New Fractional Quantum Hall States in Double Electron Layer Systems

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When confined to two dimensions and subjected to a magnetic field, electrons exhibit a range of extraordinary behavior, most notably the quantum Hall effect (QHE). This phenomenon, which comes in two flavors, integral QHE (IQHE) and fractional QHE (FQHE), each representing very different physical principles, continues to surprise those who study it. Two groups of researchers at AT&T Bell Laboratories and Princeton University have now independently and simultaneously reported one of the most interesting results found in the subject of the FQHE in recent years (*1*, *2*). Their discovery of new FQHE states is sure to spark searches for new quantum Hall properties.

Consider a conductor in a uniform magnetic field and assume that it carries a current driven by an electric field perpendicular to the magnetic field. The current in this case is not parallel to the electric field, but is deflected at an angle to it by the magnetic field. This is the Hall effect and it occurs in almost all conductors.

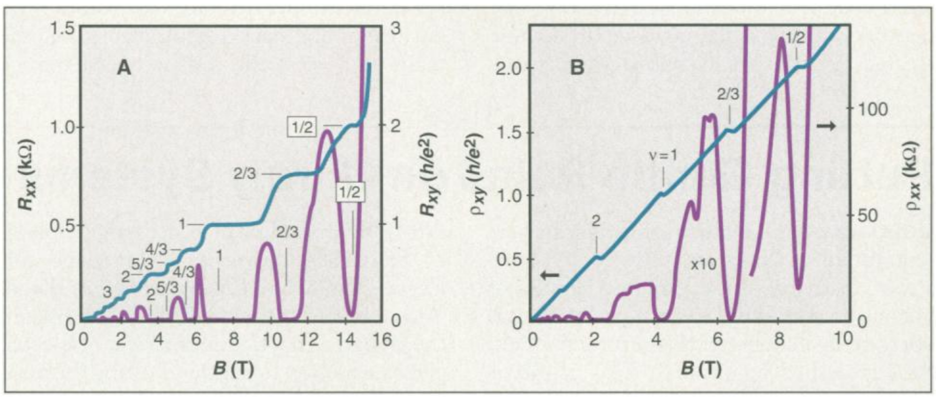
In the quantum Hall effect, the applied magnetic field quantizes the Hall conductance. The current is then precisely perpendicular to the electric field, so that no dissipation (that is, no ohmic loss) occurs. Up to now, this has been seen only in two-dimensional systems, at quite low temperatures, in quite high magnetic fields. Further, the ratio of the total electric potential drop to the total current—the Hall resistance—is precisely equal to $h/(\nu e^2)$, where e is the charge of an electron and h is Planck's constant.

The factor ν is an integer in the integer QHE and a small rational fraction $\nu = p/q$ for the fractional effect. In an experimental plot (see figure) as a function of the magnetic field, the Hall resistance exhibits flat steps precisely at these quantized resistance values whereas the regular resistance vanishes (or is very small) at these Hall steps. The fractional effect is found only at very low temperatures in very clean samples. It arises (*3*) from the effect of interaction between electrons, whereas the IQHE can be understood without needing to consider electron-electron interactions.

For some years after the discovery of the fractional effect, the only cases found for p/q were for q odd—that is, ν = 1/3, 1/5, 2/5, 4/3, and so on. In particular, ν = 1/2 was not experimentally observed. Indeed, there is an attractive theory (*3*) giving the hierarchy of possible ν values that predicts this. However, this theory is based on a certain approximation—namely that all electron spins are parallel. Electron spins are quantized and can take on two values, "up" and "down"—parallel and antiparallel to the magnetic field. Because there is a significant interaction between the field and a spin, the up spins are favored and the down spin possibility is "frozen out." A few years ago, the fraction 5/2 was observed (*4*), and this is indeed attributed to down spins mixing with up spins. Because these are rather large fractions, there are theoretical complications, but nevertheless, these results created quite a stir.

