few hundred kilometers above the cloud tops, it might be directly observable from Earth.

There is much speculation about possible effects on Jupiter's magnetosphere of the comet's passage, and particularly the cometary dust. Unlike the solid nuclei of the comet fragments, much of the dust is expected to miss Jupiter. Jupiter's radio emission may decrease as a result of a decrease in energetic electrons as they collide with the dust.[4] A new Jovian ring may form in about ten years.[5] On the other hand, there may be almost no observable consequences in this region.[6] "The magnetosphere will probably swallow these things without even a burp," asserts Dessler.

Should solid material reach the dense atmosphere, it could make waves. What planetologists call a gravity wave (because gravity is the stabilizing force) propagates slowly like a water wave. Gravity waves may appear on Jupiter's surface as concentric rings of temperature fluctuations emanating from the impact site, may be observable for impacts with energies as low as 10^{27} ergs, and may last for one or two days.[7] Faster-moving, downward-launched acoustic waves could be refracted by density gradients within Jupiter and perhaps reach as deep as the interface between molecular and metallic hydrogen.[8] These acoustic waves would appear as a set of rings in one or two hours, much sooner than the gravity waves. Seeing any of these effects would provide researchers with their first empirical insight into Jupiter's interior.

Most important, as Dessler puts it, "glorious things may well happen that no one has predicted."

—STEPHEN G. BENKA

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EXPERIMENT REVEALS A NEW TYPE OF ELECTRON SYSTEM

In most metals, the electrons behave as if they were independent of one another. Although each electron really does interact with the other electrons and phonons, the net effect is felt only as a kind of molasses through which the otherwise freely moving electron must slog. Thus one can usually treat metallic systems as a low-density gas of weakly interacting particles, accounting for the average interactions simply by assigning an effective mass to the electrons. Such a model is commonly called a Fermi liquid. In one-dimensional systems, however, the Coulomb forces between the electrons intervene more strongly and produce quite a different behavior.

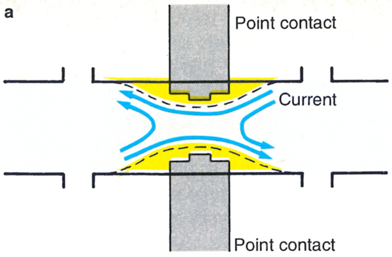
Theorists studied the one-dimensional electron system extensively in the 1970s, delineating the behavior that characterizes what is today called a "Luttinger liquid." But experimenters have been unable to find direct, conclusive evidence for such behavior in real-world conductors. Now signs of a Luttinger liquid have surfaced in a more exotic locale—in the excitations that develop at the edges of an electron system in a fractional quantum Hall state. At the March meeting of the American Physical Society in Pittsburgh, Richard Webb of the University of Maryland described the experiment he had performed with his colleagues Frank P. Milliken and Corwin P. Umbach of IBM in Yorktown Heights, New York.[1] At the same session, Xiao-Gang Wen (MIT) and Charles Kane (University of Pennsylvania) described the theoretical underpinnings of the experiment. (Kane has collaborated on this problem with Matthew Fisher of the University of California, Santa Barbara.) If confirmed, the evidence will not only substantiate years of theoretical work on the one-dimensional state, but might also open the door to further exploration of a fundamentally new interacting-electron system.

