A shot in the arm for fractional charge

Charles L. Kane and Matthew P. A. Fisher

The theory of the fractional quantum Hall effect implies the existence of quasiparticles, collective electron states that have fractional charge. New experiments provide a direct measurement of the charge of these strange states.

One of the most basic features of the physical world is the quantization of charge in units of the electron charge, *e*. The only exceptions are quarks, which have charges that are multiples of *e*/3, but they are inseparably confined inside nuclear particles. Otherwise, all observed charges in nature are integer multiples of *e*. So it was quite a surprise when Robert Laughlin[1], in his 1982 theory of the fractional quantum Hall effect, made the bold proposal that objects with fractional charge, *e*/3, could exist inside tiny semiconductor devices. In the past 15 years nearly every aspect of Laughlin's theory has been experimentally confirmed, but a direct observation of the fractional charge of the Laughlin quasiparticle has remained elusive. Now two groups (de-Picciotto *et al.* on page 162 of this issue[2], and Saminadayar *et al.*[3]) have performed a new class of experiments which probe shot noise in the quantum Hall effect, and provide compelling evidence for the fractional charge.

Imagine you were in a house with a tin roof during a hailstorm. By listening, could you determine the size of the hail stones? Small hail stones would generate a pitter-patter almost indistinguishable from continuous noise, whereas larger stones would result in less frequent yet louder crashes. Clearly, the temporal fluctuations in the sound depend on the size. This is the essence of Schottky's 1918 shot-noise theory[4] for the fluctuations in the current flowing through an electrical circuit.

Provided the particles flow independently (with an uncorrelated Poisson distribution), their charge is equal to the ratio of the mean square fluctuation in current to the average current. So by carefully measuring current fluctuations, de-Picciotto *et al.*[2] and Saminadayar *et al.*[3] were able to determine the charge of the objects carrying current in their experiments. They were not electrons, but particles with fractional charge very close to *e*/3.

The experiments were performed on a two-dimensional gas of electrons, which is confined at the interface between two semiconductors. When cooled to a few degrees Kelvin and placed in a magnetic field of several tesla, such a system shows the integer quantum Hall effect — discovered in 1980 by von Klitzing[5] — in which the Hall conductance G_H is quantized in integer multiples of the fundamental unit, $G_Q = e^2/h$ (where *h* is Planck's constant). This is a quantum-mechanical extension of the classical Hall effect, in which a current-carrying conductor in a magnetic field develops a voltage perpendicular to both field and current.

Two years later, in even stronger magnetic fields, Tsui, Stormer and Gossard[6] observed quantization with a fractional value, $G_H = G_Q/3$; and other fractional values have been observed since then. This new behaviour, dubbed the fractional quantum Hall effect, could not be explained within the conventional theory of metals. However, shortly after its discovery, Laughlin proposed that electrons in such strong fields form an exotic new collective state, which bears some resemblance to the collective state that occurs in superfluid helium.

A central feature in Laughlin's theory was the existence of quasiparticle excitations with fractional charge, *e*/3. Although they are built out of the collective motion of many electrons, the quasiparticles are spatially localized lumps of fractional charge. Moving inside the two-dimensional electron gas, they behave in much the same way as ordinary particles do. Of course, the quasiparticles can only exist inside the electron gas, unlike electrons, which can be added or removed from it.

Observation of the quasiparticles' charge is difficult because at low temperatures they tend to be pinned in place by impurities. However, quasiparticles are 'liberated' at the edges of the two-dimensional sample[7]. There they are free to flow in a single direction, determined by the magnetic field, along a narrow, effectively one-dimensional channel (Fig. 1). The experimental challenge is to measure the charge of the particles forming this exotic one-dimensional fluid.

An earlier approach to measuring this charge was to make a small island in the two-dimensional electron gas, an area depleted in electrons. The number of quasiparticles in the one-dimensional channel encircling this 'anti-dot' can be varied by changing either the magnetic field or the voltage on a nearby metallic electrode. By measuring the changes necessary to bind each additional quasiparticle, the fractional charge can be determined, provided one makes several plausible assumptions about the area and capacitance of the anti-dot as well as the effects of quantum interference. Although indirect, this procedure was successfully implemented several years ago by Goldman and Su[8].

