

angle of about 63° with the equatorial plane) progressively earlier from the late 1960s to the 1990s.

▷ Waves from earthquakes in the Kermadec Islands (northeast of New Zealand) arrived in Norway (about 45° to the equatorial plane) later in the 1990s than in the 1980s.

▷ Waves from earthquakes in Tonga (an island group about 1500 miles northeast of New Zealand) detected in Gräfenberg, Germany (about 34° to the equatorial plane) showed no systematic effect.

Assuming the rotation axes of the inner core and Earth coincide, the best fit to the data finds the inner core's seismic symmetry axis currently points toward latitude 79° north and longitude 169° east and rotates 1.1° per year faster than the crust and mantle.

Independent of the work at Lamont-Doherty, Wei-Jia Su, Adam Dziewonski (Harvard University) and Raymond Jeanloz (University of California, Berkeley) have also found evidence for an inner-core superrotation of 3° per year using 300 000 absolute arrival times (as opposed to the arrival-time comparisons used by Song and Richards) from 2000 seismological stations.⁴

Driving forces

So far, two explanations of the superrotation of the inner core have been advanced, both of which could conceivably reveal a great deal about condi-

tions in the core. In the Glatzmaier-Roberts model, a magnetic coupling mechanism maintains the inner core's superrotation in a manner analogous to the way in which a rotor rotates in a synchronous electric motor. As such, studies of the rotation's time dependence could begin to constrain future geodynamo models by yielding information about coupling between the inner and outer cores and inner-core topography—not to mention the possible evolution of the inner core's anisotropy and other properties as a function of time.

The other explanation suggests that the inner-core superrotation could be a vestige of a time before Earth's spin around its axis slowed as a result of tidal interactions. In this view, the inner core's rate of slowing lags behind the rest of the planet because the outer core's very low viscosity creates very little drag on the inner core. Based on this explanation, Su, Dziewonski and Jeanloz have already calculated an upper limit on the outer-core viscosity; more stringent measurements of the viscosity could constrain the outer core's composition and temperature. Glatzmaier, however, thinks that magnetic interactions between the inner and outer core are too strong for the two regions to be considered as independent.

All parties agree that additional studies are needed to distinguish between these two explanations and to

take advantage of what time-dependent observations could teach us about Earth's core. Song and Richards are confident they will learn a great deal from studies of how travel times have evolved along as many paths through the inner core as possible using historical seismological records. However, positions of historical seismic sources were not generally determined as accurately as those of modern sources, and early records, where they exist at all, are stored in less accurate analog form. More exact studies will require continuous records from many modern, high-quality digital seismographs that will stretch decades into the future. Dziewonski applauds as a step in the right direction the tenfold increase in the number of such stations over the past five years. He adds, "What is needed now is a long-term commitment to running these stations."

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References

1. G. Glatzmaier, P. Roberts, *Phys. Earth Planet. Inter.* **91**, 63 (1995). G. Glatzmaier, P. Roberts, *Nature* **377**, 203 (1995).
2. X. Song, P. Richards, *Nature* **382**, 221 (1996).
3. P. Shearer, K. Toy, *J. Geophys. Res.* **96**, 2233 (1991). K. Creager, *Nature* **356**, 309 (1992). W. Su, A. Dziewonski, *J. Geophys. Res.* **100**, 9831 (1995).
4. W. Su, A. Dziewonski, R. Jeanloz, submitted to *Science*.

One-Dimensional Systems Show Signs of Interacting Electrons

Conventional metals have been very successfully described by the Fermi-liquid theory, but researchers are now studying a variety of more exotic materials for which other approaches might be more appropriate. Among the alternatives is a model of interacting electrons in one dimension. The model is known as the Tomonaga-Luttinger liquid theory, after Joaquin Luttinger, who formulated it in the 1960s, and Sin-itiro Tomonaga, who did influential one-dimensional studies in the 1950s. It is frequently called simply a Luttinger liquid.

