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Pair states in one-dimensional Dirac systems

Analytic solutions of the quantum relativistic two-body problem are obtained for an interaction potential modelled as a one-dimensional smooth square well and the eigenvalues are obtained by solving a set of transcendental equations. Such a potential can be used to approximate the interaction potential between an electron and a hole in a broad range of one-dimensional Dirac systems such as narrow-gap nanotubes, certain types of graphene nanoribbons and armchair carbon nanotubes subjected to an external magnetic field applied along the tube's axis [1,2]. Currently the experimental focus is on attractive potentials to reveal the role of excitonic effects, but we show that within the same formalism, quasi-one-dimensional systems can also support bound states within the band gap for two repelling particles. Of special interest is the case where both the electron-electron and the electron-hole pair binding energy correspond to the middle of the band gap, as it enforces electron-hole symmetry without the recourse to a superconductor. This state is also energetically favorable as it reduces the Fermi energy of a doped system. Since our primary interest is the study of the optoelectronic applications of graphene nanoribbons and carbon nanotubes [3], we restrict ourselves to calculations concerning electron-hole pairs. The stationary excitonic energy spectrum for a quasi-one-dimensional Dirac system is shown below in figure 1. The binding energy of these pairs is found to never exceed the band gap and therefore at room temperature the electron-hole pairs should be fully ionized. Hence, undesirable effects due to dark excitons should not dominate optical processes. By analyzing the smooth square well's stationary excitonic wave functions, the appropriate boundary conditions are obtained for an abrupt square well which in turn enables the dynamic exciton energy levels to be found. We also consider delta function interaction - a highly non-trivial problem for relativistic particles - and show that different approximations for the delta function give the same result [4]. All our results, which are primarily aimed at graphene nanoribbons and narrow-gap carbon nanotubes, can also be applied to Weyl semimetals in a strong magnetic field which constrains free-particle motion to one dimension.

References

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Figures

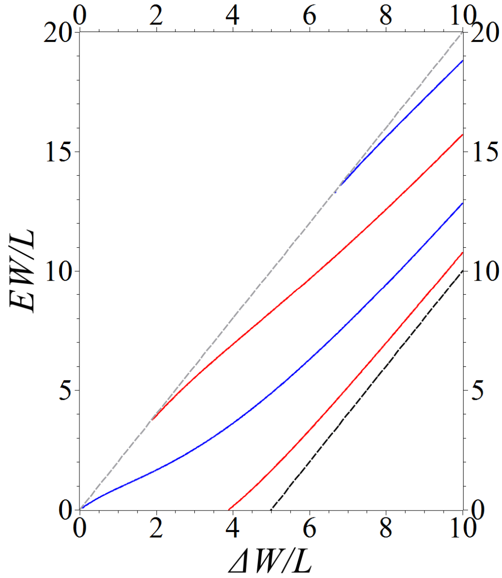

Figure 1: The energy spectrum of an electron-hole pair interacting via a one-dimensional smooth square well as a function of $\Delta W/L$ for WU_0/L=10, where W, U_0, L are the effective width and depth of the well, L is a constant and Δ half the band-gap. The gray-dashed and black-dashed lines represent $E = 2\Delta$ and $E - U_0 = 2\Delta$ respectively. The red and blue lines correspond to the even modes and odd modes respectively.