Topological Magnets in 2D & 3D

Chern, Kagome, Weyl magnets etc.

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PCCM Summer School
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Images: http://physics.princeton.edu/zahidhasangroup/
Overview

Broad theme:

**Topology & Magnetism in 3D?**

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

Specific Topics:

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

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

**Weyl fermion → Weyl-line 3D topo. magnets**
Science’15/ PhysRevLett’17/ SCIENCE 2019

**Correlated Kagome magnets**

+ some unpublished new results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

Ilya Belopolski (→ Tokyo)  Su-Yang Xu (→ Harvard)  JiaXin Yin

Guoqing Chang  Sonia Zhang (→ Columbia)  Guang Bian

**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)

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

**Facilities:**
- ALS-LBNL (Bl-4, 10), SSRL-SLAC (BL-5), SLS-PSI, NSLS-BNL
1. Surface States exist and locate inside the bandgap and ½ metallic throughout ([Nature’ 08, submit. 2007](#))


3. Topo Phase transition (BI to TI) via spin-orbit tuning ([Nature Physics, Science’ 10-11](#))

4. Robust up to room temperature ([Nature’ 09](#))

5. Absence of backscatt. by Spin-Texture ([Nature’ 09](#))

MZH & Kane, [Rev. Mod. Phys. 82, 3045 (2010)](http://physics.princeton.edu/zahidhasangroup/)

**Topological Insulators**
Tuned via UHV chemical gating

Hasan & Kane (2010)

MZH & Kane, (Review) RMP 82, 3045 (2010)
also Chen (Shen) et.al., Science (2010)

**Magnetically doped TIs (MTI)**

Hasan & Kane (2010)

FIG. 13 Room temperature topological order in Bi$_2$Se$_3$: (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 $\mathcal{T}$ breaking magnetic impurities and disorder. (a) Magnetic impurity such as Fe on the surface of Bi$_2$Se$_3$ 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 $\mathcal{T}$ 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 NO$_2$ or alkali atom adsorption (K or Na) on the surface leaves the Dirac node intact in both Bi$_2$Se$_3$ and Bi$_2$Te$_3$. Adapted from Hsieh, et al., 2009b; Xia, et al., 2009b; Wray, et al., 2010.

FIG. 16 Chemical gating a topological surface to the spin-degenerate point: Topological insulator surfaces are most
3D to 2D Topo. Insulators: $\text{Bi}_2(\text{Se/Te})_3$

MBE growth

Spin changes as one 2D -> 3D

3D $\rightarrow$ 2D (BULK)

Neupane et al., Samarth & MZH
Nature Commun. ’13 (arXiv)

Also work by Xue & Jia groups ’12 (w/out Spin)
magnetic gap in a MTI (Mn-Bi$_2$Se$_3$: 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
Spin-orbit physics in Kagome magnets (FM)

Kagome lattice:
1) **Dirac fermions** at K
2) Nearly dispersionless **Flatband**

C-axis Magnetism → **massive Dirac gap**

**M_c → Chern gap**

Xu et al., Nat. Phys 2012
Yin et al., NATURE 2018

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

Two surface terminations (Sn, FeSn): $dI/dV$ map and topography

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

Also see, Transport by Ye et.al., (MIT) 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
Anomalous gap behavior under B-field may be due to “spin Berry phase” (Theory by Z. Wang)

STM 2-fold behavior is consistent with Transport results by S. Jia
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 **discovered**

a new **Chern magnet** with large gap (> 25 meV)

And edge state accessibility

**RMn₆Sn₆**

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

To appear in NATURE J.-X. Yin, W. Ma *et.al.*, (S. Jia & M. Z. Hasan)
Searching for ideal Chern magnet with large gap (> 25 meV) → RMn₆Sn₆

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
Super-clean kagome lattice in TbMn₆Sn₆

Mn₃Sn kagome layer in Mn₃Sn

Fe₃Sn kagome layer in Fe₃Sn²

Co₃Sn kagome layer in Co₃Sn²S²
*Science* 365, 1286-1291 (2019)

Mn kagome layer in TbMn₆Sn₆
This work
Distinct Landau quantization of Mn kagome lattice

