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Introduction

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The subjects for this workshop were nanostructures and quasi-two-dimensional systems. Artificial nanostructures have structure on the scale of nanometres (10^{-9} m). The nanometre represents a limit on the miniaturisation of artificial structures since atomic diameters are of this scale. Two-dimensional systems are atomically thin layers, usually of electrons embedded in a semiconductor substrate. These fascinating systems owe their existence to the rapid advances within the last ten years in electronic device miniaturisation and manufacture. Spectacular as the technological advances have been, the focus of the workshop was not on these achievements themselves, but on the opportunities the technology provides to think up and build artificial systems having exotic physical properties that give us insight into structure on a quantum scale. Since the atomic scale is determined by the dictates of quantum mechanics it is not surprising that artificial structures on this scale should have properties which are dominated by quantum mechanical effects and strong correlations, and that these often generate novel ground states.

Many quantum phenomena manifest themselves on the nanometre scale, and it is possible to design specific nanometre systems to observe particular quantum effects predicted by theory. Nanometre systems have confirmed many of the simple 'particle in a box' properties of quantum mechanics.

More subtle is the quantum interference effect predicted by Bohm and Aharonov in which the coherent wavefunction of an electron encircles a magnetic flux line, undergoing a different phase shift depending on whether it travels in a clockwise or an anticlockwise direction. The phase shift has been measured by splitting a current through a conducting ring about a micron in diameter. The ring is made of polycrystalline gold wire a few tens of nanometres thick, embedded in an intrinsic semiconductor substrate. The resulting current displays regular oscillations as a function of the magnetic flux strength. These agree precisely with the interference pattern predicted by Bohm and Aharonov theoretically. The wire is so thin that there is only a relatively small number of possible electron paths through it. This ensures that the electron wavefunction has coherence over the length of the ring.

The electron turnstile is another ingenious circuit that was custom-designed to observe a particular phenomenon. The circuit restricts the flow of electrons so

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that they can only pass through it one at a time, rather like so many spectators at the turnstile entrance to a sports ground. The underlying physics making this happen is remarkable. It points to fundamental questions on precisely what is meant by the flow of single electrons collectively making up an electric current.

The electron turnstile uses four identical tunnel junctions placed in series. Tunnel junctions are formed by separating two conductors by an extremely thin insulating strip. Electrons can quantum-mechanically tunnel through the strip, but it is only energetically favourable for them to do so if the voltage across the strip exceeds some critical value $V > V_c$. If C is the capacitance of the junction, the corresponding critical charge on the terminals is $Q > Q_c = CV_c$.

For the turnstile, the tunnel junctions are chosen so that for each, $Q_c = e/3$. By maintaining a fixed driving voltage of $V = 0{\cdot}4e/C$ across the device, it is straightforward to establish that the charges on the junctions are initially $Q = \pm 0{\cdot}4e$. This exceeds the critical charge, and an electron can tunnel through the junctions.

When a single electron tunnels across the first junction, the charge on its terminals drops from $Q = 0{\cdot}4e$ to $0{\cdot}2e$ because of the transference of charge. This prevents the electron from retracing its steps and also prevents any other electron from following it. As the electron progresses through the four junctions, this process is repeated until the electron finds itself on the other side of the device with four gates behind it closed to it and to other electrons. A change of applied voltage at the midpoint of the device then opens the turnstile to another electron.

By cycling the midpoint voltage it is possible to let the electrons pass through the turnstile one by one so they can be counted. This is a quantum limit to the Ampère standard for an electric current, although the cycle time at present is too long to make it a practical standard. Thermal fluctuations at room temperatures are also a problem since the driving voltages needed at present are of the order of 100 μV. The junctions have insulating strips about a micron thick and capacitances of about $C \approx 10^{-3}$ pF. If the thicknesses can be reduced to nanometres, the capacitances and the driving voltages will be increased by a corresponding amount and the turnstile could operate at room temperature.

While in the Bohm–Aharonov and the electron turnstile experiments the systems were designed to study particular quantum effects, in many other cases systems have been discovered by experimentalists that exhibit novel quantum effects which had not been anticipated theoretically. The integer and fractional quantum Hall effects were just the first in a series of unexpected experimental discoveries during the 1980s.

One of the more recent surprises was the observation of the conductance quantisation of a quantum point contact. In this experiment the current in a conducting plane passes through the narrow gap formed between the vertices of two insulating triangular islands which are embedded in the plane of the conductor. The gap between the vertices is about 250 nm and the triangles have sides of about 1 μm.

