Evidence for the chiral anomaly in a Dirac Semi-metal

Jun Xiong, Tian Liang, Minhao Liu, Wudi Wang, N. P. Ong
Department of Physics, Princeton Univ.

Satya Kushwaha, Quinn Gibson, Jason Krizan, Maz Ali, R. J. Cava
Department of Chemistry, Princeton Univ.

1. Introduction to Dirac semimetals
2. Ultrahigh mobilities and giant MR in Cd₃As₂
3. Intro to Weyl physics
4. Chiral anomaly in Na₃Bi

Supported by MURI, ARO, NSF (MRSEC), Moore Foundation
Dirac node protection by Point-Group Symmetry

Murakami, *NJP* 2008
Wan, Turner, Vishwanath, Savrasov, *PRB* 2011
Young, Kane, Mele et al. *PRL* 2012
Wang, Dai et al., *PRB* 2012
Fang, Gilbert, Dai, Bernevig, *PRL* 2012

B.J. Yang and N. Nagaosa, arXiv 1404.0754

Initial idea: Dirac node is protected by TRS and IS if *pinned* to zone corners.

Later, inclusion of point-group symmetry $C_n$ extends protection to *anywhere* on symmetry axis.
Protected Dirac nodes in semimetal $\text{Na}_3\text{Bi}$

Wang, Dai, Fang et al. *PRB* 2012
Wang, Dai, Fang et al. *PRB* 2013

$\text{Na}_3\text{Bi}$

$\text{Cd}_3\text{AS}_2$

$C_3$

$C_4$
Photoemission on $\text{Na}_3\text{Bi}$ and $\text{Cd}_3\text{As}_2$

Point group $C_3$

Liu, Chen et al., *Science* 2014
Neupane, Hasan et al., *Nat Comm.* 2014
Borisenko, Cava et al., *PRL* 2014
Set A (crystals) show 1000 fold difference in RRR. Some crystals show very low residual resistivity 20 nΩcm. Correlated with large resistivity anisotropy (30). Set B samples have higher resistivity.
Change in Resistivity and Conductivity Tensors with mobility in Cd$_3$As$_2$

Tian Liang, Quinn Gibson et al. Nat. Mater. 2015

$\rho_{xx}$ and $\rho_{yx}$

Increasing mobility

Hall conductivity $\sigma_{xy}$

Field scale changed by $\sim$80
Direct measurement of mobility

Peaks in $\sigma_{xy}$ move to lower $B$ as mobility $\mu$ increases. $\mu$ correlates with residual conductivity over 3 decades.
Chiral anomaly?

Negative, longitudinal MR detected at $\theta = 0^\circ$, but swamped by positive MR term ($E_F$ is much too high).
Transport results on Na$_3$Bi

Deep purple crystals

Rapidly oxidized in ambient air (30 s)

Large linear MR similar to Set B Cd$_3$As$_2$ samples

$E_F$ 400 mV above node
H-linear MR and step-profile of Hall angle $\tan \theta_H$

Conventional

$$\rho_{xx}(B) \sim [1 + (\mu B)^2]$$

$$\tan \theta_H \sim \mu B$$

In Na$_3$Bi

$$\rho_{xx}(B) \sim B, \quad \text{linear MR}$$

$$\tan \theta_H \text{ has a } \textit{step-function} \text{ profile}$$
Breaking Time Reversal symmetry in magnetic field

Search for Weyl physics

Chiral anomaly and axial current
1969  Charged pions decay leptonically, $\pi^+ \to \mu^+ + \nu$

But, neutral pion decays electromagnetically

$\pi^0 \to \gamma + \gamma$

Chiral anomaly speeds up decay by $1,000 \times$

Earliest (?) hint of 3 colors

**Spoiler role in chiral gauge theories**

Ruins chiral charge conservation and renormal.

Topological in origin

**Anomaly-free condition**

In a chiral theory, *all* the anomalies must cancel for it to be renormalizable.

This imposes stringent constraints, e.g. number of generations.

In Glashow-Weinberg-Salaam theory, exact cancellation involving 10+ diagrams has been called “magical”.

**Nielsen and Ninomiya** (*Phys. Lett. 1983*) proposed chiral anomaly may be observable in $(1+1)d$ or $(3+1)d$ crystals ---- even spacetime dim.
Detecting the chiral anomaly in a crystal?

