Experimental Observation of the Quantum Anomalous Hall Effect in a Magnetic Topological Insulator


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Outline:

- **Introduction**: What is Quantum Anomalous Hall Effect (QAHE)?
- **Methods**: What must be done to detect QAHE?
- **Experimental Results**: Why do the authors conclude that QAHE has been observed?
- **Summary and Citation Analysis**: What are the implications of this work?
(Classical) Hall Effect: Lorentz force leads to charge accumulation

\[ R_H = \frac{V_H}{I} \propto \frac{B}{qn} \]

\[ \vec{E} = \rho \vec{j} \]

\[ \rho = \sigma^{-1} = \begin{pmatrix} \rho_{xx} & \rho_{xy} \\ \rho_{yx} & \rho_{yy} \end{pmatrix} = \begin{pmatrix} \rho_0 & \rho_H \\ \rho_H & \rho_0 \end{pmatrix} \]

Figure from: http://en.wikipedia.org/wiki/Hall_effect
Quantum Hall Effect: a quantized version of Hall Effect

- Two dimensional electron gas (2DEG)
- High mobility, strong B field

Equation:
\[ R_H = \frac{h}{ne^2}, \quad n = \text{integer} \]

- Hall resistance: plateaus
- Longitudinal resistance: minima

Landau Levels lead to Quantum Hall Effect

- Landau Levels:
  \[ E_n = \hbar \omega_c (n + 1/2) \]
  \[ \omega_c = \frac{eB}{m} \]
- Each Landau Level contributes: \( e^2 / h \)
- Impurity → Plateaus

Video from:
http://en.wikipedia.org/wiki/Quantum_Hall_effect
Electrons can move along edge (conducting)

Electrons localized in orbits (insulating)

Quantum Hall State in the absence of external magnetic field?

- Quantum Hall: external magnetic field; charge accumulation
- Quantum Spin Hall (topological insulator): spin-orbit coupling; spin accumulation
- Quantum Anomalous Hall: spin-orbit coupling + ferromagnetism; charge accumulation

Figure from: Science 340, 153 (2013)
Criteria for realizing QAHE:

- Strong spin-orbital coupling: Bulk insulating + conducting spin-dependent edge states
- A ferromagnetic material: suppress one of the spin channels

Theoretical Proposals:

  HgTe/CdTe quantum well: Quantum spin Hall effect
  Mn: ferromagnet
  Mn moments do not order spontaneously
- Cr or Fe doped Bi$_2$Se$_3$, Bi$_2$Te$_3$, Sb$_2$Te$_3$: *Science* 329, 61 (2010)
  Bi$_2$Se$_3$, Bi$_2$Te$_3$, Sb$_2$Te$_3$: Topological insulator
  Cr or Fe: ferromagnet
Methods: What must be done to detect QAHE?
Overview of materials and methods

Materials:
- A ferromagnetic sample with topological properties
- \((\text{Bi,Sb})_2\text{Te}_3\) doped with \(\text{Cr}\)

Methods:
- Make the sample
- Measure the QAH effect
- Repeat for multiple samples and understand which worked best
Creating Samples

• Molecular beam epitaxy (MBE) was used in an ultrahigh vacuum with Bi, Sb, Cr, and Te.

• Thickness and composition of the sample were determined by growth time and flux of Cr, Bi, and Sb sources and checked with an atomic force microscope.
Understanding the tools for measuring QAHE

- Measurements were done in a dilution refrigerator, a device capable of temperatures as low as 30 mK and magnetic fields as high as 18 T

- Standard Hall bar geometry was used with an AC lock-in method to probe measurements

Figure courtesy of Chang et. al. 2013
Measuring the QAH effect

- Gate voltages were fine tuned to adjust the Fermi level into the magnetically induced energy gap (this is where QAH resistance is expected)
- At the found gate voltage, QAH resistance was measured for varying magnetic field to localize dissipative states
- The QAH resistance is then measured at different temperatures
Choosing the right sample

- Samples of 3 quintuple layers (QL), 4QL, 5QL, and 8QL were made and tested. 3 and 4 QL films are too insulating for transport measurement (less than ideal sample quality).