The insulators are held at a negative potential so that the equipotential contours around the insulators create a classical exclusion zone within which the repulsive potential exceeds the external potential driving the current. The voltage on the insulators acts as a gate restricting the flow of current through

the gap. If the 'gate voltage' is made sufficiently negative compared with the driving voltage, then the exclusion zone completely fills the gap and the current through the gap is choked off. Qualitatively this is what one observes. However, the surprise is that the current does not decrease continuously but goes down in a regular series of completely flat steps. The plateaus of the conductance are separated by exactly $e^2/\pi\hbar$.

A simple quantum explanation of this phenomenon is possible if one assumes that the electrons are being transported through a narrow conducting channel of fixed width. Taking the x direction as the alignment of the channel and y as the cross section, the conductance along a channel is the k_x-weighted average over states at the two-dimensional Fermi surface $|\mathbf{k}| = k_\mathrm{F}$. The transverse momentum in the channel k_y will be quantised in standing waves. For a channel of width W the conductance is thus proportional to

$$G \propto \int \frac{\mathrm{d}^2k}{2\pi k_\mathrm{F}} |k_x| \delta(|\mathbf{k}| - k_\mathrm{F}) \frac{2\pi}{W} \sum_{n=1}^{\infty} \delta\left(k_y - \frac{n\pi}{W}\right). \tag{1}$$

The restriction $k_y \leq k_\mathrm{F}$ truncates the sum so that $n < k_\mathrm{F}W/\pi$. The two delta functions permit the integrations to be carried out giving

$$G \propto \sum_{n=1}^{k_\mathrm{F}W/\pi} \frac{e^2}{\pi\hbar}. \tag{2}$$

As the magnitude of the gate voltage is reduced, the width of the channel increases. The conductance remains constant until $k_\mathrm{F}W/\pi$ passes through an integer value, when an additional term $e^2/\pi\hbar$ is added to the sum. The conductance then jumps by this amount and the process is repeated. This is precisely the observed functional dependence of the conductance on the gate voltage.

This model would appear to be unrealistically idealised and this is probably why the effect was not anticipated theoretically. The model assumes a conductance channel of constant width with infinite sides and with no surface roughness or imperfections. The reason that it apparently adequately approximates the actual physical situation is the insensitivity of delocalised wavefunctions to spatial details which are fine compared with their wavelength. It is ironical that this smoothing property of quantum mechanics allows simple-minded models to give good descriptions of a number of nanometre systems.

Perhaps the most spectacular surprise with these systems was the quite recent discovery that the metal tip of a scanning tunnelling microscope (STM) can be used to mechanically move individual atoms or molecules that have been physisorbed on a flat metal surface laterally across the surface. They can then be positioned with atomic precision elsewhere on the surface. This again was not foreseen theoretically.

The technique was pioneered with CO molecules physisorbed on a flat Pt metal surface. The constraining force preventing lateral movement of the molecules parallel to the surface is very weak. If after positioning the nearpoint of the STM tip above a CO molecule, a small tunnelling current between the tip and the surface is switched on, the bond between the Pt surface and the C atom can

be loosened sufficiently so that, if the tip is then moved parallel to the surface, the CO molecule follows the tip until the current is switched off. This releases the CO molecule at a predetermined position elsewhere on the surface.

The results of the first demonstration projects were the letters IBM written in CO molecules—the first example of a *nanologo*—and the primitive drawing of a stick figure, a pioneering piece of *nanoart*. Subsequently it was demonstrated that using a similar technique a Xe atom that had been physisorbed on a Ni surface could actually be transferred up to an STM tip. The process was reversible since switching off the tunnelling current caused it to drop back down to the surface again. This permits Xe atoms to be lifted over steps on the Ni surface and it can also be used to produce a three-dimensional pile of Xe atoms on the surface, the first *nanocairn*.

Beyond the clear benefits to be gained from the ultimate miniaturisation of electronic circuits (structures cannot be made smaller than individual atoms), there are ground-breaking possibilities in the manufacture of new chemicals and drugs as well as in the artificial manipulation of biological systems. However, before there can be serious applications of this remarkable technique, the problem of making vast numbers of structures one by one must be solved. The obvious way over this major hurdle is to use some technique of self-replication by which a seed structure is induced to repeatedly duplicate its pattern.

From the point of view of the workshop the central point here lies in the revelation that a system as small and as manifestly quantum-mechanical as an individual atom can be mechanically lifted up and moved around on a surface. This is a revolutionary idea and coming to terms with all its implications is likely to take years.

The lectures in this volume cover a wide range of topics and a large number of striking new systems. A common thread is the central role quantum mechanics plays in determining their properties, often controlling the properties in very subtle and unexpected ways.