second term plays the same role as the vector potential term in the AB effect.

Generalizing the effect

Goldhaber and Anandan independently have observed that the motion of a nonrelativistic neutral particle with spin through a classical Maxwell field is identical to that of a spinless particle carrying isospin in the presence of a particular classical Yang–Mills field. Goldhaber feels that this analogy is interesting both pedagogically, because it gives a way to visualize the influence of this new kind of field in more familiar terms, and computationally, as the non-Abelian gauge invariance permits transforming the equations of motion in ways that simplify their solution.

Anandan has covariantly generalized the effect to include magnetic as well as electric fields.[9] In his generalization not only does the $\boldsymbol{\mu}\times\mathbf{B}$ term play the role of the vector potential, as in the counterpart to the AB effect, but the $\boldsymbol{\mu}\cdot\mathbf{B}$ term takes the part of the phase shift from the electric scalar potential.

—BARBARA GOSS LEVI

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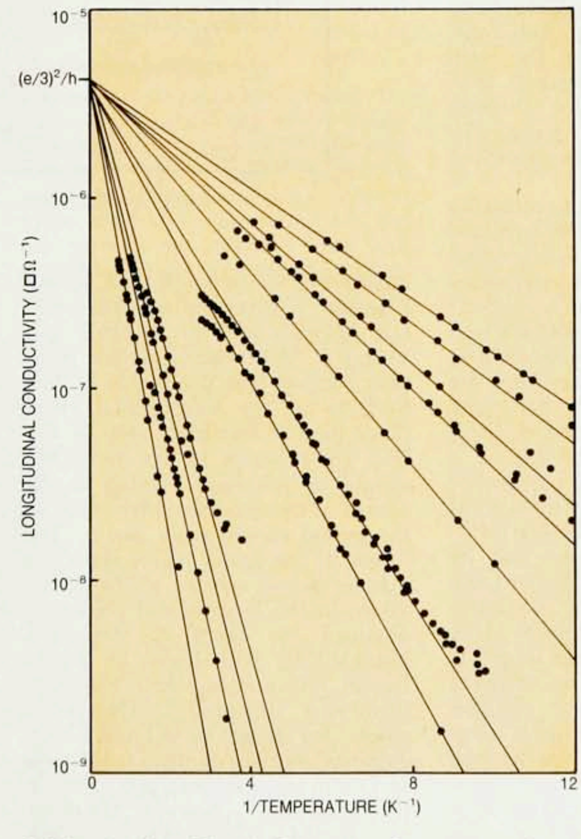
EXPERIMENTS PROVIDE EVIDENCE FOR THE FRACTIONAL CHARGE OF QUASIPARTICLES

In the fractional quantum Hall effect, the Hall conductance is quantized. In the most common manifestation of the effect, which was first observed in the two-dimensional electron gas sandwiched between the semiconducting layers of a GaAs–AlGaAs heterostructure, the magnetic field dependence of the Hall resistance shows an ascending-staircase-type behavior with increasing field strength. The steps in the staircase correspond to Hall conductance values of the form $(p/q)e^2/h$, and they occur around the magnetic field values for which the number of electrons per magnetic field quantum is p/q, with p and q integers and q usually odd.

The Hall conductance of a two-dimensional electron gas in a strong magnetic field is quantized, according to the theory of the effect developed by Robert Laughlin (Stanford), because the ground-state energy of such a gas has minima at magnetic field values corresponding to q/p flux quanta per electron—that is, at field values at which the steps in the Hall conductance occur. For magnetic field values between the steps in the Hall conductance, however, the electron gas, according to the Laughlin theory, has the intriguing feature that it may be described in terms of excitations, or quasiparticles, with a charge that is a rational fraction of the electron charge $-e$. (The excitations are about the minimum-energy states, called the incompressible quantum liquid states—which occur, as already pointed out, at field values corresponding to q/p flux quanta per electron.) Specifically, as discussed by Duncan Haldane (University of California, San Diego), for magnetic field values near a p/q step, the electron gas may be described in terms of quasiparticles or quasiholes of charge $\pm e/q$.



