The smallest particle collider

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New experiment finds direct evidence for anyons in a semiconductor heterostructure

The Standard Model of particle physics classifies all elementary particles as fermions or bosons. Fermions, such as electrons, avoid each other. Bosons, such as photons, can bunch. The classification rests on a fundamental spin-statistics theorem of quantum field theory. Yet, on page nnn of this issue, Bartolomei *et al*. report (1) an observation of particles that are neither bosons nor fermions.

The striking experiment in no way disproves the Standard Model. Indeed, the Standard Model deals with particles in three-dimensional space at the highest accessible energies. Experiment (1) deals with electric charges in two spatial dimensions at low temperatures. According to theory (2,3), in high magnetic fields, such two-dimensional systems can give rise to emergent anyon quasiparticles that are not bosons or fermions. One remarkable feature of anyons is their electric charge that can be less than the charge *e* of an electron (3). An even more interesting property is their quantum statistics. The statistics tells us what happens when identical particles exchange their positions or run in circles around each other. Bosons and fermions behave quite differently under particle exchange, but show no interesting behavior when one particle encircles another. This is not surprising, since after a full circle all particles return where they started. On the other hand, when one anyon encircles an identical particle, their long-range statistical interaction is expected to have a non-trivial effect (2,3).

An experimental observation of anyon statistics has proved to be a major challenge. The most natural approach is based on interferometry, in which anyons are made to run around each other. Promising results in that direction arrived a decade ago (4), but theoretical interpretation of interferometry data has run into difficulties. In an unexpected development, evidence for anyon statistics has recently come from thermal transport (5,6,7). Thermal transport has revealed non-Abelian anyons (2,3), which possess multiple locally indistinguishable quantum states. This property makes non-Abelian anyons ideal building blocks for a topological quantum computer (2) that would not need error correction and hence would require way fewer qubits than other approaches to quantum computing. Abelian anyons have no locally indistinguishable states. No direct experimental evidence of their statistics has been reported until the publication of this issue of *Science*.

The experiment (1) implements a theoretical proposal for an anyon collider (8). The device (1) resembles an elementary-particle collider but is much smaller in size and operates at much lower energies. Bartolomei *et al*. built a GaAs/AlGaAs heterostructure that confines electrons in two dimensions. The heterostructure was placed in a strong perpendicular magnetic field. This had two effects. First, the bulk of the heterostructure became a fractional quantum Hall insulator that hosts anyons of charge *e*/3. Second, chiral conducting channels formed along the edges of the heterostructure. The basic idea (1,8) of the experiment consisted in exploring a collision of two anyons, propagating along the edges. First, two dilute beams of anyons are created. This happens at two quantum point contacts QPC1 and QPC3. When electric charge, arriving from sources S1 and S2, reaches QPC1 and QPC3, quantum tunneling occurs across the contacts. Charge tunnels in the form of charge-*e*/3 quasiparticles. Next, tunneling particles reach contact QPC2. Quantum statistics enters the game, when two anyons approach QPC2 from two opposite sides. Consider first two identical fermions instead of anyons. The two fermions cannot reside in the same place. Hence, they would block each other from tunneling across QPC2. As a consequence, the fluctuations of the electric currents of fermions, collected in drains D3 and D4, are uncorrelated. Bosons, on the other hand, like bunching together. This would cause a correlation between the two drain currents. Abelian anyons are intermediate in their properties between fermions and bosons. A correlation of the two drain currents is thus predicted in an anyon system. The details of the correlation depend on the details of anyon statistics.