- 8 QL films measured a smaller QAH resistance possibly due to increased bulk conduction.

- 5 QL is just right.

Figures courtesy of Chang et. al. 2013 (supplementary materials)
Experimental Results: Why do the authors conclude that QAHE has been observed?
Measurements of $\rho_{yx}$ and $\rho_{xx}$ at zero magnetic field versus $V_g$ suggest QAHE

Distinct plateau in $\rho_{yx}(0)$ with quantized value $\hbar/e^2$

Sharp drop in $\rho_{xx}(0)$ to $0.098 \, \hbar/e^2$

$\rho_{xx}(0)$ (red circles) and $\rho_{yx}(0)$ (blue squares) versus $V_g$

Figure courtesy of Chang et. al. 2013
The next question: How do the results for $\rho_{yx}(0)$ and $\rho_{xx}(0)$ fair with theory?

- To answer this, first transform $\rho_{yx}(0)$ and $\rho_{xx}(0)$ to sheet conductance.

- Then use the following with $\rho_{xx}(0) = \rho_{xx}$ and $\rho_{yx}(0) = \rho_{yx}$:

  \[
  \sigma_{xy} = \frac{\rho_{yx}}{\left(\rho_{yx}^2 + \rho_{xx}^2\right)}
  \]

  \[
  \sigma_{xx} = \frac{\rho_{yx}}{\left(\rho_{yx}^2 + \rho_{xx}^2\right)}
  \]

  Hall conductance

  Longitudinal conductance
The results for $\rho_{xx}(0)$ and $\rho_{yx}(0)$ are consistent with theoretical calculations.

Plateau in $\sigma_{xy}(0)$ with value $0.987 \, e^2/h$

Dip in $\sigma_{xx}(0)$ with value $0.096 \, e^2/h$

Figure courtesy of Chang et. al. 2013
But one issue: Measurements of $\rho_{yx}$ with a magnetic field varied were needed to confirm the Quantum Anomalous Hall Effect.

$\rho_{yx}$ versus applied field.

Red and blue curves correspond to a decreasing field and an increasing field, respectively.

Figure courtesy of Chang et. al. 2013
Measurements for $\rho_{xx}$ further confirm that the quantization for fields above 10 T is due to the same QAH state when the field is zero.

$\rho_{xx}$ vs. applied field

Red and blue curves correspond to a decreasing field and a decreasing field, respectively.

Figure courtesy of Chang et. al. 2013
Final Observation: Varying the temperature also confirms QAHE

$V_g$ Dependence of $\rho_{xx}(0)$ (red circles) and $\rho_{yx}(0)$ (blue squares) at various temperatures

Figures courtesy of Chang et. al. 2013
Summary and Citation Analysis:
What are the implications of this work?
Summary

• When a topological insulator (Bi,Sb)$_2$Te$_3$ is made thin and magnetically doped, it showed the QAHE with a quantized Hall resistance of $h/e^2$ at 30 mK

• The first (and the only so far) experimental realization of QAHE
Future applications

- A macroscopic scale of 50-200 µm.
  - (QSHE < 1µm)
- Low mobility < 1000 cm²/Vs
- The edge channel could be used as a spin-filtering path for spintronic devices
- The exactly quantized Hall resistance could be used as a resistance standard
Challenges

• Extremely low temperature (30 mK)
• Non-zero longitudinal resistance indicates that the system has other dissipative conduction channels
• Need to search for other materials with QAHE
• Cited 35 times (Scopus) since April, 2013

• Theoretical calculation leads to nonzero longitudinal resistance. Suggests ways to reduce the longitudinal resistance. ([cond-mat/1306.1817])

• Higher plateaus h/\(Ce^2\), C=2 possible. ([cond-mat/1305.7500]305.750)