Fractionally Charged Quasiparticles Signal Their Presence with Noise

To particle physicists, the electron is the quintessential example of an elementary particle: The highest energy experiments to date have revealed no evidence of any internal structure, no evidence that an electron is made up of some other, more fundamental components. But for condensed matter physicists studying the behavior of matter at low temperatures in semiconductor crystals, electrons can play by a different (although ultimately equivalent) set of rules. The fractional quantum Hall effect, for example, can be explained by invoking quasiparticles, which behave like distinct particles that each carry a fraction of an electron's charge. (On a more fundamental level, quasiparticles are collective excitations of interacting electrons.) Two recent experiments in Israel and France have added to the evidence that these quasiparticles exist.[1,2]

Two experimental groups have detected the distinctive pitter-patter of quasiparticles with charge $e/3$ tunneling across a narrow region of a fractional quantum Hall system.

The Israeli and French groups observed the noise produced by quasiparticles in fractional quantum Hall systems. An ordinary electrical current has tiny fluctuations, or noise, because the current is carried by discrete electrons, each of which has charge e and travels independently of the others. A common analogy for this noise is the sound of hail clattering on a tin roof[3]—imagine that all the hailstones, having been produced in the same atmospheric conditions, have identical mass. In the quantum Hall systems of the two experiments, the current is carried by quasiparticles with charge $e/3$ tunneling through a narrow barrier. The noise that is measured has all the characteristics expected for such smaller carriers, just as the noise of hail on a roof differs if the ice falls in the form of three times as many hailstones one-third as big. (See upper figure on page 18.)

The Israeli group consists of Mordehai Heiblum, Michael Reznikov, Rafael de-Picciotto, Vladimir Umansky, Diana Mahalu and Gregori Bunin, all at the Weizmann Institute of Science.[1] The French group consists of D. Christian Glattli and Laurent Saminadayar at the CEA Center of Saclay and Yong Jin and Bernard Etienne at the CNRS Laboratory of Microstructures and Microelectronics in Bagneux.[2]

The world's quietest amplifier

A major difficulty is that the extremely low shot noise (occurring in a current of about 10^{-10} amps backscattered from the barrier) has to be amplified, but amplifiers add their own noise. To minimize the unwanted noise, the Israeli group grew its own extremely high-quality gallium arsenide transistors, from which they built their amplifiers. "We thus obtained the quietest amplifiers, at the 4–10 MHz range, in the world," Heiblum said. The Israeli data consequently has negligibly small error bars.

The French group, having noisier amplifiers, fed its signal into two amplifiers and took only the correlated noise of the two outputs—the noise generated by each individual amplifier, and by electrical leads and contacts, is not correlated. Some other contributions from the circuit to the correlated noise add a constant background, provided certain experimental parameters are not varied during the measurements.

The French experimenters, although having less precise data, used a somewhat different sample geometry (see lower figure on page 18) that allowed them to show "a perfect resonance in the tunneling," Glattli said. Thus, they confirmed that the tunneling was coherent and occurred in a single step, which ruled out the possibility that hopping or multiple tunneling was mimicking quasiparticles by reducing ordinary electron noise by a coincidental factor of three.

The results are not the first experimental indication of fractionally charged quasiparticles occurring in fractional quantum Hall systems. In work carried out in 1994, Vladimir Goldman and Bo Su (State University of New York at Stony Brook) studied

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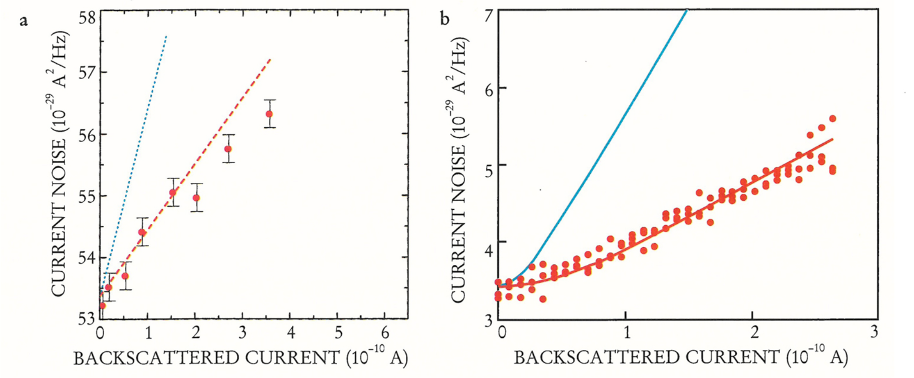


SHOT NOISE produced by quasiparticles. **a:** Data at 25 mK has the linear form of Schottky noise, with the right slope (red line) for charge $e/3$. Blue line has the slope expected for electron tunneling. (Adapted from ref. 2.) **b:** Data at 57 mK, with theoretical curves for carriers of charge $e/3$ (red) and e (blue). The slope at high currents and the position of the curve's knee are independent tests of the carrier charge. (Courtesy of Rafael de-Picciotto and Michael Reznikov.)

resonant tunneling through states around a quantum antidot, a submicrometer-sized island within the fractional Hall system that is depleted of electrons.[4] The results indicated that the charge near the island changed in steps of $e/3$. Similar samples were investigated independently by John Franklin, Christopher Ford and coworkers at the University of Cambridge.[5] It has been argued, however, that an experiment of this type “measures the average charge per state in the [island] region”[5] and that it “probes the fractional filling of the ground state.”[2] Goldman disputes this view,[6] and many others agree that he observed fractionally charged quasiparticles entering or leaving the region near the antidot. Nonetheless, the Israeli and French observations of shot noise, being a signature of individual particles carrying a current through the constriction, are important direct evidence of the quasiparticles behaving as dynamical entities.

