Quantum Hall Spin and Isospin Phases of the zero Energy States in Bilayer Graphene

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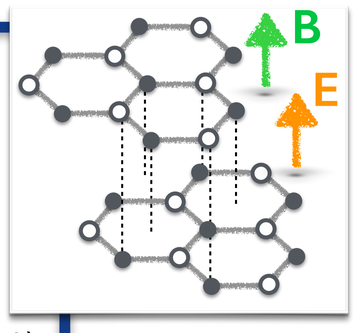
Abstract

We theoretically investigate the ground state (GS) structure of bilayer graphene (BLG) in the quantum Hall (QH) regime. In BLG the states of the zero energy Landau level (LL) carry, besides the real spin, two pseudospins: a valley isospin and an orbital isospin (LL index n = 0, n = 1). This leads to an octet of states which is eightfold degenerate when any symmetry breaking is neglected and can be treated in the frame of QH ferromagnetism. If this SU(8) symmetry is broken, a rich phase structure emerges, each phase characterized by a different spin and isospin configuration. Using a Hartree-Fock (HF) treatment, we take into account both intrinsic symmetry breaking effects as well as the influence of externally applied electric and magnetic fields and study the GS spin and isospin phases as a function of the field strengths.

The Model

- BLG: two layers of graphene on top of each other (Bernal stacking)
- External magnetic field **B**, transverse electric field **E**
- Electrons of the zero energy LL carry Spin **S** (↑ or↓), Valley isospin **T** (+ or -), and orbital isospin **L** (n=0 or n=1)



The leading Question

- Predict the GS spin and isospin textures for different fields E and B;
  Understand the various different GS phases

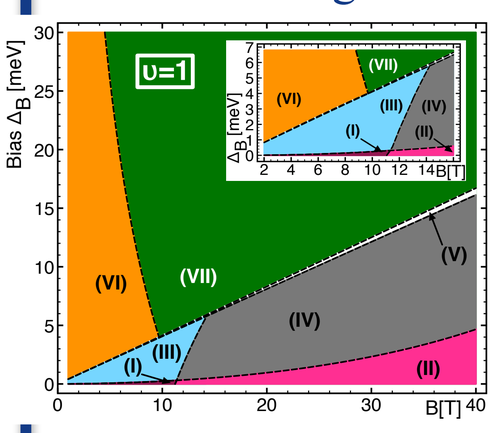
The Hamiltonian

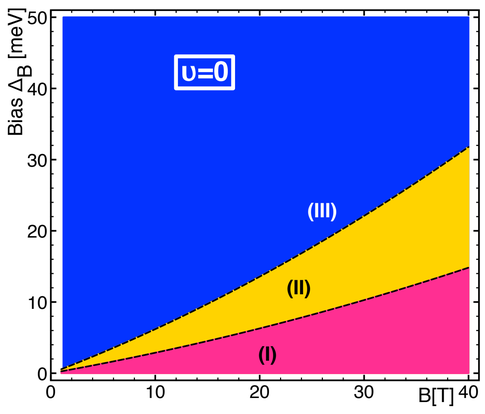
$$H = H_C + H_{Bias} + H_Z + H_{01}$$

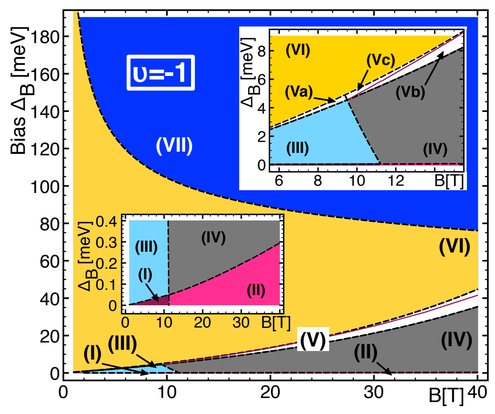
- Four-band model for electrons on the BLG lattice
- Coulomb interactions among the octet electrons as well as with the filled Dirac sea:
  depend on the filling factor ν (ν=-3, …, 3 for 1, …, 7 electrons in the octet)
- Symmetry breaking due to lattice effects, interactions, and the external **E** and **B** fields

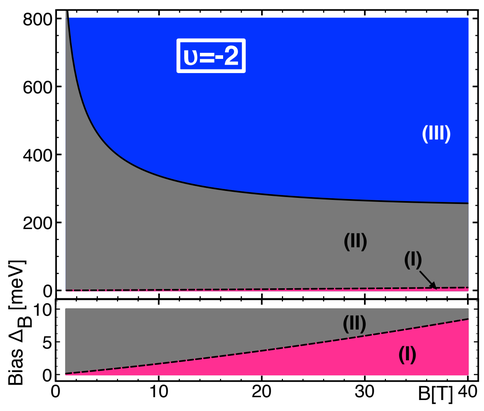
- Coulomb interaction within the octet
  - Valley splitting: Bias Δ_B = eEd due to the electric field **E**
    - Spin splitting Δ_Z: Zeeman effect due to the magnetic field **B**
      - Orbital splitting Δ_{01}: due to lattice asymmetries and interactions with the Dirac sea electrons

