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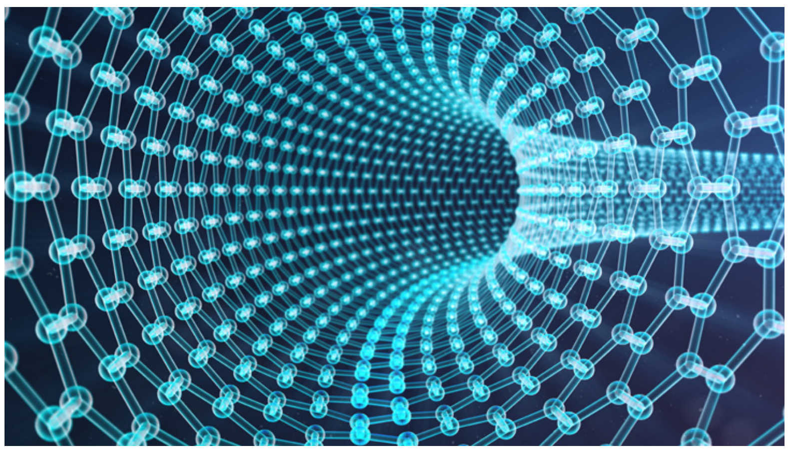
"Klein tunneling": an exotic phenomenon with implications on the speed of graphene electron devices



> Because of its extraordinary properties, graphene has been studied as a new and promising material for electronics during the last fifteen years. The dynamic of electrons in graphene is modelled by the Dirac equation which present an exotic Klein tunnelling phenomenon: a perfect transmission of electrons impinging perpendicular to a potential barrier (irrespective of the barrier height).

Molecular structure of graphene.

We argue that Bohmian explanation of quantum phenomena provides a very appropriate formalism for discussing tunneling times, because the orthodox (the usual) theory of quantum mechanics is ambiguous in the definition of tunnelling times in the sense mentioned by John Bell: “It [Bohmian mechanics] is, in my opinion, very instructive. It is experimentally equivalent to the usual version insofar as the latter is unambiguous.” The difficulties of the orthodox theory with the tunnelling times appears because the theory itself is unable to decide where the electron is without measuring it explicitly. Despite this orthodox ambiguity, tunnelling times are of paramount importance for the electronic industry because they are linked to cut-off frequencies (i.e. to the maximum speed of electron devices). The Bohmian theory allows an accurate definition of dynamic paths in terms of Bohmian trajectories independently of the measurement

(Fig. 1). The most important advantage of the Bohmian computation of the dwell time for high-frequency electron applications is its ability, not only to distinguish between transmitted (N_T) and reflected (N_R*) electrons, but also to discerns those reflected particles that spend some time in the barrier (N_R). Since such distinction is not possible in the orthodox quantum mechanics the discussion of the tunnelling times and cut-off frequencies become ambiguous/controversial with this usual theory.

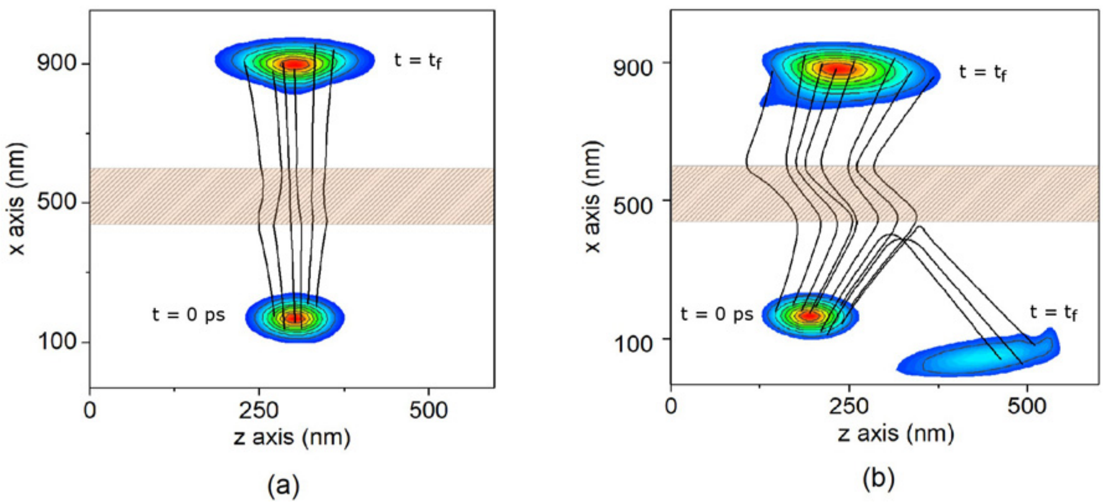


Figure 1. (a) Conditional wavefunction of the electron that impinges perpendicularly to a barrier in graphene (in the shaded orange region), along with the set of the associated Bohmian trajectories are plotted in the initial and final times computed from the BITLLES simulator. As it can be seen, from both the wave packet and the set of trajectories, the electron exhibits Klein tunneling and all trajectories traverse the barrier. (b) The same plot for an electron that impinge to the barrier at some angle. Now, there is no complete Klein tunneling and part of the wave packet and some trajectories are reflected. The transmitted part of the wave packet and transmitted trajectories suffered refraction according to Snell's law-like expression.

