

The expanding search for Majorana particles

The reports in this issue about half-quantum vortices in strontium ruthenate (page 17) and about spin-orbit coupling in a nanowire (page 19) both involve a system in which theorists have proposed that one might find an elusive Majorana particle. A system of Majorana particles might be a good candidate for a topological quantum computer.

Before his mysterious disappearance in 1938, the young Italian theorist Ettore Majorana had modified Dirac's equations for spin- $\frac{1}{2}$ particles such as electrons and holes. In Majorana's modification, the creation and annihilation operators for particles are self conjugate and the resulting Majorana particles are their own antiparticles. To date, no one has identified a physical realization of those exotic objects, although neutrinos are leading candidates.¹ Others include supersymmetric partners of known bosons and constituents of dark matter.

Recently the search has broadened to include a number of solid-state systems. Some theorists have predicted that Majorana particles might emerge as composite particles, or quasiparticles, in interacting systems. Majoranas constitute a subset of the broader category of non-abelian particles that lie at the heart of topological computational schemes. As its name implies, topological computing expects to encode information not in individual particles but in the collective degrees of freedom of the particles, which depend on their physical arrangement on a surface. The hope is that such a scheme will be largely immune to perturbations from the local environment. Local interactions might distort the collective quantum state, much as one might stretch or skew a sheet of rubber, but the state's coherence should not be lost. (See *PHYSICS TODAY*, October 2005, page 21.)

Non-abelian particles do not obey the conventional statistics that define fermions and bosons. When one interchanges identical bosons, the wavefunction is unchanged. For fermions, it reverses sign. For abelian particles known as anyons, the exchange produces a phase that can assume any value. For non-abelian particles, however, the exchange takes the entire ground state into another of a set of n degenerate ground states, or a superposition of them. Imagine then representing a system of non-abelian particles by an n -dimensional vector whose components are the amplitudes for being in a given degenerate ground state. Moving from one state of the system to another (by exchanging two particles, for example) is equivalent to a matrix multiplication. In a non-abelian system, those matrices don't commute. That's precisely the property required for topological computing. If the matrices did commute, the logical operations would be too simple and they would not lend themselves to quantum computing.

The fractional quantum Hall (FQH) state, which has been a strong focus of the topological computation effort, manifests collective interactions whose excitations are composite fermions

with fractional charges. However, only the FQH state with filling factor of $\frac{1}{2}$ is expected to be a non-abelian system. (See the article by Sankar Das Sarma, Michael Freedman, and Chetan Nayak in *PHYSICS TODAY*, July 2006, page 32.)

A decade ago, Nicholas Read and Dmitry Green of Yale University recognized that the wavefunctions for a non-abelian state such as the $\frac{1}{2}$ FQH system are formally equivalent to those describing some forms of p -wave superconductor, in which electrons are paired in a spin-triplet state.² The non-abelian equivalency does not hold for all p -wave superconductors, only for chiral superconductors, in which all the electrons orbit each other either clockwise or counterclockwise. That picture of orbiting electrons is reminiscent of the cyclotron motion of electrons about magnetic field lines in the FQH state.

Majorana particles do not lurk in the bulk of the chiral p -wave superconductor but rather in the vortices that form when magnetic field lines penetrate the sample. In a quantum computer, the vortices would presumably form the qubits of information. Researchers are exploring whether a strontium ruthenate superconductor might be home to Majorana particles.³ The observation of half-quantum vortices, reported on page 17, is necessary but not sufficient to establish the existence of a chiral p -wave.

Another formula for getting Majorana particles is to sandwich a semiconductor whose conduction electrons manifest strong spin-orbit coupling between a ferromagnetic insulator and a conventional superconductor.⁴ The latter induces superconductivity in the semiconductor through the proximity effect. The interplay of spin-orbit coupling and magnetic field ensure that any induced superconductivity is p -wave and chiral.^{5,6} A simplification of that arrangement^{7,8} involves the indium arsenide nanowires described on page 19.

Yet another variant of these proposals for a heterostructure, which chronologically preceded them, is to interface conventional superconductors with topological insulators.⁴ The latter are solids in which there is no charge conduction in the bulk but only on the surface. (See the article by Xiao-Liang Qi and Shou-Cheng Zhang in *PHYSICS TODAY*, January 2010, page 33.)

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References

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spins on neighboring dots, thereby forming two-electron spin states. The qubit then consists of a double quantum dot, whose quantum state—singlet or triplet—can be rapidly controlled by voltage pulses⁷ (see *PHYSICS TODAY*, March 2006, page 16). Last year Princeton's Petta, along with Hong Lu and Art Gossard of UCSB, introduced a technique that enables control of a spin state as fast as 1.5 ns.⁸ In addition, Amir Yacoby and his collaborators at Harvard

University and at the Weizmann Institute of Science in Rehovot, Israel, have demonstrated techniques to extend the decoherence times for double quantum-dot qubits⁹ to values as long as 200 μ s. Charles Marcus and his colleagues at Harvard and at UCSB reported similar results.¹⁰

Nanowire qubits

The device built by Kouwenhoven and his team is shown in figure 1a. The elec-

trostatic potentials on five electric gates below the nanowire define two quantum dots, as shown in figures 1b and 1c. One dot is the qubit; the other is used for reading out the state of the qubit. The qubit operation scheme is depicted schematically in figure 1c. To initialize the information, the potentials are adjusted so that electrons can flow from one quantum dot to the next, but they do so one at a time and only if consecutive electrons have opposite spins.