Luttinger liquids

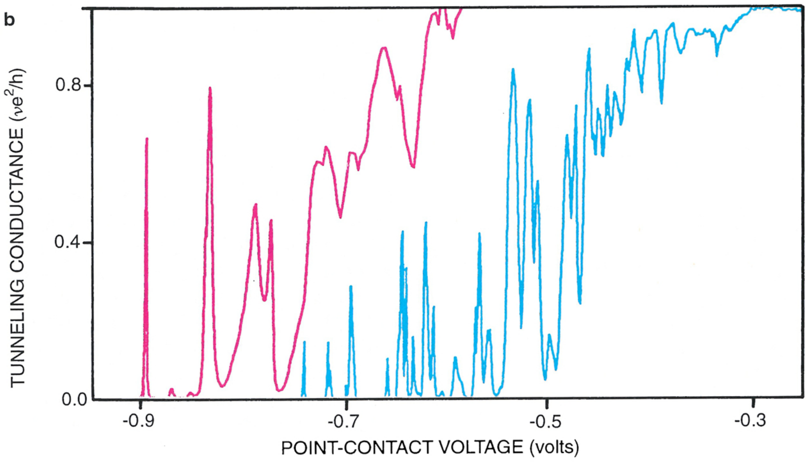
In a Fermi liquid the Coulomb forces from other charges are treated, if at all, as a perturbation. But in one dimension, the electrons are effectively replaced by exotic new collective excitations, which can have spin and charge. One might picture the electrons in a Luttinger liquid as blocks connected by springs. The collective excitations are then oscillatory modes of this linear chain of blocks, which can carry a fraction of an electron charge. Whereas individual electrons get scattered off one another if they try to move in a particular direction, charged excitations can travel up and down the chain like a traveling wave, passing through but not scattering off one another.

The Luttinger-liquid picture produces predictions that differ from those of the standard Fermi-liquid model regarding the temperature dependence of measurable parameters. One example is the tunneling behavior of electrons: In a Fermi liquid an electron from outside the Fermi surface can always enter the system and occupy one of the single-particle states above the Fermi surface. But in a Luttinger liquid the states above the Fermi surface are collective modes and cannot be occupied by an individual electron. Thus, one hallmark of a Luttinger liquid is that there is no tunneling of electrons at zero temperature. More specifically, theorists have predicted that the tunneling conductance through a barrier between two Luttinger liquids will vanish as a power of the temperature, with the exact exponent depending on the details of the electron–electron interaction.

Interest in Luttinger liquids peaked 20 years ago when researchers were studying organic metals in the hopes of finding a high-temperature superconductor. An organic metal, such as TTF-TCNQ (tetrathiofulvalene-tetracyanoquinodimethane), consists of tight stacks of flat organic molecules and is closely approximated by a one-dimensional model. Joaquin Luttinger of Columbia University, working in the 1960s, defined the model that now bears his name.[2] It resembled the quantum field model developed in 1958 by Walter Thirring (University of Vienna). Sin-itiro Tomonaga had also published influential studies on the one-dimensional state around 1950. Subsequently, Daniel C. Mattis (now at the University of Utah, Salt Lake) and Elliott Lieb (Princeton University) correctly solved Luttinger's model.[3] In the 1970s theorists found that a wide class of one-dimensional models has the same behavior at low temperatures as the Luttinger model. Such models have been collectively called "Luttinger liquids" since Duncan Haldane coined the term in a 1981 paper proposing that a general low-



Tunneling conductance in a quantum Hall state. **a:** Quantum Hall sample (outlined in black) is pinched in the middle by the voltage V_{pc} applied between point contacts (gray), giving rise to a region (dark shading) that excludes electrons. The current carried by the edge states (blue) either squeezes through the central region or, for very negative V_{pc}, is entirely reflected. **b:** Tunneling conductance at 42 mK decreases as V_{pc} gets more negative, falling off faster for the $\nu=1/3$ state (blue) than for the $\nu=1$ state (red). Peaks are resonances where electrons find a path through the constriction. (Adapted from ref. 1.)



energy effective theory of one-dimensional metals could be based on Luttinger's model just as Landau had based his Fermi-liquid theory on the model of the ideal Fermi gas.[4] More recently, Philip Anderson (Princeton University), in connection with work on the high-temperature oxide superconductors, has argued that the behavior seen in Luttinger liquids is not necessarily confined to one dimension.

Quantum Hall edge states

Besides organic metals, another candidate for manifesting Luttinger-liquid behavior has come forward in the past few years: the fractional quantum Hall edge states. These states exist on the periphery of a two-dimensional system of electrons that is trapped at the interface between two semiconductors such as GaAs and AlGaAs. When a strong magnetic field is applied at right angles to the plane of the interface, the electrons within the two-dimensional gas circulate in cyclotron orbits about the magnetic flux lines. For certain values of the magnetic field, these electron orbits can just fill the available space, and interesting phenomena appear, such as a plateau in the Hall conductance as a function of magnetic field. Researchers have uncovered intriguing behavior whenever the filling factor ν, that is, the ratio of the density of electrons to the density of magnetic flux quanta threading the plane, is either an integer or a rational fraction with an odd denominator.

