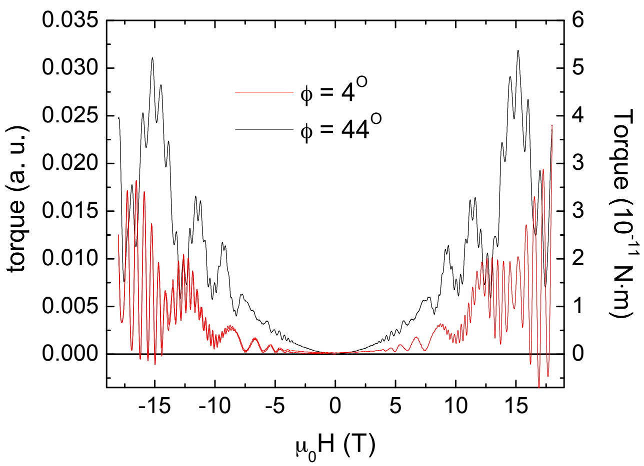
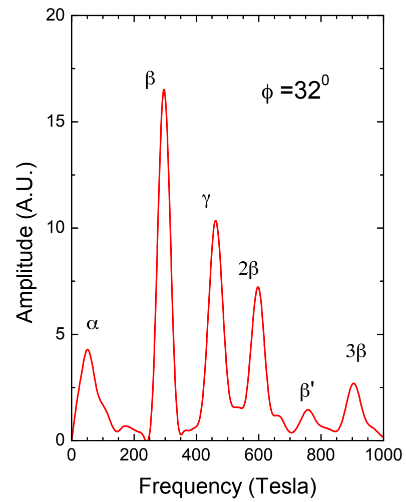
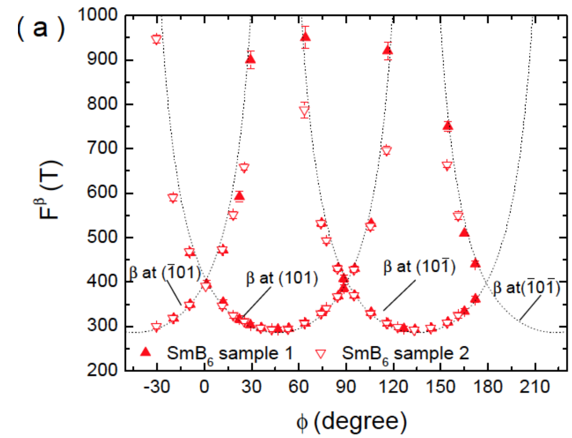
Two-dimensional Fermi surfaces in Kondo Insulator SmB_6

Lu LI
University of Michigan







G. Li, *et al. Science 2014*

Acknowledgement

Dae-Jeong Kim, Zachary Fisk *UC Irvine*

X. H. Chen *Univ. Science & Tech. China*

Xiangfeng Wang, Johnpierre Paglione *Univ. Maryland*

Tyrel McQueen *John Hopkins Univ.*

Zihqiang (Jason) Li, NHMFL

Jim Allen, Kai Sun *Univ. Michigan*

Kurdak, Eo, Wolgast *Univ. Michigan*

Yayu Wang, *Tsinghua Univ.*

U.S. DEPARTMENT OF ENERGY | Office of Science

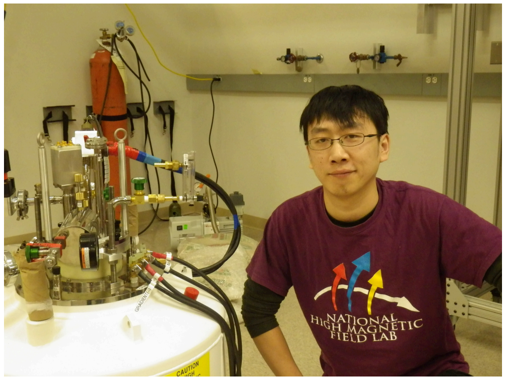
NSF

University of Michigan
MCUBED project

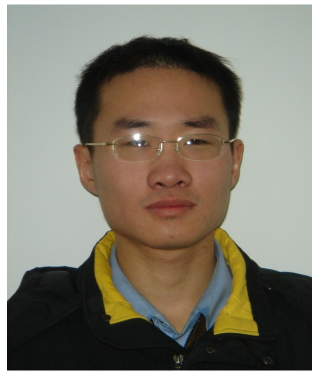
NATIONAL HIGH MAGNETIC FIELD LAB

Acknowledgement

Gang Li



Fan Yu

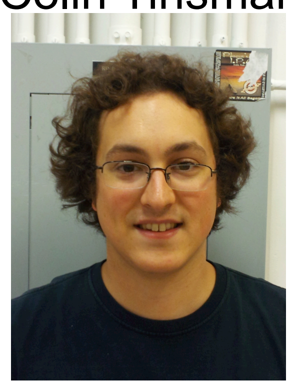


Ben Lawson

Tomo Asaba

Applied Physics Student

Colin Tinsman



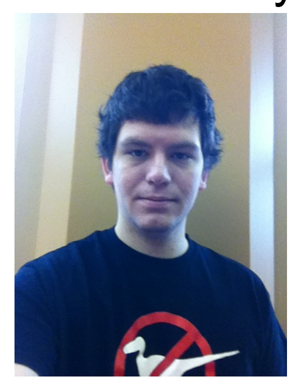
Visiting students

Peng Cai

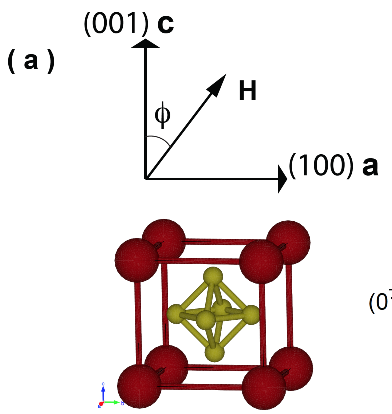
Ziji Xiang

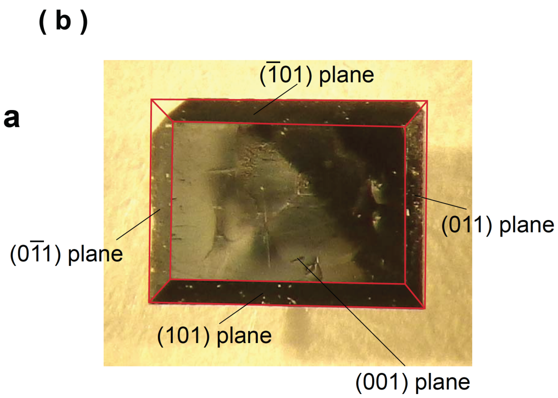
Undergraduates

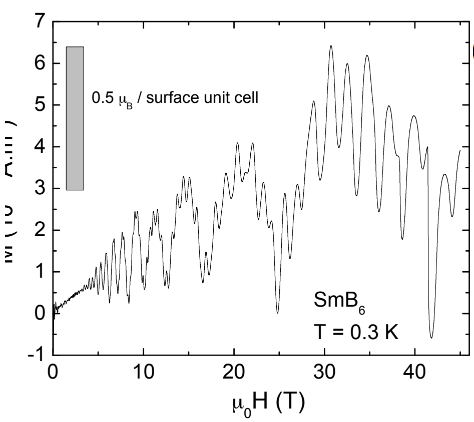
Adam Berkley

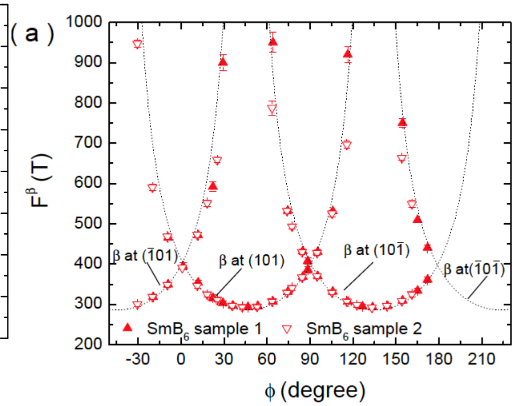


Topological Kondo insulators SmB_6







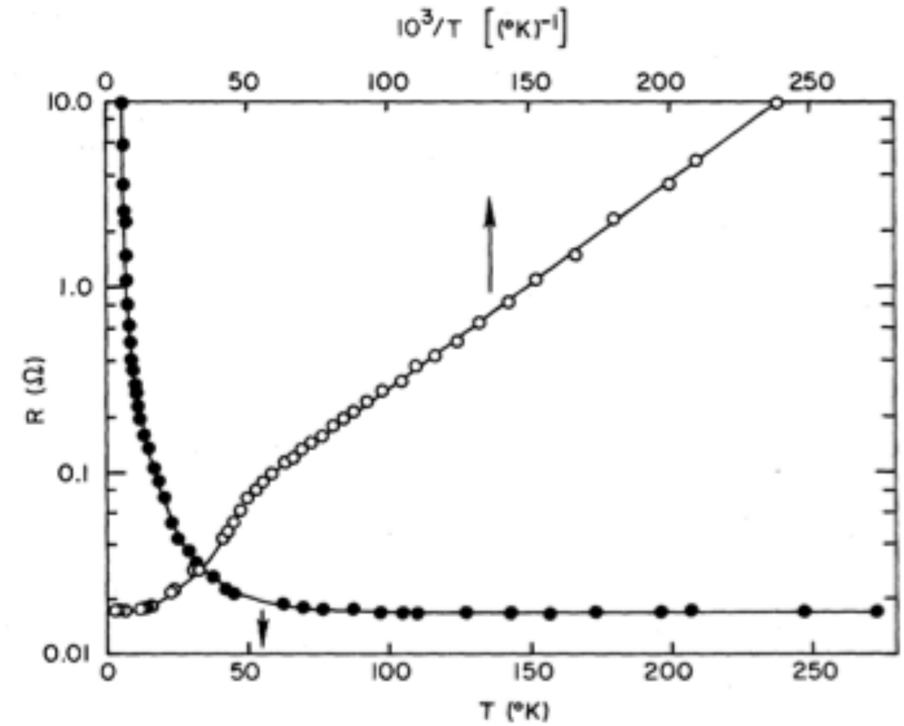


1. **WHY?** Kondo Insulator SmB_6

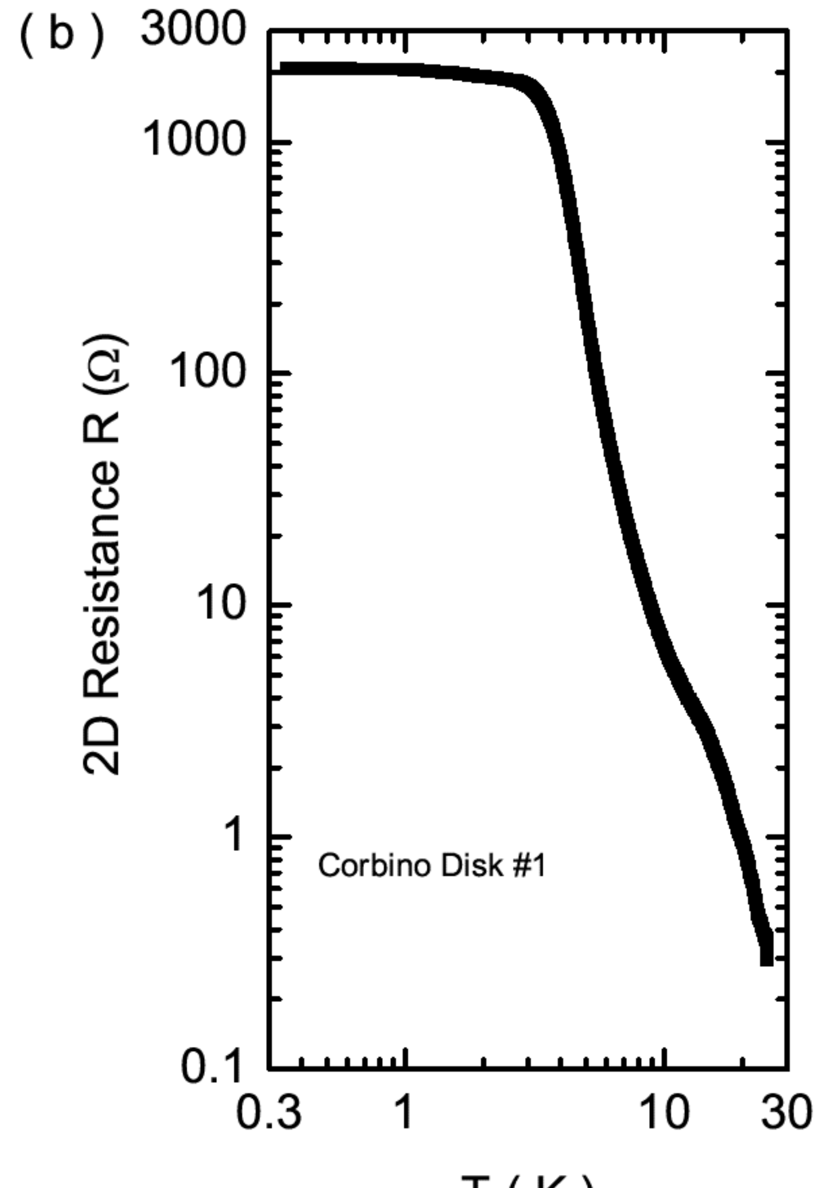
2. **HOW?** Torque magnetometry

3. **Result?**
   - Quantum oscillations in **M**
   - 2 dimensional surface state
     F ~ 1 /cos (angle)
   - Landau Levels index plots →
     -1/2 Berry phase factor for
     Dirac dispersion
   - Heavy Mass observed in
     Floating-zone samples

