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Electrons jump lights in graphene

Sheets of graphene, a form of carbon, could provide the means to demonstrate an esoteric, relativistic quantum mechanical phenomenon, says S.Ananthanarayanan.

A team of scientists in the Netherlands and in the UK have worked out that grapheme, an everyday, ‘down here on earth’ material, although recently discovered, mimics the conditions in the vicinity of black holes, where nature shows some highly counter-intuitive behaviour.

Quantum mechanics

The discovery of radioactivity, towards the end of the 19th century, the structure of the atom and theories to explain how warm objects radiated heat led to the conjecture that energy consists not of a continuous stream, like a stream of water, but is more like a stream of pellets, each a ‘packet’ of energy. The light that an atom emits, then, is a packet of light that corresponds to just the energy difference between two ‘energy states’, or separate ‘shelves’ of energy that the atom could be transitioning between.

This ‘quantum theory’ has been incredibly successful in explaining all aspects of the behaviour of nature and it only now remains to connect the theory with the General Theory of Relativity, which deals with the nature of the force of gravity. But quantum theory has already been connected with the Special Theory of Relativity, which deals, not with gravitation, but with the way things need to be viewed when they move with speeds near the speed of light. And even this merger with the Special Theory, which was first done by the English scientist, Sir P.A.M. Dirac, leads to results that sound like science fiction –of an ocean of ‘negative’ energy and that every particle should have an ‘antiparticle’ (with which contact would result in instant annihilation).

Barrier penetration

Just the ordinary quantum theory, with no relativity built in, was counterintuitive enough. It said that even a particle that did not have the energy to cross a barrier still had a chance to get to the other side. This was linked with the astonishing notion that there was always an uncertainty in the measurement of anything, regardless of the quality of instrument, because the value of the thing being measured itself was not exact, but had some built-in ‘spread’.

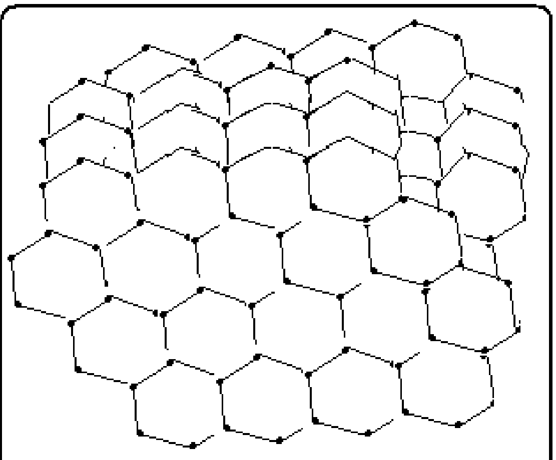
‘Barrier penetration’ was demonstrated in the phenomenon of radioactivity, where a nuclear particle escapes through a barrier of higher energy, something like a golf ball popping out of the hole which is on a mound, and rolling down the fairway! And the theory was able to explain exactly the kind of radioactivity that different atomic nuclei would show.

The Klein paradox

In radioactivity, the theory said, and this was accurately verified, the probability of a particle escaping the barrier reduced as the barrier grew higher. But the relativistic theory took the cake, with the prediction that when the height of the barrier was more than the full energy of the particle, including the energy equivalent of the particle’s mass, the particle started to pass freely through the barrier! In fact, the passage grew freer as the barrier grew higher and sufficiently high barriers were completely transparent!

This effect, which is called the Klein paradox, can be explained by considering that the barrier, which is repulsive to approaching electrons, is attractive to ***positrons***, the ‘antiparticles’ of electrons, which leads to positron states inside the barrier. The result is alignment with an electron state on the other side of the barrier and apparent passage of the electron without let or hindrance!

Graphene


sheets of graphene

Graphene is a single layer of carbon atoms, densely packed in a honeycomb lattice. It could even be considered to be a sheet of atoms drawn out of slab of graphite. The energy distribution within the sheet of carbon atoms is a series of energy barriers for an electron trying to pass through. The various fields and spins associated with the lattice and the electrons make the behaviour follow mathematics quite akin to what PAM Dirac had devised for the electron.

Now, the structure of graphene, with electrons at large, also sports ‘gaps’, or atom shells where electrons should have been, and these gaps, or ‘no-electrons’, behave like positrons, the electron antiparticles. The mathematics used to describe the electron-‘no-electron’ pairs turns out to be very similar to the mathematics that appear in the consideration of the electrons in the Klein paradox.

Thought experiments

The Klein paradox is now clearly understood, in theory, and should occur in the vicinity of very heavy atomic nuclei, or around the surface of black holes. Typically, spontaneous electron-positron pair production could result in a virtual positron being sucked into the black hole while the corresponding electron streams out, in the ‘Hawking radiation’, which would paradoxically emanate from an all-consuming black hole. But the conditions for the Klein paradox to happen in the laboratory are still out of reach.

The Dr Andre Geim, at Manchester, and colleagues now propose that Graphene could now provide the medium where relativistic tunneling may be tested experimentally. Introducing barriers inside graphene chips could then be made to control the flow of electric current flow and this could result in a new class of electronic devices