Zero-energy states in graphene

M. E. Portnoi, C. A. Downing, R. R. Hartmann, N. J. Robinson and D. A. Stone
School of Physics, University of Exeter, Stocker Road, Exeter EX4 4QL, UK
M.E.Portnoi@exeter.ac.uk

Abstract
There is a widespread belief that electrostatic confinement of graphene charge carriers, which resemble massless Dirac fermions, is impossible as a result of the Klein paradox. We show that full confinement is indeed possible for zero-energy states in pristine graphene. We present exact analytical solutions for the zero-energy modes of two-dimensional massless Dirac fermions confined within a smooth one-dimensional potential given by hyperbolic secant [1], which provides a reasonable fit for the potential profiles of existing top-gated graphene structures [2-5]. A simple relationship between the characteristic strength and the number of confined modes within this model potential is found. A numerical method for finding the number of fully confined zero-energy modes in any smooth potential, decaying at large distances faster than the Coulomb potential, has also been developed and used to evaluate the conductivity of a channel formed by a realistic top-gate potential [6]. The long-range behaviour of the potential defines the threshold condition for confinement, with power-decaying potentials demonstrating drastically different behaviour from exponentially-decaying and square well models. An experimental setup is proposed for the observation of fully-confined electronic guided modes (see Fig. 1).

We also show that full confinement is possible for zero-energy states in electrostatically-defined quantum dots and rings with smooth potential profiles. The necessary condition for confinement for potentials decaying faster than an unscreened Coulomb potential is a non-zero value of angular momentum, i.e. the confined states are vortices (see Fig. 2). Again, analytic solutions are found for a class of model potentials [7]. These exact solutions allow us to draw conclusions on general requirements for the potential to support fully confined states, including a critical value of the potential strength and spatial extent. The implications of fully-confined zero-energy states for STM measurements and minimal conductivity in graphene are discussed.

We demonstrate that the excitonic insulator gap predicted some time ago [8] and revisited recently by several groups [9,10] cannot exist in graphene samples with back gates as confirmed by experiments [11]. A qualitatively different picture based on Bose-Einstein condensation of zero-energy electron-hole vortices (excitons) is proposed to explain the Fermi velocity renormalization in gated graphene structures which is observed instead of the gap.

References

[1] R. R. Hartmann, N. J. Robinson, and M. E. Portnoi, Phys. Rev. B **81**, 245431 (2010).
[2] R. V. Gorbachev et al., Nano Lett. **8**, 1995 (2008).
[3] G. Liu et al., Appl. Phys. Lett. **92**, 203103 (2008).
[4] A. F. Young and P. Kim, Nat. Phys. **5**, 222 (2009).
[5] J. R. Williams et al., Nature Nanotechnology **6**, 222 (2011).
[6] D. A. Stone, C. A. Downing, and M. E. Portnoi, Phys. Rev. B **86**, 075464 (2012).
[7] C. A. Downing, D. A. Stone, and M. E. Portnoi, Phys. Rev. B **84**, 155437 (2011).
[8] D. V. Khveshchenko, Phys. Rev. Lett. **87**, 246802 (2001).
[9] J. E. Drut and T. A. Lähde, Phys. Rev. Lett. **102**, 026802 (2009).
[10] T. Stroucken, J. H. Grönqvist, and S. W. Koch, Phys. Rev. B **84**, 205445 (2011).
[11] D. C. Elias et al., Nature Physics **7**, 201 (2011).

Figures

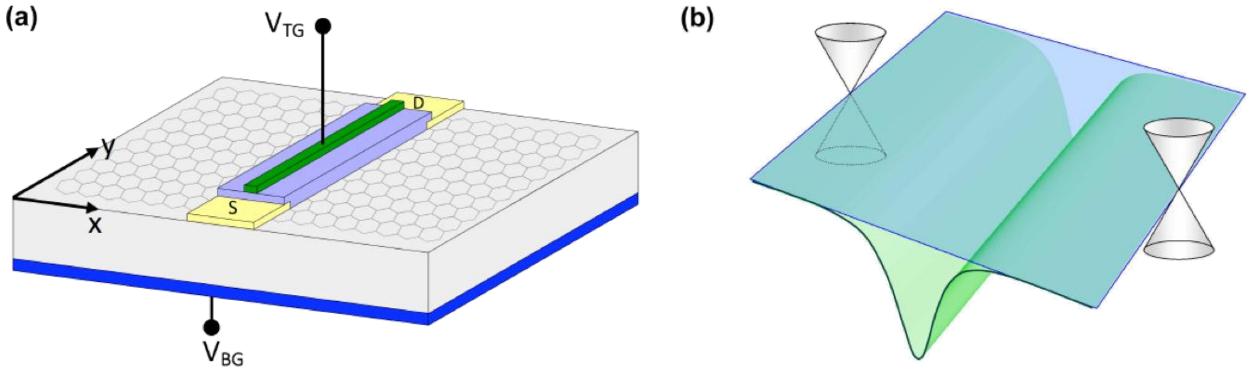

Fig 1. (a) A schematic of a gedanken experiment for the observation of localized modes in graphene waveguides created by a top-gate. (b) The electrostatic potential created by the applied top-gate voltage is modeled as a hyperbolic secant. The plane shows the Fermi-level position.

