Observation of Helical Edge States and Fractional Quantum Hall Effect in a Graphene Electron-Hole Bilayer

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22 Feb 2016
arXiv:1602.06815v1

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FAM 15.04.2016
Introduction

Helical 1D Conductor

Quantum Hall Edge States
Opposite chirality
Opposite Spin

Coexisting electron-like and hole like bands
Lifted Spin degeneracy

- M.Z.Hasan, C.L.Kane, Rev Mod Phys 82, 3045 (2010)
Twisted Bilayer Graphene

Stack of two monolayers with a twist angle
- Decoupling the layers
- * Two sets of Dirac cone dispersions localized on a different layer
- * Under B, Each layer develops a Landau Level spectrum similar to monolayer graphene
- ** Under E, layer degeneracy is broken (no band gap)

\[ n_{\text{tot}} = \frac{(C_T V_T + C_B V_B)}{e} \]

\[ v_{\text{tot}} = n_{\text{tot}} \left( \frac{\hbar}{e} \right) / B \]

\[ D = \frac{(C_T V_T - C_B V_B)}{2} \]

* A.F. Young et al. Nature 505, 528 (2014)
* J.D. Sanchez-Yamagishi et al. PRL 108, 076601 (2012)
**QHE Measurements**

2-probe conductance $D=0$

$$G(e^2/h)$$

$B=1T$

$$B$$

$B=4T$

Small $D$

Electron exchange interaction
Breaking spin and valley symmetry
Quantum Hall Ferromagnetism**

$(v_{bottom}, v_{top})$

$(0, -1)$

$(+1, 0)$

Spin * Valley * Layer = 8-fold

$v_{top} = v_{bottom} = v_{tot}/2$

Due to Quantum Hall Ferromagnetism
in monolayer graphene $v = \pm 1$ is spin polarized
Electron like $v = +1$ spin is aligned with $B$
Hole like $v = -1$ spin is flipped

$$D$$

$(\pm 1, \mp 1)$

*J.D. Sanchez-Yamagishi et al. PRL 108, 076601 (2012)*

*H.Schmidt et al. PRB 81, 121403(R) (2010)*

**Y.Zhang et al. PRL 96, 136806 (2006)**

**J.G.Checkelsky et al. PRL 100, 206801 (2008)**

\[ v_{\text{top}} \neq v_{\text{bottom}} \quad \rightarrow \quad \text{Conductances cancel} \]

\[ \rightarrow \quad \text{Backscattering} \quad \rightarrow \quad \text{Interlayer Tunneling} \]

**Exception**: \((\pm 1, \mp 1) \quad \rightarrow \quad \text{Spin polarized states} \quad \rightarrow \quad \text{No Tunneling}\)
Nonlocal Resistance

\[ R_{NL} = \frac{V_{NL}}{I_M} \]

Expected: \[ 2 \frac{e^2}{h} \]

Measured in 9 devices:

\[ 0.8 \text{ – } 1.5 \frac{e^2}{h} \]

Edge lengths:

\[ 0.2 \text{ – } 16 \mu m \]
Fractional Quantum Hall States

2-probe Conductance at 31T

Plateaus at multiples of $\frac{1}{3} \frac{e^2}{h}$

Too high Contact Resistances high B field to observe Helical State

Conclusions

Based on the data:
- Mapping of QH plateau sequence with filling factors
- Edge state nonlocal signal

At filling factors \((\pm 1, \mp 1)\), conduction occurs through 1D edge modes corresponding to QH edge states with opposite chiralities.

Backscattering is strongly suppressed in counterpropagating modes.

Because counterpropagating modes have opposite spin polarizations, this forbids the interlayer tunneling and so protects the edge modes from backscattering.

This is contrasted in spin degenerate \((\pm 2, \mp 2)\) where interlayer tunneling leads to insulating behavior.

