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

Chang *et al.*, Science *340*, 167 (2013).

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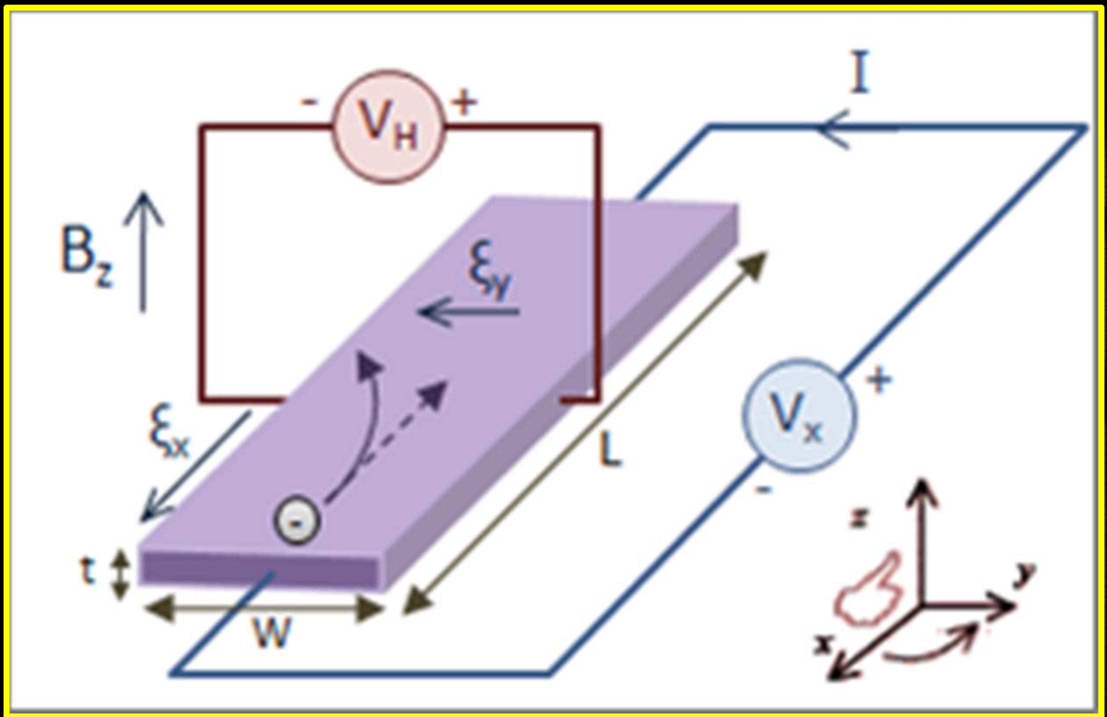
Outline:

- 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



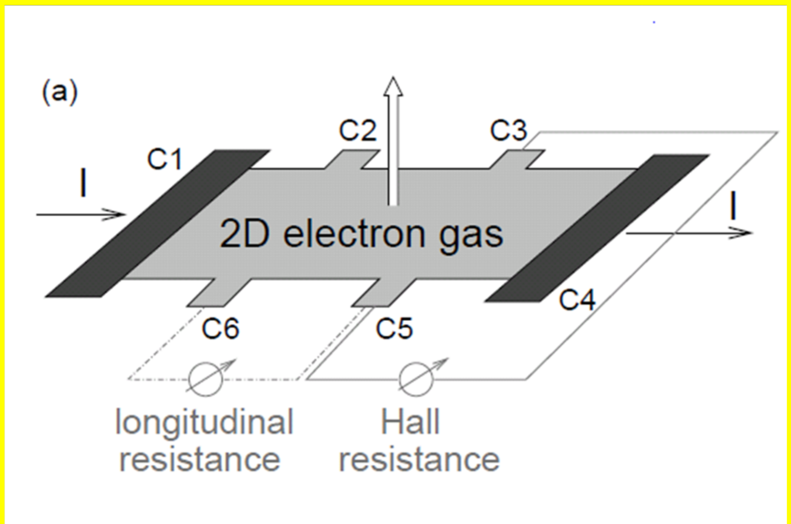
$$R_H = \frac{V_H}{I} \propto \frac{B}{qn}$$