The idea of using shot noise to measure fractional charge dates back to Stormer and Tsui in the mid-1980s (see ref. 9). This is an appealing idea because shot noise is a classical effect, which is simpler to interpret. In 1994, we suggested[10] that a 'quantum point contact', formed by pinching together the edges of an electron gas (Fig. 1), would be an ideal geometry for such an experiment. There, Schottky's assumption of uncorrelated motion is satisfied provided the charge carriers flow through the pinch-off point at a very low rate, by quantum tunnelling. This occurs in two geometrical regimes.

If it is strongly pinched off, the sample is effectively split into two (Fig. 1a), so the weak tunnelling current must be carried by electrons, and shot noise with charge *e* is expected. However, in the opposite extreme of weak pinch-off (Fig. 1b), quasiparticles can tunnel from the top to the bottom edge *through* the quantum Hall fluid. Provided the rate for this is small, the resulting shot noise should be exactly *e*/3 times the average tunnelling current.

Both of the new experiments[2,3] measured the fluctuations of a small current flowing

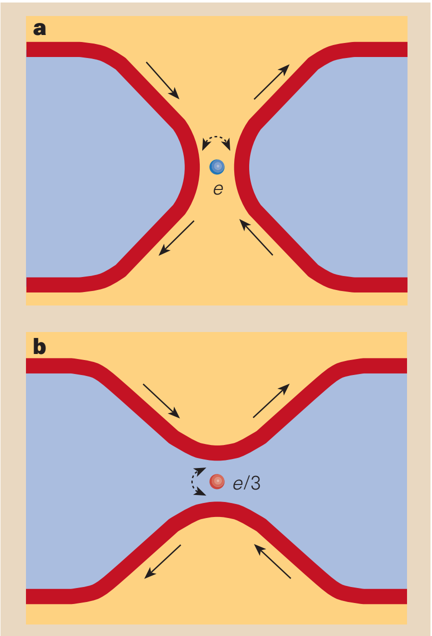

Figure 1 **A quantum point contact in a two-dimensional electron gas (blue). Quasiparticles flow along the one-dimensional edges, as indicated by the arrows.** a, **In the strong pinch-off limit, electrons tunnel from left to right.** b, **With weak pinch-off, fractionally charged quasiparticles have been observed to tunnel through the electron gas between the top and bottom edges[2,3].**

through such a point contact, constructed using state-of-the-art lithographic techniques. Elaborate filtering minimized the noise of the external circuitry, allowing the intrinsic fluctuations generated by the point contact to be isolated. The charge of the quasiparticle was determined from the measured shot noise in the limit of a weak pinch-off.

The final results were unambiguous: the quasiparticles have fractional charge. Fractional charge is no longer solely in the domain of elementary particle physics. □

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***E. coli* genome sequence**

A blueprint for life

E. Richard Moxon and Christopher F. Higgins

"*This is truly the age of bacteria: as it was in the beginning, is now and ever shall be.*" — Stephen Jay Gould.

Life appeared on Earth soon after the formation of liquid water. For about three billion years, the only organisms were microbes, predominantly prokaryotes (archaea and bacteria). These organisms display immense diversity and biochemical versatility, as well as showing complex behaviours such as sex, memory, decision-making and communication (Fig. 1). Furthermore, bacterial diseases exact a huge toll of morbidity and mortality in animals and plants. Shigella is essentially *Escherichia coli* with a superinfecting virulence plasmid[1]; outbreaks of *E. coli* O157:H7 have been of worldwide concern[2]; and encapsulated strains are a cause of meningitis and urinary-tract infections[3].

Given this perspective, and the abundance and diversity of microbes past and present, surely no one would argue the priority afforded by prokaryotes in our efforts to understand the fundamentals of life? Historians of science may find it difficult to escape the conclusion that the limited funding for prokaryotic genome sequencing up to 1995 was extraordinary. The complete genome sequence of *Haemophilus influenzae* from scientists at the Institute of Genome Research began to change the course of biology[4]. With the publication of the complete *E. coli* genome sequence by Blattner and colleagues[5] in *Science*, we might consider that we have reached 'the end of the beginning'.

