Recent progress of 2D topological insulators in both experiments and theories

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Outline

- Background
  - The family of Hall effects
- 2D topological insulators in theories and experiments
  - Quantum Wells type
  - Graphene type
  - 2D limit from 3D topological insulators
- Outlook
- Summary
New states of matter in condensed matter physics

We have known many kinds of fundamental states of matter, including metals, insulators, superconductors, magnets,… And most of them can be differentiated by breaking symmetries.

- Crystal: break the translation symmetry
- Superconductors: break the U(1) gauge symmetry
- Magnets: break the rotation symmetry
The Hall effect and quantum Hall effect

In mathematics, known as the first Chern number, related to Berry’s phase.

\[ R_H = \frac{E_y}{j_x B} \]

\[ \sigma = v \frac{e^2}{h} \]
The family of Hall effects

Ordinary Hall effect
with magnetic field $H$
Hall voltage but
no spin accumulation

Anomalous Hall effect
with magnetization $M$
(carrier spin polarization)
Hall voltage and
spin accumulation

(Pure) spin Hall effect
no magnetic field necessary
No Hall voltage but
spin accumulation

Quantum Hall effect 1980
Quantum Anomalous Hall effect 2013
Quantum Spin Hall effect 2007
The quantum anomalous Hall (QAH) states

- No external magnetic field
- Dissipationless charge current!

In QAH systems, electrons move just like cars on a highway!

[Image: Energy vs. Momentum diagram showing the separation of conduction and valence bands with a gap, and edge states forming a purple band.]

[Image: A busy street scene with cars and rickshaws, and a highway at sunset with light trails.]
QAH states could get born in quantum spin Hall (QSH) states.

Time reversal symmetry breaking.
2D topological insulators in quantum Wells
HgTe/CdTe Quantum Wells

\[
H_{\text{eff}}(k_x, k_y) = \begin{pmatrix} H(k) & 0 \\ 0 & H^*(-k) \end{pmatrix},
\]

\[
H(k) = \varepsilon(k) + d_i(k)\sigma_i
\]

\[
|E1, m_j = 1/2\rangle, |H1, m_j = 3/2\rangle,
\]

\[
|E1, m_j = -1/2\rangle, |H1, m_j = -3/2\rangle
\]

Bernevig et al. Science 2006; Markus et al. Science 2007
Type-II quantum wells

Liu et al. PRL 2008; Du et al. PRL 2013
pn doping to make type-II quantum Wells

Zhang et al. PRL 2014
Polar quantum Wells

Chen et al. Nature Physics 2013

Be prepared
Magnetic doping in type-II quantum Wells

\[ H = H_0 + H_{BIA} + H_{SIA} + H_{ex}. \]

\[ H_{ex} = \sum_{\vec{R}_n} S_M(\vec{R}_n) \cdot \vec{s}, \]

\[ \tilde{\chi}_s = \lim_{q \to 0} \text{Re} \left[ \sum_{i,j,\sigma,\sigma',\vec{k}} \frac{\left| \langle u_{i\sigma,\vec{k}} | \vec{s} | u_{j\sigma',\vec{k}+\vec{q}} \rangle \right|^2 \left[ f_{i\sigma}(\vec{k}) - f_{j\sigma'}(\vec{k}+\vec{q}) \right]}{E_{j\sigma'}(\vec{k}+\vec{q}) - E_{i\sigma}(\vec{k}) + i\Gamma} \right] \]

\[ \chi_{\text{inter}} \]

\[ \chi_{\text{intra}} \]

\[ \chi_{\text{total}} \]

Wang et al. PRL 2014
2D topological insulators in Graphene type compounds
Graphene-type QSH states

Xu et al. PRL 2013
Magnetic proximity in Graphene-type QSH states

Difficulty:
1) Out of plane magnetic moment at the interface
2) Strong magnetic proximity
3) Charge transfer

FM insulators
Or
AFM insulators

BiFeO$_3$
Multiferroic materials
G-type antiferromagnet
$T_N=653$K

CrGeTe$_3$
Ferromagnetic Insulator.
Out of plane.

Qiao et al. PRL 112, 116404 (2014)

Be prepared
2D topological insulators from the 2D limit of 3D topological insulators
From 3D topological insulators

Liu et al. PRB 2010

Zhang et al. Nature Physics 2010
Magnetic impurity doping in QSH states

\[ H = H_{sf} + H_{Zeeman} \]

\[
\begin{pmatrix}
    m_k + gM & iv_F k_- & 0 & 0 \\
    -iv_F k_- & -m_k - gM & 0 & 0 \\
    0 & 0 & m_k - gM & -iv_F k_- \\
    0 & 0 & iv_F k_- & -m_k + gM
\end{pmatrix}
\]

- \( m_k \) a finite mass
- \( g \) the effective factor
- \( M \) the exchange field along \( z \) direction

Yu et al. Science 2010
Liu et al. PRL 101, 146802 (2008)
Zhang et al. PRL 112, 216803 (2014)
Really observed QAH Effect in experiments

Chang et al.  *Science* 2013
Kou et al. *PRL* 2014
Checkelsky  *Nat. Phys.* 2014

Further optimize the Position of the chemical position for $\rho_{xx}$?

$\sigma_{xy} \sim 1.0e^2/h; \rho_{xx} \sim 2\Omega$

Bestwick et al  
*PRL* 114, 187201 (2015)
Precise quantization of the QAH effect—V-doped case

\[ 4 \text{QL} \, V_{0.11}(\text{Bi}_{0.29}\text{Sb}_{0.71})_2\text{Te}_3 \]

\[ \sigma_{xy} \sim 0.9998e^2/h, \rho_{xx} \sim 3.3\Omega \]

1) Self-driven, without magnetic training
2) A large coercive field \( H_c \)

Chang et al. Nat. Materials 2015

1) Impurity bands and the QAH effect
2) Exchange mechanism
Outlook

- How to understand the ‘surprised’ observation?
- How to improve the working temperature to K or ten K level?
- Can we realize the QAH effect in much cheaper systems?
- Superconductor + the QAH effect?
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Summary

● Background

● Design 2D topological insulators
  ● Type-II Quantum Wells, polar Quantum Wells
  ● Graphene, Silience, Stanene et al.
  ● 2D limit from 3D topological insulators

● Outlook

Thank you for your attention!
Intrinsic magnetic insulators

Intrinsic FM insulators + Type-II Quantum Wells structure

Xu et al. PRL 107, 186806 (2011)

Zhang et al. PRL 112, 096804 (2014)
The toy model of the QAH effect

\[ H = \sum_k H(k) \]

\[ H(k) = \epsilon(k) + Vd_{a}(k)\sigma^a \]

\[ \begin{align*}
E_{\pm}(k) &= \epsilon(k) \pm V\sqrt{\sum_{a} d_{a}^{2}(k)} \\
\min_{k\in BZ} E_{+}(k) &> \max_{k\in BZ} E_{-}(k)
\end{align*} \]

The Hall conductivity:

\[ \sigma_{xy} = -\frac{1}{8\pi^2} \int_{FBZ} \int dk_{x}dk_{y} \hat{d} \cdot \hat{\partial}_{x}\hat{d} \times \hat{\partial}_{y}\hat{d} \]

\[ = -\frac{n}{2\pi} \]

with

\[ \hat{d}_{a}(k) = d_{a}(k)\sqrt{\sum_{a} d_{a}^{2}(k)} \]

Quantized conductivity without the Landau levels!