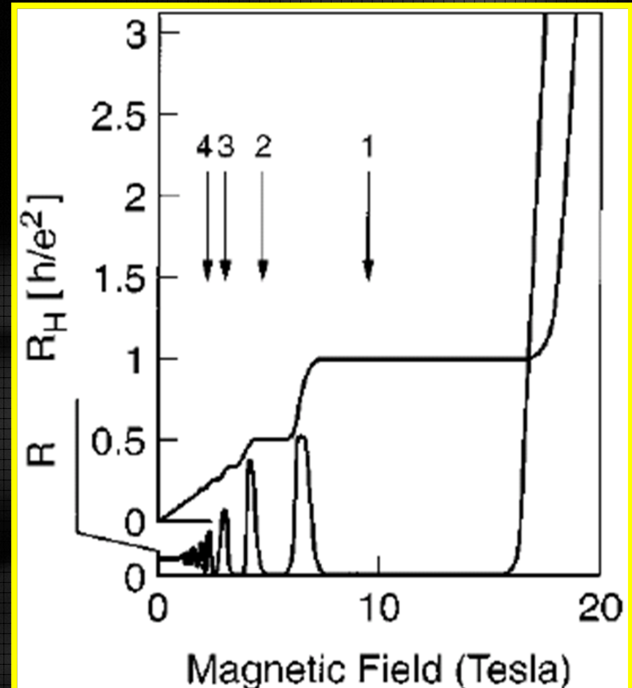
$$\vec{E} = \rho \vec{j}$$

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

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

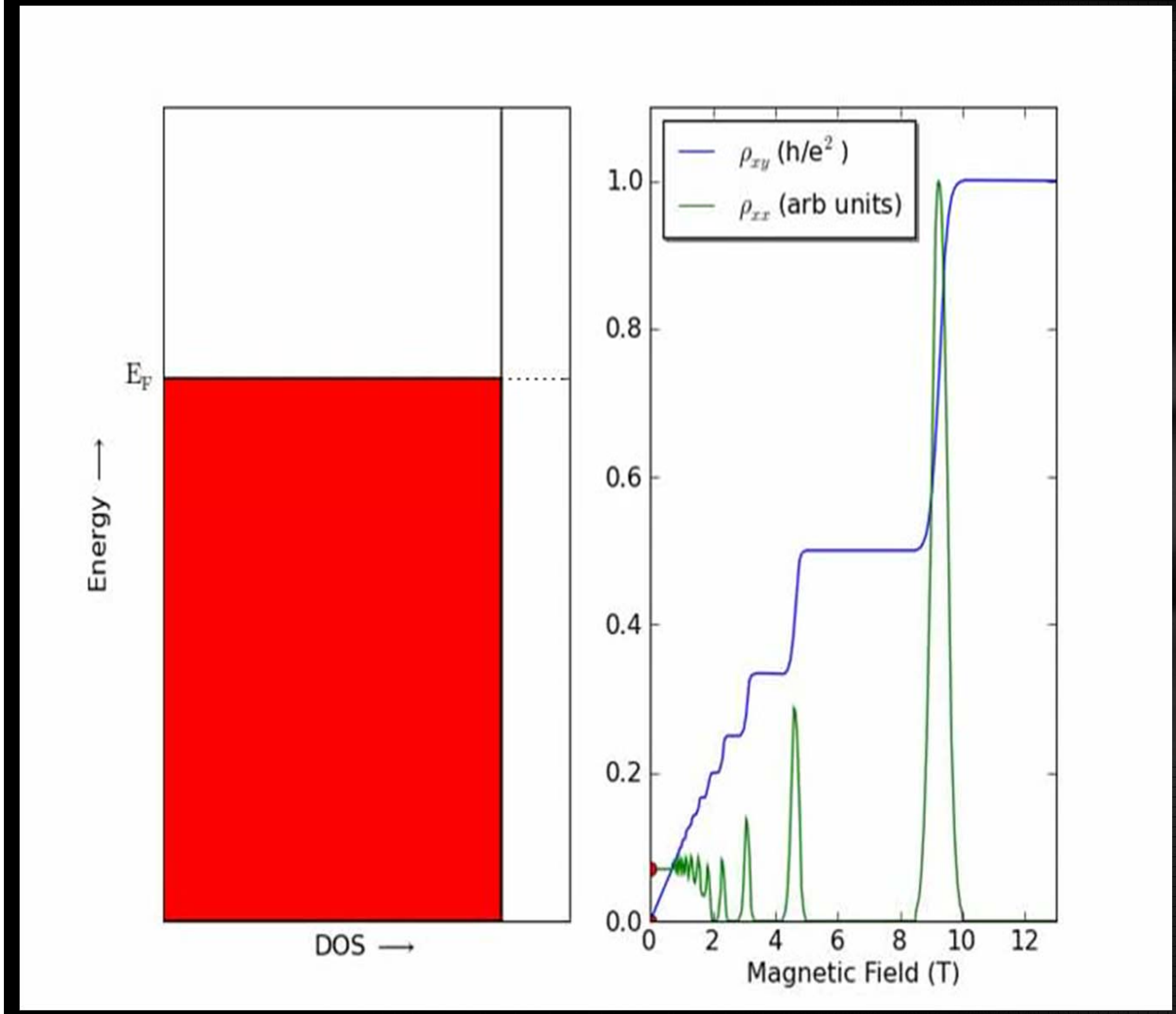
- Hall resistance: plateaus

$$R_H = \frac{h}{ne^2}$$, n = integer

- Longitudinal resistance: minimas

Figures from: arXiv: 0909.1998v2; Rev. Mod. Phys. 71, 875–889 (1999)