When the electron system is in either the integer or the fractional quantum Hall state, it acts as an incompressible fluid. Although the area of the two-dimensional fluid cannot change, the shape can; thus, all the low-energy excitations in this system appear at the edges, rather like ripples on the surface of a liquid droplet. These vibrational modes are the edge states. In 1982 Bertrand Halperin (Harvard University) started focusing on these edge states and the important role they play in the integer quantum Hall effect. He confined his studies to the integer quantum Hall effect, where electrons in the edge state are successfully described by the conventional Fermi-liquid picture.[5]

Several years ago Wen turned to the *fractional* quantum Hall edge state and found that the appropriate model is not a Fermi liquid but a Luttinger liquid. Wen calls it a "chiral Luttinger liquid" because the charged excitations can only travel in one direction around the sample—that is, clockwise or counterclockwise, depending on the orientation of the magnetic field.[6] Thus, the excitations on one side of a given sample might travel to the right and those on the opposite side to the left.

Wen made some specific predictions about how a chiral Luttinger liquid might manifest itself in experiments that measure the tunneling between the edges of a quantum Hall state. In particular, Wen found that there would be a power-law dependence of the current on the voltage, as well as a power-law dependence of the tunneling conductance on temperature. Subsequently, Kane and Fisher undertook a renormalization-group approach to the more general problem of a Luttinger liquid and came up with similar predictions, which applied to the fractional quantum Hall state under a wider range of conditions.[7]

One of the key predictions of both papers is that the tunneling conductance will decrease as T^4, vanishing at $T=0$, for a system with filling factor $\nu=1/3$. This power-law dependence is similar to the result derived two decades ago for one-dimensional metals by Alan Luther (now at NORDITA, the Nordic Institute for Theoretical Physics, Copenhagen) and Ingo Peschel (now at the Free University of Berlin),[8] as well as Mattis, working independently.[9] For the one-dimensional metal, however, the exponent governing the temperature dependence of the tunneling conductance depends on the details of the particular system, whereas for a chiral Luttinger liquid, it is universal and depends only on the value of the filling fraction or, more precisely, on the universality class of the bulk fractional quantum Hall liquid. That's one reason why experiments on a fractional quantum Hall edge state have a greater potential for definitively demonstrating the predictions.

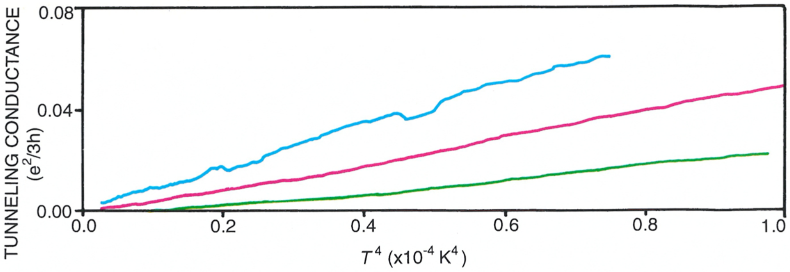
Another experimental advantage of the quantum Hall fluid is that the edge excitations can only move in one direction, so they cannot be backscattered or possibly localized by spurious impurities, unlike the electrons in a one-dimensional metal. According to Allan MacDonald (Indiana University), the fractional quantum Hall edge state is the closest we have come to an ideal one-dimensional system. One-dimensional organic metals are not as good an approximation to a linear system, and disorder plagues quantum wires, which are made narrow enough to confine the charge carriers to quantum wells in the dimensions perpendicular to the wire. In fact, many researchers are excited about the Maryland–IBM experiment because it demonstrates that quantum Hall edge states are indeed a more easily controlled one-dimensional electron system that can be exploited to test a host of predictions.

Experimental evidence

Armed with good theoretical predictions about how a chiral Luttinger liquid might behave, Webb and his colleagues started to explore the behavior of quantum Hall edge states, both at $\nu=1$, where one expects to have a Fermi liquid, and at $\nu=\frac{1}{3}$, where a chiral Luttinger liquid should appear. One can tune between one Hall state and the other by adjusting the strength of the magnetic field applied to the sample. The ability to compare the behavior of a Fermi liquid and a Luttinger liquid in the same sample helps to strengthen the evidence for the latter.