Insulating above 4 K, but metallic at lower T



Menth, Buehler, Geballe, PR 1968



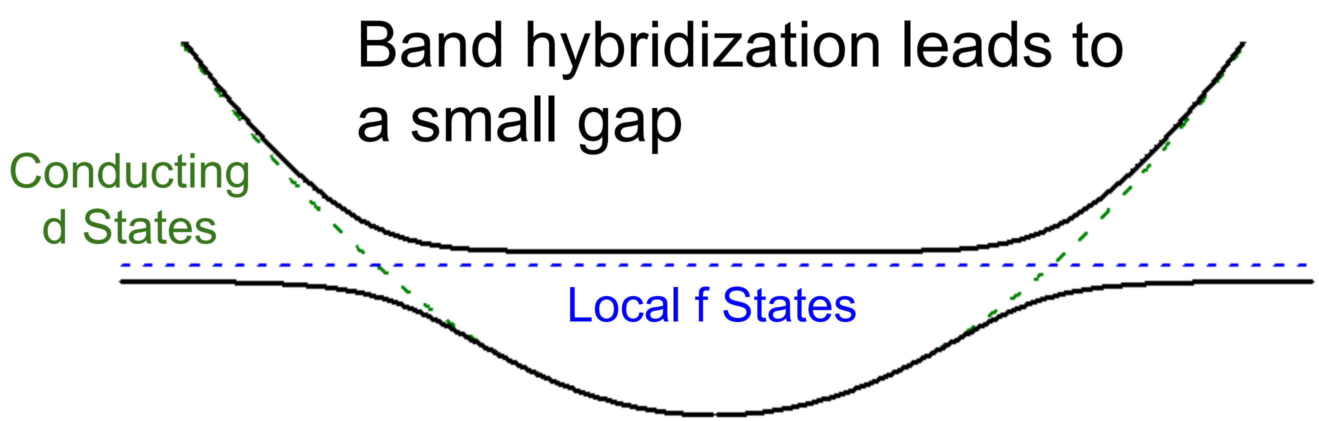
G. Li, *et al. Science*

Kondo Insulator SmB_6

- Mixed valence: Sm^{3+} and Sm^{2+} both present

- Kondo insulator
  - Metallic properties at low T
  - Non-magnetic insulator properties at low T

- Behavior is attributed to mixing of localized f states and conduction d states



3D Topological Kondo Insulators

Theoretical Kondo TI prediction:

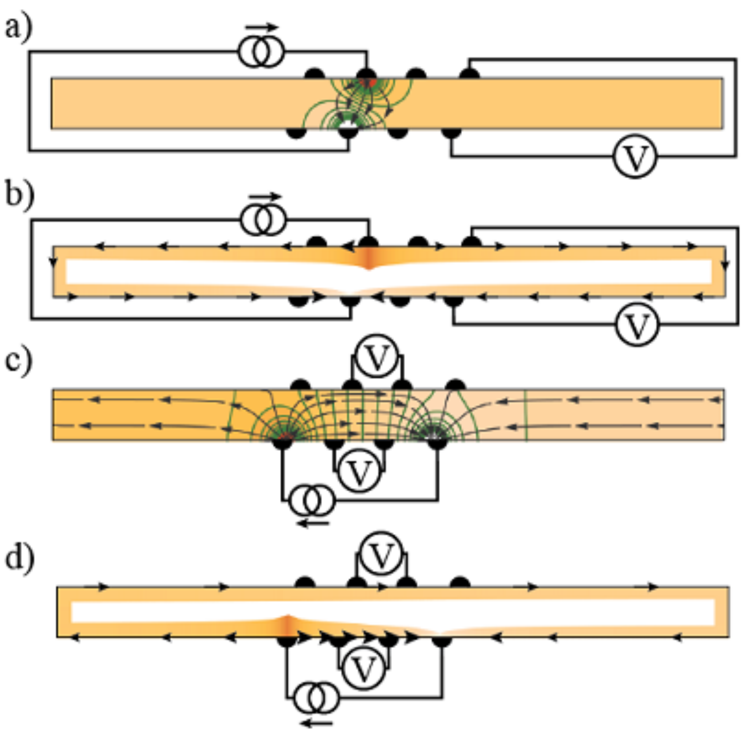
- SmB_6 Dzero, Sun, Galitski, Coleman, *PRL 2010*

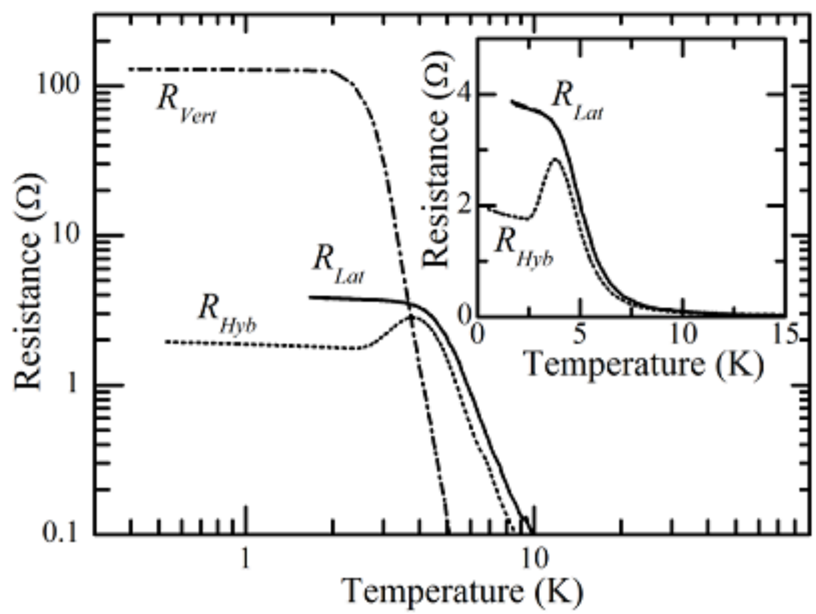
Topological Insulator w weak interaction

- Robust (protected) surface state
- Insulating bulk
- Odd number of Dirac cones
- Helical spin structure

Kane, Fu, Zhang, Xi, Moore, Balents ….

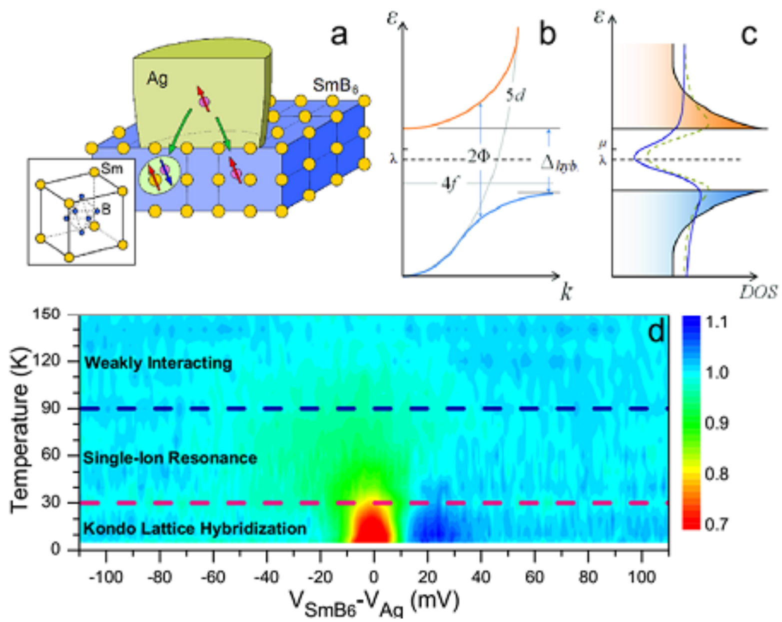
Surface conductance



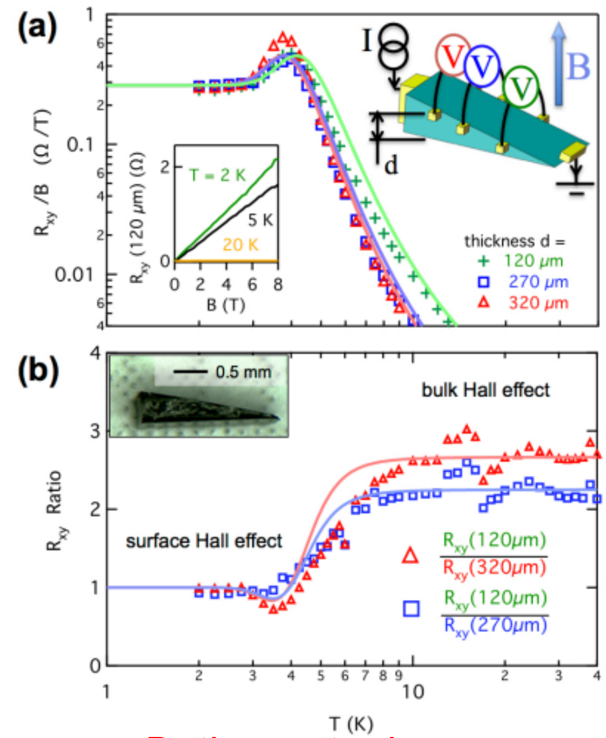


Wolgast et.al.
arxiv: 2012, PRB 2013
Michigan

Surface conductance and bulk gap

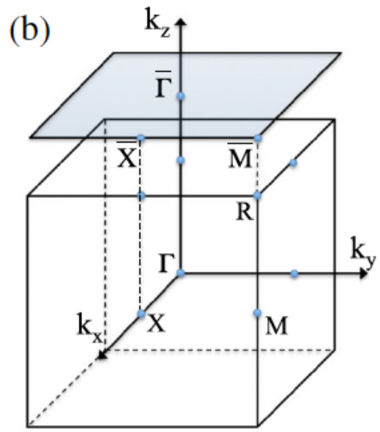


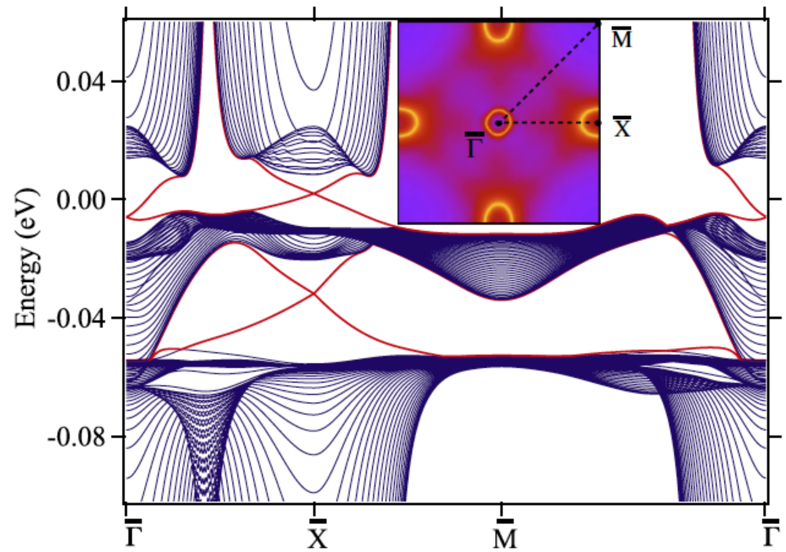
Zhang et.al.
arxiv:1211.5532
PRX 2013
Maryland



Botimer et. al.
arXiv:1211.6769
Scientific Report 2013
UCI

Advanced Calculation shows possible surface state on the 100 cleavage plane





3 Dirac Cones, 2 Fermi Surface Areas

Lu, *et al. PRL (2013)*

Experimental approach demonstrating the topological surface state

1. **ARPES** *Hasan, Shen, …*
    - Dirac dispersion
    - Helical spin structure
2. **STM** *Yazdani. …*
3. **Quantum oscillations** *Ong, Ando, Fisher …*

Experimental approach demonstrating the topological surface state in SmB_6

1. **ARPES** shows Dirac dispersion
   N. Xu, et al., Phys. Rev. B. 88, 121102 (2013).
   M. Neupane, et al., Nat. Commun.4, 2991 (2013).
   J. Jiang, et al., Nat. Commun.4, 3010 (2013).
   E. Frantzeskakis, et al., Phys. Rev. X. 3, 041024 (2013).
   J. D. Denlinger, et al., arXiv:1312.6637 (2013).
   Z.-H. Zhu et al., Phys. Rev. Lett. 111, 216402 (2013).