Landau Levels lead to Quantum Hall Effect



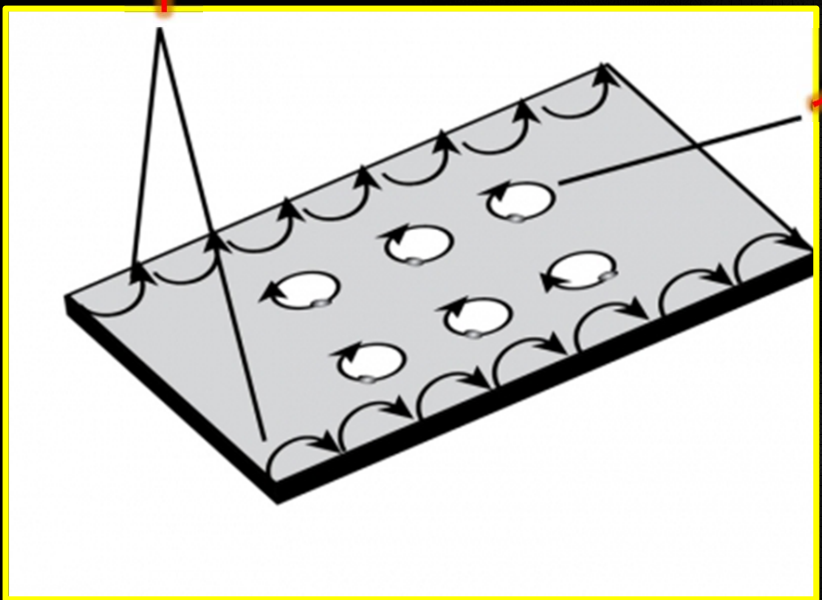
- Landau Levels:
  $E_n = \hbar\omega_c(n + 1/2)$
  $\omega_c = \frac{eB}{m}$
- Each Landau Level contributes: e^2/h
- Impurity → Plateaus

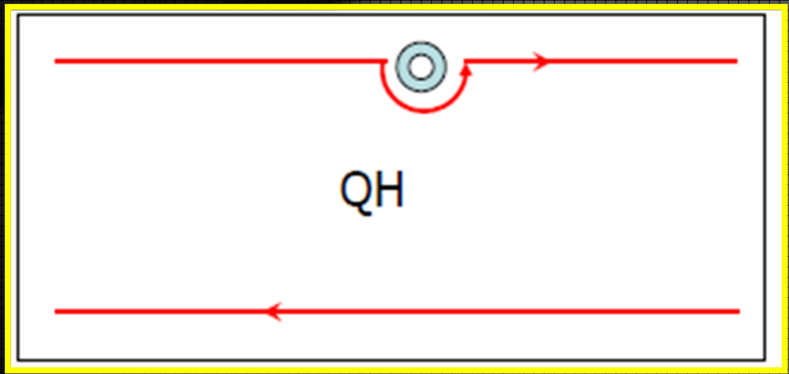
Video from: http://en.wikipedia.org/wiki/Quantum_Hall_effect

Semi-classical Picture of Quantum Hall Effect: Edge States

Electrons can move along edge (conducting)

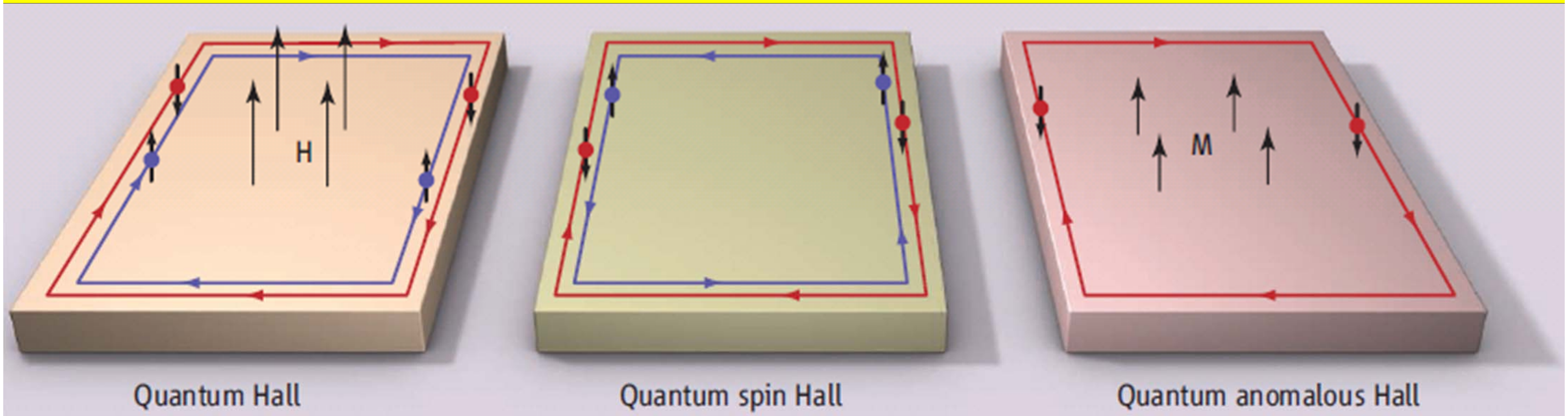
Electrons localized in orbits (insulating)





Figures from: http://jqi.umd.edu/glossary/quantum-hall-effect-and-topological-insulators; arXiv: 1001.1602v1

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:

- $Hg_{1-y}Mn_yTe$ quantum wells: *Phys.Rev.Lett. 101, 146802 (2008)*
  HgTe/CdTe quantum well: Quantum spin Hall effect
  Mn: ferromagnet
  Mn moments do not order spontaneously
- Cr or Fe doped Bi_2Se_3, Bi_2Te_3, Sb_2Te_3: *Science 329, 61 (2010)*
  Bi_2Se_3, Bi_2Te_3, Sb_2Te_3: Topological insulator
  Cr or Fe: ferromagnet

Methods: What must be done to detect QAHE?

