, Clarke and colleagues suggest using a quantum interaction between electronic charges and swirling vortices of magnetic fields that can be controllably introduced into the system. A phenomenon known as the Aharonov-Casher effect causes the quantum state of a charge—such as a Majorana fermion—to change when a magnetic vortex travels around it. Intriguingly, that modification is different if the vortex travels above the charge than if it travels below it.

In the paper, the team proposes a physical layout for using the effect in an experiment. As shown in the figure above, three superconductors—one with a semiconductor wire—surround a hole. In this empty region, the team imagines gently turning up a magnetic field. As the field increases, it draws in a single magnetic vortex, vacuuming it in through one of two junctions. Clarke says that he typically thinks of the vortices as coming from outside the superconductors, although their physical origin is in the junctions between superconducting islands.

Importantly, the process does not reveal which junction the vortex travels through. If it were possible to tell, the operation would not produce a useful quantum gate on the qubit stored in the wire. But because there is no way to tell which path it takes to enter the empty region, it must be treated as a quantum particle with a probability to take each. This quantum motion results in an interference between the two paths and produces a useful logic gate on the Majorana qubit.

The new gate—the details of which experimenters would tune by adjusting electrical controls—can be combined with those generated by braiding Majorana zero mode particles to do any arbitrary quantum calculation. The paper discusses how the proposal could be scaled up to include many qubits and even how to perform quantum computations in this system without actually doing any braiding. This relies on a "measurement-only" approach in which particles are swapped and braided by making sequences of measurements on neighboring qubits.

The team also notes that their method of gently turning up a magnetic field doesn't depend on the precise timing of any electrical signal, a feature that makes it immune to errors that afflict other proposals based on Majorana zero modes.

The team singles out one milestone as a first test of whether their technique works: creating verifiable entanglement between two qubits. "The ability to perform these non-braiding gates is necessary to allow quantum computation," says Clarke. "The test we propose goes a step further, and would show that the gate that has been produced is also sufficient for quantum computation, given braiding and measurement."

More information: David J. Clarke et al. A Practical Phase Gate for Producing Bell Violations in Majorana Wires, *Physical Review X* (2016). DOI: 10.1103/PhysRevX.6.021005

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