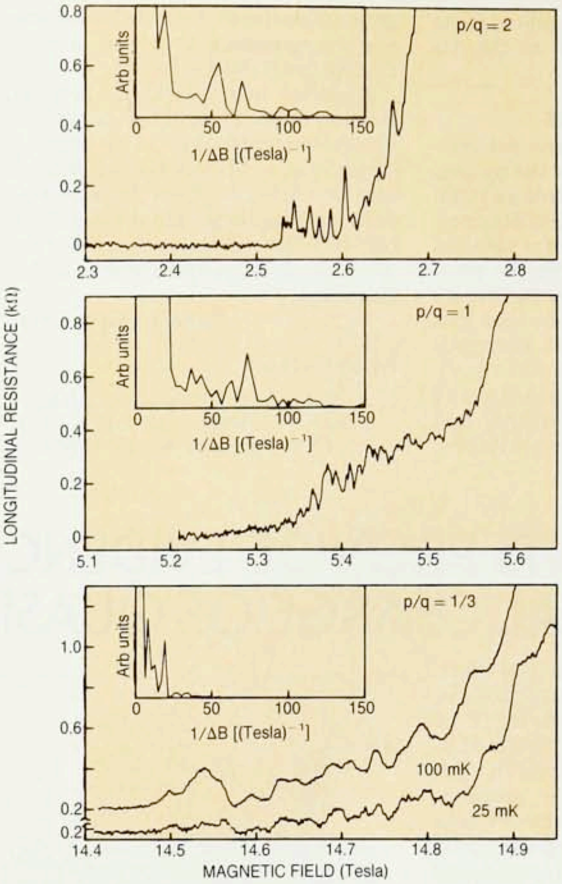
Intercepts of the longitudinal conductivity at infinite temperature have the value $(\frac{1}{3}e)^2/h$ for magnetic fields near the Hall conductance steps $\frac{2}{3}$, $\frac{4}{3}$ and $\frac{5}{3}$ in several high-mobility samples. Similar data[1] for Hall steps p/q with $q = 5$, 7 and 9 give a value of $(e/q)^2/h$ for the intercept. At integer steps, where the transport is by electrons, the intercept is e^2/h. The q dependence provides striking evidence that the charge transport occurs through quasiparticles of charge $\pm e/q$. (Courtesy of Robert G. Clark, University of Oxford.)

Three experiments in the past two years have provided evidence for the fractional charge of quasiparticles. Two of those experiments probed the behavior of the longitudinal resistance (the resistance in the direction of the applied electric field) at magnetic field values in the vicinity of the steps, because the quasiparticles are expected to be responsible for the transport of charge at those field values. The third experiment probed electron transmission and reflection coefficients between two adjacent samples of the two-dimensional electron gas that were in different minimum-energy states.

The first of the two experiments to probe the longitudinal resistance extrapolated the value of that resistance to very high temperatures.[1] Robert G. Clark, Jenny R. Mallett and Simon R. Haynes (all from Oxford University) and Jeffrey J. Harris and C. Thomas Foxon (Philips Research Laboratories, Redhill, UK) measured the temperature dependence of the longitudinal resistance at several Hall conductance steps. The longitudinal resistance shows a minimum at the Hall steps, and the minimum value is expected to be identically zero at zero temperature. The Oxford–Philips researchers fitted the measured temperature dependence of the resistance minima to the activated form $\rho_{xx}(T) = \rho_{xx}(\infty)\exp(-\Delta/T)$, where Δ is the energy required to excite quasiparticles. They found that the longitudinal conductance at high temperatures, which can be easily obtained once $\rho_{xx}(\infty)$ is known and the value $(q/p)h/e^2$ is used for the Hall resistance, could be fitted to the form $\sigma_{xx}(\infty) \simeq (e/q)^2/h$, suggesting that charge transport occurs through quasiparticles of charge $\pm e/q$. (Selected conductance data are shown in the figure on page 19.)

The second experiment to probe the longitudinal resistance determined the frequency of the random-noise-like oscillations in the resistance when the magnetic field is varied.[2] The conductance of a small electron system placed in a magnetic field at low temperatures fluctuates when the magnetic field is varied. For weak magnetic fields, the period of these fluctuations depends on—and is a measure of—the phase coherence length, according to the theoretical ideas developed by Patrick Lee (MIT) and Douglas Stone (Yale) and by Dimitri Khmel'nitzkii (Landau Institute, Moscow) and Boris Al'tshuler (Leningrad Institute of Nuclear Physics). (The phase coherence length is the distance over which the phase of the electron wavefunction changes significantly due to *inelastic* electron–electron and electron–phonon scattering.) The conductance fluctuations have universal amplitude e^2/h for samples of size comparable to the phase coherence length. (See the article by Richard Webb and Sean Washburn in PHYSICS TODAY December 1988, page 46.)