Albert Chang, Loren Pfeiffer and Ken West at Bell Laboratories, Lucent Technologies, recently found good agreement with one of the predictions of the Luttinger-liquid theory by measuring the tunneling conductance from a normal, three-dimensional metal into a novel one-dimensional system.¹ Theirs is not the first experiment to find behavior suggestive of interacting electrons,^{2,3} but it has attracted considerable attention because it was per-

Do electrons in one dimension interact in a way prescribed by the Luttinger-liquid theory? To answer that question, researchers are studying the tunneling through barriers in one-dimensional wires and across the edges of fractional quantum Hall states. A Bell Labs group has intriguing new results.

formed on a particularly clean system.

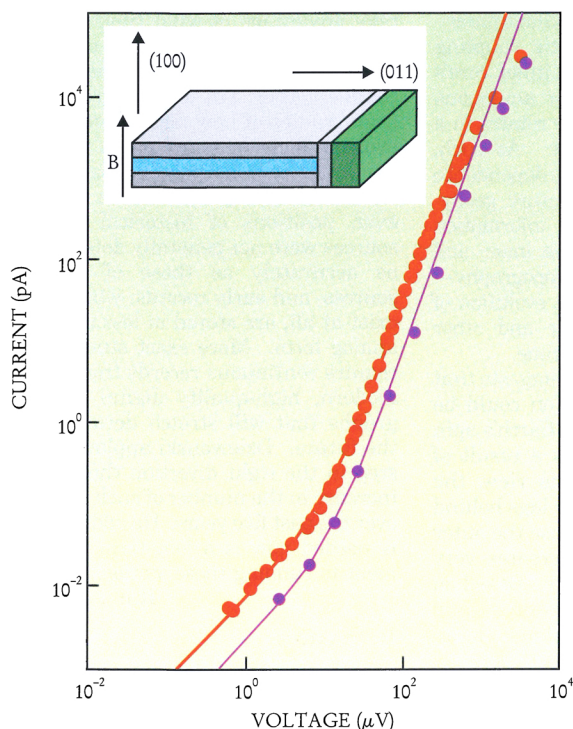
Collective states

In the Fermi-liquid theory, the Coulomb interaction of a given electron with the sea of surrounding electrons is folded into an effective mass for each electron; the resulting quasiparticle is then treated essentially as a noninteracting entity. In a Luttinger liquid, however, the Coulomb interactions give rise to collective modes of the one-dimensional string of electrons, like the vibration modes of a chain of springs and blocks.

If a one-dimensional system does indeed behave as a Luttinger liquid rather than as a Fermi liquid, the

difference would show up in the tunneling conductance. As Charles L. Kane of the University of Pennsylvania and Matthew Fisher of the University of California, Santa Barbara, showed in 1992, the tunneling conductance across a barrier in a quantum wire should vanish as a power of the temperature as the temperature approaches absolute zero.⁴ (A quantum wire is one whose width is smaller than the wavelength of the propagating electron.)

In principle, it should be straightforward to validate the Luttinger-liquid model by measuring the tunneling in a quantum wire. (One can make such a quantum wire, for example, by forming a high-mobility, two-dimensional electron gas at an interface between gallium arsenide and aluminum gallium arsenide and using electrical gates to define a very narrow—essentially one-dimensional—channel.) In reality, however, it is hard to find a wire sufficiently free of impurities that the backscattering does not destroy the collective modes. Moreover, the exact



THE CURRENT-VOLTAGE CURVE for tunneling from the edge of a $\nu = \frac{1}{3}$ fractional quantum Hall state into a three-dimensional metallic region. Insert illustrates the sample: The blue region is the quantum Hall state and the green region is n-doped gallium arsenide, which acts as a metal. Data points are from two different samples in the Bell Labs experiment, and the solid curves represent fits to a universal form predicted by Luttinger-liquid theory. The exponents determined by the fits are lower than theoretically expected.

exponent in the power law dictated by the theory depends on the properties of the individual wire.