Overview of materials and methods

Materials:

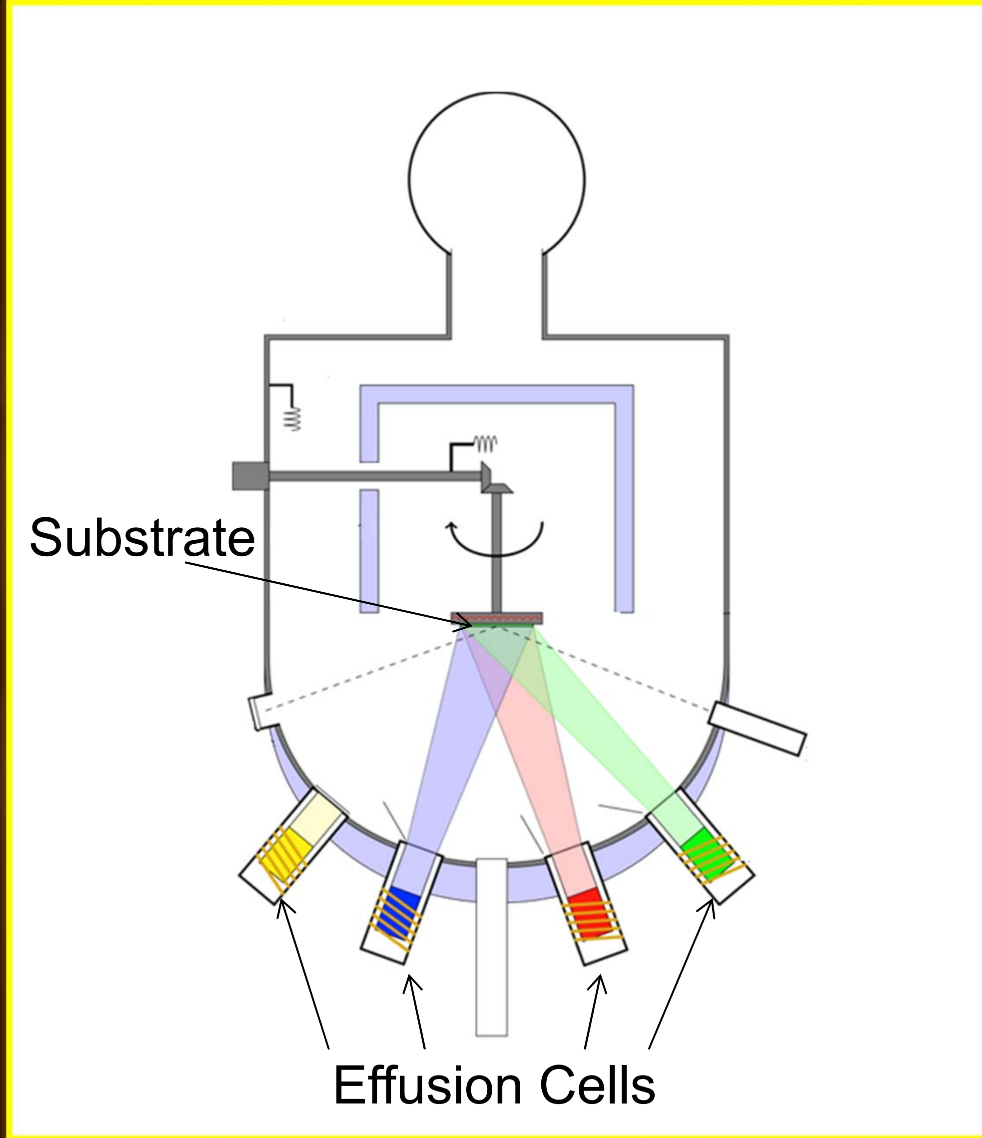
- A ferromagnetic sample with topological properties
- $(Bi,Sb)_2Te_3$ doped with Cr

