Zero-energy vortices in graphene

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Contrary to a widespread belief, full electrostatic confinement is possible for Dirac-Weyl fermions with linear dispersion in gapless 2D systems such as graphene, surface states on the surface of topological insulators and gapless HgTe quantum wells. The confinement is possible precisely at the Dirac point where the particles pseudospin is ill-defined, and these bound states must possess non-zero angular momentum (vorticity) [1]. Formation of zero-energy vortices provides an alternative explanation for various STM experiments in graphene.

We also show [2] that a pair of two-dimensional massless Dirac-Weyl fermions can form a bound state independently on the sign of the inter-particle interaction potential, as long as this potential decays at large distances faster than Kepler's inverse distance law which is always the case in back-gated graphene. The coupling occurs only at the Dirac point, when the charge carriers lose their chirality. These two-particle states must have a non-zero internal angular momentum, meaning that they only exist as stationary vortices. This leads to the emergence of a new type of energetically-favorable quasiparticles: double-charged zero-energy vortices. Their bosonic nature allows condensation and gives rise to Majorana physics without invoking a superconductor. Arguably, the reservoir of bosonic vortices can play a similar role to that of a superconductor in proximity to a Weyl semimetal by enforcing electron-hole symmetry. Indeed, adding an electron to the considered system is equivalent to adding a hole and another zero-energy vortex which makes this system a promising candidate in the on-going search of Majorana modes in solids. The presence of dark-matter-like immobile vortices explains a range of poorly understood experiments in gated graphene structures at low doping. The formation of bielectron vortices depends on the dimensionless strength α^* of electron-electron interaction – the fine structure constant divided by the dielectric permittivity and multiplied by the ratio of the speed of light to the Fermi velocity. For suspended graphene the value of α^* is very close to the threshold required for electro-electron binding. Local strains (ripples in the case of graphene) help reinforcing binding, which is energetically favorable as it allows reducing the Fermi energy of the system. In other 2D Weyl systems, which have smaller Fermi velocities, the formation of double-charged vortices is even more favorable. The predicted peak in the density of states at the apex of the Dirac cone can also serve as a source of carriers with energies corresponding to the strong non-linear electromagnetic response making low-doped graphene and other 2D Weyl semimetals better suited for relevant applications.

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References

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