QUANTUM DOTS

When a barrier is not an obstacle

Electrons in ultraclean carbon nanotubes can tunnel through barriers in a way not previously observed for particles with mass in condensed-matter physics experiments.

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In the quantum world, particles are able to tunnel through the potential energy barriers that would reflect them in the classical world. In non-relativistic quantum theory the probability of tunnelling through such an energy barrier falls exponentially as the height or the width of the barrier increases, but 80 years ago Oskar Klein used Dirac's relativistic theory of the electron to show that relativistic particles can tunnel without any resistance through barriers that are higher than twice the rest-mass energy of the particles[1]. However, this Klein tunnelling is almost impossible to observe directly with electrons or other elementary particles because huge electric fields are needed to produce such high potential energy barriers. On page 363 of this issue, Gary Steele, Georg Gotz and Leo Kouwenhoven of the Delft University of Technology demonstrate[2] a new type of tunnelling in a table-top experiment with carbon nanotubes that is analogous to Klein tunnelling (Fig. 1a). Their work may also pave the way towards spin-based quantum information processing in solid-state devices[3].

Klein tunnelling can be understood in terms of the relationship between the energy and momentum of the particle. In Dirac's theory, energy and momentum are related through two hyperbolic curves that have a gap $\Delta = 2mc^2$ between them, where m is the mass of the particle and c is the speed of light in a vacuum (Fig. 1b). At low energies the relationship between the energy and the momentum is not linear, but for energies much higher than the gap energy, the energy–momentum relation is approximately linear. Similarly, when a Dirac particle encounters a potential energy barrier with a height that is larger than Δ, the energy–momentum relation becomes linear, with the slope inside the barrier being equal to the slope outside the barrier. The particle does not, therefore, recognize the barrier and passes straight through it without any reflection.

One way to overcome the difficulty of making energy barriers with heights greater than $2mc^2$ is to use particles that do not have any mass. Such particles have a linear energy–momentum relation at all energies and can pass freely through barriers of