Nielsen and Ninomiya \textit{(Phys. Lett. 1983)}

\[ i \gamma^\mu \partial_\mu \Psi = 0 \]
TRS breaking splits Dirac node into 2 Weyl nodes

Berry curvature: \( F(k) = \nabla_k \times A(k), \quad A(k) = i(u_k | \nabla_k u_k) \)

- Weyl nodes come in pairs with \( \chi = \pm 1 \)
- Acts as monopole source or sink of Berry curvature \( F \) (or Chern flux \( \Phi \))

\[
\chi = \frac{1}{2\pi} \oint F(k) \cdot dS(k)
\]

Non-conservation of chiral charge in \( E \) field \( \rightarrow \) the chiral anomaly

Wan, Turner, Vishwanath, *PRB* 2011
Burkov, Hook, Balents, *PRB* 2011 \( \ldots \) and 80+ theory uploads on arXiv
Son, Spivak, *PRB* 2013
Charge pumping and the chiral anomaly

\[ W = -\frac{L^2}{2\pi \ell_B^2} \frac{Le k}{2\pi} = -V \frac{e^3}{4\pi^2\hbar^2} \mathbf{E} \cdot \mathbf{B} \]

In weak $B$, charge pumping gives (Son and Spivak, PRB 2013)

\[ \sigma_{\chi} = \frac{e^2}{4\pi^2\hbar c} \frac{\nu (eBu)^2}{c} \tau_v, \]

$\tau_v$ is intervalley scattering time

Nielsen, Ninomiya, *Phys. Lett.* 1983
Wan, Turner, Vishwanath, *PRB* 2011
Burkov, Hook Balents, *PRB* 2011
Son, Spivak, *PRB* 2013
Parameswaran et al. *PRX* 2014
Hosur and Qi, *Comp. Rend. Phys.* 2013

Chiral anomaly engenders large, negative longitudinal MR

*Locked* to $B$ field
Non-metallic resistivity and negative longitudinal MR in Na$_3$Bi

Long-term annealed crystals with $E_F \sim 30$ mV

Jun Xiong, S. Kushwaha, Krizan et al., submitted
A crucial test for chiral anomaly -- $\mathbf{B}$ is locked to $\mathbf{E}$

Jun Xiong, S. Kushwaha et al., submitted

Negative MR appears only when $\mathbf{B}$ is locked to $\mathbf{E}$.
Test: if $\mathbf{E}$ is rotated by $90^\circ$ (right panel), neg. MR shifts to new direction of $\mathbf{E}$. For weak $\mathbf{B}$, this locking is novel and unexpected in semiclasscl transport
A narrow plume of chiral current, B in-plane

Enhanced cond. in a narrowly collimated beam for B in the x-y (horizontal) plane
Width of chiral conductivity “plume”, $B$ normal to plane

Enhanced cond. in a narrowly collimated beam for $B$ rotated in the $x$-$z$ (vertical) plane
Signature of chiral anomaly: $B$ locks direction of axial current

In conventional transport, we cannot “rotate” FS parameters, e.g. scattering rate anisotropy, by rotating direction of a weak $B$.

Locking of observed axial to $B$ (even in *weak $B$*) seems to be a signature characteristic of the chiral anomaly.

Axial plume direction fixed by $B$ (and $E$)

Observation of negative, longitudinal MR is necessary but insufficient.
Determine intervalley scat. lifetime using Son-Spivak expression

In semiclassical regime, Weyl node conductivity grows as $B^2$ (Son, Spivak, PRB ‘13)

From fit, we find $\tau_V = 40-80 \, \tau_0$
Transport experiments on Dirac semimetals

In Cd$_3$As$_2$, we observe very high mobility (9 million cm$^2$/Vs) in zero $B$. Appears to be protected by a zero-$B$ mechanism. Giant MR observed when protection is lifted.

In Na$_3$Bi, in samples with $E_F \sim 30$ mV, we see evidence for the chiral anomaly.

Signature: The enhanced-conductivity “plume” is locked to the direction of $B$ (and $E$). YES

Estimated inter-valley lifetime is 40-80 x longer than Drude value.

A surprise: Width of plume is much narrower than anticipated by theory.
Thank you
Hall conductivity curves collapse to universal curve when plotted in dimensionless variables. $B_{\text{max}}$ equals $1/\mu$
Protection of nodes against gap formation

1. Gap inversion pulls (Na 3s) $S$ band 0.3 eV below HH (Bi 6p) $P$ band

2. Retain the two orbitals $|S, 1/2\rangle$ and $|P, 3/2\rangle$ near node. With spin, we have a 4x4 Hamiltonian

\[
H_\Gamma(k) = \epsilon_0(k) + 
\begin{pmatrix}
M(k) & A k_+ \\
A k_- & -M(k) \\
0 & B(k) \\
B(k) & 0
\end{pmatrix}
\begin{pmatrix}
0 & B^*(k) \\
B^*(k) & 0 \\
M(k) & -A k_- \\
-A k_+ & -M(k)
\end{pmatrix},
\]

Entries fixed by TRS and P (inversion symm.)
At crossing, bands do not mix because they belong to different representations of $C_3$ rotation group

3. Point group symmetry (PGS) e.g. $C_3$, dictates that off-diagonal terms

\[
B(k) \sim k_z k_+^2
\]

Near node, $H$ decomposes to two diagonal 2x2 blocks (Weyl fermions)
If TRI is restored → Weyl points of opposite chirality mutually annihilate
Left with a gapped spectrum

Point group symmetry prevents annihilation -- we have a 4-comp Dirac metal

Each node is a 4-comp massless Dirac point
Has 4-fold degeneracy (lifted by breaking of TRI or Inv.)
3D Analog of graphene

Young, Kane et al., PRL (2012)
Wang, Dai et al., PRB (2012)
Bernevig et al., (2013)