The specific system in which the QHE is observed consists of a layer of electrons at the interface of a semiconductor and an insulator. Tricks in the fabrication of layered structures are known, involving doping, and so forth, that permit these electrons to be captured in a "quantum well" at the interface, while still allowing them to move freely along the interface. The idea of the AT&T and Princeton experiments is to construct two quantum wells, leading to two nearby parallel layers of electrons that interact only via their Coulomb interaction. The strong applied magnetic field then forces all the real spins to be "up." However, an electron can be specified by its position in the layer, and by "up" and "down" depending on whether it is in the "upper" or "lower" well. Therefore, this experiment provides, at least to first approximation, a two-dimensional layer of electrons with an artificial spin (referred to as a pseudospin) not frozen out by the magnetic field. On the basis of this pseudospin analogy (*5*) the possibility of a ν = 1/2 FQHE has earlier been predicted (*6*, *7*) for suitable values of interwell separations.

In fact, the experimenters do see the fraction ν = 1/2, loud and clear (see figure), and this is in accord with the best available theory. When the two wells are far from each other, they can be thought of as two independent electron layers each with ν = 1/4 and, consequently, no FQHE is observed. If, on the other hand, the two wells are very close (with considerable overlap of their electron wavefunctions), the system is effectively a single two-dimensional layer with ν = 1/2 and, again, no FQHE is observed. Theory predicts (*6*, *7*) that over intermediate values of the well separation there should be a ν = 1/2 FQHE state arising from competition between intralayer and interlayer interactions between electrons. At high magnetic fields B (*7*) the intralayer interaction is characterized by the magnetic length $\ell = [ch/(2\pi eB)]^{1/2}$ with c the speed of light, whereas the interlayer interaction strength is naturally described by the interwell separation d. For $d \sim \ell$, the inter- and intralayer interactions are comparable, leading to the stabilization of the ν = 1/2 FQHE. This theoretical



Fractional quantum states. The ν = 1/2 FQHE was observed by groups at (**A**) Princeton (plotted as Hall resistance versus magnetic field strength), and (**B**) AT&T Bell Laboratories (plotted as Hall resistivity versus field strength). The quantization of the Hall steps is accurate to about 0.3% and 1.5%, respectively, and is comparable to other known fractional and integral QHE results. A number of these known fractions can also be seen in the data. [Adapted from (*1*) and (*2*) with permission]

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expectation is directly confirmed by the AT&T experiment (*2*), where (panel B of the figure) the $\nu = 1/2$ FQHE is observed at $d/\ell \sim 2.5$ as predicted (*7*) in a recent calculation.

The experimental situation is actually somewhat more complicated by the fact that each quantum well has a finite thickness λ that introduces a new length scale into the problem, reducing the intrawell interaction energy. The original theoretical work assumed (*6*) $\lambda \sim 0$, finite values of λ explain (*7*) the occurrence of the $\nu = 1/2$ FQHE at $d \sim 2.5\ \ell$ rather than at $d \sim \ell$. Even though the observation of the $\nu = 1/2$ FQHE is quite similar in the two experiments (*1, 2*) a striking difference is that $d/\ell \sim 2.5$ in the Princeton results (*1*), and, 7 in the AT&T (*2*). It is noteworthy that the effective well thickness is also different [($\lambda/\ell \sim 3$ in (*1*) and ~ 1 in (*2*)] in the two experiments, and, in the Princeton sample (*1*) there may be considerable quantum tunneling between the two layers, but not in that in the Bell sample (*2*). Larger values of λ/ℓ in (*1*) compared to those in (*2*) probably lead to the stabilization of $\nu = 1/2$ FQHE at larger values of d/ℓ. Thus, while the $\nu = 1/2$ FQHE in double-layer electron systems was theoretically anticipated (*5–7*) many details of the experimental results remain to be understood.

This stimulating observation of a clear-cut even-denominator FQHE, which was thought to be "impossible" at one time, should lead to considerable activity looking for other "unusual" fractions exhibiting FQHE. Among the possibilities that are likely to be experimentally explored in the near future are the search for other unusual states in double layers with unequal electron populations in individual wells, a detailed investigation of the interlayer tunneling effect on the new FQHE states, and a systematic investigation of the phase diagram of possible double-layer FQHE states as a function of magnetic field strength and orientation, layer separation, layer width, and interlayer tunneling rate. Observation of unusual states in three or more well structures is another exciting possibility.