Several groups have been doing measurements on quantum wires. Last year, Seigo Tarucha, Takashi Honda and Tadashi Saku of NTT Basic Research Laboratories outside Tokyo reported evidence of mutual Coulomb interaction between electrons based on their measurements of wires between 2 μm and 10 μm long.² Specifically, they found that the conductance (not the tunneling conductance) decreased as the temperature dropped from about 1.17 K to around 0.29 K; the decrease was stronger in longer wires. A Luttinger liquid would behave this way, but a Fermi liquid would not.

Quantum Hall states

Another place to look for Luttinger-liquid behavior is in a fractional quantum Hall state; there, the exponent in the temperature-dependent tunneling conductance is universal and the backscattering is not a problem. In such a two-dimensional gas, electrons move in little orbits about the flux lines, but at the edges they all skip and dance in the same direction along the periphery. Xiao-Gang Wen of MIT found that such an edge state is a Luttinger liquid, but only in the fractional quantum Hall state and not in the integer case.⁵ Because of the handedness of the electronic motion, Wen called the edge state a "chiral" Luttinger liquid. Backscattering cannot occur in this system because the electrons all move in one

direction. Furthermore, according to theoretical predictions by both Wen and a group of theorists including Kane and Fisher,⁶ the tunneling conductance of a chiral Luttinger liquid not only obeys a power-law dependence, as does the quantum wire, but the exponent is universal, depending only on the filling factor ν (the ratio of electrons to flux lines).

Two years ago, Frank P. Milliken and Corwin P. Umbach of IBM in Yorktown Heights, New York, together with Richard Webb of the University of Maryland, College Park, measured³ the tunneling conductance across a barrier between two quantum Hall edge states whose filling factors were $\nu = \frac{1}{3}$ (see PHYSICS TODAY, June 1994, page 21). They found that the tunneling conductance G , plotted as a function of the point-contact voltage that created the barrier, exhibited resonance peaks whose widths varied as the $\frac{2}{3}$ power of the temperature, as predicted by theory. They also found the expected power-law variation of G with temperature T , although their measurements extended over a limited temperature range (roughly from 40 mK to 140 mK), so that it was hard to distinguish a power relationship from, say, an exponential variation.

One difficulty with the IBM-Maryland experiment was that the boundary between the two quantum Hall states was not sharp. Near the junction, there could be regions occupied by edge states with different filling factors. Thus, Chang and his cowork-

ers at Bell Labs fabricated an atomically sharp junction between a quantum Hall state and a doped semiconductor by exploiting a technique known as cleaved-edge overgrowth, which had been developed at Bell Labs in 1990 by Pfeiffer and Horst Stormer and their colleagues.⁷ (See the inset in the figure at left.)

The Bell Labs group found a power-law dependence of tunneling conductance G on temperature T for tunneling into the $\nu = \frac{1}{3}$ state but not into the $\nu = 1$ state. Their data extended from 20 mK to about 1 K, a much wider temperature range than in the experiment by Milliken and his colleagues, so that Chang and his coworkers were able to determine an exponent. It turned out to be 1.75 ± 0.08 rather than the theoretically expected 2.0.

Chang's group also tested the theoretical predictions for the current-voltage characteristics, according to which the current is linear in voltage up to a specific value, $V = 2\pi\hbar kT/e$ (12 μV at 25 mK), and varies as the third power of voltage above that. The data had the linear variation at low voltage and the expected kink at 12 μV . Here again though, the exponent governing the power law behavior was somewhat lower than expected: 2.7 ± 0.06 rather than 3.0. See the figure on this page. The curves drawn there are based on the experimentally determined exponents. The linear relationship persists over nearly three orders of magnitude in current and over roughly two orders in voltage.

