Are electrons mere billiard-balls?

Electrons near the top of an electronic band appear to behave at low temperatures as if they were classical particles and not particles best represented by quantum mechanics.

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ALL of us have found ourselves on whistle-stop tours of other people's laboratories — fifteen minutes for each laboratory, but, because the visit begins twenty minutes late, nobody quite knows whether there is any time in which to talk. So it was last week at the Dutch research laboratory of Philips, the multinational company that does not object if it is called an "electronics giant", which used to be the case before the Sonys and Hitachis of this world stole the show in the hardware shops.

One stumbles into a spanking clean laboratory with a clever cryostat in the corner, one of half a dozen shining faces begins describing how they have together worked out a technique for explaining that the motion of electrons can be accounted for as if they were billiard balls even in circumstances in which quantum theory should apply (the cryostat is not irrelevant). Rashly, one volunteers that there is a paper on just that topic in the latest issue (23 October) of *Physical Review Letters* and, foolishly (because unecessarily) one adds "from somewhere like Bell Labs". In unison they cry, "But that's *our* paper!" (The reference is **63**, 1857; 1989).

What follows is more than a monument to that fleeting embarrassement, because the underlying issues are both interesting and important. One of the objectives of electronic device development is the further reduction of the physical dimensions of the circuit elements that conduct, store or change the phase of (usually to delay) alternating currents (resistors, capacitors and inductors respectively).

Recent technology, notably the development of techniques for making, by epitaxial growth, alternating layers of materials such as GaAs and its alloy with aluminium (AlGaAs), each of which may be given a predetermined shape, have made it possible to make measurements of essentially one-dimensional conductors in which the chemical potential (in simple language, the availability) of electrons can be varied at will. People would like to have a simple picture in their heads to describe the behaviour of electrons in these circumstances.

The place to start is not with quantum mechanics but with a model of what may be expected of the behaviour of an electron-sea in a reasonably well-conducting semiconductor which may, or may not, be immersed in a uniform magnetic field. It is also easy to imagine that electrons may be injected (by the application of a voltage) from one layer in an epitaxial sandwich into the next, for example through a small aperture a fraction of a micrometre across (250 nanometres seems fashionable). The injected electrons will come from the top of a Fermi band in the layer of material that constitutes the source. They may be injected into a material whose band structure is different, but in general will have an energy that does not coincide with one of those allowed for the material in which they find themselves. How, then, will they move?

One way of dealing with it is to use the states accessible to electrons as representative of a complete set of wave functions in terms of which the motion of the injected electron may be described. It would be a straightforward if complicated calculation, especially if there were a magnetic field. Curiously, there seems to be a simpler way. C. W. J Beenakker and his colleagues at the Philips Laboratory have followed others with an especially neat way of studying the behaviour of electrons in situations such as these.

Two years or so ago, they began with the simple objective of measuring the conductance of electrons through a single gateway between one epitaxial layer and the next. The conductance is a function both of the geometry of the gate and of its voltage. What most clearly emeges is that, at liquid helium temperatures, the conductance increases with the voltage in equal steps, each of which is numerically equal to $e^2/\pi h$ (B.J. van Wees *et al. Phys. Rev. Lett.* **60**, 848; 1988). The conductance, it appears, is quantized.

The explanation may not be far to seek, although it has not been pinned down. The electrons injected from one region into another have energy corresponding to the Fermi energy, that of a filled band in one section of the material. It is possible to represent the transmission from one region to the next by the properties of the wave function of electrons at the top of a filled band, and then to calculate thelikelihood of transmission through the gate by averaging over all states near the Fermi surface. Early last year, van Wees and colleagues at Philips were claiming that this process could yield the particular quantization of conductance observed, but the point remains to be confirmed.

Now, the group has moved on to a more sophisticated way of studying the transport of electrons near the top of the Fermi surface in materials such as GaAs. Following others, but with more sophisticated small-scale fabrication, they have built two gates into the boundary between one layer of GaAs and another, using one as a source of electrons and the other as a detector. In these circumstances, the effect of a magnetic field on the electrons can be followed, even at the temperature of liquid helium or a fraction of it. The technique seems to have been developed by the Soviet physicist V. S. Tsoi as a means of studying experimentally the behaviour of electrons in materials in which the mean free path of elecrons is relatively high micrometres).

If one believed in simple quantum mechanics, one would guess that the chance that an elecron leaving the gate would be deflected towards the detector by a transverse magnetic field would be a smooth but fluctuating function of the field strength. A field that would just suffice to deflect a classical electron from the gate to the detector would probably yield the maximum current, but neighbouring values of the field would carry almost equal numbers of electrons to the detector.

But again, it seems, there is a simpler way. What the Philips group appears to have found is that the electrons can be thought to behave ballistically, as if they were billiard balls. At least at sufficiently low temperatures, the chance that there will be a large current a the detector depends critically on the manetic field, and is greatest when the magnetic field is such that the distance between the emitter and the collector is an integral multiple of the cyclotron radius of an electron in the applied magnetic field. Again, it seems, the electrons behave ballistically.

Nobody pretends, on evidence such as this, that quantum mechanics is a pack of lies, or that it is always safe and proper to regard electrons as little billiard balls. After all, the electrons are not moving in a vaccuum but in the electric field of complicated lattice structures where they are denied a natural place. No doubt, it is only a matter of time before their apparently ballistic character is related to the properties of the wave functions of electrons such as these. But it is a fair guess that, when that is done, many other curious magnetoresistive properties with a quantized structure, the quantum Hall effect among them, will be more easily understood than at present.

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