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

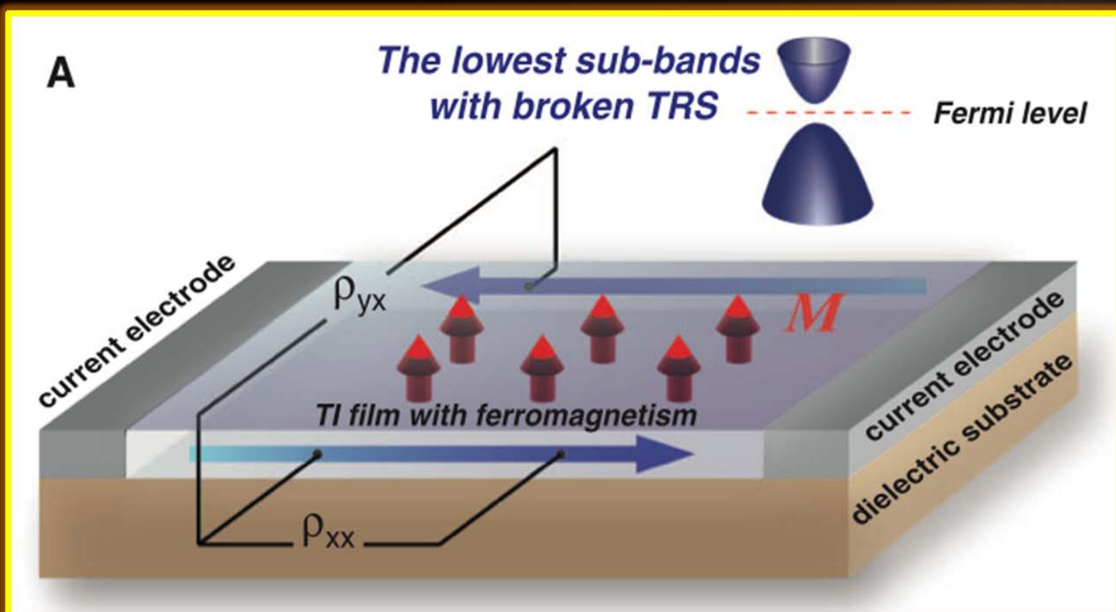


Figure courtesy of Chang et. al. 2013

Measuring the QAH effect

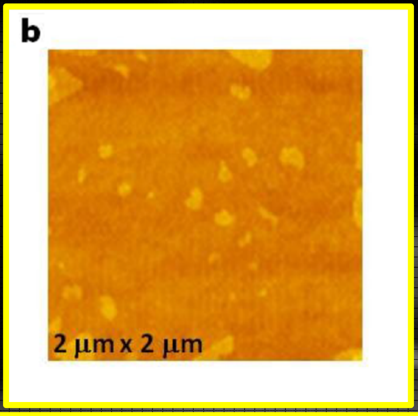
- Gate voltages were fine tuned to adjust the Fermi level into the magnetically induced energy gap (this is where QAH resistance is expected)
- At the found gate voltage, QAH resistance was measured for varying magnetic field to localize dissipative states
- The QAH resistance is then measured at different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

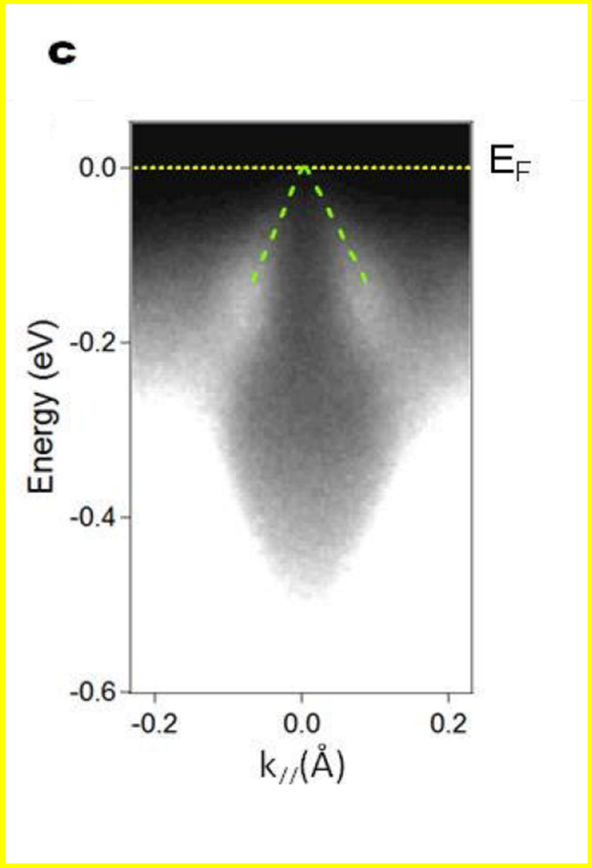
Choosing the right sample

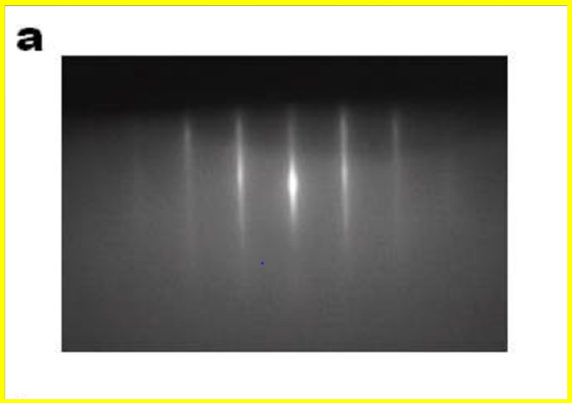
- Samples of 3 quintuple layers (QL), 4QL, 5QL, and 8QL were made and tested. 3 and 4 QL films are too insulating for transport measurement (less than ideal sample quality)