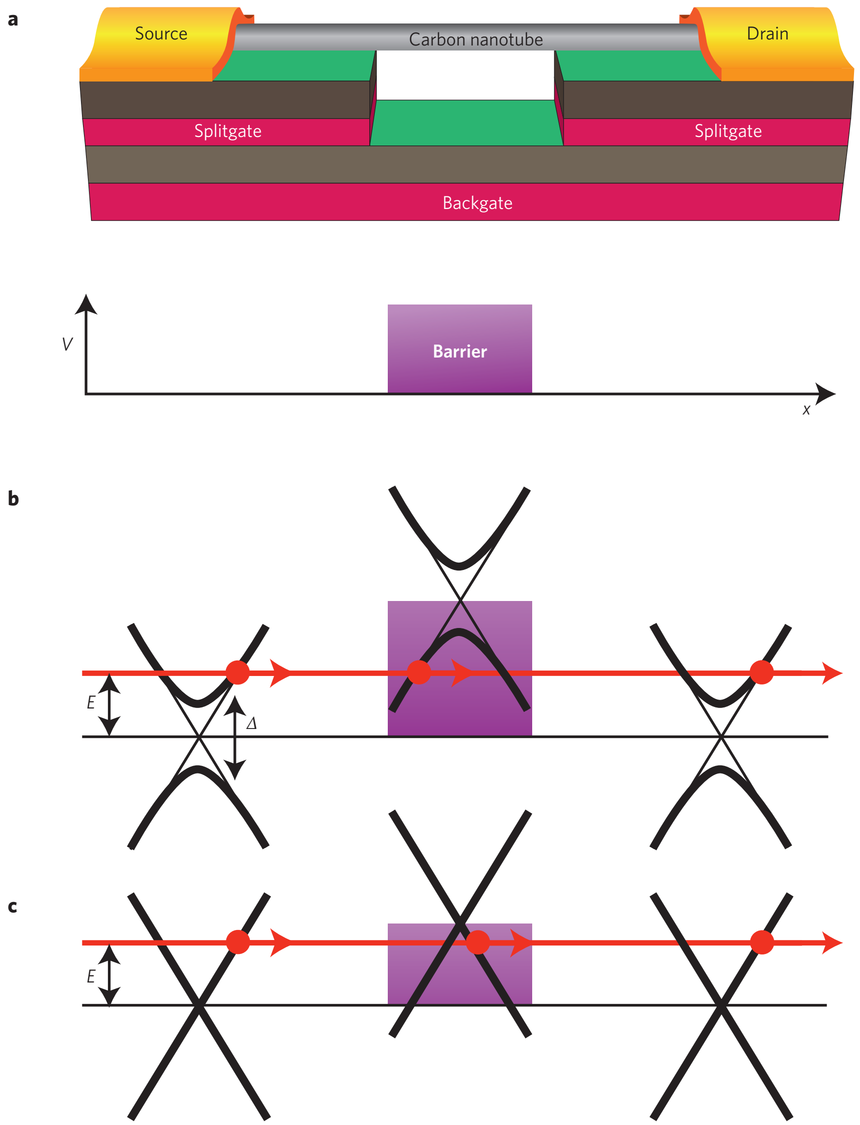

Figure 1 | Klein tunnelling in carbon nanotubes. **a**, A carbon nanotube suspended between source and drain electrodes. The local backgate together with two splitgates can define two quantum dots in the nanotube, and the backgate can be used to control the height of the potential energy (*V*) barrier (bottom) between these dots. **b**, The relationship between energy (*y* axis) and momentum (*x* axis) for a massive Dirac particle in regions with (centre) and without (left and right) a potential energy barrier. The positive energy curve is for particles (such as electrons) and the negative energy curve is for antiparticles (such as positrons). The red circle shows a particle with energy *E* Klein tunnelling through the barrier. Klein tunnelling is only possible when the height of the barrier is much higher than the gap Δ between the positive and negative energy curves. **c**, The energy–momentum relations of a Dirac particle without mass in regions with and without a potential barrier. A massless particle can tunnel through a barrier of any height.

any height, as has been demonstrated in experiments with graphene[4–6]. Due to its unique lattice structure, quasiparticles in graphene behave like massless Dirac particles over a wide range (a few electron volts) of energy, with a linear relationship between their energy and momentum (Fig. 1c).

Steele and co-workers adopt a different approach, using the energy gap between the valence and conduction bands in semiconducting carbon nanotubes as a proxy for the energy gap between the two solutions to the Dirac equation[2]. They select nanotubes with small bandgaps (25 or 60 meV) so that it is possible to form a potential energy barrier that is much larger than the energy gap with a relatively low electric field.

However, the experimental observation of Klein tunnelling in carbon nanotubes is not straightforward because it requires an extremely clean sample as well as the ability to define and control the potential energy barrier. Placing gate electrodes on top of the nanotubes, the approach taken in many previous experiments, does not work because of the disorder introduced by the deposition process. Recently, very clean devices were made by suspending carbon nanotubes between source and drain electrodes[7], but it was difficult to add the local gates needed to define the quantum dots and control the height of the barrier in these experiments. Steele and co-workers developed a new fabrication method to integrate three independently tunable gate electrodes (one local backgate and two splitgates) with suspended nanotubes. In one device with good contacts between the nanotube and the source and drain electrodes, they were able to construct a potential energy barrier by tuning all three gates, and they went on to observe Klein tunnelling through the barrier.

Furthermore, in another device with less transparent contacts, they constructed double quantum dots, and were able to tune the coupling between them with the backgate. As the gate voltage was varied, they observed both normal tunnelling and Klein tunnelling between the dots. This demonstration is significant because it shows that such a double-quantum-dot device might offer enough tunability to make practical spin-based quantum bits[3], limited only by the effects of Klein tunnelling.

There are, however, still a few issues that need to be clarified. For example, perfect Klein tunnelling (that is, 100% transmission) was not achieved, and an effect called the spin blockade (in which the presence of an electron with, say, spin 'up' on a quantum dot blocks other spin 'up' electrons, while spin 'down' electrons can pass through the dot) was not observed either, so there is still plenty of scope for further breakthroughs. ❐

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