Orbital Lamb Shift of the pseudo-zero-mode Landau Levels in Bilayer and Trilayer Graphene

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Graphene supports massless Dirac fermions that lead to its unique and promising electronic properties. Recently interest appears to center on bilayers and few layers of graphene, where the added layers make the physics and applications of graphene richer, with, e.g., a tunable band gap in bilayer graphene [1].

A notable signal of Dirac fermions is the fact that graphene, in a magnetic field, supports a special set of zero-energy Landau levels. Bilayer graphene, in particular, has eight such zero-energy levels, with an extra twofold degeneracy [1] in Landau orbitals $n = 0$ and 1. This orbital degeneracy is a consequence of topology and the added layer, and is a feature intrinsic to few-layer graphene. In real samples these zero-energy levels evolve into (nearly degenerate) pseudo-zero-mode (PZM) levels, or broken-symmetry states, as explored theoretically and experimentally.

The interplay of orbital degeneracy and Coulomb interactions brings about a new realm of quantum phenomena in graphene few-layers. At EP2DS-20, I would like to report my recent study [2] on this subject. I point out the following:

(1) The orbital degeneracy of the PZM levels in few-layer graphene is lifted by Coulombic quantum fluctuations of the valence band (the Dirac sea). This is a many-body quantum phenomenon analogous to the Lamb shift in the hydrogen atom (i.e., the $2P_{1/2}$ *vs* $2S_{1/2}$ splitting due to vacuum fluctuations).

(2) This "orbital" Lamb shift has been unnoticed in earlier approaches. It is a vacuum effect but is intimately correlated with the Coulomb interaction acting among the PZM levels, and it essentially governs the structure and spectrum of the PZM sector of few layers. It is shown for both bilayers and ABC-stacked trilayers how these "Lamb-shifted" orbital modes, with filling, get mixed via the interaction; see Fig. 1.

(3) Experimental signatures for the orbital Lamb shift come from the interaction-enhanced spin or valley or orbital gaps observed via quantized conductance within the lowest Landau level of few-layer graphene. Clear evidence for the $\nu = 0$ gap, in particular, is the $\nu = 0$ insulating state, which, normally, is first observed as a nontrivial feature within the lowest Landau level in bilayers [3] and trilayers [4].

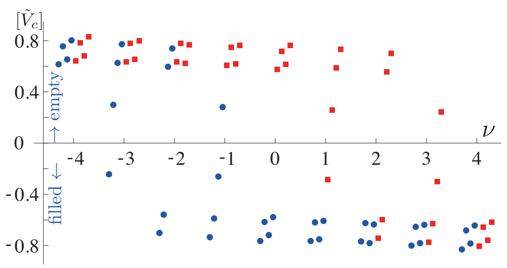

Fig.1 Spectra of the PZM octet at each integer filling factor $\nu \in [-4, 4]$. Each level is specified by spin, valley and orbital ($n = 0, 1$). Band gaps are enhanced by Coulomb exchange interactions.

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