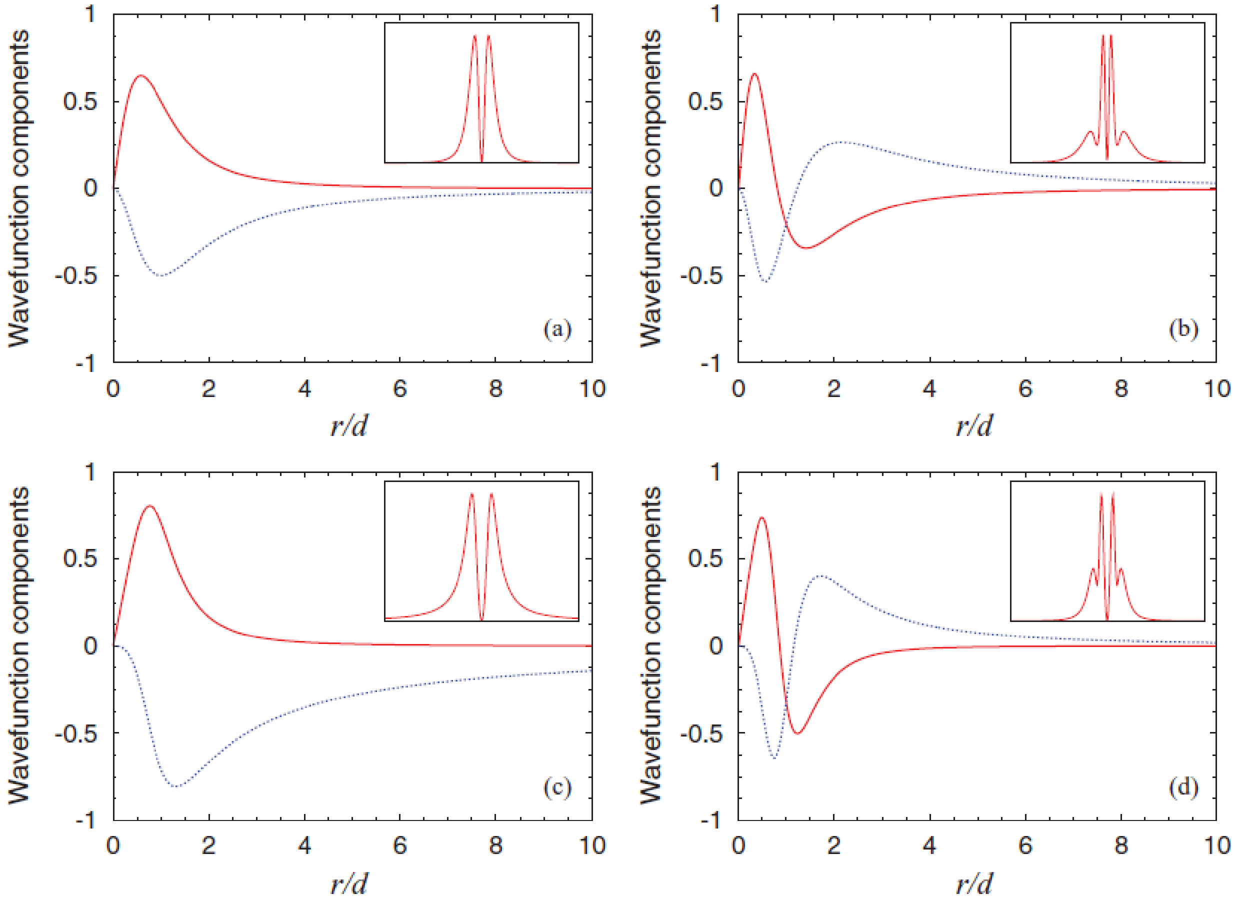

Fig 2. (a) Radial wave-function components for the first two states with angular momentum m = 1 for the Lorentzian potential (a) N = 0; (b) N = 1; and for a model ring-like potential (c) N = 0; and (d) N = 1. Here N is the number of non-zero nodes in the wavefunction component, which has the smallest number of nodes. Solid (dotted) lines correspond to the upper (lower) wavefunction components. Insets: shape of the probability density for each state.