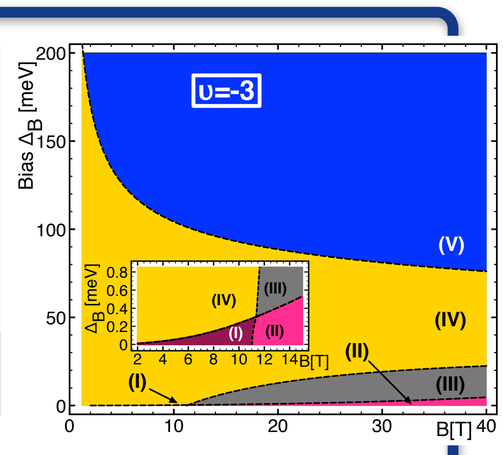
HF Phase Diagrams

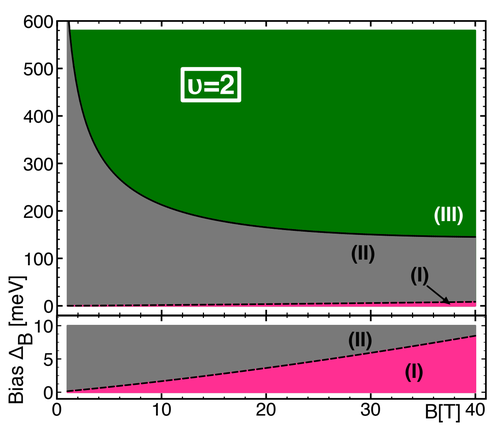


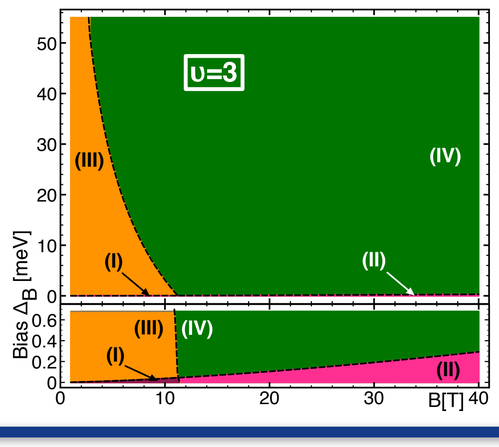












HF GS Properties

- General features

  $\Delta_B \neq 0$: Valley polarised phase

  Phases with non-trivial coherence in valley and/or orbital isospin

  $\Delta_B = 0$: Spin polarized phase

- For odd fillings

  At Δ_B = 0 or small Δ_B :

  Canting in **L** | B_{crit} | **L** polarised → B

  Transition to an orbitally polarized phase with B

- For even fillings

  No orbital coherent phases

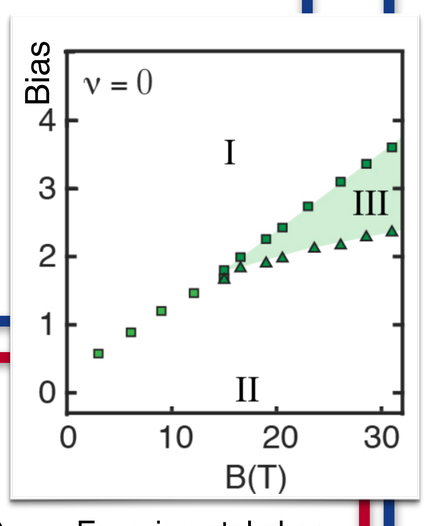
  For Δ_B = 0: No phase transition with B

- Color code

  Bordeaux/Magenta: **S** ∝ $\mathbf{e}_z$, **T** in a canted state → valley coherence

  Cyan/Yellow/Orange: **S** ∝ $\mathbf{e}_z$, **L** in a canted state → orbital coherence

  Gray/Blue/Green: **S**,**T** ∝ $\mathbf{e}_z$ for **L** = 0 or **L** ∝ $\mathbf{e}_z$ → partial polarization



Experimental phase diagram from [Ex4]

Comparison with Experiment

- In [Theo1], we relate the phases and properties to those observed in experiment:

[Ex1] R. T. Weitz et al, Science **330**, 812 (2010)
[Ex2] Velasco et al, Nat. Comm. 5550 (2014)
[Ex3] Maher et al, Science **345**, 6192 (2014)
[Ex4] B. M. Hunt et al, arXiv:1607.06461

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Further Reading

[Theo1] A. Knothe, T. Jolicœur, arXiv:1609.04983
[Theo2] K. Shizuya, PRB **86**, 045431 (2012)
[Theo3] J. Lambert, R. Côté, PRB **87**, 115415 (2013)
[Theo4] A. Knothe, T. Jolicœur, PRB **92**, 165110 (2015)