Milliken, Umbach and Webb started with a GaAs–AlGaAs heterostructure and applied a point-contact voltage V_{pc} across a midsection of the sample. (See the top panel of the figure on page 22.) As the researchers apply an increasingly negative voltage, they pinch off a narrow channel in the middle of the sample, essentially creating two separate Hall fluids. The average conductance through the channel thus falls off with increasing voltage, as shown in the bottom panel of the figure on the previous page. The fall is more rapid when the quantum Hall state has a filling factor of $\nu=\frac{1}{3}$ than it is when $\nu=1$. When the channel is pinched hard enough, the only way that current can flow is by the tunneling of electrons across the constriction. At a low enough temperature tunneling should cease in a Luttinger liquid but persist in a Fermi liquid.

In either case, the figure shows that as the V_{pc} grows increasingly negative, the conductance does not fall monotonically but instead manifests a number of transmission resonances, a well-known phenomenon in low-dimensional disordered systems. These resonances occur at values of the potential where the electrons can find a favorable path to tunnel through. The IBM–Maryland team set the point contact voltage V_{pc} such that the edge state was away from a resonance and studied the temperature dependence of the conductance there. The results for several values of V_{pc} at $\nu=\frac{1}{3}$ are shown in the figure above. The tunneling conductance there varies as T^4, as predicted by chiral Luttinger-liquid theory, while, for $\nu=1$, it is independent of temperature, consistent with the Fermi-liquid picture.



Power-law dependence of tunneling conductance on temperature is a hallmark of the Luttinger liquid. The curves shown here are measured for a quantum Hall state with $\nu=\frac{1}{3}$ at three different values of point-contact voltage V_{pc}, corresponding to three different minima of the curve shown on page 22. (Adapted from ref. 1.)

The researchers also looked at the shape of the transmission resonances as a function of V_{pc} in order to check some predictions made by Kane and Fisher, together with Kyungsun Moon and Steve Girvin of Indiana University and Hangmo Yi of the University of Pennsylvania.[10] For an integer quantum Hall edge state at low temperature, the resonances should not depend on temperature, and even at zero temperature, they should have a finite amplitude due to tunneling. However, the resonances for the fractional edge states were predicted to grow increasingly narrow as the temperature approached zero. More precisely, the theory predicts that the halfwidths of the resonances go as $T^{2/3}$. The behavior of the resonances studied by Webb and his colleagues confirms these expectations. The behavior is also consistent with the universal scaling function that Kane, Fisher and coworkers proposed. Because the resonance line shape is universal it is possible to calculate it with a model that captures the essential physics but does not depend on the microscopic details of a particular quantum Hall sample, other than an overall calibration.

While the new results have aroused considerable interest, Webb would be the first to advise caution. Although the IBM–Maryland team has already done a lot of checks to be sure the behavior they measure is that of the edge states and not caused by any spurious effects, they are continuing to probe. The evidence would certainly be strengthened by experiments using the kind of high-quality samples that have supported some of the newer results on the fractional quantum Hall effect. Paul McEuen (University of California, Berkeley) commented that further evidence for a Luttinger liquid would be an experiment that directly demonstrates the electron correlations: One example would be the verification of a prediction by Wen that, when you irradiate a sample with microwaves of frequency f, you can see steps in the tunneling current I at voltages equal to integer multiples of hf/e^*, where e^* is the fractional charge of the tunneling quasiparticle.

Before undertaking the experiment on fractional quantum Hall edge states, Webb and his group had searched for similar behavior in a one-dimensional quantum wire. However, they found the task to be formidable because of the problem of spurious impurities. Recently, Seigo Tarucha and his group from the NTT Basic Research Labs in Atsugi, Japan, have claimed some success with a similar quantum-wire experiment, but their results are still preliminary.

At the very least, Webb's experiment has uncovered some very rich and unique behavior in the fractional quantum Hall edge states. If the behavior is pinned to the Luttinger liquid, the regime will become even more enticing.

—Barbara Goss Levi

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