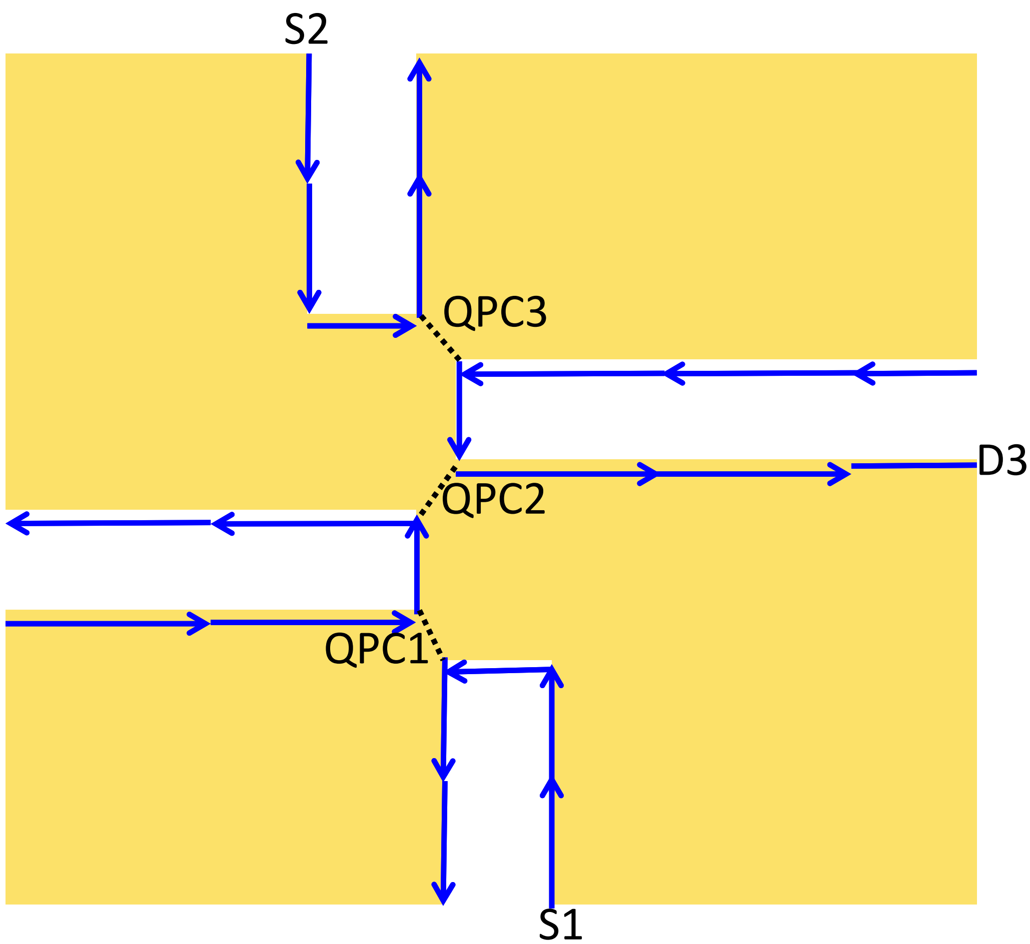

Fig. 1. Schematics of anyon collider. Quantum Hall liquid is colored yellow. Dotted lines represent anyon tunneling. Arrows show the charge propagation directions along the edges.

The experiment (1) shows excellent agreement with the theory (8) for Laughlin anyons (3). This gives experimental support to long-predicted anyon statistics of quasiparticles in fractional quantum Hall liquids, but also brings a surprise. Indeed, the calculations in Ref. (9) are based on the simplest model of edge channels (the chiral Luttinger liquid model) that often fails to quantitatively describe experimental data (3). It is tempting to think that the observed signature of anyon statistics has a deep reason that goes beyond a particular model. Indeed, this happens with a related non-equilibrium fluctuation-dissipation theorem, which was first discovered in the simplest model but applies very generally (9).

Extending the experiment (1) to other types of Abelian and non-Abelian anyons would be of great interest, as would be other probes of anyon statistics. Recent progress includes a new approach to interferometry (10) and the extension of the thermal conductance technique to graphene (11). Such advances may eventually contribute to the development of topological quantum computing. They are also of interest to basic science: The search for the smallest particles in the Universe has long been a central quest in physics. In terms of their charge, quantum Hall anyons are the smallest known particles.

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