\( \beta \)-crystobalite \( \text{BiO}_2 \)
\( A_3\text{Bi} \quad (A = \text{Na, K, Rb}) \)
\( \text{Cd}_3\text{As}_2 \)
Giant MR in Cd$_3$As$_2$

Ultrahigh mobility results from unknown protection mechanism against $2k_F$ scattering

B field removes protection, giving giant MR
Transport quantities in 7 samples of Cd\textsubscript{3}As\textsubscript{2}

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\rho_1$ (nΩcm)</th>
<th>$\gamma$</th>
<th>RRR</th>
<th>$\mu_1$ (cm$^2$/Vs)</th>
<th>MR (9T)</th>
<th>$n_H$ (9T) (10$^{18}$ cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>32</td>
<td>32.7</td>
<td>781</td>
<td>$\sim 3 \times 10^6^*$</td>
<td>582</td>
<td>9.1</td>
</tr>
<tr>
<td>A4</td>
<td>14,600</td>
<td>2.72</td>
<td>21.4</td>
<td>$40 \times 10^3$</td>
<td>34.5</td>
<td>4.4</td>
</tr>
<tr>
<td>A5</td>
<td>21</td>
<td>18.7</td>
<td>4,100</td>
<td>$8.7 \times 10^6$</td>
<td>1,336</td>
<td>7.4</td>
</tr>
<tr>
<td>A6</td>
<td>4,000</td>
<td>22.6</td>
<td>32.2</td>
<td>$320 \times 10^3$</td>
<td>112</td>
<td>12.0</td>
</tr>
<tr>
<td>A8</td>
<td>110</td>
<td>12.8</td>
<td>118</td>
<td>$4.0 \times 10^6$</td>
<td>404</td>
<td>13.3</td>
</tr>
<tr>
<td>B1</td>
<td>46,500</td>
<td>–</td>
<td>5.37</td>
<td>$\sim 10 \times 10^3^*$</td>
<td>36.9</td>
<td>–</td>
</tr>
<tr>
<td>B7</td>
<td>32,200</td>
<td>–</td>
<td>7.26</td>
<td>$\sim 20 \times 10^3^*$</td>
<td>62.2</td>
<td>15</td>
</tr>
</tbody>
</table>
Topological phases of matter

Topological Crystalline Insulator
PbSnSe, PbSnTe

Kagome
HerbertSmithite
Cu(1,3 carboxylate)

Pyrochlore
Eu$_2$Ir$_2$O$_7$

Z2 TRI SYSTEMS

HgTe-CdTe
Bi$_2$Se$_3$

Bi$_2$Te$_3$

Bi$_2$Te$_2$Se

Weyl semimetal
Dirac metal

Cd$_3$As$_2$, Na$_3$Bi

Large U solids
Iridates, SmB$_6$

3d-Chalcogenides
MoS$_2$, WTe$_2$

Relation of Topological ideas --- from Z2-TRI solids to other materials. An sub-terra theme is the Berry curvature (Chern flux)

4x4 basis $|S,\frac{1}{2}\rangle, |P,\frac{3}{2}\rangle, |S,-\frac{1}{2}\rangle, |P,-\frac{3}{2}\rangle$

B field also breaks TRI $\rightarrow$ Weyl nodes move apart, Lifshitz transition

Tests need higher B and higher mobility
\[ v_F = (6 - 10) \times 10^5 \text{ cm/s} \]

16 \times 10^5 \text{ cm/s (Hasan)}

SdH oscillations provide more accurate meas.
Three Dimensional Dirac Semimetal and Quantum Spin Hall Effect in \( \text{Cd}_3\text{As}_2 \)

Zhijun Wang, Hongming Weng,* Quansheng Wu, Xi Dai, and Zhong Fang†

Point Group C4

4x4 basis set

\[ |S, \frac{1}{2}\rangle, |P, \frac{3}{2}\rangle, |S, -\frac{1}{2}\rangle, |P, -\frac{3}{2}\rangle \]

\[ H_\Gamma(k) = \epsilon_0(k) + \begin{pmatrix} M(k) & Ak_+ & 0 & B^*(k) \\ Ak_- & -M(k) & B^*(k) & 0 \\ 0 & B(k) & M(k) & -Ak_- \\ B(k) & 0 & -Ak_+ & -M(k) \end{pmatrix} \]

4-comp Dirac
Conductivity tensor is anomalous

**Conventional**

\[
\sigma_{xx}(B) = \frac{ne\mu}{1 + (\mu B)^2} \sim \frac{1}{B^2}
\]

\[
\sigma_{xy}(B) = \frac{ne\mu^2 B}{1 + (\mu B)^2} \sim \frac{1}{B}
\]

Differ by one power of B

**In Na\textsubscript{3}Bi**

Both \(\sigma_{xx}\) and \(\sigma_{xy}\) \(\sim \frac{1}{B}\)
Dual Dirac nodes in Cd$_3$As$_2$

Wang, Dai, Fang et al. *PRB* 2012
Wang, Dai, Fang et al. *PRB* 2013