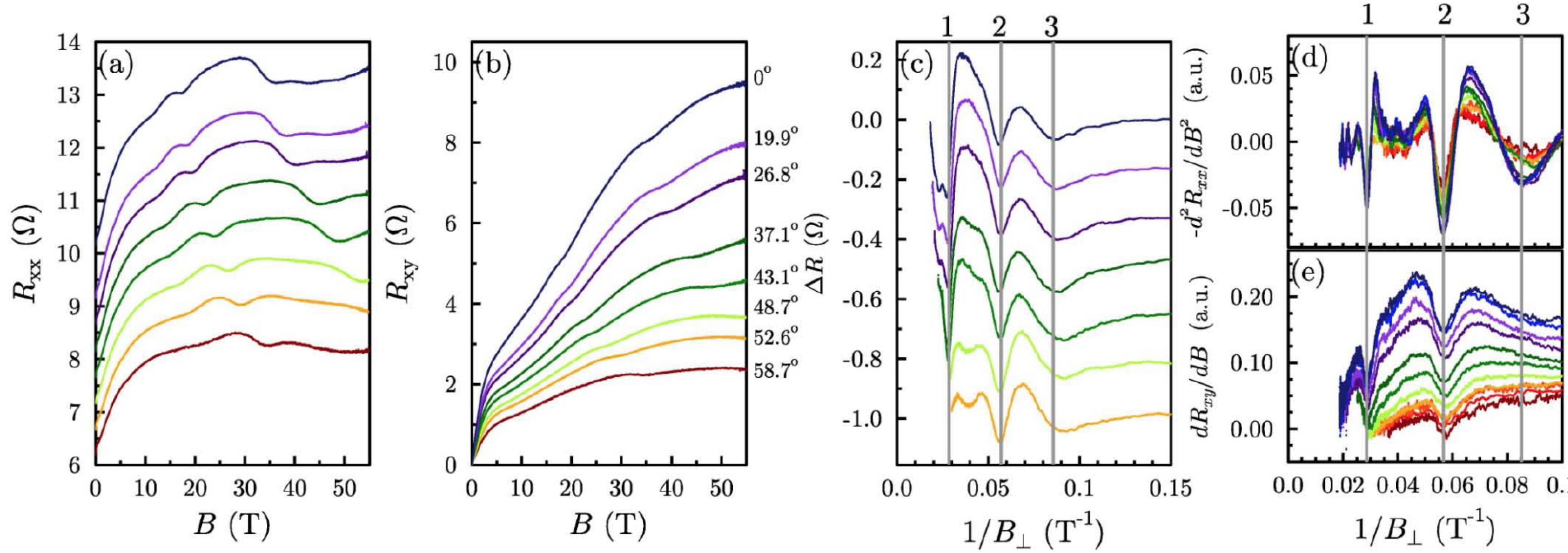
2. **STM** *Yayu Wang, PRL 2014,*
   S. Wirth, PNAS 2014
   Hoffman, arXiv:2013

3. **Quantum oscillations**
   Gang Li & L. Li, Science 2014
   J. Xia et al….
   Sebastian et al… Science 2015

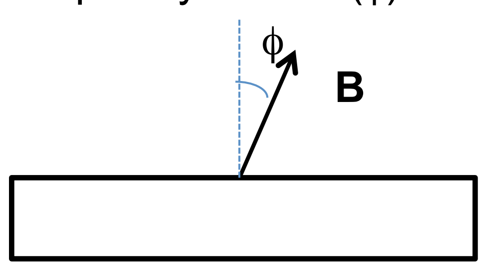
Quantum Oscillations reveal

1. Dimensionality

Bi_2Se_3



Scale as $1/B_{perp}$, frequency ~ $1/\cos(\phi)$

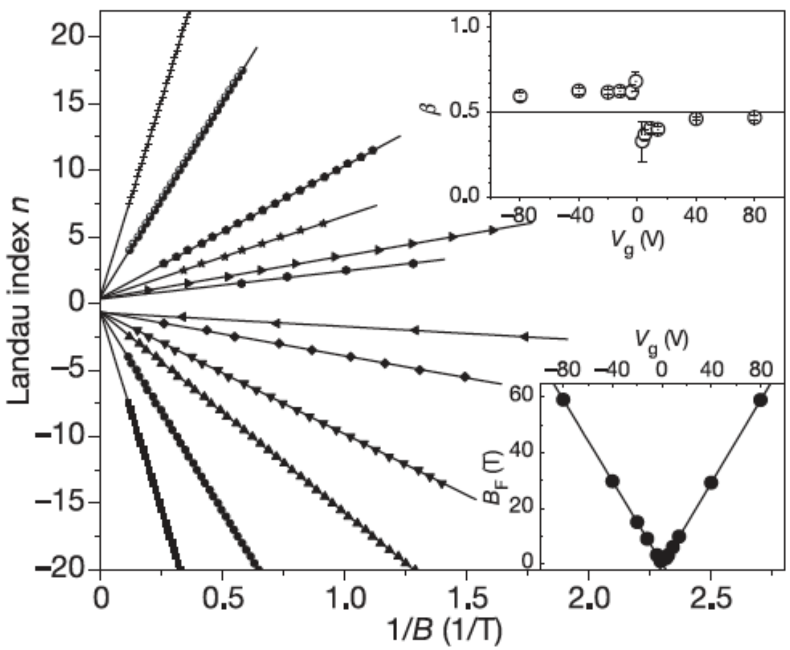


Analytis et al. Nature Physics 2010

Quantum Oscillations reveal

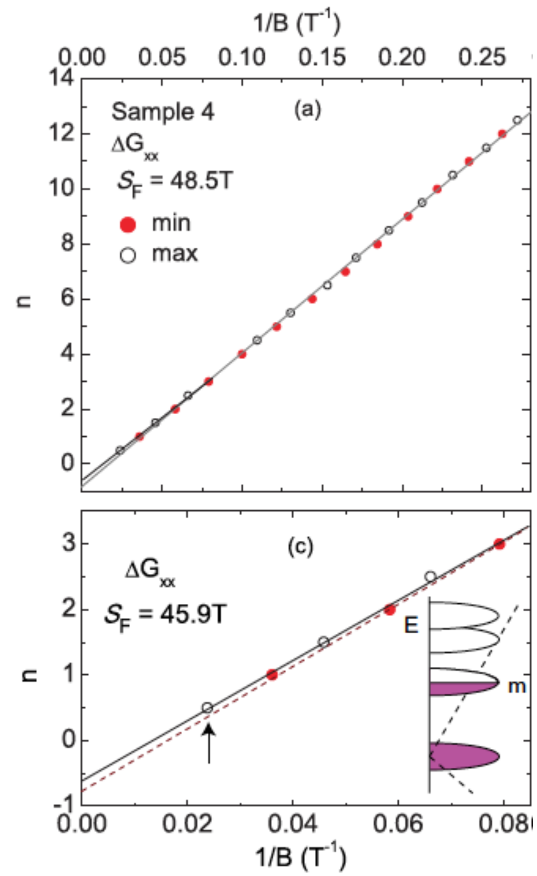
2. Signature of Dirac dispersion in the Landau Levels index plot

graphene



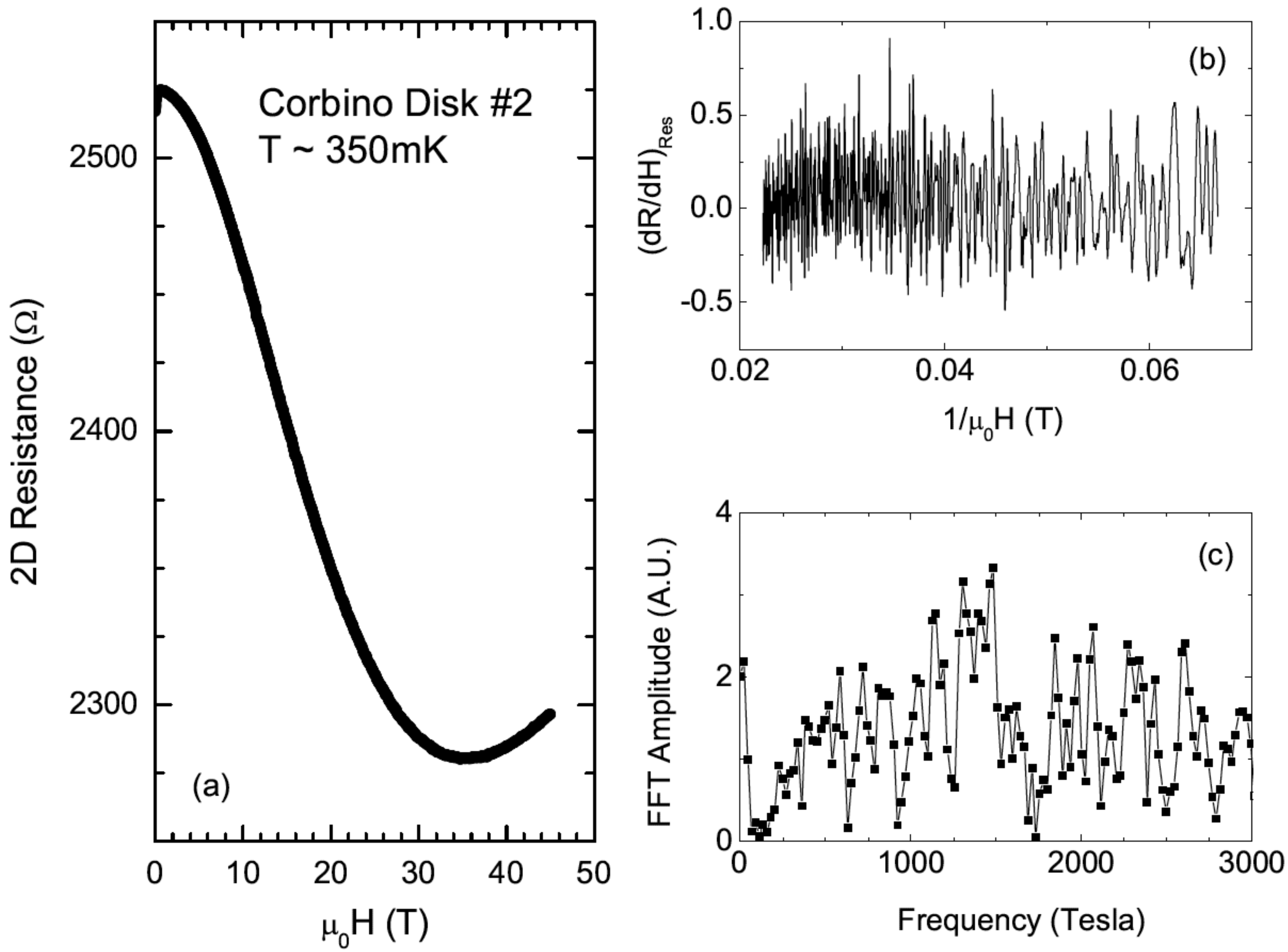
Zhang & Kim *Nature (2005)*

Bi_2Te_2Se



Xiong & Ong PRB *(2012)*

Missing: quantum oscillation in magnetoresistance



G. Li, *et al. Science 2014*

Challenge: how to measure the magnetic moment of surfaces?

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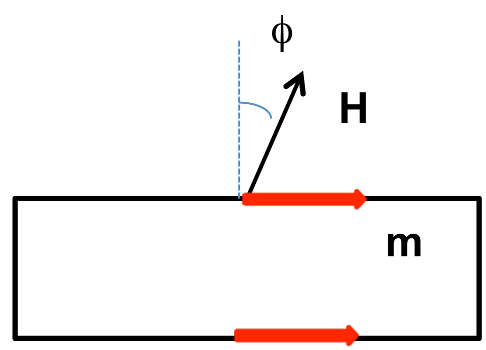


Torque on moment: $\tau = \mathbf{m} \times \mathbf{B}$

Torque magnetometry

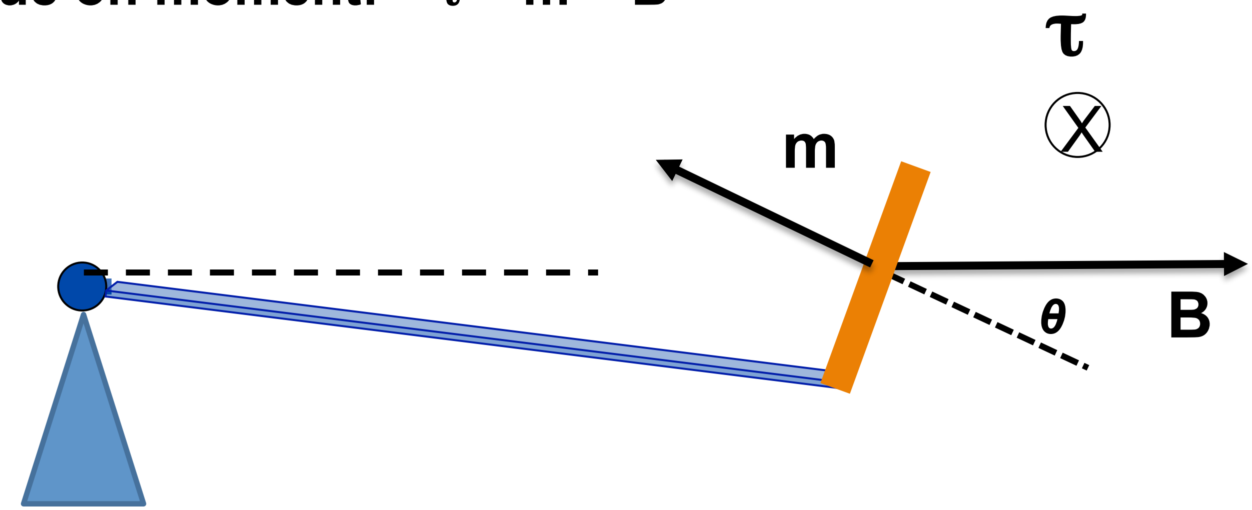
Torque on moment: $\tau = \mathbf{m} \times \mathbf{B}$