Kagome

non-Kagome

Strong DOS modulation

To appear in NATURE (J.-X. Yin et.al., Shuang Jia & M. Z. Hasan)
Quantum-limit visualization of Chern gapped Dirac fermions.

\[ E_n = E_D \pm \sqrt{(\Delta/2)^2 + 2|n|e\hbar v^2 B} - \frac{1}{2} g \mu_B B \]

\[ E_{\text{Dirac}} = 130 \pm 4 \text{ meV}, \quad \Delta = 34 \pm 2 \text{ meV}, \]
\[ \nu = 4.2 \pm 0.3 \times 10^5 \text{ m/s}, \quad g = 52 \pm 2. \]

First-principles cal. Gap due to SOC

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

To appear in NATURE (J.-X. Yin et.al., Shuang Jia & M. Z. Hasan)
Topological bulk-boundary correspondence
Normal/Kagome

To appear in NATURE (J.-X. Yin et.al., Shuang Jia & M. Z. Hasan)
Berry curvature → Intrinsic AHE

\[ \sigma_{xy} = \frac{\Delta}{2E_D} * \frac{e^2}{h} = 0.13 \pm 0.01 \frac{e^2}{h} \text{ based on STM} \]
Quantum oscillation/ARPES
Fe$_x$ (Fe$\leftrightarrow$Mn, electron doping, close to Chern gap)
doping-AHE support

To appear in NATURE (J.-X. Yin et.al., Shuang Jia & M. Z. Hasan)
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. -X. Yin, W. L. Ma, T. A. Cochran et al. *Nature* (accepted in April)
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 & Ilya: to search in the database to find I-broken materials
Materials algorithm for finding Weyl
Determination of Weyl topology without comparing with band calculations

Chiral edge modes co-propagate

3D TSM (Weyl & TNL): Topo. Nodal-Line Semimetals $\rightarrow$ 3D Topo. Magnet

Burkov-Hook-Balents

*nodal line*

winding number

$\gamma / \pi = \pm 1$

bulk-boundary correspondence

topo. surface states


particle-hole symmetry

general case-1

general case-2

“drumhead”
$T$-broken crystals with Mirror planes → 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$^{3,6,‡}$
Nodal-line/Weyl to Hopf-link topology

Topological Hopf and Chain Link Semimetal States and Their Application to $\text{Co}_2\text{MnGa}$

A new topological semimetal state is predicted, featuring three-dimensional band crossings that manifest as perpendicular, nontrivial links.

Guoqing Chang et al.
FIG. S9: Predicted Weyl lines in Co$_2$MnGa. (A) \textit{Ab initio} prediction of Weyl lines in...
DFT visualization of nodal-lines/band topology:

Cartoon:
visualization of nodal-lines/band topology
visualization of Weyl nodal-lines/band topology
Berry curvature field (q. geometry) in Co$_2$MnGa

Belopolski, Manna et.al., Science (2019)
Many-body resonance in correlated Kagome magnets

Kondo lattice-like effect in a frustrated antiferromagnet

S. S. Zhang, J.-X. Yin et al.
(submitted)
-- Engineered 2D \textbf{Chern-gap} in magnetically doped topo. insulators (spectroscopic)
\textit{NaturePhys 2012} and \textit{NatCom 2016}
\textit{NATURE 2020} in press

-- Weyl $\rightarrow$ Nodal-line $\rightarrow$ 3D Topo. Magnet
Room temp. topo.magnet ($T_c \sim 600$K)
\textbf{Weyl-line topo.magnet} in $\text{Co}_2\text{MnGa}$
\textit{Science 2015} and \textit{PhysRevLett 2017}
\textit{SCIENCE 2019} (Weyl loop 3D magnet)

-- \textbf{Correlated Kagome}
Two-fold QPI/transport; and field control
Kondo lattice type many-body resonance
\textit{Nature 2018} and \textit{Nature Physics 2019}
\textit{PhysRevLett} (submitted) 2020

-- \textbf{Discovered a Chern magnet family in the q-limit}

\textit{Thanks!}
24 Weyl nodes in the bulk of TaAs, NbAs

Theory FIGURES from
S. Huang, Suyang Xu, Belopolski et.al., Nature Commun. 2015
Weyl Fermi arcs – *Copropagating!*

Counter-propagating (opposite slopes) $\rightarrow$ Closed contour

Co-propagating (same slope) $\rightarrow$ Fermi arcs

Weyl Fermi arcs – Copropagating!

