Zero-energy states and magnetic-field-induced deconfinement of Dirac fermions in two-dimensional Weyl materials

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There is a widespread belief that electrostatic confinement of two-dimensional (2D) massless Dirac fermions (such as the charge carriers in graphene, the surface states of topological insulators and other Weyl materials with ultra-relativistic quasiparticle dispersion) is impossible as a result of the Klein paradox. We show that full confinement is indeed possible for zero-energy states due to the absence of pseudo-spin at a Dirac point. However, this confinement requires a careful modulation of the strength and spatial extent of the trapping potential. We show that several smooth fast-decaying potentials support square-integrable analytic vortex-like solutions, propose a numerical variable-phase method for more realistic potentials and discuss possible experimental manifestations of these zero-energy vortices. The addition of a localized magnetic field, which is traditionally seen as a way to confine elusive Dirac particles, to the trapping scalar potential instead results in deconfinement. This opens a possibility for a new type of devices with magnetic field readout.

We also discuss hitherto overlooked zero-energy two-particle vortices in 2D Weyl systems. We establish conditions for their existence and show how these vortices can explain the apparent renormalization of the Fermi velocity in graphene near the Dirac point and the observed order of magnitude increase in the number of charged carriers in the quantum Hall effect regime.