Electron-hole asymmetric integer and fractional quantum Hall effect in bilayer graphene


M. Lafkioti
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Motivation

• Bilayer graphene: symmetric electron-hole dispersion. Single-particle quantum Hall states at filling factor $\nu = 4M$

• Low disorder $\rightarrow$ eightfold degeneracy of the lowest LL is lifted by e-e interactions $\rightarrow$ QH states at all integer filling factors.

• Knowledge of the ground state at integer filling factors is especially important for investigating the physics of partially filled LLs, where, in exceptionally clean samples, the charge carriers condense into fractional quantum Hall (FQH) states.

• FQH states determined by the interplay between Coulomb interaction and the symmetries of the system. Interplay between externally applied fields and intrinsic e-e interactions breaks degeneracies of bilayer graphene $\rightarrow$ rich phase diagram.

• Spin, valley, and orbital degeneracies in bilayer graphene can produce unusual and tunable sequence of FQH states (spin and valley degeneracy +degenerate N = 0 and 1 orbital states occurring at zero energy)

• Local electronic compressibility measurements of FQH effect in the lowest LL of bilayer graphene.
Sample and IQHE

- Bilayer graphene device on h-BN.
- Mechanically exfoliated and placed on graphite-h-BN stack.
- Cleaned with Ar/H\textsubscript{2} and current annealed.

Local compressibility measurements with scanning SET.

- Inverse compressibility $d\mu/dn$ as a function of filling factor at $B = 2$ T.
- Incompressible features present at all nonzero multiples of $\nu = 4$.
- FWHM of $\nu = 4$ peak provides measure of disorder.
- Order of magnitude $10^{10}$ cm$^{-2}$, similar to suspended bilayers.
IQHE and Compressibility

• Broken-symmetry states at $\nu = 0$ and 2 further indicate low disorder.
• Inverse compressibility appears more negative for $|\nu| < 4$ than in higher LLs.
• Averaging the inverse compressibility between 8 and 11.5 T reduces fluctuations caused by localized states.
• Inverse compressibility between integer QH states close to zero at $4 < \nu < 8$ but more negative for $0 < \nu < 4$
• Qualitatively consistent with observations in the lowest LL in monolayer graphene.
Even Odd effect

- Background inverse compressibility more negative and less flat when increasing from an even than from an odd \( n \).

- As states are filled from an even \( n \), e-e interactions break degeneracy between \( N = 0 \) and 1 orbital LLs, so that only the \( N = 0 \) LL is occupied.

- From an odd \( n \), \( N = 0 \) LL is already full, so electrons start to occupy the \( N = 1 \) LL.

- More negative background inverse compressibility between \( n = 0 \) and 1 and between \( n = 2 \) and 3 \( \rightarrow \) less screening or more e-e correlations in the \( N = 0 \) LL compared to \( N = 1 \) LL with an underlying filled \( N = 0 \) LL.
FQHE states

- inverse compressibility as a function of $\nu$ and B-field after current annealing.
- QH states appear as vertical features
- localized states curve with B-field
- incompressible FQH states at $n = -10/3, -4/3, 2/3, \text{ and } 8/3$
- $n = 2p + 2/3$ sequence, $p = -2, -1, 0, \text{ and } 1$
- Above 10 T:
  - developing states at $\nu = -17/5, -7/5, 3/5, \text{ and } 13/5$, following similar $\nu = 2p + 3/5$ sequence.
- FQH states closer to CN-point are more incompressible than those at higher $\nu$, persisting to low magnetic fields $\sim 6$ T.
- Line plots show average inverse compressibility from 7.9 to 11.9 T.
- FQH states and even odd effect
- FQH states coincide with areas of more negative background inverse compressibility
- Consistent with attribution to Coulomb interactions
- Despite theoretical predictions of robust FQH states in the N = 2 LL, no FQH states between $|\nu| = 4$ and 8.
FQHE

- sequence of FQH states and background inverse compressibility pattern break particle-hole symmetry and instead follow a $n \rightarrow n + 2$ pattern.

