Topological Quantum Matter: New Frontiers

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R. H. Dicke Symposium
PRINCETON UNIVERSITY
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Images: http://physics.princeton.edu/zahidhasangroup/
As a R.H. Dicke fellow, among other things, I learned **Photoelectric effect** based spectroscopies which allow to measure the quantum numbers and degrees of freedom of electrons (energy, momentum, spin, time, ...)

H. Hertz (1880s)
**Einstein’s Photoelectric effect theory** (1905)
Nobel Prize 1922

Modern ARPES systems (2017)

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Quantum Epistemology/Philosophy:
"Experiments are the only means of (real) knowledge at our disposal. The rest is poetry, imagination" --Max Planck
M.Z.H. and C.L. Kane
“Topological Insulators” (& Superconductors)
*Rev. of Mod. Phys., (RMP)* 82, 3045 (2010)

M.Z H., S.-Y. Xu, I. Belopolski, S-M. Huang
“Discovery of Weyl Fermions in Topological Semimetals”

S. Jia, S.-Y. Xu and M.Z H.
“Weyl Semimetals, Fermi arcs & chiral anomaly ”
*Nature Materials* 15, 1140 (2016)

M.Z.H., D. Hsieh, Y. Xia, L. Wray
Experimental Discovery of Topological Surface States:
book Chapter in “Topological Insulators” (2013)

M.Z.H., G. Chang et al,
“Weyl, Dirac & High-fold chiral fermions in topological matter”
*Nature Reviews Materials* 784–803 (2021)
Broken Symmetry → Phases of Matter/Forces

Interaction | Carriers | act on | Fundamental Particles
---|---|---|---
Gravitation | Graviton |  | electrons, muons, neutrinos
Weak | $W^+, W^-, Z^0$ |  | quarks
Electromagnetic | Photon |  |  
Strong | Gluon |  | 

TFT (strings..)

Topo. Phases
Topo Insulators

Magnets

Semimetals

Superconductors

Topo Insulators

Hedgehog Magnet

Fermi-Arc Metal

Kondo Insulators

Topological insulator (Bi2Se3)

s wave supercond (Nd5Se2)

Fermi surface proximity gap

BDP1, BDP2

Surface Fermi surface topology

Weyl Fermion Crystal

Rashba, Rashba

k(1/A)

kx (1/A)

kz (1/A)

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Spectroscopy STM + ARPES + Theory team (present & past members) for results in this Talk

Tyler Cochran
Zijia Cheng
M. Litskevich
Dan Multer
Dan Sanchez
Nana Shumiya
Xian Yang
Z. Guguchia

Theory: FP/DFT/TBT:
Guoqing Chang, G. Bian, S.Y. Xu, I. Belopolski, S. Huang, T.-R. Chang, Hsin Lin et.al.,

Samples: Raman Sankar (India), Feng-Chang Chou (Taiwan), CL Zhang, Xitong Xu, Shuang Jia (Peking), Nitin Samarth (PennState), Weiwei Xie (LSU), C. Felser, K. Manna (Germany), Chang Zhang, Hechang Lei (Beijing), Wenhong Wang (China)

Facilities: ALS-LBNL (Bl-4, 10), SSRL-SLAC (BL-5), NSLS-BNL, SLS-PSI
QHE & Non-trivial insulators

$\sigma_{xy} = ne^2/h$

Quant. Hall physics

$\left(i\hbar \partial_{\mu} - m\right)\psi = 0$

$\mathcal{A}\mathcal{F}\mathcal{T}$

3D TI is a novel topological state
first NON-quantHall-like topological matter

IQHE, TKNN, Haldane; Kane-Mele, Fu-Kane-Mele, Moore-Balents; et.al.,
\[ \sigma_{xy} = ne^2/h \]

Chern no.
(D. Thouless et al., M. Berry)

\[ \chi = \Theta_{\text{ME}}/\pi \]
\[ \Theta = \pi \text{ (odd)} \]

Topo Insulators

\[ \nu_0 = \Theta_{\text{ME}}/\pi \]

How to experimentally “measure” the topological quantum numbers \( \nu_i \) ?