ARPES: Surface vs. Bulk

Low Photon Energy (surface sensitive)

Original Photon Energy

High Photon Energy (Bulk sensitive)

ARPES-2: Bulk Weyl fermions
Away from Kramers points or rotational axes

Spin polarization in TaAs  
> 80%

- Singly degenerate
- Spin pol. > 80%
- $P_z = 0 (C_2T)$

Weyl quasiparticles & Topological Fermi arcs

Weyl nodes and Fermi arcs in TaAs

Weyl Semimetals

K-space: Monopole - Anti MP

Weyl Fermions

Fermi Arcs

Discovery of a Weyl Fermion semimetal and topological Fermi arcs
16th July, 2015
Su-Yang Xu,1,2* Ilya Belopolski,1* Nasser Alidoust,1,2* Madhab Neupane,1,3* Guang Bian,1 Chenglong Zhang,4 Raman Sankar,5 Guoqing Chang,6,7 Zhujun Yuan,4 Chi-Cheng Lee,6,7 Shin-Ming Huang,6,7 Hao Zheng,1 Jie Ma,8 Daniel S. Sanchez,1 BaoKai Wang,6,7,9 Arun Bansil,9 Fangcheng Chou,5 Pavel P. Shibayev,1,10 Hsin Lin,6,7 Shuang Jia,4,11 M. Zahid Hasan1,2†

Discovery of a Weyl fermion state with Fermi arcs in niobium arsenide
Su-Yang Xu1,2†, Nasser Alidoust1,2†, Ilya Belopolski1,2†, Zhujun Yuan3, Guang Bian1, Tay-Rong Chang1,4, Hao Zheng1, Vladimir N. Strocov5, Daniel S. Sanchez1, Guoqing Chang6,7, Chenglong Zhang3, Daixiang Mou8,9, Yun Wu8,9, Lunan Huang8,9, Chi-Cheng Lee6,7, Shin-Ming Huang6,7, BaoKai Wang6,7,10, Arun Bansil10, Horng-Tay Jeng4,11, Titus Neupert12, Adam Kaminski8,9, Hsin Lin6,7, Shuang Jia3,13 and M. Zahid Hasan1,2†
REVIEWS (invited)

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. and J.E.Moore
“Three Dim. Topological Insulators”

M.Z.H. and C.L. Kane
“Topological Insulators” (& Superconductors)
*Rev. of Mod. Phys.*, *(RMP)* 82, 3045 (2010)
Thanks !
STM/S study of kagome magnet with vector field

Vector magnetic field

Flat band

Dirac cone
Giant and anisotropic spin-orbit tunability in Fe$_3$Sn$_2$

A kagome quantum state featuring vector magnetization ($\mathbf{M}$) tunability

Giant and anisotropic spin-orbit tunability in Fe$_3$Sn$_2$

**Vector field control of nematic electronic matter**

Consistent transport anisotropy in Fe$_3$Sn$_2$

Giant transport response supporting the STM data indicating weak localization behavior of Dirac electrons

Kagome flat band and orbital magnetism in

\[ m = \frac{k^2 t^2 \lambda}{k^4 t^2 + 48 \lambda^2} \]

Negative flat band magnetism arising from the Berry curvature field, which is a quantum phase effect.


MAGNETISM

An upside-down magnet

Kagome lattice materials combine a frustrated lattice with...
Spin orbit quantum impurity in Co$_3$Sn$_2$S$_2$

A nonmagnetic impurity can introduce spin-orbit coupled magnetic resonance in topological magnets.

Spin polarized STM/S measurement

J-X. Yin, N. Shumiya, Y. Jiang et al.

Spin orbit quantum impurity in Co$_3$Sn$_2$S$_2$

Spin-orbit coupled quantized orbitals

J-X. Yin, N. Shumiya, Y. Jiang et al.  
Thermal induced magnetic competition in Co$_3$Sn$_2$S$_2$

FM-AFM magnetic competition drives the AHE response

Doping induced magnetic competition in $\text{Co}_3\text{Sn}_2\text{S}_2$  

Z. Guguchia et al. (submitted)
Later Experimental Papers on TSM physics


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

First principles support