"Although not everyone is mindful of it, all cell biologists have two cells of interest: the one they are studying and *Escherichia coli*."[6] Until three years ago, most thought it a foregone conclusion that *E. coli* would be the first bacterial genome to be completely sequenced. Yet it is actually the seventh, each genome project representing an enormous achievement, and contributing in an eclectic way to a revolution in biology.

But to consider *E. coli* as merely one more bacterium would be a serious error. Far more is known about it than about any other living organism. *E. coli* is the complete organic chemist — using glucose and inorganic salts it can synthesize everything needed for life, yet it can also utilize an impressive array of organic compounds as a source of nitrogen or carbon. Its extraordinary versatility makes *E. coli* the perfect model organism in which to study gene regulation and adaptive evolution. Work on *E. coli* and its 'phages (bacterial viruses) has led to many of the key achievements in biology (recognized by several Nobel prizes), such as elucidation of the major biosynthetic pathways; discovery of the mechanisms of gene regulation; refinement of the concept of the gene; elucidation of the genetic code; the concepts of transcription and translation; and the fundamentals of DNA replication, mutagenesis and repair. Most cell and molecular biologists also use *E. coli* as a simple reagent — without it, DNA cloning and sequencing as we know and love them would not exist. It is no accident that the two-volume classic "*Escherichia coli and Salmonella*"[7] is known affectionately in microbiology laboratories as 'The Bible'.

How, and why, did a ubiquitous commensal of the gastrointestinal tract come to occupy such a pre-eminent position in biology? In the 1940s, a far-sighted group of physicists, chemists and geneticists concluded that only by working on the simplest of biological systems could an understanding of individual genes — let alone the complexity of the independent life of a cell — prove tractable. The starting point was the discovery, in the 1930s, that biosynthetic processes of cells were pathways of sequential steps catalysed by enzymes. The problem was to correlate genotype and phenotype — a problem that had created an impasse for fruitfly geneticists who could not assess the biochemical defects of their mutants. The small size of *E. coli*, its lack of pathogenicity, rapid doubling time (20 minutes), and the simplicity of its nutritional requirements, made it ideal for the isolation and study of mutants defective in the synthesis or use of essential metabolites. The demonstration of sex (genetic recombination between cells) in *E. coli* completed the opportunity to combine the powers of biochemistry and genetics[8].

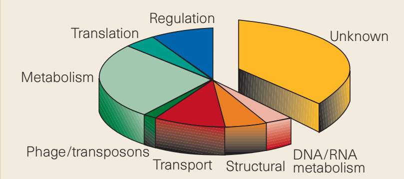
How does the genome sequence of *E. coli* help to solve the seemingly insurmountable problem of understanding the fundamental workings of a living cell? All of the functions that are required by the *E. coli* cell are encoded by a 1-mm circular DNA duplex, the chromosome, the total chemical make-up of which has now been determined by Blattner

Functions for orphan genes

From the paper by Blattner *et al.*[5], the proportion of genes in *Escherichia coli* that are dedicated to known functions is estimated. Importantly, 30–40 per cent of genes have no known function, and are not obviously related to genes of known function. So what do they do? It is generally accepted that by conventional biochemistry and genetics we have identified most (perhaps 80 per cent) of the genes that are required for the biochemical and regulatory pathways necessary for the normal life of the *E. coli* cell: it seems unlikely that all these 'orphan' genes will be required to fill in the 'gaps'. Perhaps the unidentified genes serve complex functions, such as:

- Survival in unusual environments, or within host cells
- Integrating and coordinating the known metabolic pathways
- Organizing the chromosome, replication and transcription within the confined space of the cell
- Creating local environments within the cell
- Memory or communication

Finally, we should not discount the possibility that although these orphan genes may not encode a communication system with Alpha Centauri, they may yet yield surprises. **E.R.M. & C.F.H.**



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