It's unclear what is causing the discrepancy with theory. Fisher points out that the exponents are predicted to be universal only in the limits of vanishing temperature and voltage. In practice, that means temperatures well below the lowest energy scale of the problem, presumably the quantum Hall gap, which is on the order of 1 K. Chang and others are planning new experiments to clarify the behavior.

Ilari J. Maasilta and Vladimir Goldman of the State University of New York at Stony Brook have also studied the tunneling from the edge of one fractional quantum Hall state to another, but through a quantum antidot, a microscopic potential hill created by lithography. They observe behavior that is fully consistent with that of a Luttinger liquid—and also of a Fermi liquid; at the experimental temperatures, the expected behaviors coincide. Goldman points out that, in any case, he and Maasilta were studying the tunneling of the fractionally charged quasiparticles, not electron tunneling, as in the experiment by Chang and his colleagues.

More to come

Recently, Amir Yacoby has teamed up with Pfeiffer, Stormer and others at Bell Labs to use the cleaved-edge overgrowth method to make a one-dimensional wire so clean that the electrons have an exceptionally long mean free path, around $10\text{ }\mu\text{m}$, as inferred from measurements on the one-dimensional wire.⁸ Moreover, the energy spacing between the one-dimensional modes is more than ten times larger than in any previous wire; the wide separation demonstrates the tight confinement of

the one-dimensional states, which helps reduce backscattering. Yacoby and his coworkers have already found the conductance of wires to be quantized to non-universal values; soon they plan to look for Luttinger-liquid behavior by conducting tunneling experiments with this particularly clean wire.

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References

1. A. M. Chang, L. N. Pfeiffer, K. W. West, to appear in *Phys. Rev. Lett.*
2. S. Tarucha, T. Honda, T. Saku, *Solid State Commun.* **94**, 413 (1995).

3. F. P. Milliken, C. P. Umbach, R. A. Webb, *Solid State Commun.* **97**, 309 (1996).
4. C. L. Kane, M. P. A. Fisher, *Phys. Rev. B* **46**, 15233 (1992).
5. X. G. Wen, *Phys. Rev. B* **41**, 12838 (1990); *Int. J. Mod. Phys. B* **6**, 1711 (1992).
6. K. Moon, H. Yi, C. L. Kane, S. M. Girvin, M. P. A. Fisher, *Phys. Rev. Lett.* **71**, 4381 (1993).
7. L. Pfeiffer, K. W. West, H. L. Stormer, H. P. Eisenstein, K. W. Baldwin, D. Gershoni, J. Spector, *Appl. Phys. Lett.* **56**, 1697 (1990).
8. A. Yacoby, H. L. Stormer, K. W. Baldwin, L. N. Pfeiffer, K. W. West, to appear in *Solid State Commun.*

LEP is Now Making Pairs of W Bosons

Shortly after noon on 9 July, an important new experimental regime of high-energy physics was inaugurated with the first observation of a W^+W^- pair at CERN's Large Electron-Positron (LEP) collider. The charged W 's and their neutral cousin, the Z^0 , are the three spin-1 bosons that mediate the weak interactions. Because they are almost 100 times heavier than the proton, these "intermediate vector bosons" present a particular challenge to accelerator builders and experimenters. Though their existence and their masses were predicted by the Glashow-Salam-Weinberg unification of the electromagnetic and weak forces in the late 1960s, they could not be observed until the 540-GeV CERN proton-antiproton collider was completed in the early 1980s. (See *PHYSICSTODAY*, November 1983, page 17.)

But when one makes W 's and Z^0 's in a high-energy proton-antiproton collider, the physics of the individual collisions is messy; the initial state is ill defined and the final state is swamped with hadronic debris. Electron-positron colliders are therefore much to be preferred for the detailed study of the intermediate vector bosons.