Deflection of cantilever: $\tau = k\,\varphi$

$$M_{eff} = \tau / \mu_0 H V \sin(\theta)$$

Torque magnetometry

Torque on moment: $\tau = m \times B$

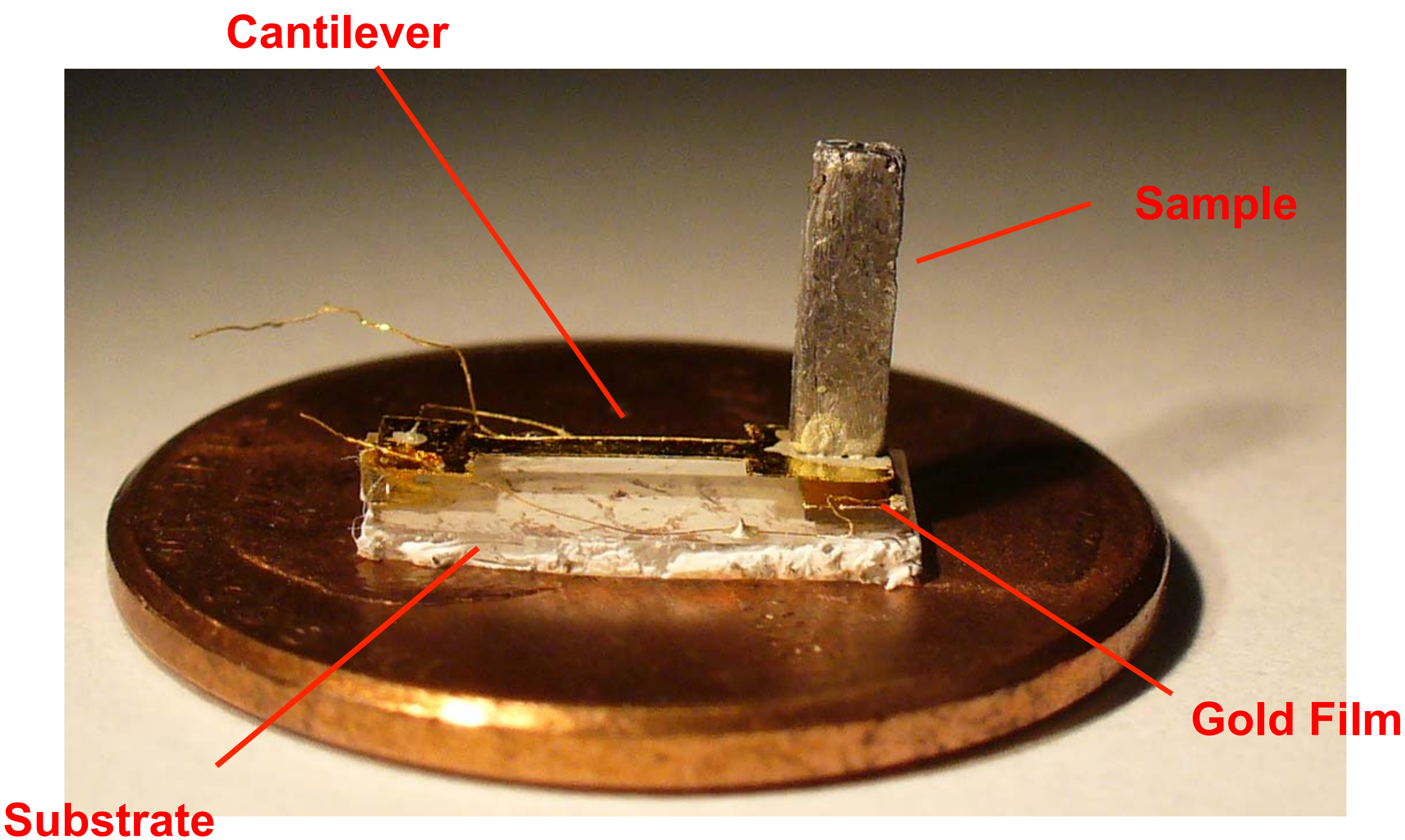


Deflection of cantilever → torque τ

$M_{eff} = \tau / \mu_0 HV\sin(\theta)$

Only sensitive to magnetic anisotropy

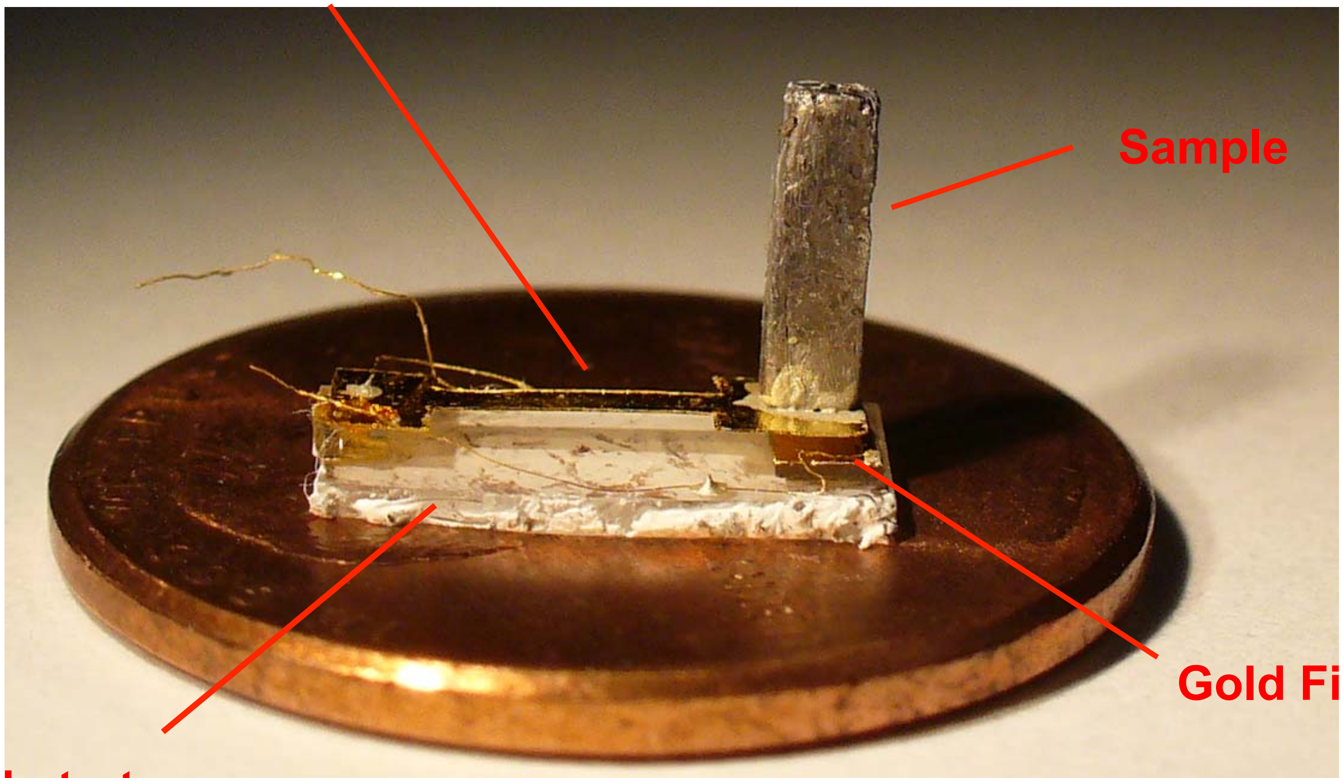
Cantilever setup of bismuth



1. Magnetic moment $\Delta m \sim 10^{-13}$ A.m^2 at 10 T ($10^{10}\ \mu_B$)
(SQUID MPMS, $\Delta m \sim 10^{-9}$ A.m^2)
2. Works up to 45 Tesla, at 20 m K ~ 300 K

Li, Cava, Uher, Hebard, Ong ... Science (2008)

Cantilever setup of bismuth



Magnetic moment $\Delta m \sim 10^{-13}$ A.m^2 at 10 T (10^{10} μ_B)

For a 3 mm X 2 mm X 0.2 mm SmB_6 crystal,

$\Delta m \sim 10^{-4}$ μ_B /u.c.