4 TQNs \( \rightarrow 15+1 \) distinct insulators

No quantized transport via:
\[ \{ \nu_i \} \]

Topological “order parameters!”

\[ \{ \nu_0, \nu_1, \nu_2, \nu_3 \} \]

Transport

Spin-sensitive
Momentum-resolved
Edge vs. Bulk
(Bulk-Boundary Correspondence)
1. Surface States exist and locate inside the bandgap and ½ metallic throughout \((\textbf{Nature’ 08, submit. 2007})\)


3. Topo Phase transition (BI to TI) via spin-orbit tuning \((\textbf{Nature Physics, Science’ 10-11})\)

4. Robust up to room temperature \((\textbf{Nature’ 09})\)

5. Absence of backscatt. by Spin-Texture \((\textbf{Nature’ 09})\)


7. Superconducting gap in topo. Dirac surface states \((\textbf{Nature Physics’ 10 ’14})\)

\[\text{MZH & Kane, Rev. Mod. Phys. 82, 3045 (2010)}\]

\[\text{Nature News/Scientific American (July, 2017)}\]

\[\text{http://physics.princeton.edu/zahidhasangroup/}\]
Helical Dirac fermions
One-to-One Spin-LinearMomentum Locking

Berry’s phase $\theta = \pi$
Invariant $= \theta/\pi = 1$

Hsieh, Qian, Wray et.al., (MZH) KITP’2007, Nature’08, Science’09, Nature’09
Spin-ARPES $\rightarrow$ Calculations
(SPT or $Z_2$) Topo.Order at Room Temperature
QH-like topological effect at 300K, No magnetic field

Protected Surface States (New 2DEG)

Hsieh, Qian, Wray, Xia et.al., Nature’08, Science’09, Nature’09
Experiments on Topo.Insulators (3D)

Hsieh et al., NATURE 08 (sub. 2007)
Hsieh et al., SCIENCE 09
Roushan et al., NATURE 09

Xia et al., 2008 (arXiv’08, KITP 08)
Xia et al., 2009 (Nature Phys.) and
Hsieh et al., Nature 2009
Chen et al, Sci ’09, Zhang et. NatP ‘09

Wray et al., Nphy’10

Ando et al, PRL ’11

Magnetic TI

Bi$_2$X$_3$

STM Landau quantization
Xue et al., PRL 2010
Analytis et al, NatPhys ’10
Xiong et al., arXiv’11

Quantum Hall effect

QAHE

Topo. Q. Phase Transition
S.-Y. Xu et al., 2011
Science ’11, arXiv’11

QAHE

500+
Papers on Bi-based TIs

Hor et al., PRL 2010
Wray et al., Nphy’10
Ando et al, PRL ’11

Superconductivity

Hsieh et al., NATURE 08 (sub. 2007)
Hsieh et al., SCIENCE 09
Roushan et al., NATURE 09

Xia et al., 2008 (arXiv’08, KITP 08)
Xia et al., 2009 (Nature Phys.) and
Hsieh et al., Nature 2009
Chen et al, Sci ’09, Zhang et. NatP ‘09

Papers on Bi-based TIs
Topological Matter in one form or the other ..... 

CMP faculty

Theory:

Philip Anderson
1977

Bogdan A. Bernevig

Duncan Haldane
2016

David Huse

Shivaji Sondhi

Experiment:

M Zahid Hasan

N Phuan Ong

Jason Petta

Sanfeng Wu

Ali Yazdani
QFT: “Half” Fermions --> Weyl and Majorana

Two ways to decompose a Dirac fermion

Dirac fermion $H = \begin{pmatrix} k \cdot \sigma & m \\ m & -k \cdot \sigma \end{pmatrix}$

- separate in momentum space
- pair of Weyl fermions
- pair of 2x2 matrices
- H. Weyl 1929

$4 \times 4$ matrix

$m \neq 0$

$m = 0$

electron $\sim$ 2 Majoranas

$c = (\gamma + i\gamma')/2$

$c^\dagger = (\gamma - i\gamma')/2$

Majorana = anti-Majorana

$\gamma = \gamma^\dagger$

2 Majoranas $\sim$ 2-level system

Ettore Majorana 1937
Topology & spin-orbit Magnetism

Building up on what is known in 2D
What is their spectroscopic → transport signature?