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

- 5 QL is just right





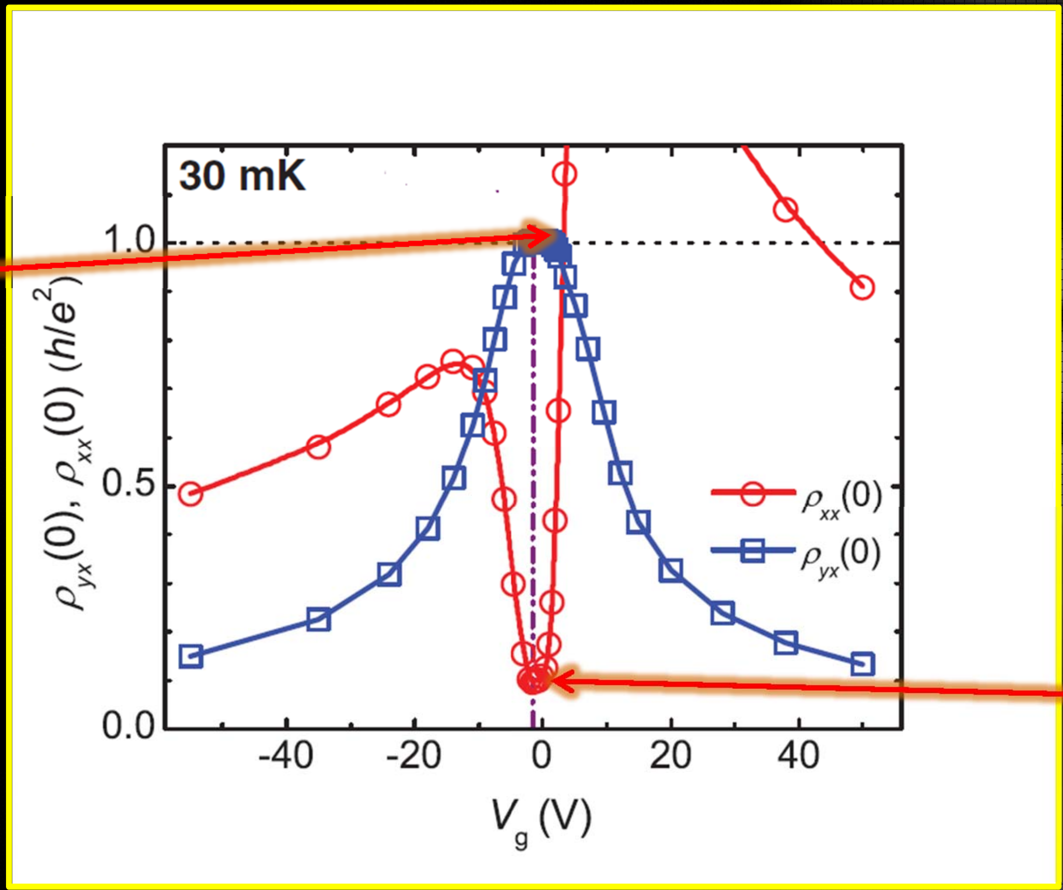


Figures courtesy of Chang et. al. 2013 (supplementary materials)

Experimental Results: Why do the authors conclude that QAHE has been observed?

Measurements of ρ_{yx} and ρ_{xx} at zero magnetic field versus V_g suggest QAHE

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



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

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

Figure courtesy of Chang et. al. 2013

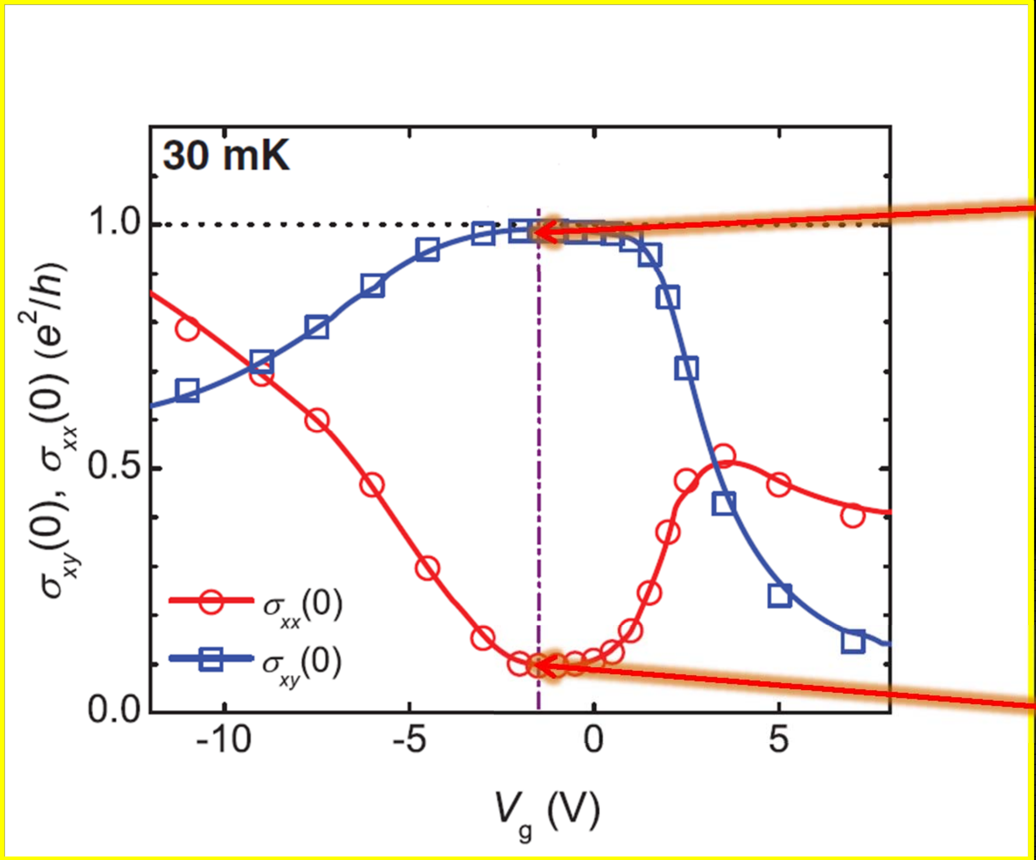
The next question: How do the results for ρ_{yx} (0) and ρ_{xx} (0) fair with theory?