Susceptibility resolution (at 10 T) $\Delta\chi \sim 10^{-6}$

Laboratory

Dilution Refrigerator

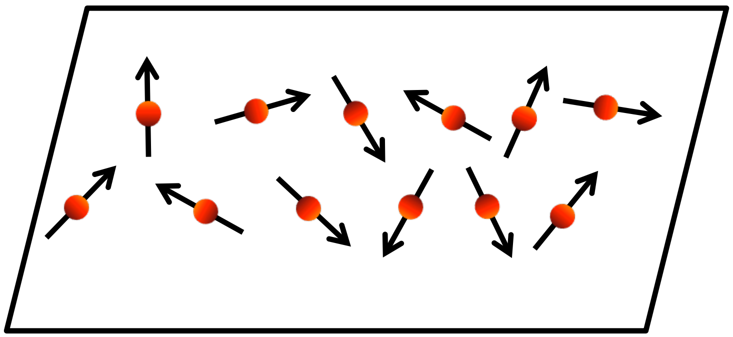
18 mK – 40 K
Magnetic field up to 8 T

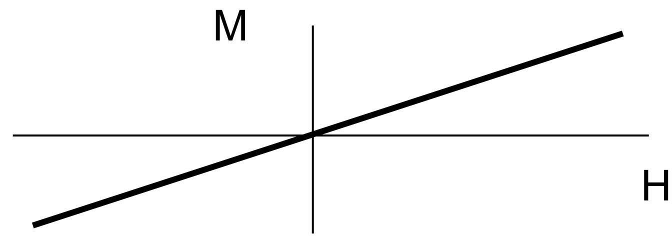
NHMFL Hybrid

Magnetic field up to 45T

Torque curve examples

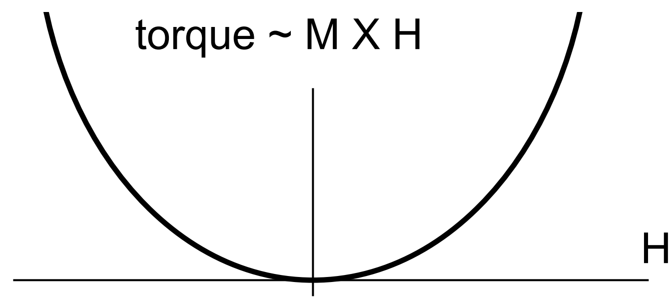
Paramagnet





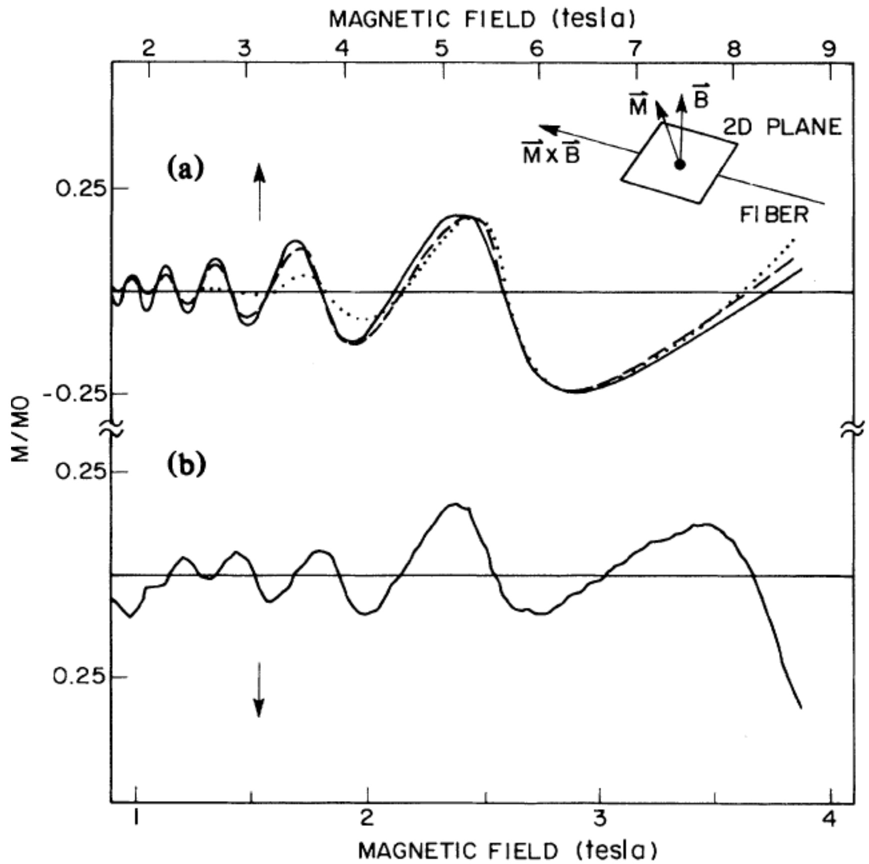
M proportional to H

torque = M X H $\sim H^2$



Torque curve examples

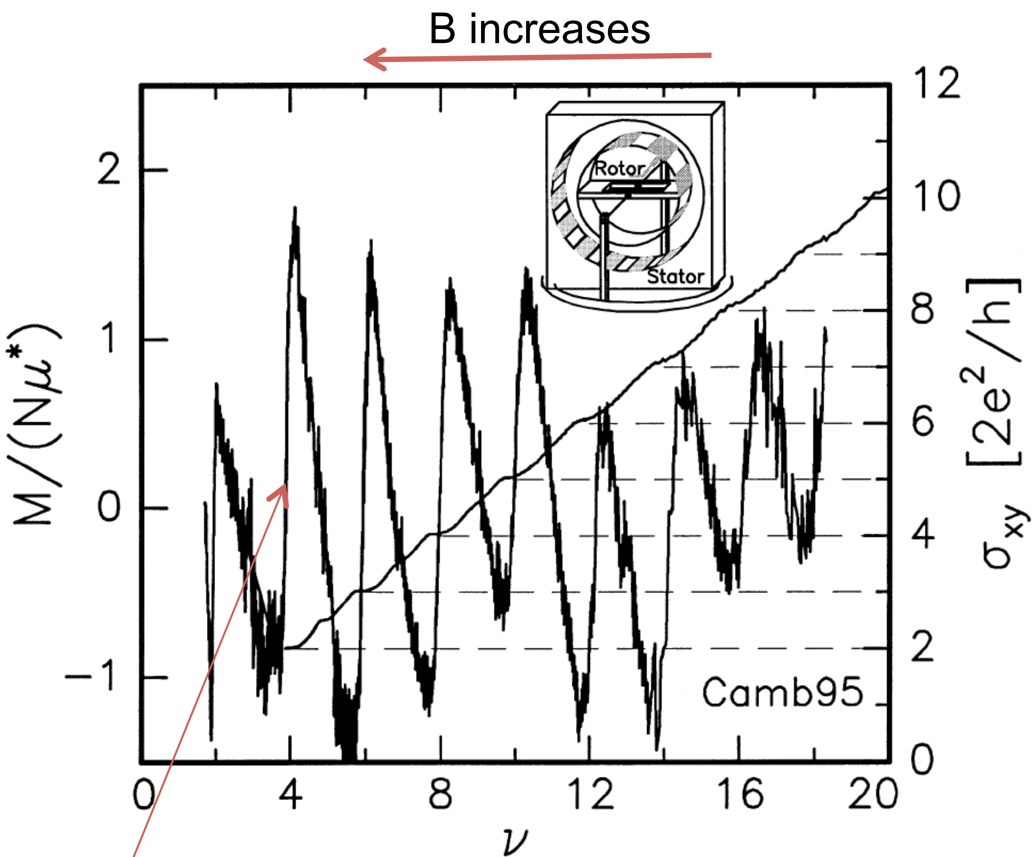
2D electronic system



Eisenstein et al. PRL 1985

Torque curve examples

2D electronic system



At integer ν filling,

M drops sharply,

dM/dH is minimum

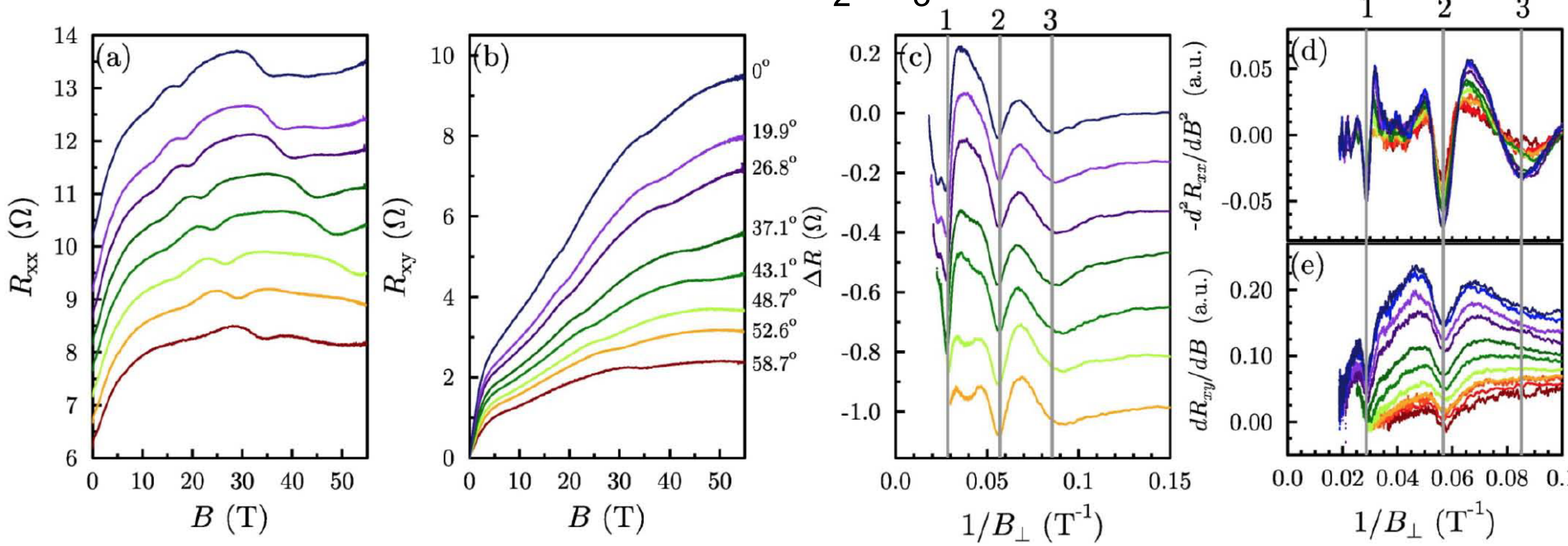
2 μ_B change at each LL

Wiegers et al. PRL 1997

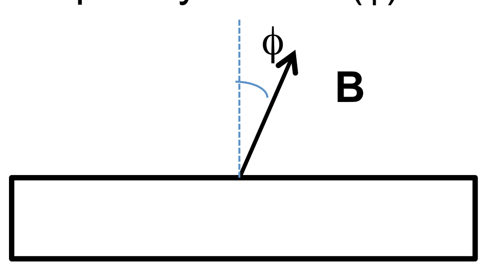
2DEG oscillation F ~ 1/cos(ϕ)

1. Dimensionality

Bi_2Se_3



Scale as $1/B_{perp}$, frequency ~ 1/cos(ϕ)



Analytis et al. Nature Physics 2010

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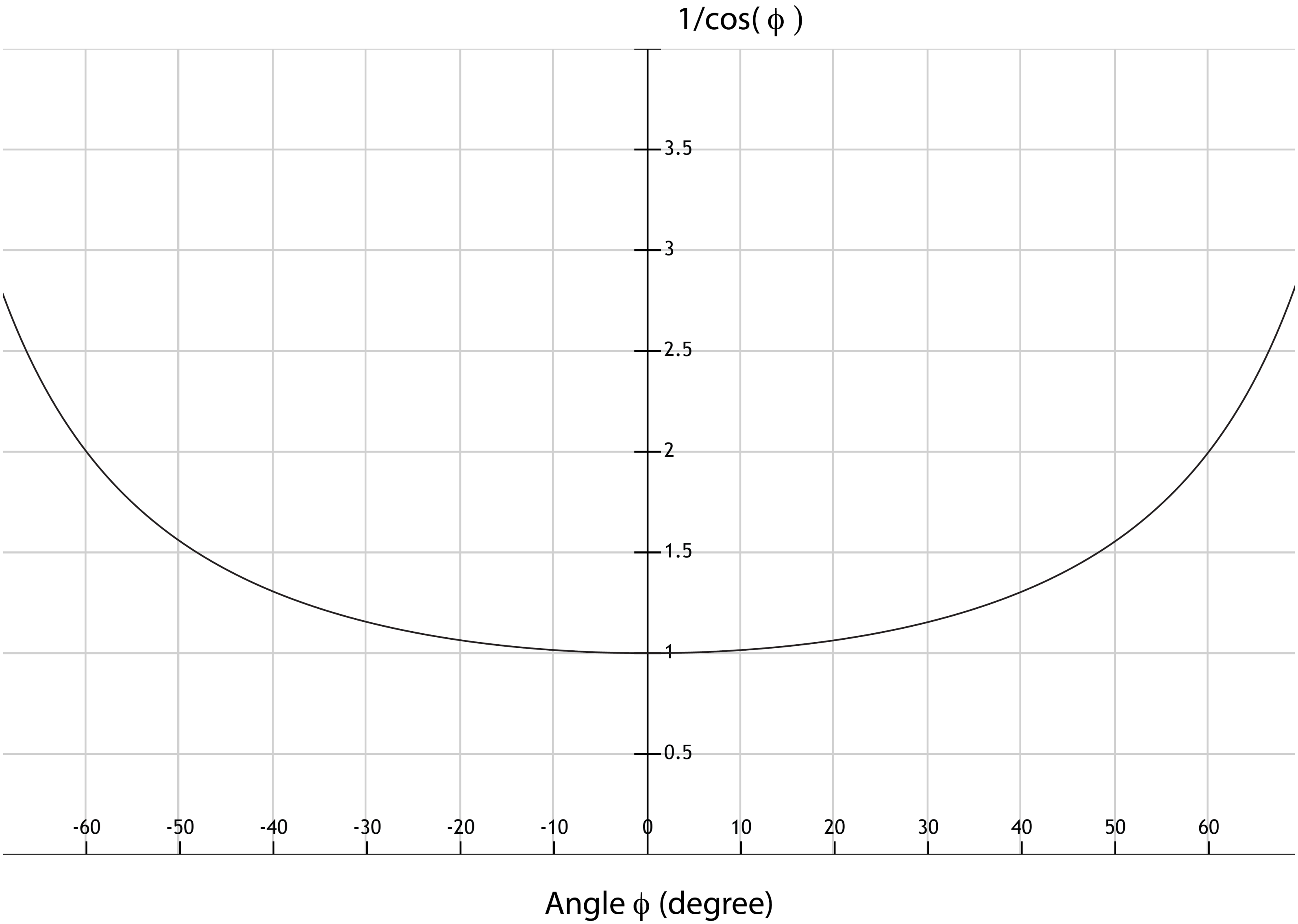
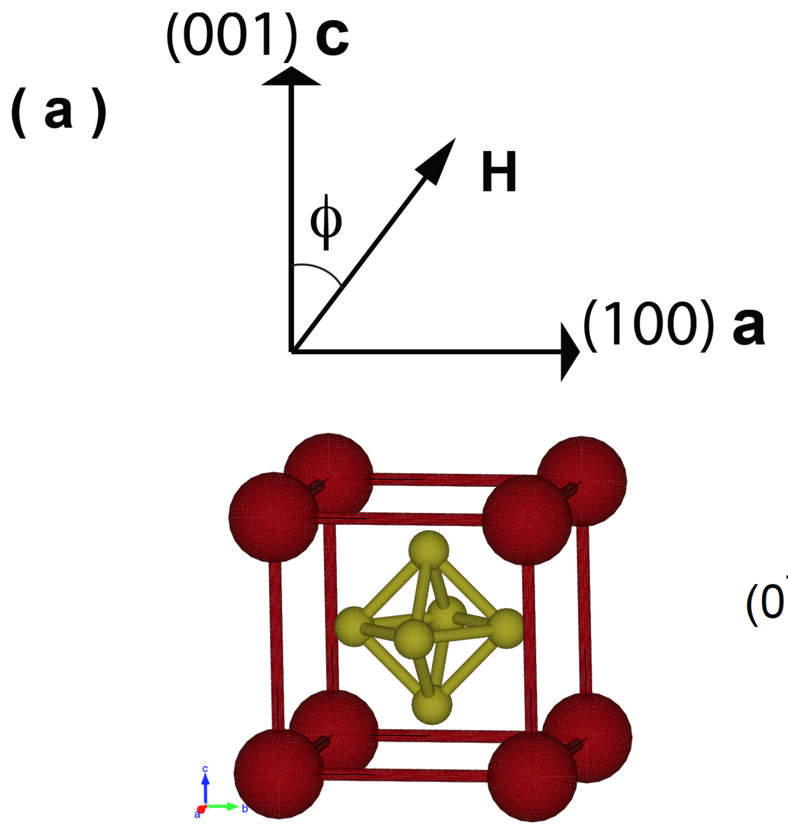
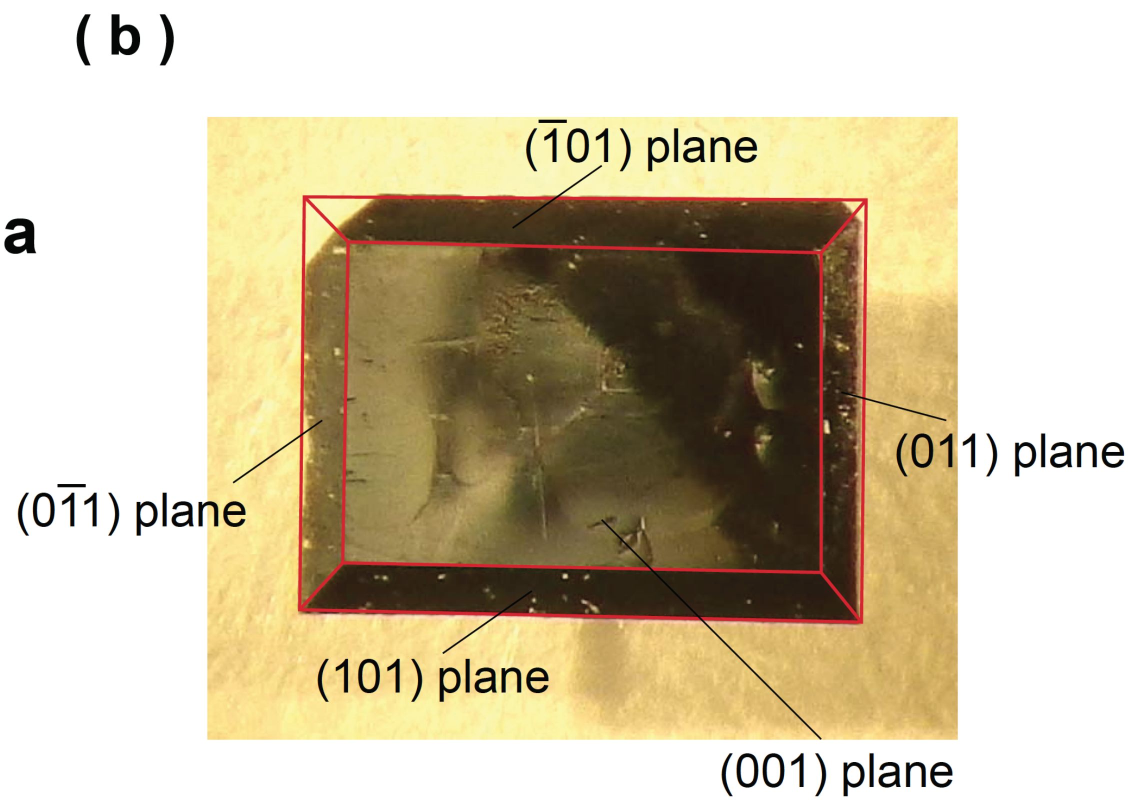