Specific Topics:

- **Magnetic Topo.Insulators (pre 2010)**
  Some early-papers & review/ RMP’10

- **Chern-gap 2D magnets (Hedgehog magnets)**

- **Correlated Kagome magnets (2D)**

- **Weyl-line 3D topo. magnets**
  SCIENCE 2015 -> PhysRevLett’17/ SCIENCE 2019

- **Chiral 3D materials**
  PhysRevLett’ 2020
  NATURE 2019/ NatureMat’18/ PhysRevLett’17
Topological Insulators  
Tuned via UHV chemical gating, Hsieh et. NATURE’09

Magnetically doped TIs (MTI)
arXiv 2008 (Xia et.al.), Hasan & Kane RMP (2010)

FIG. 13  Room temperature topological order in Bi₂Se₃: (a)

FIG. 15 Protection by time reversal symmetry: Topological surface states are robust in the presence of strong non-magnetic disorder but open a gap in the presence of T breaking magnetic impurities and disorder. (a) Magnetic impurity such as Fe on the surface of Bi₂Se₃ opens a gap at the Dirac point. The magnitude of the gap is set by the interaction of Fe ions with the Se surface and the T breaking disorder potential introduced on the surface. (b) A comparison of surface band dispersion with and without Fe doping. (c,d) Non-magnetic disorder created via molecular absorbent NO₂ or alkali atom adsorption (K or Na) on the surface leaves the Dirac node intact in both Bi₂Se₃ and Bi₂Te₃. Adapted from Hsieh, et al., 2009b; Xia, et al., 2009b; Wray, et al., 2010.

MZH & Kane, (Review) RMP 82, 3045 (2010)  
also Chen (Shen) et.al., Science (2010)
magnetic gap in a MTI (Mn-Bi2Se3: spectroscopic signature)

Samples from N. Samarth group (PennState)

2D magnetic gap in a MTI (spectroscopic signature)

S.-Y. Xu et al., Nature Physics (2012)
2D Chern gap (2D Topo. Magnet)
(if in-gap weak spectral weight is ignored)

Bulk spin-texture for a Chern gap magnet

FIG. 5: Chemical potential tuned to lie inside the magnetic gap. a, Measured surface
Kagome lattice: 1) **Dirac fermions** at K
2) Nearly dispersionless **Flatband**

C-axis Magnetism $\rightarrow$ **massive Dirac gap**

$M_c \rightarrow$ Chern gap

**Xu et al., Nat. Phys 2012**
**Yin et al., NATURE 2018** (Hasan group)

Bulk spin-texture for a Chern magnet
Spin-orbit magnetism in Kagome lattice

Jia-Xin → Two surface terminations (Sn, FeSn, 32): dI/dV map and topography

Kagome-resolved STM/STS: Jiaxin Yin, Sonia Zhang et.al., NATURE 2018

Also see, Transport by Checkelsky et.al., NATURE 2018
QPI (inversion sym):
Fe-Sn surface (double Kagome layer)
Two-fold to six-fold transition driven by field

Jiaxin Yin, Sonia Zhang et.al., NATURE 2018
Magnetic control of Kagome lattice electrons

Jiaxin Yin, Sonia Zhang et.al., NATURE 2018
To sum up so far:

**Topo. Magnetism in 2D**

**2012-**
Mn-doped Bi-based TIs: *Observed magnetism & Chern gap (spin-texture)*  
**But** edge-states not accessible to expts  
Landau levels not resolved in transport

**2013-**
Cr-doped Bi-based TIs: *Observed QAHE (edge-states) at mK and sub-K temp.*  
**But** Chern gap is very small *(Tsinghua group)*

**2018-**
Fe-based Kagome 2D magnets: *Observed magnetism & Chern gap (STM spin-QPI)*  
**But but** edge-states not accessible to expts  
AHE effect seen in transport *(MIT group)*