- To answer this, first transform ρ_{yx} (0) and ρ_{xx} (0) to sheet conductance
- Then use the following with $\rho_{xx}(0)= \rho_{xx}$ and $\rho_{yx}(0)=\rho_{yx}$:

Hall conductance → $\sigma_{xy} = \rho_{yx}/(\rho_{yx}^2 + \rho_{xx}^2)$

Longitudinal conductance → $\sigma_{xx}= \rho_{yx}/(\rho_{yx}^2 + \rho_{xx}^2)$

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



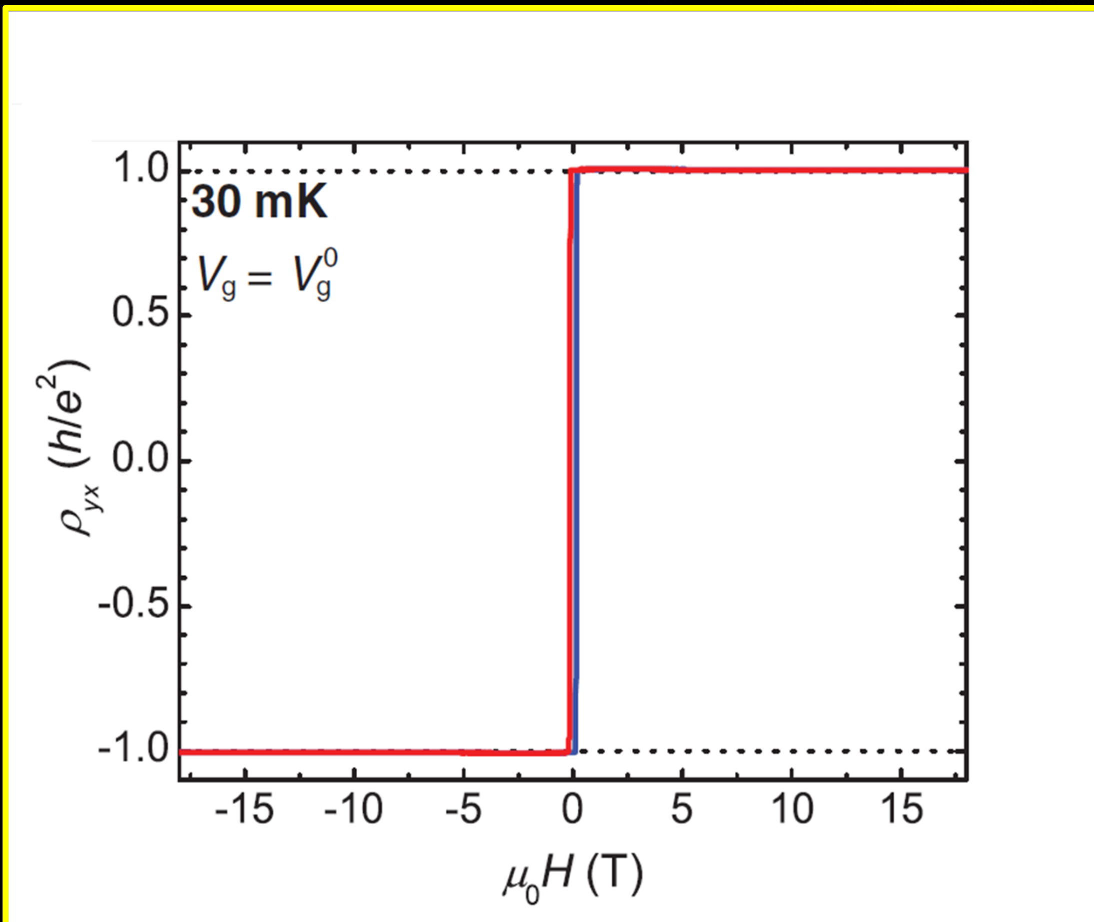
Plateau in $\sigma_{xy}(0)$ with value $0.987\ e^2/h$

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

$\sigma_{xx}(0)$ (red circles) and $\sigma_{xy}(0)$ (blue squares) versus V_g

Figure courtesy of Chang et. al. 2013

But one issue: Measurements of ρ_{yx} with a magnetic field varied were needed to confirm the Quantum Anomalous Hall Effect



ρ_{yx} versus applied field.
Red and blue curves correspond to a decreasing field and a increasing field, respectively