- $n \rightarrow n + 2$ symmetry indicates importance of orbital degeneracy and polarization.

- predicted considering strong screening and LL mixing in the lowest LL of bilayer graphene.

- absence of FQH states in $-3 < n < -2$ and at $n \rightarrow n + 2$ from there suggests different e-e interactions between partial filling when $N = 0$ and 1 LLs are empty and partial filling of the $N = 1$ LL with full $N = 0$ LL.

- increased LL mixing present at full $N = 0$ LL weakening the strength of FQH states in the $N = 1$ LL?
Tunability

• effective interactions and screening different in suspended and substrate-supported bilayer graphene → different sample preparations result in different FQH states theoretically predicted tunability of the FQH effect in bilayer graphene?

• perpendicular E- /parallel B-field may provide insight into the conditions under which different FQH states are favored

• monolayer graphene: both suspended and substrate-supported samples have shown similar sequences of FQH states

• changes in only the spin and/or valley polarization; the sequence of observed FQH states did not change.

• bilayer graphene, sample geometry and/or substrate play an important role in determining the relative strengths of various incompressible FQH states.
FQH Gaps

- Integrate inverse compressibility to obtain the energy cost of adding an electron to the system, divided by the quasi-particle charge to determine the corresponding energy gap $\Delta \nu$.

- BUT: nature of the FQH states in bilayer graphene is not yet fully understood $\rightarrow$ extracted steps in chemical potential $\Delta \mu_\nu$.

- For $\nu = -4/3$ and $2/3$, $\Delta \mu_\nu$ is $\sim 0.75$ and $\sim 0.6$ meV, at $B = 12$ T. Assuming a quasi-particle charge of $e/3$, the energy gap at $\nu = -4/3$ is comparable with other studies.
FQH Gaps

- FQH state gaps further away from CN are smaller; \( \Delta \mu_{-10/3} \) and \( \Delta \mu_{8/3} \) only \( \sim 0.5 \) and \( \sim 0.3 \) meV. Gaps increase monotonically with B.

- Gaps scale approximately linearly or superlinearly with B.

- \( B^{-1/2} \) -dependence possible (\( \nu = 8/3 \) and \( -10/3 \)).
IQH Gaps

- broken-symmetry integer states in suspended bilayers $\rightarrow$ linear B dependence because of LL mixing.

- Gaps probably sensitive to the details of disorder in the system and perhaps also to the ratio between magnetic length and sample-gate distance.

- Integer gaps increase with B, except for $\nu = 0$, which is fairly constant around 23 to 25 meV over almost the full range in the magnetic field.

- Around 4 T, the gap dips slightly before increasing again at $B = 0$ T.
IQH Gaps

- If $v \rightarrow v + 2$ symmetry arises from orbital degree of freedom, sequence of symmetry-breaking in the sample becomes clear.
- Valley $\rightarrow$ Spin $\rightarrow$ Orbital polarization.
- Large valley polarization here caused by interactions with the substrate.
- Difference in distance to the graphite gate creating potential difference in the two layers.
- Different environments experienced by each layer.
IQH Gaps

- The ground state at $\nu = 0$ is layer-polarized.

- Even if $\nu = 0$ gap is caused by single-particle effects, constancy over 12 T is surprising.

- Both the potential difference between the layers and the Coulomb energy are expected to contribute to the gap.
Summary

• Local electronic compressibility measurements of the FQH effect in the lowest Landau level of bilayer graphene.

• Electron-hole asymmetric sequence of FQH states as intrinsic property of bilayer graphene, no disorder or other local effect.

• FQH states at $v = 2p + 2/3$, with hints of additional states at $v = 2p + 3/5$, where $p = -2, -1, 0, \text{ and } 1$.

• Sequence breaks particle-hole symmetry with $v \rightarrow v + 2$ symmetry, highlighting orbital degeneracy for many-body states in BG.

• The unconventional sequence of FQH states in bilayer graphene shows importance of its underlying symmetries.

• Exploring the nature and tunability of the FQH effect. Possible in BG through different sample geometries, fabrication and substrates.