**Goal:**

-- Identify or make a 2D Chern magnet in the quantum limit  
where edge-states are accessible, Landau levels are accessible  
and Chern gap is large ( > 25 meV)

-- In the interacting limit, there might also be some many-body physics  
(one example would be Kondo lattice physics)
Guided by our past experience on topo.magnets
We have now/recently discovered (2018-19) a new Chern magnet with large gap (> 25 meV)
And edge state accessibility

**RMn$_6$Sn$_6$**

Kagome Lattice in 166 system does not have additional Sn atom in kagome plane and the kagome layers are spatially well separated (by x2) compared with other kagome magnets including Fe3Sn2, Co3Sn2Sn2, Mn3Sn, FeSn et al.
Pure Mn based FM (out-of-plane) kagome lattice

J. Yin et.al., *NATURE* 583, 533–536 (2020)
Searching for ideal Chern magnet with large gap (> 25 meV)

→ $\text{RMn}_6\text{Sn}_6$

Kagome Lattice in 166 system does not have additional Sn atom in kagome plane and the kagome layers are spatially well separated (by x2) compared with other kagome magnets including Fe3Sn2, Co3Sn2Sn2, Mn3Sn, FeSn et al.

Pure Mn based FM (out-of-plane) kagome lattice

J. Yin et. al., *NATURE* 583, 533–536 (2020)
Super-clean kagome lattice in TbMn$_6$Sn$_6$

J. Yin et al., *Nature* 583, 533–536 (2020)
Distinct Landau quantization of Mn kagome lattice

J. Yin et al., NATURE 583, 533–536 (2020)
Quantum-limit visualization of Chern gapped Dirac fermions.

$E_{\text{Dirac}} = 130 \pm 4 \text{ meV}$, $\Delta = 34 \pm 2 \text{ meV}$,

$v = 4.2 \pm 0.3 \times 10^5 \text{ m/s}$, $g = 52 \pm 2$.

First-principles cal.
Gap due to SOC

Higher LL are non-linear $\rightarrow$ Dirac physics; Linear $\rightarrow$ Parabolic bands

J. Yin et al., NATURE 583, 533–536 (2020)
Topological bulk-boundary correspondence

Normal/Kagome Side cleave

J. Yin et al., NATURE 583, 533–536 (2020)
Berry curvature $\rightarrow$ Intrinsic AHE

\[ \sigma_{xy} = \frac{\Delta}{2E_D} \cdot \frac{e^2}{h} = 0.13 \pm 0.01 \frac{e^2}{h} \] based on STM

J. Yin et al., NATURE 583, 533–536 (2020)
Our results point to the realization of a quantum-limit Chern phase in TbMn$_6$Sn$_6$, (Terbium-Manganese-Tin, FM-c-axis) opening up an avenue for discovering topological quantum phenomena in the RMn$_6$Sn$_6$ (R = rare earth element) family with a variety of magnetic structures. Our visualization of the magnetic bulk-boundary-Berry correspondence covering real and momentum space demonstrates a proof-of-principle method revealing topological magnets.

J. Yin et al., *Nature* 583, 533–536 (2020)
Chern gap --> 3D Topo. (Weyl) Magnet?


Wray: to magnetize the Dirac critical point
Neupane & Sankar: to magnetize Bi-Sb, Bi-Se/S, Cd-As analogs
Suyang Xu & Belopolski: to search in the database to find I-broken materials

(2013) Search for Weyl materials
A Weyl Fermion semimetal with surface Fermi arcs in the transition metal monopnictide TaAs class

Shin-Ming Huang\(^1\), Su-Yang Xu\(^3\), Ilya Belopolski\(^3\), Chi-Cheng Lee\(^1\,\(^2\), Guoqing Chang\(^1\), BaoKai Wang\(^1\), Nasser Alidoust\(^3\), Guang Bian\(^3\), Madhab Neupane\(^3\), Chenglong Zhang\(^7\), Shuang Jia\(^7\), Arun Bansil\(^5\), Hsin Lin\(^1\) & M. Zahid Hasan\(^3\)
**Weyl Fermi arcs – Copropagating!**

Determination of Weyl topology without comparing with band calculations

Chiral edge modes co-propagate

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Bulk Weyl fermions
Away from Kramers points or rotational axes