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Conodonts: A Major Extinct Group Added to the Vertebrates

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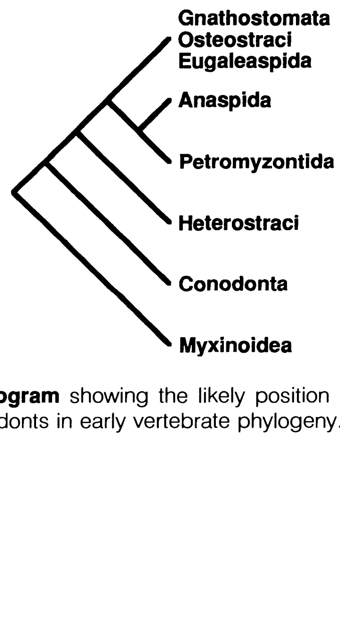
After more than 130 years of the debate, definitive evidence has finally been discovered that allows the conodonts to be assigned to the vertebrates. The conodonts are a group of marine organisms that flourished for about 300 million years, ranging from Late Cambrian to Late Triassic. They are represented in the fossil record by tooth-like microfossils (conodont elements) usually from 0.2 to 2 mm in dimension, rarely as long as 14 mm. These elements are composed of calcium phosphate (carbonate fluorapatite) and are readily extracted from the host rock. They receive considerable attention in the paleontological literature (some 280 publications in 1991) because of their importance as biostratigraphic indicators in the correlation of sedimentary sequences. Conodont elements can reveal the thermal history of sedimentary basins, because they undergo a proportional color change on heating due to their content of organic matter. In addition they retain a trace element and isotopic ratio signature that reflects the chemistry of the oceans in which they lived. Although conodont elements were first reported in 1856, the rest of the organism was completely unknown until specimens preserving traces of the soft tissues were described from the Lower Carboniferous of the Edinburgh district, Scotland, in 1983 (*1*). This discovery cast some light on the enigma of conodont affinities (they had previously been assigned to a range of invertebrate and vertebrate groups, and even plants) but a number of crucial questions remained unresolved.

The Scottish specimens which preserve the soft tissue morphology of conodonts revealed that the animal was elongate, laterally compressed, and somewhat eel-like (*1, 2*). These examples, at least, represent a swimming carnivore. The elements form a bilaterally symmetrical feeding apparatus in the head, flanked by a pair of dark lozenge-shaped lobes that may represent the eyes. The trunk is divided into a series of V-shaped structures, traces of the muscle blocks that were separated by myosepta. Two parallel lines run the length of the trunk. Their nature is problematic, but comparison with observations on decaying specimens of the lancelet *Branchiostoma* supports their interpretation as the margins of the notochord rather than the gut. The tail region bears short, closely spaced fin rays. The evidence of the soft tissues indicates that the conodonts belonged among the primitive craniates (*2*). However, in the absence of evidence that the histology of the mineralized conodont elements had clear homologs among living craniates, this placement remained controversial. Vertebrate workers continued to regard conodonts as beyond their purview (*3*), and some authorities preferred to retain a separate phylum Conodonta for the group (*4*).

Now the taxonomic affinities of conodonts have been confirmed. Nomarski interference contrast microscopy and scanning electron microscopy of polished slices of conodont elements have revealed, for the first time, a number of tissue types characteristic of vertebrates (*5*). Conodont elements consist of a crown made up of centrifugally deposited lamellar tissue, overlying a less consistently preserved basal body. The new investigation shows that the growth pattern and arrangement of crystallites within the lamellae in the elements of many conodonts are typical of the structure of enamel in vertebrate teeth. Areas of opaque "white matter" that often occur in the crown include features histologically identical to the lacunae and canaliculi of cellular bone, and structures in the basal body are similar to globular calcified cartilage in various vertebrates. Dentine is absent.

The demonstration that the conodonts



Cladogram showing the likely position of the conodonts in early vertebrate phylogeny.

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