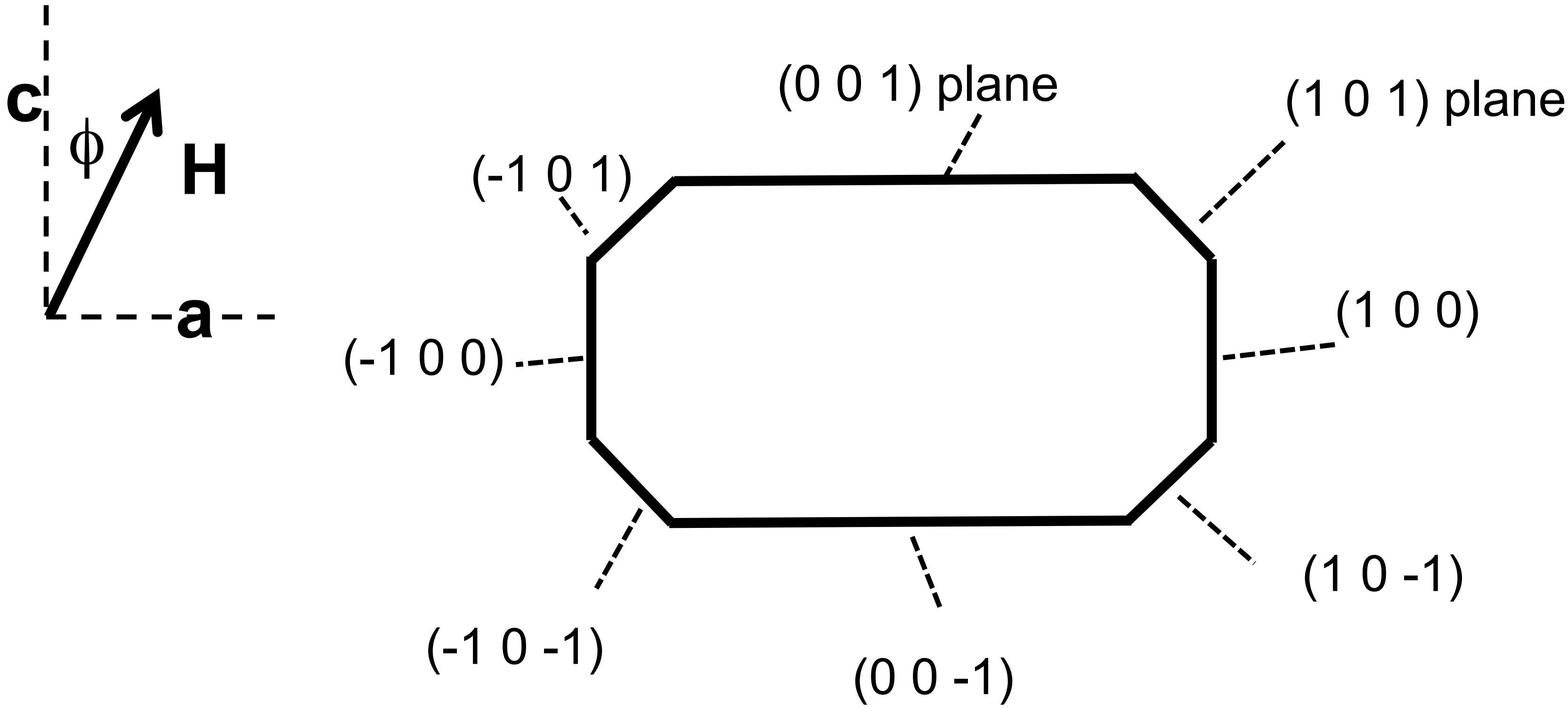
SmB_6 samples



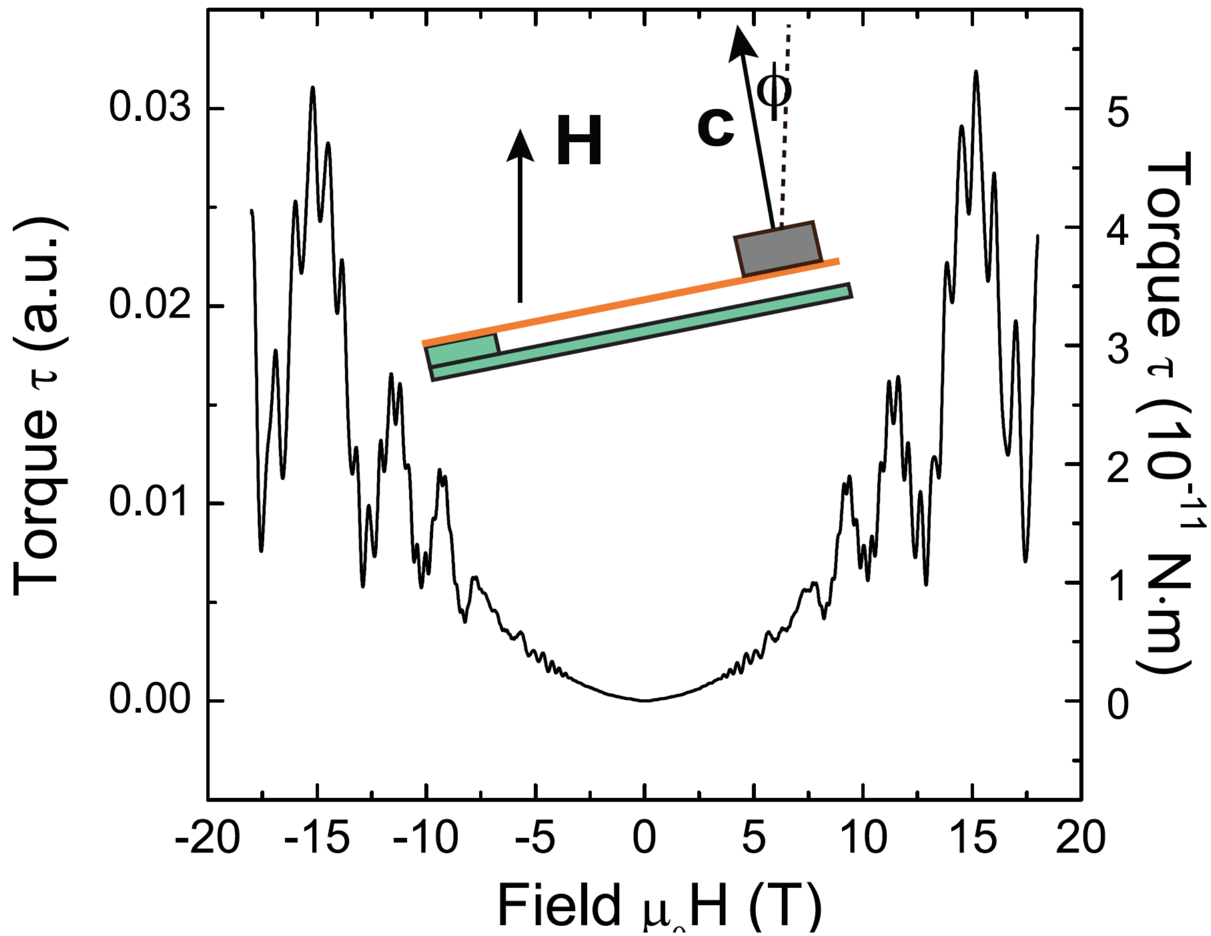


G. Li, *et al. Science 2014*

Sketch Sample sideview

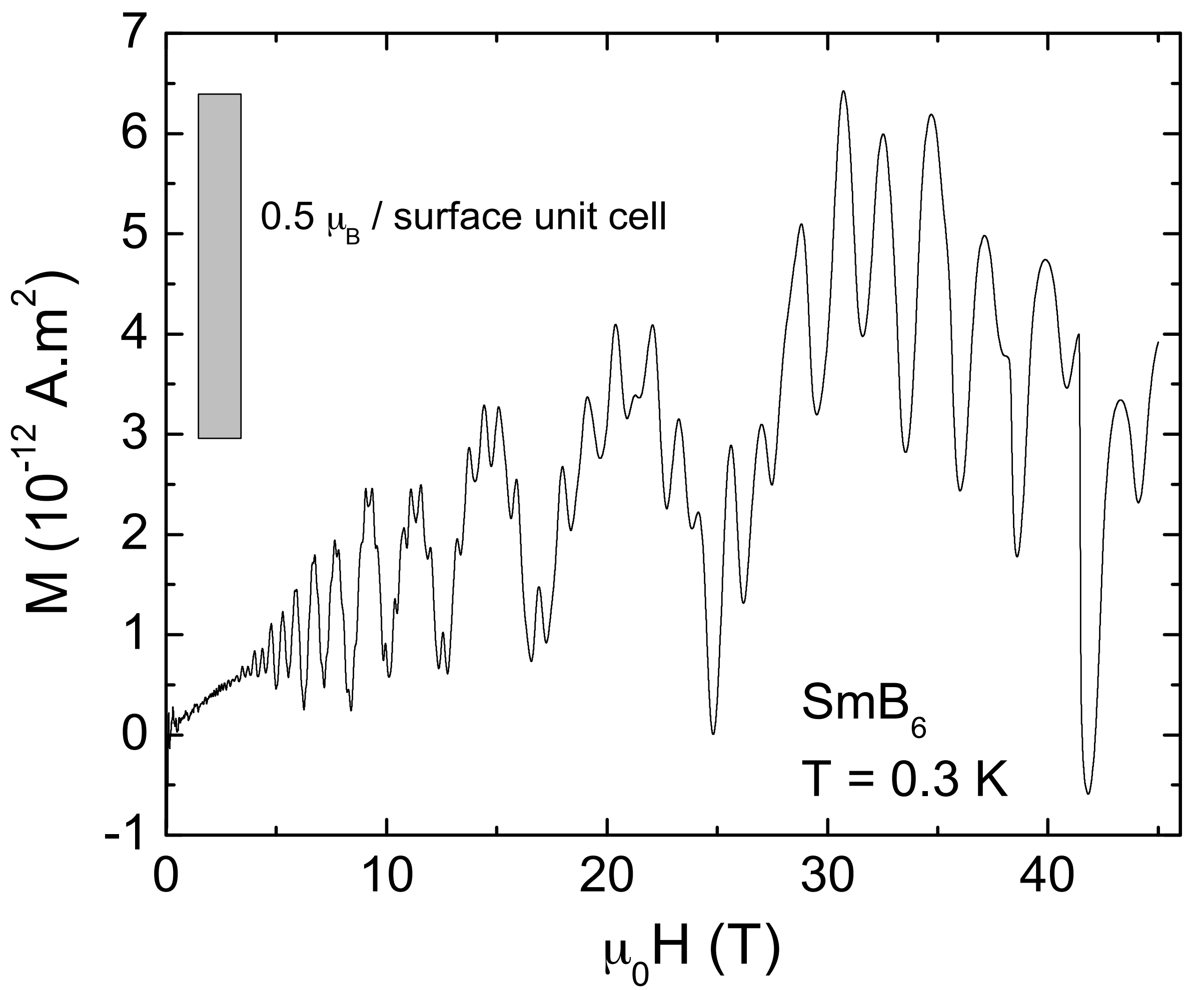


Quantum oscillations in magnetic torque



G. Li, *et al. Science 2014*

Magnetization resolved for surfaces



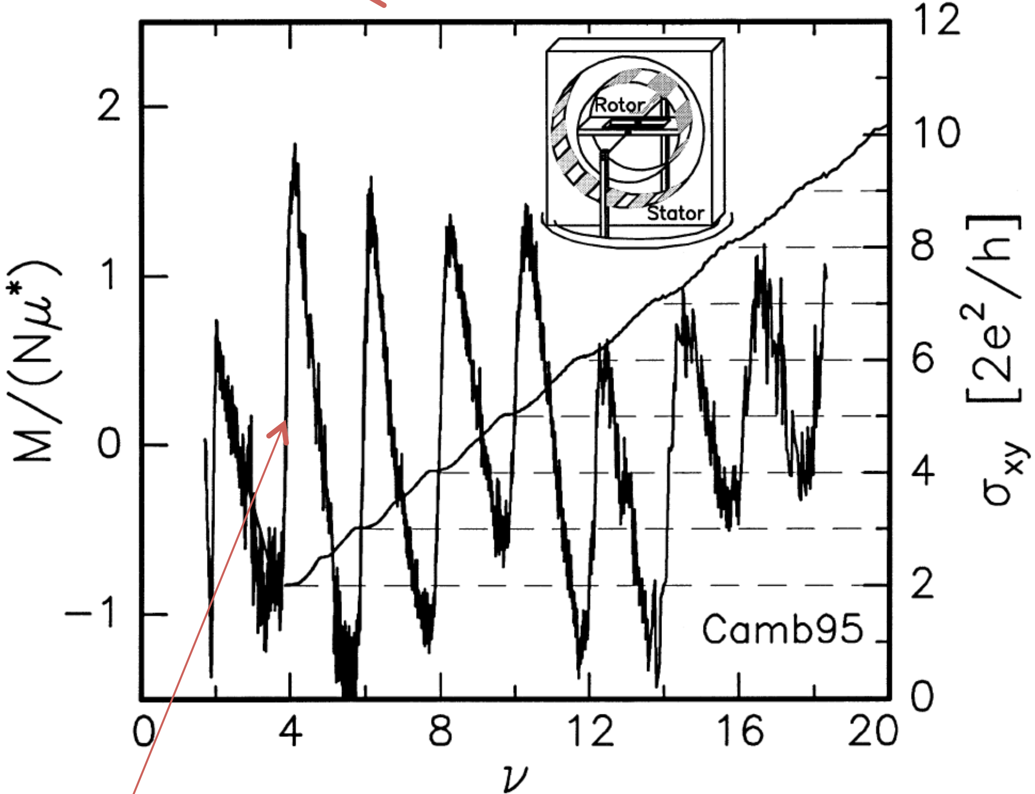
For a 3 mm X 2 mm X 0.2 mm SmB_6 crystal,
resolution $\Delta m \sim 10^{-4}\ \mu_B$ /u.c.