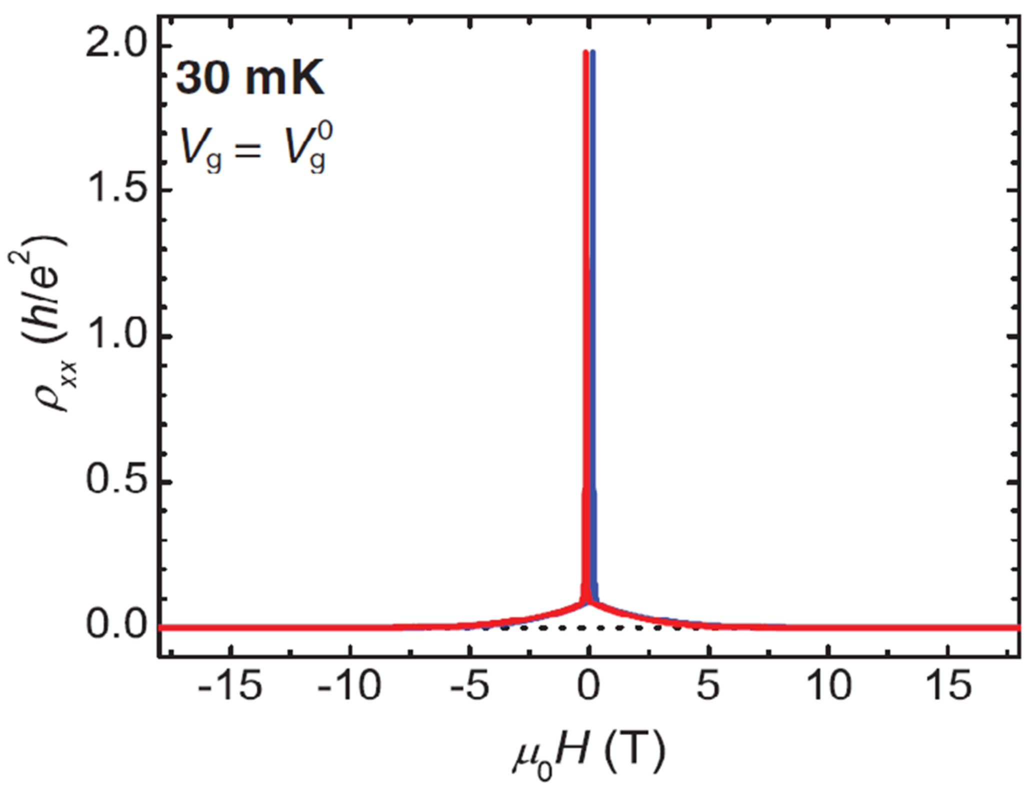
Figure courtesy of Chang et. al. 2013

Measurements for ρ_{xx} further confirm that the quantization for fields above 10 T is due to the same QAH state when the field is zero

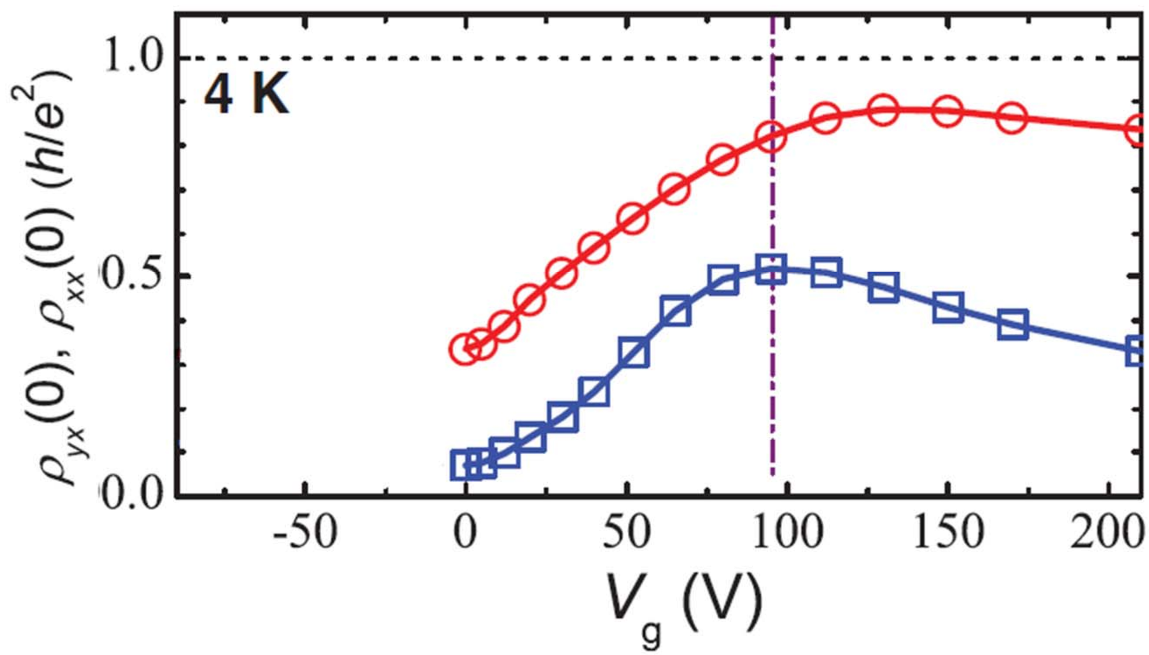
ρ_{xx} vs. applied field

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 $(Bi,Sb)_2Te_3$ 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 cm^2/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

Citations

- 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)