Two-Dimensional Electron Gas Continues to Exhibit Intriguing Behavior

The starting discoveries of the integral and fractional quantum Hall effects were made in two-dimensional electron gases subjected to very high magnetic fields (see the story on page 17). Now, a new generation of physicists await us at lower fields. In a recent study, the longitudinal resistivity exhibited a strong step-like change in the range of temperature and magnetic field: When plotted as a function of the magnetic field, the resistivity has a dip when the current flows in one direction and a strong peak when it flows in an orthogonal direction. There's no a priori reason to think that these two directions are different.

Researchers at Bell Laboratories, Lucent Technologies, and Bell Laboratories, Lucent Technologies, reported these results last August at a meeting of the American Physical Society's Topical Group on Two-Dimensional Systems held at the Institute for Theoretical Physics in Santa Barbara, California. The most significant aspect is that the anisotropy is now attracting increasing interest from the theorists.

Researchers have taken a closer look at some funny structure noted years ago in the resistivity of a quantum Hall sample at low magnetic fields. The prevalent explanation for what they see is that the electrons are forming charge density waves. The leading speculation is that the geometry of the material reflects the familiar theoretically predicted charge-density waves, with the electrons all lined up in rows.

Shades of the past

The work reported in Santa Barbara began last May, when Jim Eisenstein of Caltech set out to explore in more depth on effect that he and Robert Willett had seen in quantum Hall samples back in 1988 when both were working at Bell Labs. Similar anoma-

lyes were subsequently reported in March 1993 meeting of the American Physical Society by Horst Storment, who was also working with Daniel Rui Rio Da. Other groups also had evi-

dence of anisotropic behavior, but no one explored it further for the time. For his second look, Eisenstein was joined by Michael Lilly and Kenneth Cooper of Caltech; they enlisted Lore Pfeiffer and Kenneth West of Bell Labs to prepare very clean, high-mobility samples. The samples were gallium arsenide/aluminium gallium arsenide heterostructures, in which an electron gas forms at the interface.

The researchers zeroed in on the regions around a filling factor of 5/2 and 7/3. By contrast, strong fractional quantum Hall states usually show up at filling factors less than 2, such as 5/2 or 7/3. The filling factor, ν, indicates the number of electrons for each flux quantum. Thus, one gets a filling fac-
lor of 5/2 at a high value of the magnetic field, where there are three flux quanta for every electron, whereas at the very lowest Landau level (ν = 0) is not filled (it is filled when there is one flux quantum for each electron).

One gets higher filling fac-
lors of 7/3 and 7/4 by decreasing the field. The behavior of the two-dimensional gas at these higher filling factors is summarized graphically in the figure at right, data taken at 295K. The color of each curve is keyed to one of the two diagrams indicating the direction of the magnetic field. When the current is driven as shown in the purple dia-

gram, sharp peaks appear in the longi-

dudinal resistivity at filling factors of 5/2, 7/3 and higher. With the cur-

dent driven at right angles, as shown in the red diagram, the same minimum at the same value of the magnetic field where the peaks were seen. Moreover, the resistivity was driven to a hundred times greater than the resistivity minimum.

Lilly and company noticed three other intriguing details. First, the peaks seem to grow linearly as the temperature drops from 150 mK to 25 mK, although the widths of the peaks may vary widely. Second, the anisotropy is seen only near half filling. Finally, the behavior at 5/2 and 7/3 is qualitatively very different from that at 1/3 or 2/3.

Is it an extrinsic effect?

Can this observed anisotropy be attrib-
uted to some geometric bias in the experimental setup, not caused by anything in the electron density within the sam-

p!e? The researchers think not. Their sample appears to be so good that they minimize such gradients, so that the variation in density appeared to be less than 0.3%.

To check on the robustness of the effect, Lilly and company repeated their measurements on what are known as Hall bar samples, and found the same anisotropy. Unlike their original square samples, where one is not sure what the current distribution is, Hall bars provide a low temperature and a low magnetic field. (below 150 mK) of strong temperature dependence and low anisotropies in just a few millimeters of the sample. In 1/3, they survive, some previously anomalous behavior remains. When it works.

Eisenstein does add, however, that their extrinsic effect may also be present to break the symmetry and pick out a preferred axis.

What can it be?

The structure seen at these high filling factors indicates that electron interac-
tions are strongly anisotropic. Unlike from those that produce the quantum Hall plateau at lower filling factors. One of the most obvious is the anomalous behavior at 1/3 and 2/3 is the formation of charge-density stripes. The first two years by Alex Koulakov, Michael Fogler and Boris Shklovskii at the University of Minnesota4 and later by Rodolfo Moessner and John Chalker at the University of Oxford5. Both groups applied mean-field theory to the electron interaction at high Landau levels and predicted that electrons would condense in some regions, leaving other regions free of charge.

The Minnesota theorists offer a qualitative explanation of how this charge separation comes about. They treat the wavefunction of each electron in the partially filled level as a charged ring whose radius is that of a correlated orbit. The Coulomb interactions are large enough, leaving only short-

range Hall sample. It turns out that for two electrons, or disks, to overlap, but that energy cost is independent of the extent of the overlap. If two orbits are to overlap, they may as well overlap all at a lot. Electrons tend to condense in either bubbles or stripes, the latter being favored at half filling. The filling factor is 1 inside a bubble or stripe, and 0 outside.

Charge-density waves had been predicted for two-dimensional gases back in 1979 by Yoshihiko Fukuyama, Philip Platzman and Philip Anderson, who used the Hartree–Fock approxi-

mation—a mean-field approach—to study electrons in the partially filled, lowest Landau level. It later turned out that the states suggested by Robert Laughlin (see the story on page 17) to explain the fractional quantum Hall eff-
ect were a bit lower in energy than the charge-density wave states predicted by Fukuyama, Platzman and Anderson.

DIFFERENT RESULTS IN DIFFERENT DIRECTIONS. The longitudinal resistivity for a two-dimensional electron gas exhibits peaks when the current flows in one orori-

antion (blue curve and circuit diagram) and dips when the current flows at right angles to that (red). These effects are seen at filling factors of 5/2, 7/3 but not at any filling factors below that. (Adapted from ref. 4.)

At filling factors above v = 4, how-

ever, calculations show that the mean-
field states do not last out to the Laughlin states. In fact, Moessner and Chalker proved formally that the mean-field states are unstable at very high Landau levels. While agreeing that uniaxial charge-density waves are currently the most likely explanation for the aniso-
tropies, Bertrand Halperin (Harvard University) cited some observations that are hard to explain with a single model. In addition, further experiments pose the question of what determines the preferred orientation of the charge-
density stripes. Possibly, it's the sample itself. The formation of steps at the heterojunction interface or the slight misaligning of the substrate might determine a preferred direction. Lilly said he and his colleagues are planning several experiments with different samples to check out some of these possibilities.

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References

1. A. Koulakov, K. B. Cooper, J. P. Eisen-
stein, J. L. Pfeiffer, K. W. West, pre-
print cond-mat/9805277 at the Los Al-
tamos National Laboratory.
4. H. Fukuyama, P. M. Platzman, P. W. An-

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