The conductance fluctuations at the very high magnetic fields at which the quantum Hall effect sets in are not very well understood. But theoretical ideas discussed by Lee, by Jainendra Jain (State University of New York, Stony Brook) and Steven Kivelson (University of California, Los Angeles) and by Kivelson and Valery L. Pokrovsky (Landau Institute) suggest that the period of fluctuations in the longitudinal resistance near a fractional step in the Hall conductance of the form p/q should be inversely related to the charge of the quasiparticles—that is, the period should scale like q. The insets in the figure above show the Fourier power spectra of the fluctuations in the longitudinal resistance obtained by Jerry A. Simmons, Hsuang-Ping Wei, Lloyd W. Engel, Daniel Tsui and Monsour Shayegan (Princeton University). The power spectra for integer steps 1 and 2 show dominant periods of about 0.014 tesla and 0.016 tesla, respectively. For the fractional step $\frac{1}{3}$, however, the dominant period is 0.05 tesla to an accuracy of 25%. The limited data the Princeton group has so far reported therefore provide stong evidence that the magnitude of the charge of quasiparticles around a $1/q$ step in the Hall conductance is e/q.



Resistance in the direction of current flow, near the Hall-conductance steps 2 (top), 1 (middle) and $\frac{1}{3}$ (bottom). The insets show the corresponding Fourier power spectra. The dominant frequency in the power spectrum for the $\frac{1}{3}$ step is smaller by almost a factor of three than the dominant frequency in the spectrum for each of the two integer steps. (Adapted from ref. 2.)

In the third experiment reporting evidence for the fractional charge of quasiparticles,[3] Albert M. Chang and John E. Cunningham (AT&T Bell Labs, Holmdel, New Jersey), prepared, by adjusting the strength of the magnetic field, a sample of the two-dimensional electron gas in a $p/q = 1$ state. They then diminished the electron density in a well-defined part of this sample by applying a negative bias above that region. They reduced the electron density in the diminished-density region so that the Hall conductance of the region was $\frac{1}{3}e^2/h$—that is, so that the electron gas in that region was in a minimum-energy state corresponding to the $\frac{1}{3}$ step in the Hall conductance. From measured values of the resistances between the $p/q = 1$ and $p/q = \frac{1}{3}$ regions of their sample, Chang and Cunningham obtained a transmission probability of $1/3 \times (1.013 \pm 0.010)$ and a reflection probability of $2/3 \times (0.993 \pm 0.008)$ between the two electron liquids. An interpretation of these values by Allan MacDonald (Indiana University, Bloomington) yields a charge of $-\frac{1}{3}e$ for the quasiparticles in the $p/q = \frac{1}{3}$ electron liquid. Chang and Cunningham have also obtained values for transmission and reflection probabilities between the $p/q = \frac{2}{3}$ and $p/q = 1$ electron liquids. But the data in that case may be interpreted two ways; only one of the two interpretations identifies the quasiparticles in the $^2/_3$ liquid as having a charge of $^1/_3 e$.

—ANIL KHURANA

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EARTHQUAKE JOSTLES THE NEW STANFORD LINEAR COLLIDER

On 12 October the Stanford Linear Accelerator Center announced its finding that Nature has only three families of elementary particles.[1] (See PHYSICS TODAY, October, page 17) Five days later, as if in anger at having its secret revealed, Nature shook the offending instrument—the recently completed Stanford Linear Collider—by the throat. All things considered, the SLC has suffered relatively little damage from the historic earthquake that struck the San Francisco Bay area at 5:04 pm on 17 October. Still, the small misalignments caused by the quake have interrupted the physics schedule of the collider for more than a month. As of this writing, the fond expectation at SLAC is for "a few more Z^0"s by Christmas."