Weyl quasiparticles & Topological Fermi arcs

Weyl nodes and Fermi arcs in TaAs

Weyl Semimetals

K-space: Monopole - Anti MP

Weyl Fermions


Weyl discovery methods: United States Patent #10214797
Later Experimental Papers on TSM physics


2. L. Lu et al., (MIT); *Science* 349, 622 (2015) Weyl photonic (bosonic) crystal


and now more ....(by many groups)
3D TSM (Weyl & TNL): Topo. Nodal-Line Semimetals $\rightarrow$ 3D Topo. Magnet

- **Burkov-Hook-Balents**
- **particle-hole symmetry**
- **general case-1**
- **general case-2**

$g_p = \pm 1$

winding number

$$\gamma = i \oint \langle \psi(k) | \nabla \psi(k) \rangle \cdot dk$$

topo. surface states

bulk-boundary correspondence

**T**-broken crystals with Mirror planes $\rightarrow$ 3D Topological Magnet?

$[M_x, M_z]$ mirror evs of the VB and CB along $k_y$

$[Z_x; Z_z]$ describe the no. of VBs with pos. Mirror evs

on the $M_x, M_z$ plane.
Topological Hopf and Chain Link Semimetal States and Their Application to Co$_2$MnGa

Guoqing Chang, $^{1,2}$ Su-Yang Xu, $^{3,*}$ Xiaoting Zhou, $^{1,2}$ Shin-Ming Huang, $^{4}$ Bahadur Singh, $^{1,2}$ Baokai Wang, $^{5}$ Ilya Belopolski, $^{3}$ Jiaxin Yin, $^{3}$ Songtian Zhang, $^{3}$ Arun Bansil, $^{5}$ Hsin Lin, $^{1,2,†}$ and M. Zahid Hasan$^{3,6,‡}$

FIG. S9: Predicted Weyl lines in Co$_2$MnGa. (A) Ab initio prediction of Weyl lines in
DFT visualization of nodal-lines/band topology:

Cartoon:

I. Belopolski et al., SCIENCE 365, 1278 (2019)
visualization of nodal-lines/band topology

I. Belopolski et al., SCIENCE 365, 1278 (2019)
visualization of Weyl nodal-lines/band topology

I. Belopolski et.al., SCIENCE 365, 1278 (2019)
Drum-head surface states in Weyl loop magnets

I. Belopolski et al., *SCIENCE* 365, 1278 (2019)
Berry curvature field (q. geometry) in Co$_2$MnGa

Physics Today
“Search & Discovery”
News (Dec. 2019)

I. Belopolski et al., SCIENCE 365, 1278 (2019)
Chern magnets (2D)
NATURE 2020/ NatureCom’16
NaturePhys’12/ NaturePhys’11

Kagome magnets
NATURE 2018/ NaturePhys 2019
NatureCom’2020/ NatureCom’19

Weyl-line 3D magnets
SCIENCE 2015 -> PRL 2017
SCIENCE 2019/ arXiv 2020
Future Weyl devices

Nonlocal transport

Parameswaran et al. PRX (2014)

Fermi arc transport


Chiral photon driven AHE

M.Z.H. and C.L. Kane
“Topological Insulators” (& Superconductors)
*Rev. of Mod. Phys., (RMP) 82, 3045 (2010)*

M.Z H., S.-Y. Xu, I. Belopolski, S-M. Huang
“Discovery of Weyl Fermions in Topological Semimetals”
*Ann. Rev. of Cond. Mat. Phys., 8, 16 (2017)*

S. Jia, S.-Y. Xu and M.Z H.
“Weyl Semimetals, Fermi arcs & chiral anomaly ”
*Nature Materials 15, 1140 (2016)*

M.Z.H., D. Hsieh, Y. Xia, L. Wray
Experimental Discovery of Topological Surface States:
*book Chapter in “Topological Insulators”* (2013)

M.Z.H., G. Chang et al,
“Weyl, Dirac & High-fold chiral fermions in topological matter”
*Nature Reviews Materials 784–803 (2021)*
Thanks!