Laughlin quasiparticles

The integer and fractional quantum Hall effects occur in a two-dimensional electron system, in a cryogenically cooled semiconductor in a strong magnetic field. The electrons' quantized energy states are equally spaced Landau levels, with each level capable of holding one electron per magnetic flux quantum ($\Phi_0 = h/e$). The ratio of electrons to flux quanta is the filling factor ν, and the integer quantum Hall effect occurs at integer values of ν—the exactly filled Landau levels act as an incompressible fluid, with an energy gap to the next available state.

The clearest case of the fractional quantum Hall effect occurs when the magnetic field is so strong there are three flux quanta for each electron. Thus, the first Landau level is only one-third full ($\nu = 1/3$). Robert Laughlin, now at Stanford University, explained the fractional quantum Hall effect by showing that there is a many-body wavefunction that acts as an incompressible fluid at $\nu = 1/3$. (See the article by Philip Anderson in PHYSICS TODAY, October, page 42.) Elementary excitations of such a fluid occur when one flux quantum is added or removed, resulting in a charge imbalance of $e/3$—a quasiparticle.

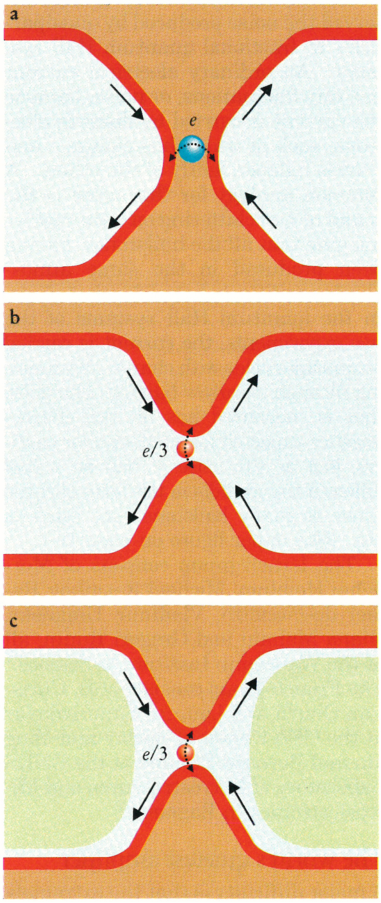
In the (two-dimensional) bulk of such a fractional Hall system, the quasiparticles generally don't carry a net current, but at the boundary of the system they form edge states that are free to move in one direction around the perimeter. (See PHYSICS TODAY, September 1996, page 19.)

Tunneling

How can all this be put together to study a current carried by quasiparticles? The figure at right shows the key features of the sample geometry, which was suggested by Charles Kane (University of Pennsylvania) and Matthew Fisher (University of California, Santa Barbara) a few years ago. The blue regions are a two-dimensional electron fluid with filling factor $1/3$. A current can be carried in edge states along the red boundaries. In the geometry shown in part a, current can flow between the two edges by means of electrons tunneling across the barrier. Quasiparticles cannot tunnel across because the quasiparticle wavefunction goes completely to zero on the isthmus of depleted semiconductor that separates the two lakes of $\nu = 1/3$ fluid. The geometry shown in part b, however, allows tunneling by quasiparticles, because they can flow across the straits of the bulk fractional Hall region. Furthermore, the tunneling of whole electrons is negligible.

In the French experimenters' modified geometry (shown in part c), the bulk of the Hall fluid is at $\nu = 2/3$ (green), and only the constricted saddle region is at $\nu = 1/3$. As mentioned earlier, this gives them greater control in verifying the coherent nature of the tunneling taking place.

The tunneling current contributes to what is known as the backscattered current, and generates shot noise that can be observed. At zero temperature, the shot noise S is predicted by the



TUNNELING GEOMETRIES. **a:** In this configuration, only electrons (blue sphere) can tunnel across a depleted isthmus between the current-carrying edge states (red) of two regions of $\nu = 1/3$ fractional quantum Hall electron fluid (blue). **b:** A quasiparticle of charge $e/3$ (red sphere) can tunnel through a narrow strait of $\nu = 1/3$ quantum fluid. **c:** By using a smaller region of $\nu = 1/3$ within a larger expanse of $\nu = 2/3$ fluid (green), the detailed coherence properties of the tunneling process can be verified. (Parts a and b adapted from ref. 3.)

Schottky formula to be $S = 2qI_B$, where q is the charge of the carriers and I_B is the backscattered current. As the temperature is increased to exceed the applied voltage (that is, $kT > qV$), the form of the noise crosses over to the more complicated Johnson–Nyquist formula.