The earthquake occurred one day after the beginning of a scheduled collider shutdown, during which vertex detectors were to be installed in the large Mark II detector that surrounds the point where the accelerator's electron and positron beams collide. The quake, whose epicenter was some 30 miles south of SLAC in the Santa Cruz mountains, shook the laboratory violently for 15 harrowing seconds. As SLAC spokesman Michael Riordan described the scene, "People dashed for doors or dove under desks to avoid the hail of books, ceiling tiles and other falling objects. Physicists standing on top of a teetering endcap of the partially assembled SLD detector [which will eventually replace the venerable Mark II] clung to its railing, hoping that this 50-foot-high upright iron slab would not topple to the concrete floor. A hapless technician suspended in a bucket from the overhead crane swung helplessly above the gaping pit as the hundred-ton crane rocked back and forth in its tracks."

But the SLAC Earthquake Safety Committee had done its job well. Aside from a few cracks and leaks there was no major gross damage, and no one was injured. The proper functioning of the Stanford Linear Collider, however, depends on the very precise alignment of its two-mile-long linac, with tolerances on the order of 100 microns, and on equally precise positioning of the bending magnets in the two great arcs that bring the electron and positron beams from the end of the linac into head-on collision. Though there were no gross disruptions to be seen in this complex array of rf cavities and magnets after the quake, there were clearly a number of small displacements that would have to be put right before the SLC could resume doing physics.

High-energy geology

The linac rests on bedrock, except for a small region of fill, where subsidence had been observed in the past and dealt with by means of built-in jacks. The laser-beam survey undertaken after the quake found a $^1/_2$-cm dip in this fill region. That was straightened out in short order. More surprisingly, a shift of about 1 cm was found near the downstream end, in a place where the linac sits on 25-million-year-old Miocene sandstone. Nearby, there were fresh cracks in the wall. "We had rediscovered an obscure hairline fault," Riordan told us. "This is the first time anyone has done geology with a high-energy linac."

At this fault line, the end of the linac, together with the entire SLC arc structure, had in fact shifted by more than a centimeter relative to the rest of the linac. The distorted linac sections had to be reconfigured into a smooth curve. Nonetheless, four weeks after the earthquake, electron and positron beams were once again emerging from the linac into their respective collider arcs with emittances (the product of the spatial and angular beam spreads) back down to pre-quake levels.

These beams were indispensable for surveying the arcs, whose horizontal and vertical undulations make lasers useless. With the 50-GeV electron and positron beams showing the way, many of the bending magnets in the arcs were realigned. By mid-November, the positron beam was coming all the way through the south arc to the final straight section where the beams collide. The electron beam in the north arc, however, was getting lost about a third of the way down the arc. The search for the missing beam turned up yet another fault, which had shifted magnets by about a centimeter. This time the SLC had made a real contribution to geology: The second fault was unknown before the errant electron beam pointed the way.

With the arc magnets realigned early in December, both beams were emerging from their downstream arc ends into the 200-meter final straight section with beam quality almost back to normal. In this final section, where the beams are focused down to 3-micron spots at the collision point, alignment tolerances are comparably stringent. Here optical surveying is of little use; one needs precision beam monitors to see if the final-focusing quadrupole magnets have moved a few microns. This last bit of surveying was expected to be completed by mid-December. If the final quadrupoles have indeed shifted by as much as 10 microns, a new collision axis might have to be set up, delaying the resumption of the Z^0 harvest by another week.

Santa Cruz

Elsewhere in the San Francisco Bay area, the Lawrence Laboratories at Berkeley and Livermore suffered little damage. The Santa Cruz campus of the University of California, just 10 miles west of the epicenter, was less fortunate. The physics department's office, classroom and laboratory building suffered the worst damage of any major structure on the campus. Chunks of broken concrete testified to the severe stresses the building had endured in the quake. It had to be closed to students and staff for two weeks, until its concrete pillars had been shored up with 200 timbers. Longer-term measures to assure the building's safety are still being assessed.

Equipment damage in the building's laboratories was, by comparison, relatively minor—a few hundred thousand dollars worth. "It wasn't all bad," recalls physicist Donald Coyne. "When the building was closed we had to hold colloquia in the university theater. Somehow, talks on the standard model sound better from behind the footlights."

—BERTRAM SCHWARZSCHILD

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