Fractional Quantum Hall States are observed in high magnetic fields.
2 monolayer G but not bilayer G

In AB-BLG displacement field breaks bilayer’s inversion symmetry and opens a band gap

Gate induced insulating state in bilayer graphene – nature paper

QHE of bilayer Graphene


Low magnetic field measurements

- Onset of QH plateaus at \( \pm 1 \) state
Spin Filtered Edge States and Quantum Hall Effect in Graphene

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Electron edge states in graphene in the Quantum Hall effect regime can carry both charge and spin. We show that spin splitting of the zeroth Landau level gives rise to counterpropagating modes with opposite spin polarization. These chiral spin modes lead to a rich variety of spin current states, depending on the spin flip rate. A method to control the latter locally is proposed. We estimate Zeeman spin splitting enhanced by exchange, and obtain a spin gap of a few hundred Kelvin.

A new electron system with low carrier density and high mobility was recently realized in two-dimensional graphene [1]. By varying the carrier density with a gate one can explore a range of interesting states, in particular the anomalous quantum Hall effect [2, 3] (QHE). In contrast to the well-known integer QHE in silicon MOSFETs [4] the QHE in graphene occurs at half-integer multiples of 4, the degeneracy due to spin and orbit. This has been called the half-integer QHE. The unusually large Landau level spacing makes QHE in graphene observable at temperatures of 100 K and higher.

Here we explore the spin effects in graphene QHE. In the presence of Zeeman splitting transport in graphene is described by an unusual set of edge states which we shall call chiral spin edge states. These states are reminiscent of the ordinary QHE edge states [5], but can propagate in opposite directions at zero energy.

FIG. 1: (a) Graphene energy spectrum near the armchair boundary obtained from Dirac model, Eq.(1). The boundary condition, Eq.(5), lifts the $K, K'$ degeneracy. The odd integer numbers of edge modes lead to the half-integer QHE. (b) Spin-split graphene edge states: the blue (red) curves represent the spin up (spin down) states. These states propagate in opposite directions at zero energy.
Quantum Hall Ferromagnetism in Graphene

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(Received 4 April 2006; published 28 June 2006)

Graphene is a two-dimensional carbon material with a honeycomb lattice and Dirac-like low-energy excitations. When Zeeman and spin-orbit interactions are neglected, its Landau levels are fourfold degenerate, explaining the $4e^2/h$ separation between quantized Hall conductivity values seen in recent experiments. In this Letter we derive a criterion for the occurrence of interaction-driven quantum Hall effects near intermediate integer values of $e^2/h$ due to charge gaps in broken symmetry states.

DOI: 10.1103/PhysRevLett.96.256602 PACS numbers: 72.10.−d, 73.21.−b, 73.50.Fq, 75.50.Dd

FIG. 1 (color online). Phase diagram for $SU(4)$ quantum Hall ferromagnetism in the $n = 0$ and $n = 1$ Landau levels of graphene. In our model the ordered region is bounded by a maximum value of $\nu_s$, the ratio of the density of Coulomb scatterers to the density of a full Landau level. $\nu_s$ is inversely proportional to the product of the sample mobility and the external field strength and order near integer filling factors requires the minimum values for this product indicated on the right-hand vertical axis.
Fig. S13

Gate-tunable contacts can switch from making good contact to either negative $v_{tot}$ states or positive $v_{tot}$ states (Sample B). (A) Conductance maps for a device with gate tunable contacts. P-doped contacts result in clear measurements of the p-side of the data (negative filling factor) with strong suppression of the conductance for the n-side (positive filling factor). The converse is true for n-doped contacts. In both measurements the contact resistance in the well-measured plateaus is less than 100 $\Omega$. (B) Conductance plateaus for p-doped (red) and n-doped (blue) contacts. (C) Cross-section cartoon of device. The contact topgates (cTg) and the global backgate control the doping of the twisted bilayer graphene between the primary region of the device and the metal electrodes.