G. Li, *et al. Science 2014*

Torque curve examples

2D electronic system

B increases



At integer ν filling,

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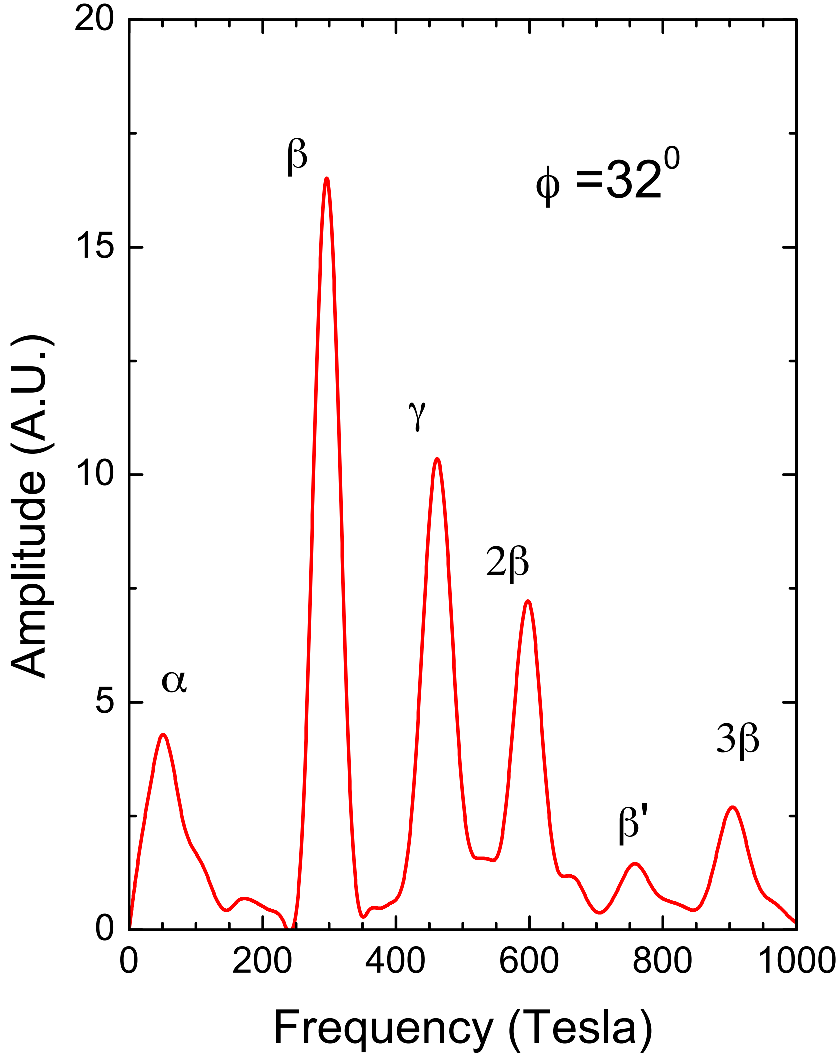
2 μ_B change at each LL

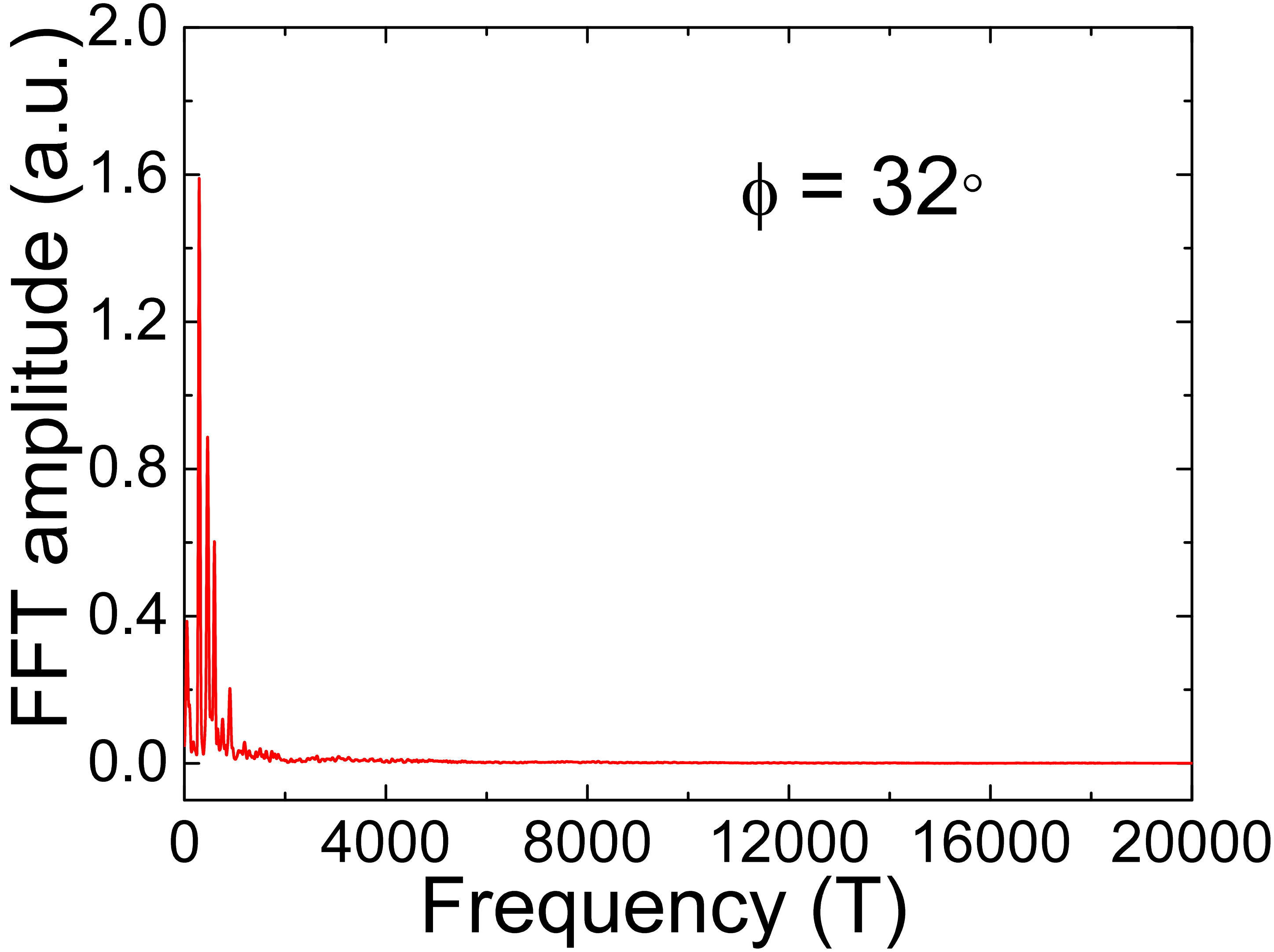
Wiegers et al. PRL 1997

Fourier Transform shows oscillation frequencies



G. Li, *et al. Science 2014*

No oscillation frequencies observed above 2 kT



G. Li, *et al. Science 2014*

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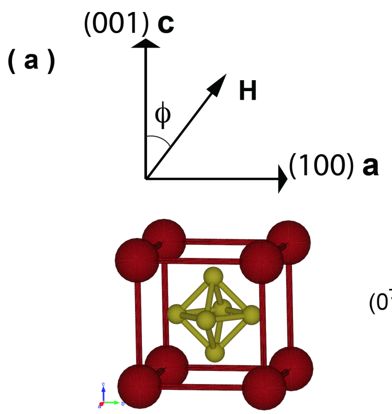

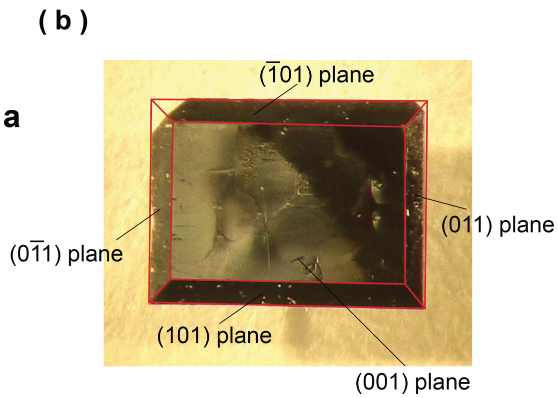

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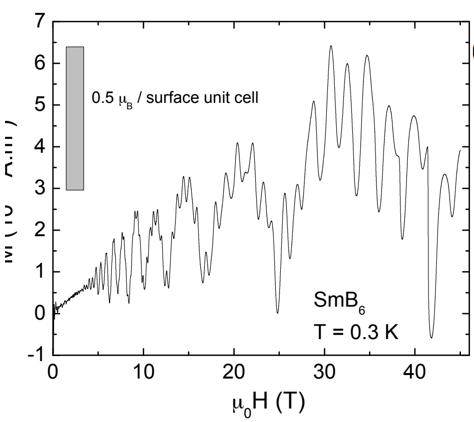
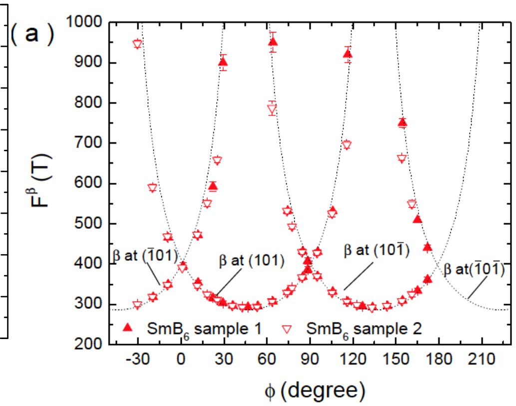
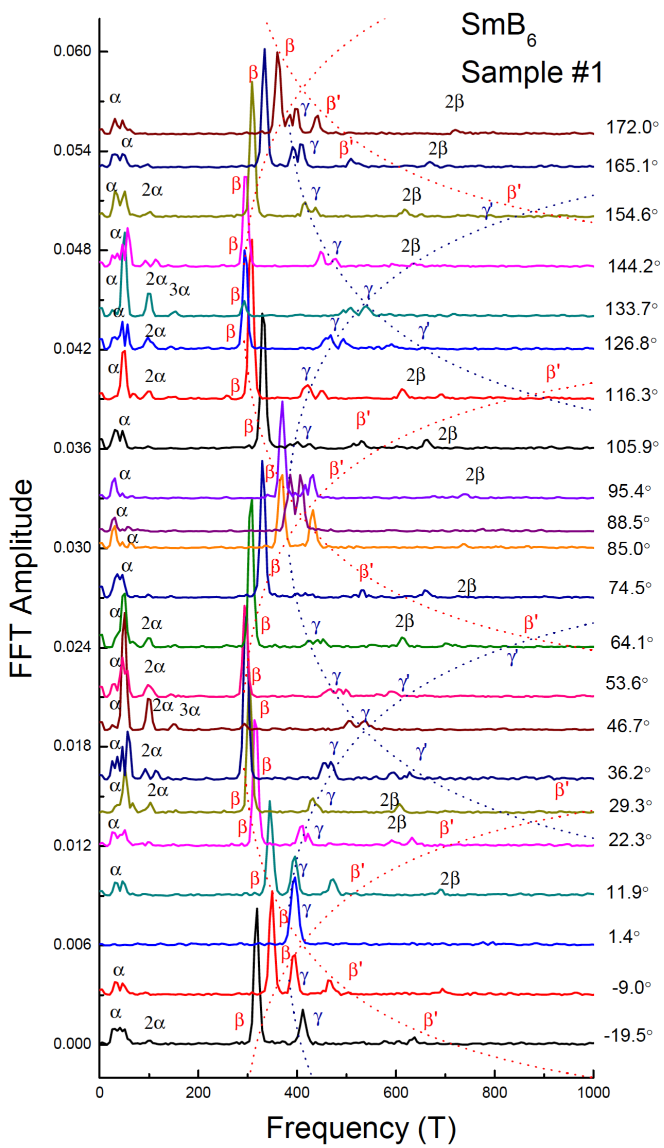
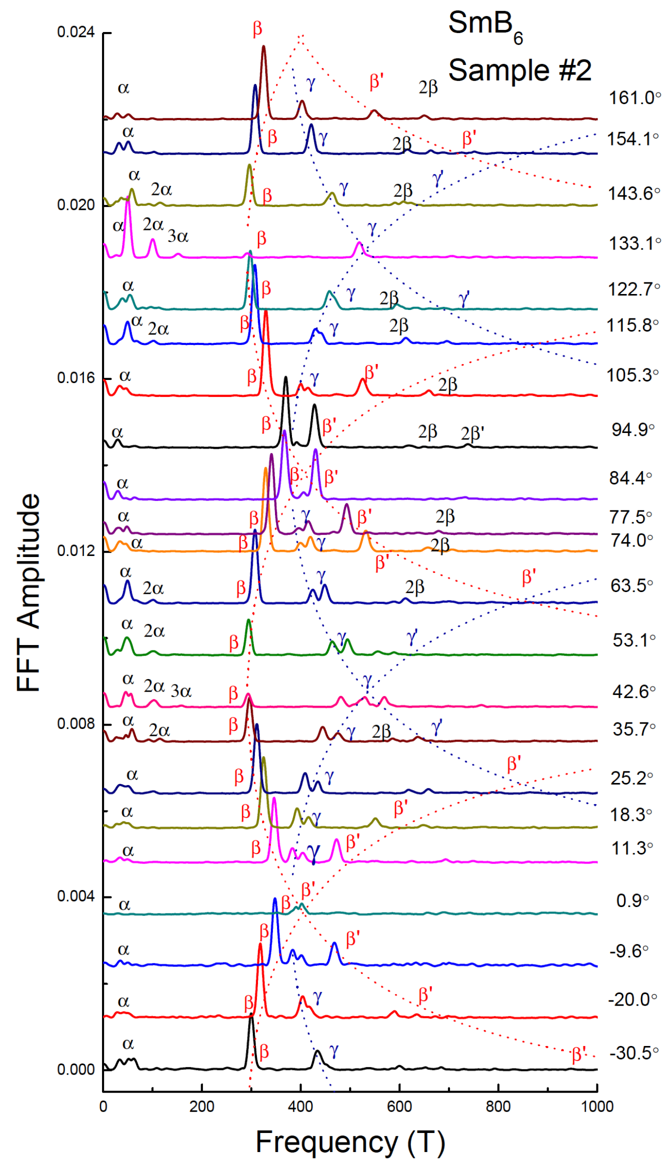




