SCIENCE NEWS of the week

Fractional Hall Effect by Electrons in Chorus

Modern physics is rather well organized into a dialectic between theory and experiment: Theory predicts. Experiment finds or does not find. Theory incorporates changes from experiment and makes new predictions, and the cycle begins again. Serendipity rarely enters, but when it does, it can often produce quite a sensation. One such event took place a couple of years ago at what is now AT&T Bell Laboratories in Murray Hill, N.J. Experimenters Horst Störmer, Arthur C. Gossard and Dan Tsui — who were looking for something quite different — discovered what is known as the fractionally quantized Hall effect.

Quantized effects are changes that can come only in certain discrete jumps. Usually they are integral multiples of a basic unit. The Hall effect is the first to include rational fractions of the basic unit as well. And now, Robert Laughlin of the Lawrence Livermore National Laboratory in Livermore, Calif., has found a quantum mechanical wave equation that explains why these fractions come about. His theory was discussed, and some Japanese experiments that tend to confirm some of its predictions were reported, at the recent 17th International Conference on the Physics of Semiconductors, held in San Francisco. "Everybody is very excited," says Marvin Cohen of the University of California at Berkeley, chairman of the meeting's organizing committee. Off in the future somewhere there is even a prospect of new and now-unimagined devices.

The discovery of fractional quantization also gives physicists a system in which electrons in a solid join together to behave in collective ways that no one had expected before, and this collective behavior yields a quasiparticle, something that behaves as if it were a particle, with precisely one-third the electric charge of an electron — with none of the niggling higher-order corrections that usually mar the precision of such numbers in physics.

The ordinary, integrally quantized Hall effect, to which the fractional form is intimately related, was already enough of a bonanza for condensed-matter physicists. The Hall effect occurs in semiconductors in the presence of a magnetic field. If an electric current passes through the semiconductor, a voltage will appear in the material transverse to the direction of the flowing current. A current wants to move in that direction, too, and there appear a corresponding voltage and resistance. It is this Hall resistance that is the subject of these investigations.

Some theoretical work done in Japan in the 1970s indicated that the Hall resistance should be quantized, and in 1980 Klaus von Klitzing of the University of Würzburg in West Germany found the quantization. Almost simultaneously Shinji Kowaji of Gakushuin University in Tokyo found it, too.

The Hall resistance is quantized in units that simply fascinate physicists. The basic quantum is equal to the fine-structure constant, the fundamental constant that measures the relative strength of electric and magnetic forces. This constant is itself a fraction composed of constants from three different branches of physics: the charge of an electron (electromagnetism), Planck's constant (quantum mechanics) and the speed of light (relativity). The circumstance has physicists excited about the possibilities of precisely measuring the numerical values of fundamental constants and studying the relationships among the different branches of physics. The quantum Hall effect has already been used for a very precise measurement of the fine-structure constant (SN: 1/16/82, p. 39), and standards laboratories are interested in it for a more precise and reproducible standard of electrical resistance than the wires now used.

Suspecting that the quantization resulted from some collective action of electrons, Störmer, Tsui and Gossard looked for electron crystallization, the formation of a two-dimensional crystallike structure of electrons within the solid. Instead they found quantization of the Hall effect in thirds of the basic unit.

Laughlin's theory explains this fractional quantization as the result of a somewhat different collective behavior of electrons, more like that of a liquid. As he explains the phenomenology, any collective behavior of electrons is unexpected, and this is why any phenomenon that seems to come from such relations makes such a sensation. The electrons in a solid that are relatively free of tight binding to the atoms are expected to be free of relations to each other also, like atoms in a gas. Physicists thus speak of an electron gas inside the solid.

The rationale under which electrons might form a "crystal" depends on their mutual repulsion for each other. They want to get as far away from each other as they can, but where there are a lot of them, there is a limit to how far one can get away from a second without coming too close to a third. The ideal solution is for them to arrange themselves at equal, optimum distances from all neighbors in what amounts to a crystalline structure.

However, Laughlin says, quantum mechanics intervenes. According to quantum mechanics, the location of an object is always intrinsically uncertain. For heavy atoms, iron for instance, this uncertainty is very small, so they can be fairly precisely located at the nodes of a crystal structure and maintain its rigidity. Helium, however, never becomes a solid no matter how cold you make it, because for helium atoms the uncertainty of position is a large fraction of what would be the interatomic distance of a helium crystal, so helium stays a liquid. Electrons, which are even lighter, are even more likely to form a liquid structure.

In their more fluid state these electrons maintain their distance in a way that Laughlin describes as "like a chorus line holding hands [while they dance back and forth]." Except that there is a kink in the line, as if two of the dancers were holding their hands upward instead of laterally. This produces a shortening of the distance between them. The others adjust, and the totality of adjustments forms a structure that acts like a particle, a quasiparticle, with precisely one-third the charge of the electron.

This could explain fractions like 1/3, 1/5, 1/7, etc. Laughlin says, "I called Störmer. He said, 'Wait a minute.'" Meanwhile the Bell Labs people had discovered fractions like 2/5, 2/7, 2/9, etc. It was back to the theoretical drawing board. The solution that Laughlin now brings forth is to propose that these quasiparticles form similar structures of their own, and then these new structures form yet another level. This explains the more complicated fractions. Eventually randomness (dislocations and impurities in the crystal of the semiconductor) cuts off the formation of new hierarchies.

The theory predicts that what fractions show up will be dependent on temperature. Experiments reported at the conference by Kawaji and Hiroyuki Sakaki of the University of Tokyo confirm such an effect although they get 2.7 kelvins for the basic temperature difference between the hierarchical levels, whereas Laughlin had predicted 5. Nobody is worried by the discrepancy, which arises from certain numerical assumptions Laughlin made.

The physicists generally tend to agree that these effects could lead to devices, but what kind is not immediately obvious. The analogy is Brian Josephson's discovery of quantized magnetic flux some 20 years ago. Nobody knew immediately what to do with that, but as the years passed by, inventors have developed devices that employ the Josephson effect in ways not dreamed of in 1960. In the last century a famous British physicist, lecturing on a newly discovered electrical effect, was confronted by a woman who asked of what use it was. "Madam," he replied, "what use is a newborn baby?"

— *D.E. Thomsen*