Observation of the fractional quantum Hall effect in graphene


Team One
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Overview

**Goal**: observe the fractional quantum Hall effect in graphene

**Contribution**: fabricate highly pure graphene sample

**Outline**:

- Quantum Hall Effect
- Optimization of Graphene Sample
- Results
- Criticism
- Impact
What is the Quantum Hall Effect?
The Classical Hall Effect

- A magnetic field $B$ will deviate the path of charges towards the sides of a conducting material, creating a potential $U_H$ transverse to the initial current $I$

- Measurements of $U_H$ probe properties of the material, e.g. charge density, resistivity, conductivity
The Quantum Hall Effect

- QHE regime: low temperatures and large magnetic fields
- Plateaus of conductivity identified in a 2D semiconductor\(^1\):
  \[ \sigma_{xy} = \nu \frac{e^2}{h}, \nu \text{ an integer} \]
- The integer QHE: electrons are localized at the edge of the surface and only conduct when their Landau level is filled\(^2\)

1 Von Klitzing, Dorda and Pepper, PRL (1980)
2 Laughlin, PRB (1981)
3 Tsui and Gossard, AIP (1981)

Transverse \((xy)\) and longitudinal \((xx)\) resistivities of a sample as a function of magnetic field.\(^3\)
The Fractional Quantum Hall Effect

- Plateaus began to be identified at fractional \( \nu \) soon afterward\(^1\) (see left)
- IQHE can be explained by non-interacting electrons; the fractional effect implies interactions!
- The fractional QHE: electrons form composite quasi-particles of fractional charge\(^2,3\)

1 Tsui, Stormer and Gossard, PRL (1982)
2 Laughlin, PRL (1983)
3 Jain, PRL (1989)
Fractional quantum hall effect: fractional charges!

A host of quasi-particle physics awaits, some Nobel Prizes

- 2D surfaces allow for anyons (rather than just bosons and fermions)
  - These probe physics due to topology, geometric phases

- Graphene is expected to contain such quasi-particles
Graphene: A Motivated Material for FQHE

- Observation of FQHE in graphene would advance study of e-e interactions
  - Graphene has nearly perfect lattice
- Complicated by electron scattering from residual impurities
  - Caused by interactions of graphene with underlying substrate
- Suspending graphene above its substrate reduces scattering\(^1\)


Mobility of graphene sample before (blue) and after (red) suspension
Fabricating Clean Graphene for FQHE Experiment

- Applied graphene on top of SiO₂/Si substrate
- Conductive layers deposited to make contacts
- Adjacent substrate layer removed with hydrofluoric acid
- Sample placed in alcohol to remove impurities
- These steps optimize graphene purity

Example of experimental apparatus
Results
Observing the $v=\frac{1}{3}$ State

- Only $v=1$ state for $B = 2.5$ T
- At $B = 9$ T, state $v=1/3$ starts to appear (A)
Observing the $v=\frac{1}{3}$ State

- Only $v=1$ state for $B = 2,5$ T
- At $B = 9$ T, state $v=1/3$ starts to appear (A)
- At $B = 12,13,14$ T the state $v=1/3$ is clear.
Observing Two More FQH States

- **Blue**: $G$ is decreasing with $n$
- **Red**: $G$ is increasing with $n$
- FQH states are found in light blue regions

\[
\frac{dn}{dB} = \frac{\nu}{\phi}
\]
Observing Two More FQH States

- **Blue**: $G$ is decreasing with $n$
- **Red**: $G$ is increasing with $n$
- FQH states are found in light blue regions

- Below is a table for the found fractional states

<table>
<thead>
<tr>
<th></th>
<th>$\nu$</th>
<th>$G \ (e^2/h)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.30 ± 0.02</td>
<td>0.32 ± 0.02</td>
</tr>
<tr>
<td>B</td>
<td>0.46 ± 0.02</td>
<td>0.54 ± 0.02</td>
</tr>
<tr>
<td>C</td>
<td>0.68 ± 0.05</td>
<td>0.94 ± 0.02</td>
</tr>
</tbody>
</table>
T-dependence of the Conductance

Higher temperatures wash out FQH states.
Paper Summary

- Observation of FQHE in graphene was of great interest since it would provide a probe into its interesting e-e phenomena. However, previous attempts had failed due to impure samples.

- Authors constructed ultraclean suspended graphene samples and were able to observe FQH factors at $\nu = 1/3$ and $\nu = 2/3$.

- Authors were also able to get a resistivity profile (as a function of T) of graphene’s insulating state.
Criticism
Criticism

- Unclear plots (odd axes, poorly balanced dG/dn gradient)
- Discussion about insulating state of graphene left vague
- Some statements left unexplained (e.g. QAHE not mentioned later)
- No true conclusion (ends with results, no future approaches)
Impact
Impact of Paper: Citation Evaluation

- Paper was highly cited, with over 700 citations since 2009
- It received a Field-Weighted Citation Impact of 10.79
- Most citations were in physics, with the expected fields following
Impact of Paper: Review Paper

- Review articles cited this paper the most within its most cited year (2010-2012)

Electronic transport in two-dimensional graphene

S. Das Sarma

Condensed Matter Theory Center, Department of Physics, University of Maryland, College Park, Maryland 20742-4111, USA
Impact of Paper: Continuation of Research

- Paper on rigorous measurement for $\nu = 1/3$ released by the same group later

Measurement of the $\nu = 1/3$ fractional quantum Hall energy gap in suspended graphene

Fereshte Ghahari, Yue Zhao, Paul Cadden-Zimansky, Kirill Bolotin* and Philip Kim

Department of Physics, Columbia University, New York, New York 10027

We report on magnetotransport measurements of multi-terminal suspended graphene devices. Fully developed integer quantum Hall states appear in magnetic fields as low as 2 T. At higher fields the formation of longitudinal resistance minima and transverse resistance plateaus are seen corresponding to fractional quantum Hall states, most strongly for $\nu = 1/3$. By measuring the temperature dependence of these resistance minima, the energy gap for the 1/3 fractional state in graphene is determined to be at $\sim$20 K at 14 T.

PACS numbers: 73.63.-b, 73.22.-f, 73.43.-f
Impact of Paper: Recent Paper of Interest

- Paper on observation of anyon braiding statistics

Direct observation of anyonic braiding statistics

J. Nakamura\textsuperscript{1,2}, S. Liang\textsuperscript{1,2}, G. C. Gardner\textsuperscript{1,2,3} and M. J. Manfra\textsuperscript{1,2,3,4,5}

Anyons are quasiparticles that, unlike fermions and bosons, show fractional statistics when two of them are exchanged. Here, we report the experimental observation of anyonic braiding statistics for the $\nu = 1/3$ fractional quantum Hall state by using an electronic Fabry-Perot interferometer. Strong Aharonov-Bohm interference of the edge mode is punctuated by discrete phase