Quadriexcitons, excitonic condensate and excitation energies in a symmetric electron-hole bilayer with valley degeneracy

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The realization of systems of spatially separated electrons and holes, in the search of the equilibrium excitonic condensate foreseen by [1], has gone on for more than two decades, but so far the condensate has eluded experimental detection [2], in the absence of a magnetic field. It has been recently suggested that a substantial enhancement of the electron-hole attraction, to favour the condensate, could be obtained in coupled graphene bilayers [3], systems that have a quadratic energy dispersion on a wide density range and a twofold valley degeneracy in each bilayer.
We have performed extensive QMC simulations of a paramagnetic electron-hole bilayer with mass symmetry and twofold valley degeneracy in each layer, partially mimicking the system proposed in [3], to determine the effects of the valley degeneracy on the $T = 0$ phase diagram, inferred by comparison with the conventional electron-hole bilayer without valley degeneracy [4]. We have studied a system of 168 particles, at in-layer densities corresponding to $1 \leq r_s \leq 8$ and inter-layer distances $1 \leq d/a_B \leq 4$.
For the first time we observe the formation of quadriexcitons, predicted by Wang and Kittel [5] 45 years ago. We find an excitonic condensate for $r_s \gtrsim 1$ at intermediate distances, whereas a quadriexciton fluid [5] and a plasma fluid are stable respectively at smaller and larger distances. The region of stability of the excitonic condensate is significantly shrunk with respect to the system without valley degeneracy [4]. We estimate excitation energies and discuss their modelling, to extract a paring gap.
The first experiments on coupled graphene bilayers in zero magnetic field [6] have found no evidence of excitonic condensation, at variance with the very recent mesaurement on the same system in the quantum Hall regime [7]. However, a strong enhanced tunnelling between graphene bilayers at charge neutrality and zero magnetic field has just been reported [8], pointing (in the words of the authors) *towards the presence of an emerging many-body state with electron-hole pair condensation.* We shall discuss possible relations between such results and our own findings.

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