Results

Part a of the upper figure on page 18 shows the current noise versus backscattered current measured at a temperature of 25 mK by the French group. The noise, measured in a frequency range of 4 to 8 kHz over a time of 25 minutes, is well fit by Schottky noise with slope appropriate for particles of charge $e/3$. Analogous measurements for the $\nu = 4$ integer quantum Hall state yielded data closely fit by Schottky noise of whole electrons. Glattli suggested that the deviation at higher currents is due to the quasiparticles' statistics, which can be expected to be anyonic—intermediate between bosonic and fermionic.

Part b of the same figure shows data taken by the Israeli group at 57 mK, along with curves for Johnson–Nyquist noise due to particles of charge $e/3$ and e. (The French researchers also have data analogous to this, but with error bars and background levels comparable to their data in part a.) The noise was measured near 4 MHz and, because of the much lower levels of amplifier noise, integration times of about 5 seconds could be used.

A natural extension for both groups will be to study the noise at other filling factors. The Israeli group, for example, saw clear quantum Hall plateaus in its samples at $\nu = 2/5$, $3/5$ and $2/3$, but has not yet studied the noise of any of these. At $\nu = 2/5$, both the current and the quasiparticle charge ($e/5$) will be smaller, making the sensitivity of the measurements even more critical. In addition, contributions from $e/3$ quasiparticles at $\nu = 2/5$ may further complicate the analysis. (Goldman published measurements of $e/5$ charges at $\nu = 2/5$ using the quantum antidot system in 1996.[7])

Physics in quantum Flatland

How "real" are the quasiparticles that these groups have detected? Theorist Steven Girvin of Indiana University points out that Laughlin's theory doesn't just explain the fractional quantum Hall effect, rather it demonstrates that the effect *requires* that such quasiparticles exist. He stresses that a quasiparticle can be pinned at a definite location, and because its state is then completely determined by the location (there is no degeneracy), the behavior is just as for an elementary particle.

Girvin offers the charming analogy of life near absolute zero in a quantum Hall Flatland: "Flatland particle theorists decide that the apparently featureless vacuum in which everyone lives each day is actually a roiling sea filled with strange but invisible objects that have precisely three times the charge of an ordinary quasiparticle. To study this possibility, a Flatland high-energy particle accelerator is constructed that can reach the unprecedented energy scale of 10 K. Upon smashing together three charged particles, it is found that they do indeed temporarily coalesce into an object with the bizarre property of having charge $3q$. It is decided to name this short-lived object the electron."

"If the gap were 10 GeV instead of 10 K," Girvin says, "we (living at room temperature) would have no trouble accepting the concept of fractional charge."

Graham P. Collins

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Tunneling Experiments in High-T_c Superconductors Resolve a Puzzle

Like the pea that disturbed the sleep of the fairy-tale princess, a Josephson tunneling experiment upset the consensus favoring a d-wave pairing of the electrons in high-temperature superconductors. Further studies of the tunneling behavior have now resolved the discrepancy.

A key question regarding high-temperature superconductors has been the nature of the pairing state of the electrons responsible for the supercurrent: Do the electrons couple in an s-wave state, as in conventional superconductors, or in a d-wave state, specifically $d_{x^2-y^2}$, whose wavefunction resembles a four-leaf clover. The argument was largely settled in favor of d-wave symmetry when several precise experiments were able to sense the phase of the electron-pair wavefunction and found that it changed signs, suggestive of the alternating positive and negative lobes of the d-wave clover leaf. But not all the evidence lined up: One study of the Josephson tunneling by Robert Dynes and his colleagues at the University of California, San Diego, simply wasn't compatible with a d-wave interpretation.[1]

By a clever twist on the original tunneling experiment, the situation now appears to be resolved in favor of a d-wave, with some admixture of s-wave.[2] To conduct this new measurement, Dynes and his San Diego group teamed with John Clarke and others at their sister institution in Berkeley. They performed separate but similar experiments using crystals grown both by Brian Maple and his group at San Diego and by Don Ginsberg and his team at the University of Illinois at Urbana–Champaign.

The view along the c axis

All of the early phase-sensitive studies of the electron-pairing state in the high-T_c copper oxide materials had probed these materials in the plane containing the copper and oxygen atoms—that is, the ab plane. In their 1994 experiment, the San Diego group looked in a different direction: along the c axis, perpendicular to the ab planes.

Specifically, Dynes and his group measured the Josephson pair tunneling current along the c axis from conventional lead superconductors across thin insulating layers into crystals or thin films of yttrium barium copper oxide, commonly called YBCO. Lead is an s-wave superconductor, so the researchers expected to see a tunneling current only if the YBCO were also in an s-wave state; if the YBCO were in a d-wave state, tunneling from the positive lobe would cancel the tunneling from the negative lobe. The experiment came down on the side of s-wave symmetry.

The picture of the pairing state in YBCO is not quite so simple, however. In YBCO, the lattice is orthorhombic—that is, the lattice spacings are slightly