We consider a two terminal device whose band structure (energy of the Dirac point as a function of the x position) is plotted in Fig. 2. The wave nature of the electrons is given by a bispinor solution of the Dirac equation.

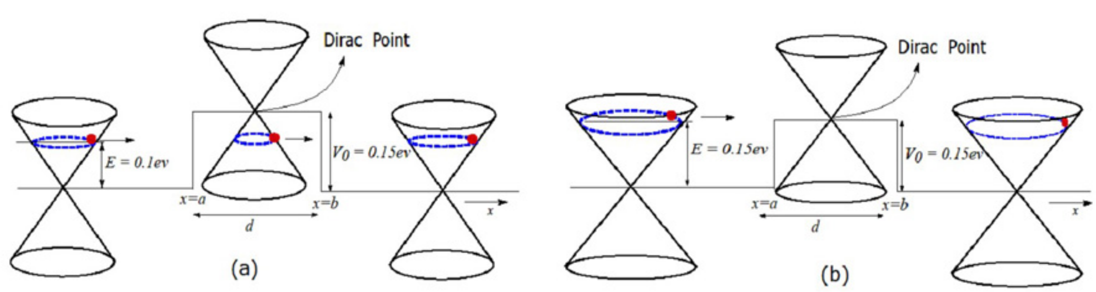


Figure 2. (a) Klein tunneling barrier region where the electron, which impinges perpendicularly to the barrier, has an energy E lower than the barrier height V_0. The cones represents the linear energy momentum dispersion of graphene at different positions. The electron has available states in the valence band of the barrier region which allows them to tunnel freely. The transmission coefficient in such cases is close to unity. (b) The same plot for an electron with energy similar to the barrier height $E = V_0$. In this case the electron has to occupy the Dirac point in the barrier region which has almost no available energy states. In these scenarios the transmission probability almost vanishes.

The correct computation of the dwell time through Bohmian trajectories is computed through the use of the BITLLES simulator. In Fig. 3(a) we show how the number of these trajectories vary with the angle of incidence ($\theta_{\vec{k}c}$), the simulations show that for ($\theta_{\vec{k}c}$)=0, almost all the particles are transmitted. Increasing ($\theta_{\vec{k}c}$) leads to an increase in the reflected particles. By construction, the behavior of N_T in Fig. 3(a) just reproduces the transmission coefficient *T* in Fig. 3(b). The estimation of the current delay in an electron device takes into account only the particles entering in the barrier, either N_T or N_R. Thus for an unequivocal description of the tunnelling times it is very important to classify and discard the contribution by the trajectories N_R* which do not contribute to the electrical current and thus, to the tunnelling times. In the orthodox computation, just with the bispinor (without trajectories), N_T, N_R and N_R* cannot be treated separately, and thus the mentioned ambiguity appears.

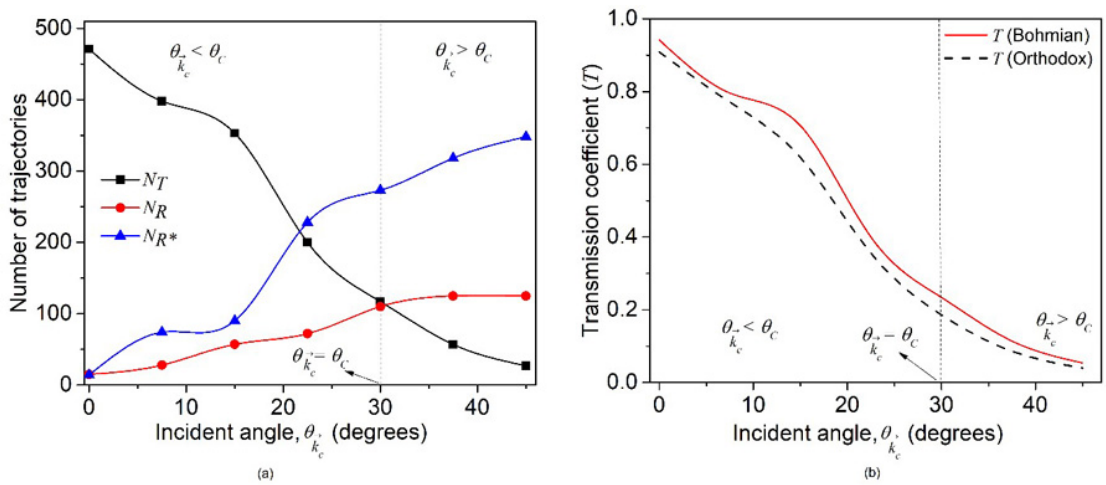


Figure 3. (a) Number of transmitted particles, N_T, particles entering into the barrier but eventually reflected, N_R and particles that are reflected before entering the barrier N_R as a function of the incident angle. (b) Transmission coefficient as a function of the incident angle computed from the orthodox quantum mechanics (dashed black line) and from Bohmian trajectories (solid red line)*

In conclusion, we have demonstrated the ability of Bohmian mechanics to discuss tunnelling times in graphene and we show that electrons with positive or negative kinetic energies in graphene materials can move in arbitrary direction but with a constant (Fermi) velocity since the so-called Klein tunnelling is, in fact, not a genuine tunnelling phenomenon, but arises from wave interference.

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References

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