The problem, however, is that synchrotron radiation makes it much harder to get to the requisite beam energies with an e^+e^- machine. To accommodate the circulating 46-GeV electron and positron beams needed to make the 91.2-GeV Z^0 , the LEP collider ring required a circumference of 27 km, much larger than that of any existing hadron accelerator.

Studying the charged W bosons is even more demanding. In e^+e^- collisions, the cross section for producing single W 's is uselessly small; for all practical purposes, they have to be made in W^+W^- pairs. But that requires more beam energy than LEP was capable of in the first seven years of its existence. For most of that time the collider ran in a mode now called LEP 1, with beam energies in the vi-

CERN's big electron-positron collider has finally crossed the energy threshold for producing pairs of the heavy bosons that mediate the weak force.

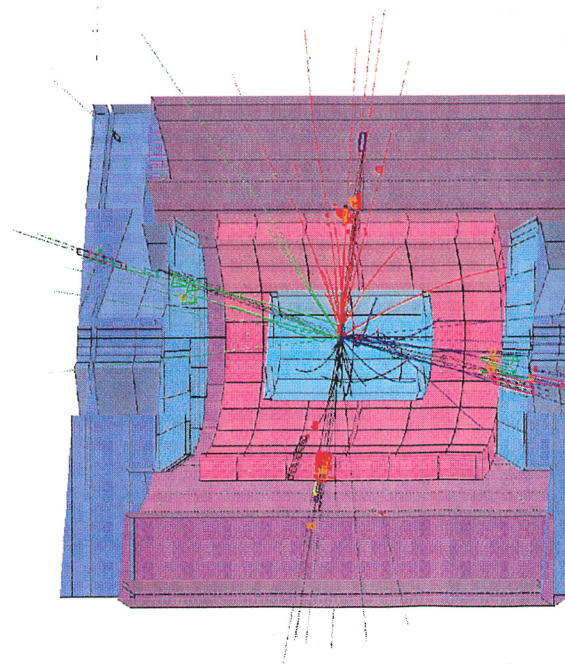
cinity of 46 GeV creating millions of Z^0 's for exquisitely detailed tests of the predictions of the unified electroweak model. The mass of the $W^\pm$ is 80.3 GeV, somewhat less than that of the Z^0 . But because it has to be made in pairs, W production has a collision energy threshold of about 161 GeV.

To cross this W^+W^- production threshold, CERN has been installing more and more superconducting RF cavities into the LEP accelerating system in recent years. Last November, with 60 superconducting cavities installed, the LEP beam energies could reach 70 GeV for the so-called LEP 1.5 phase, a brief run with collision ener-

gies from 130 to 140 GeV. That wasn't enough energy to make W^+W^- pairs, but it was uncharted territory. So the experimenters combed the LEP 1.5 data for any hint of new physics, especially any manifestation of supersymmetry. (See *PHYSICSTODAY*, February, page 19.) But in fact LEP 1.5 gave no convincing evidence of new physics.

Crossing the W-pair threshold

When the LEP 1.5 run ended just before last Christmas, the installation of superconducting RF cavities resumed. By the end of June, 144 superconducting cavities were in place and the collider was ready to assault the W^+W^- threshold. On 8 July the electron and positron beams were ramped up to 80.5 GeV and in the evening all four LEP detectors began to see 161-GeV collisions. The next day, the DELPHI detector recorded what appeared to be the first $e^+e^- \rightarrow W^+W^-$ event.



THE FIRST W^+W^- pair produced at LEP 2 was recorded by the 3500-ton DELPHI solenoidal magnetic detector, seen here in cross section. Charged and neutral particles traversing the magnetic field are recorded by tracking arrays, Čerenkov detectors and calorimeters. Electron and positron beams, counter-circulating in the LEP ring, collide at the detector's center. In this event, a 161-GeV e^+e^- collision produces a W^+W^- pair at rest that shows up as four 40-GeV jets of hadrons, indicating that each W decayed into a pair of quarks.