Fractional quantum Hall states in graphene

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We study the ground state and low-energy excitations of single-layer graphene (SLG) and bilayer graphene (BLG) taking into account the valley degrees of freedom K and K'. The Coulomb interaction between the electrons is projected onto a certain Landau level (LL) and exactly diagonalized by the density matrix renormalization group (DMRG) method.[1]

To study the role of valley degrees of freedom in graphene, we calculate the ground state valley polarization at effective filling factors $\nu_n = 1$, 1/3, 2/3 and 2/5 in the $n = 0$ and 1 LLs of SLG and in the second lowest LL of BLG. The obtained results show that the ground state is valley polarized at $\nu_n = 1$ and 1/3 in the $n = 0$ LL and at $\nu_n = 1$, 1/3, 2/3, and 2/5 in the $n = 1$ LL of SLG and at those fillings in the second lowest LL of BLG, while it is valley unpolarized at $\nu_n = 2/3$ and 2/5 in the $n = 0$ LL of SLG.

The elementally charge excitations are also studied by the DMRG method and it is shown that the lowest charge excitation is a topological valley-skyrmion excitation at $\nu_n = 1$ and 1/3 in the $n = 0$ and 1 LLs of SLG. The valley-skyrmion excitation has a finite gap, Δ_s, even in the thermodynamic limit as shown in Fig. 1. It is shown that Δ_s is smaller than the valley polarized charge excitation gap, Δ_c, for the $n = 0$ and 1 LLs of SLG. In the second lowest LL of BLG, Δ_s is larger than Δ_c.

These results show that for $n = 0$ and 1 LLs of SLG, the topological valley-skyrmion excitations dominate over the valley polarized excitations at low temperatures. Since Δ_s is larger than Δ_c in the second lowest LL of BLG, stable fractional quantum Hall states are realized in the second lowest LL of BLG, which are then good candidates for experimental observations of fractional quantum Hall states.

[1] N. Shibata and D. Yoshioka, Phys. Rev. Lett. **86** 5755 (2001) N. Shibata, J. Phys. A **36** R381 (2003); N. Shibata and K. Nomura, Phys. Rev. B **77**, 235426 (2008).

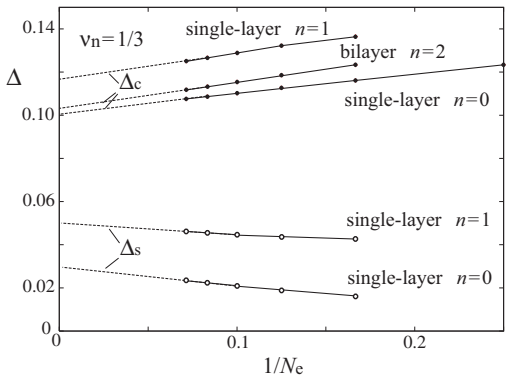

Figure 1: The charge excitation gap Δ_c and the valley-skyrmion excitation gap Δ_s at $\nu_n = 1/3$ in the $n = 0$ and 1 LLs of single-layer graphene and in the second lowest LL of bilayer graphene. N_e is the total number of electrons on the sphere geometry. The units of energy gap Δ is $e^2/(\epsilon \ell_B)$.