Track the angular dependence of the frequency

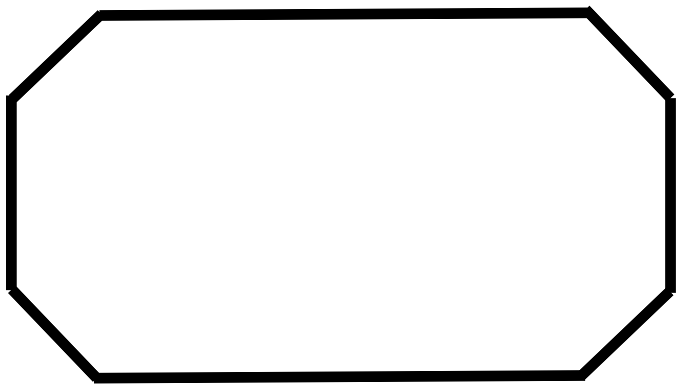


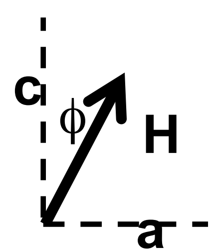


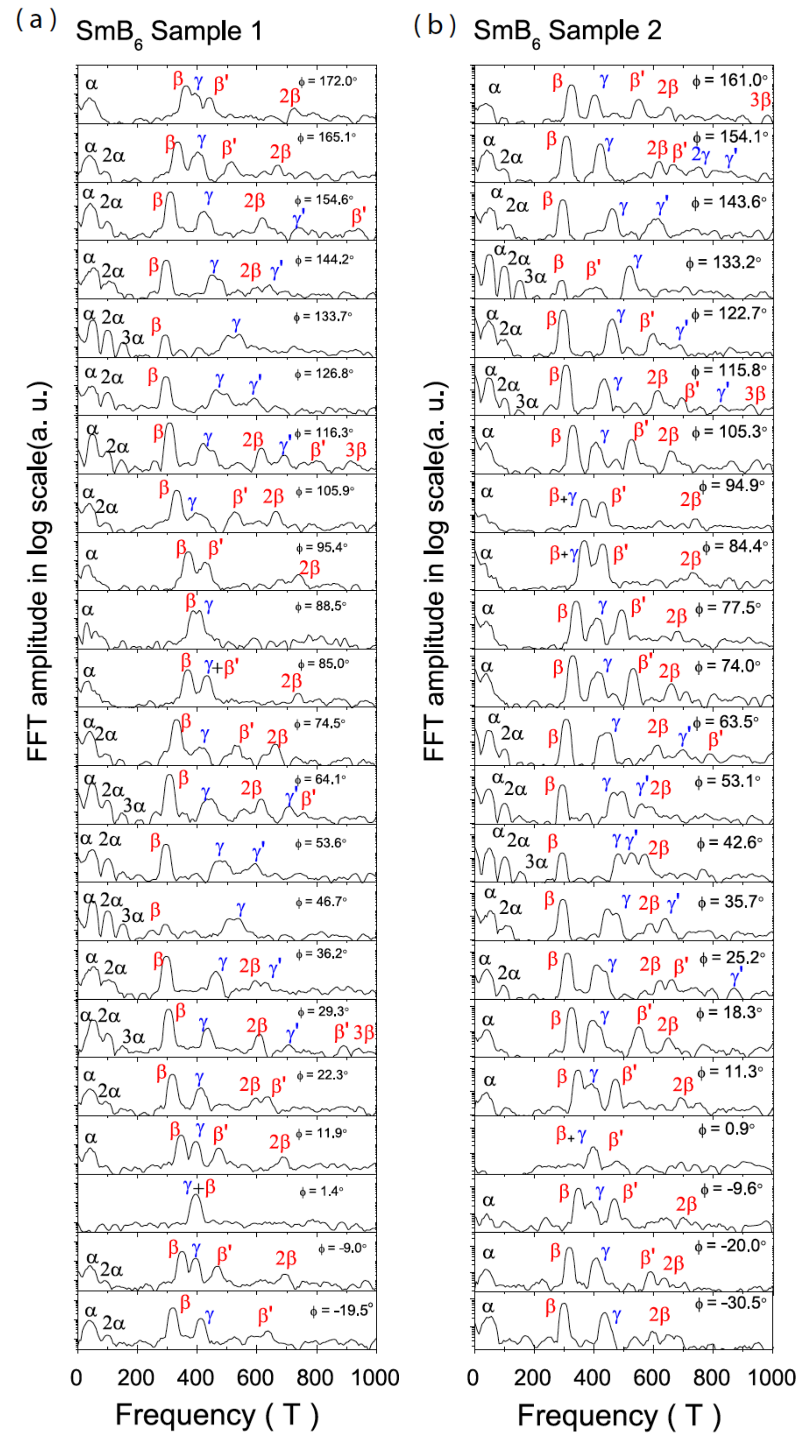
~ 10 degree between each trace

G. Li, *et al. Science 2014*

FFT in logarithmic scale helps track F vs. angle







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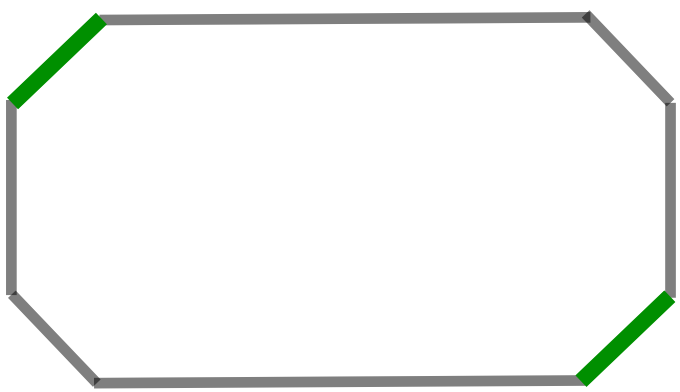
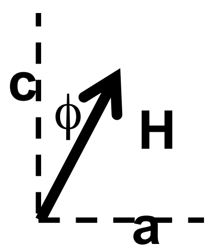
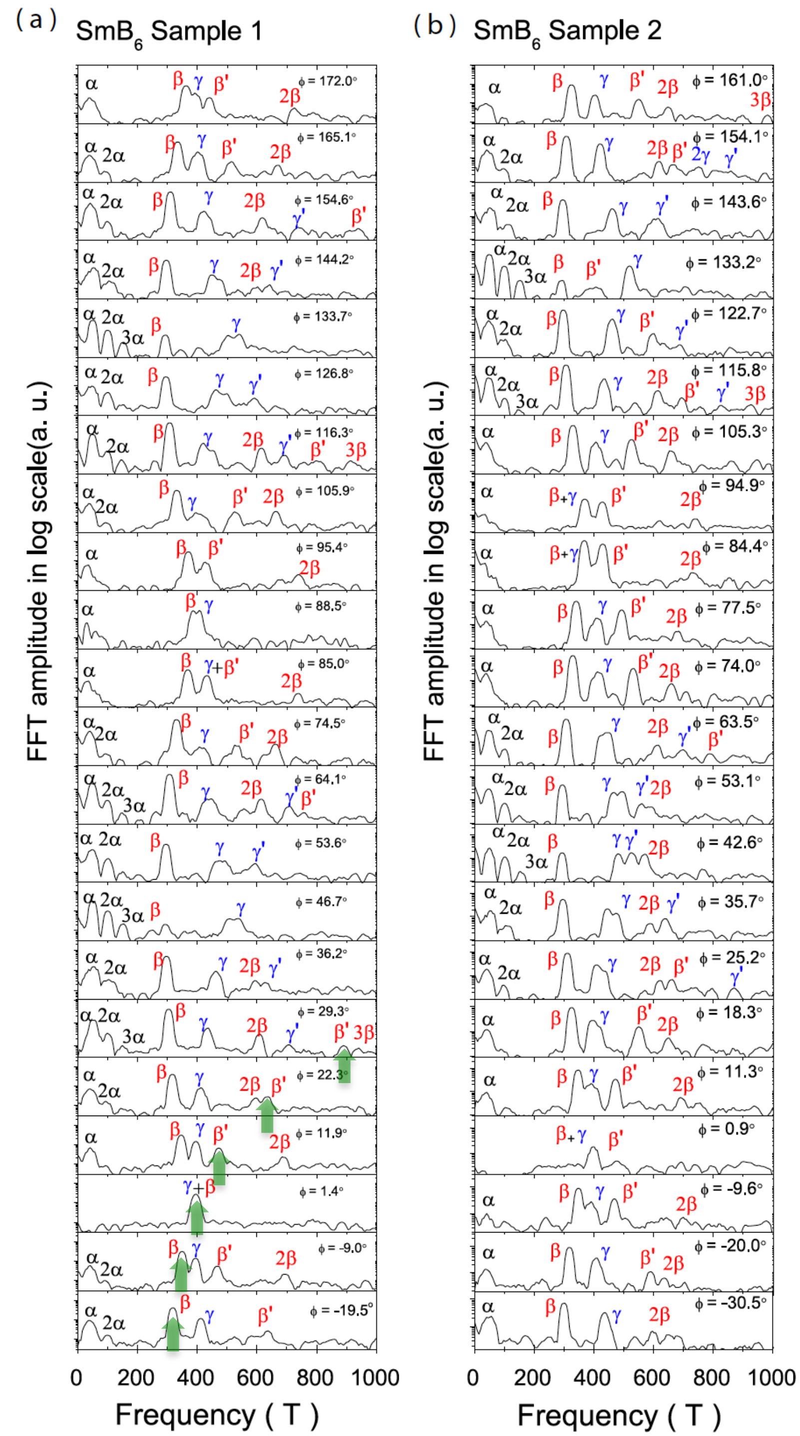
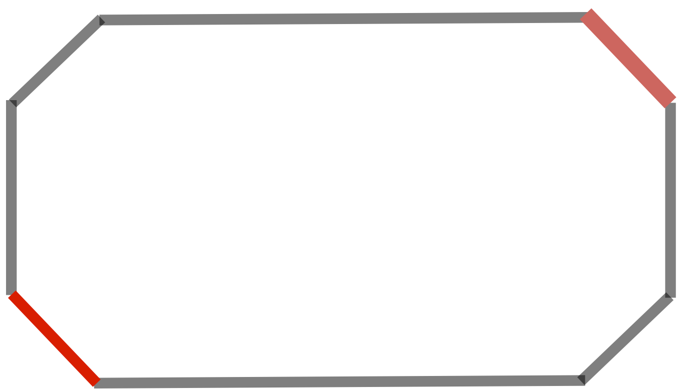
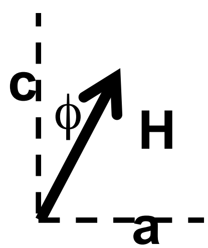


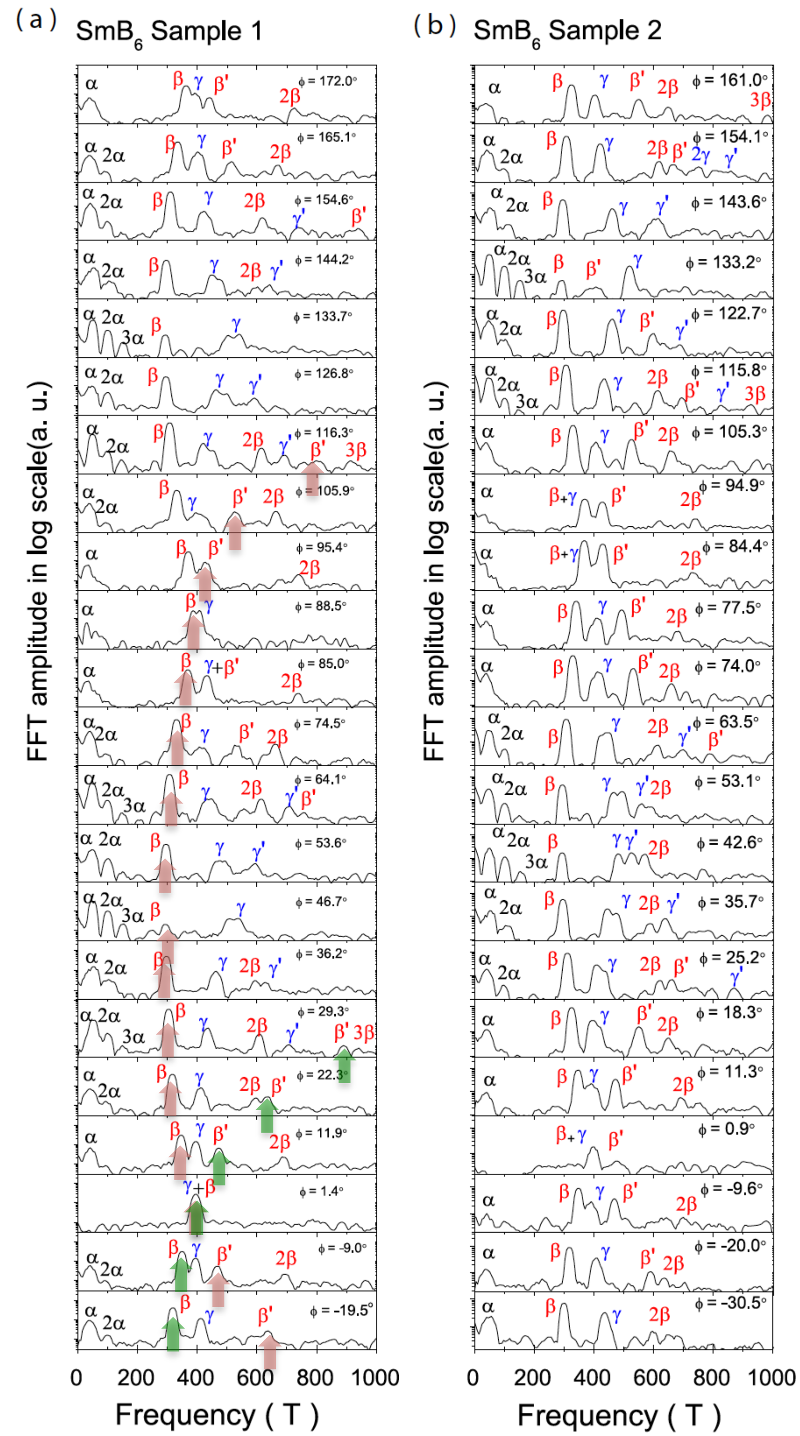




FFT in logarithmic scale helps track F vs. angle







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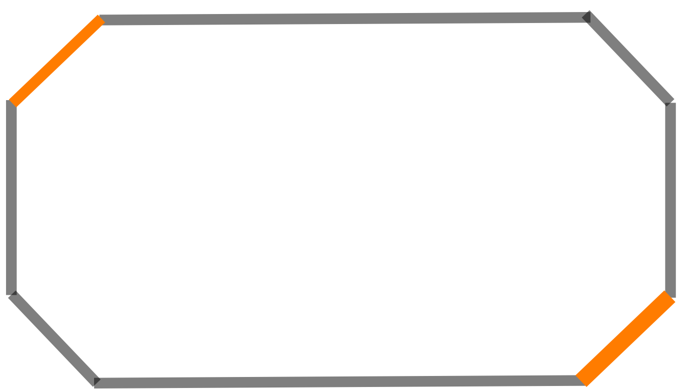

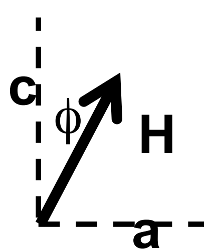

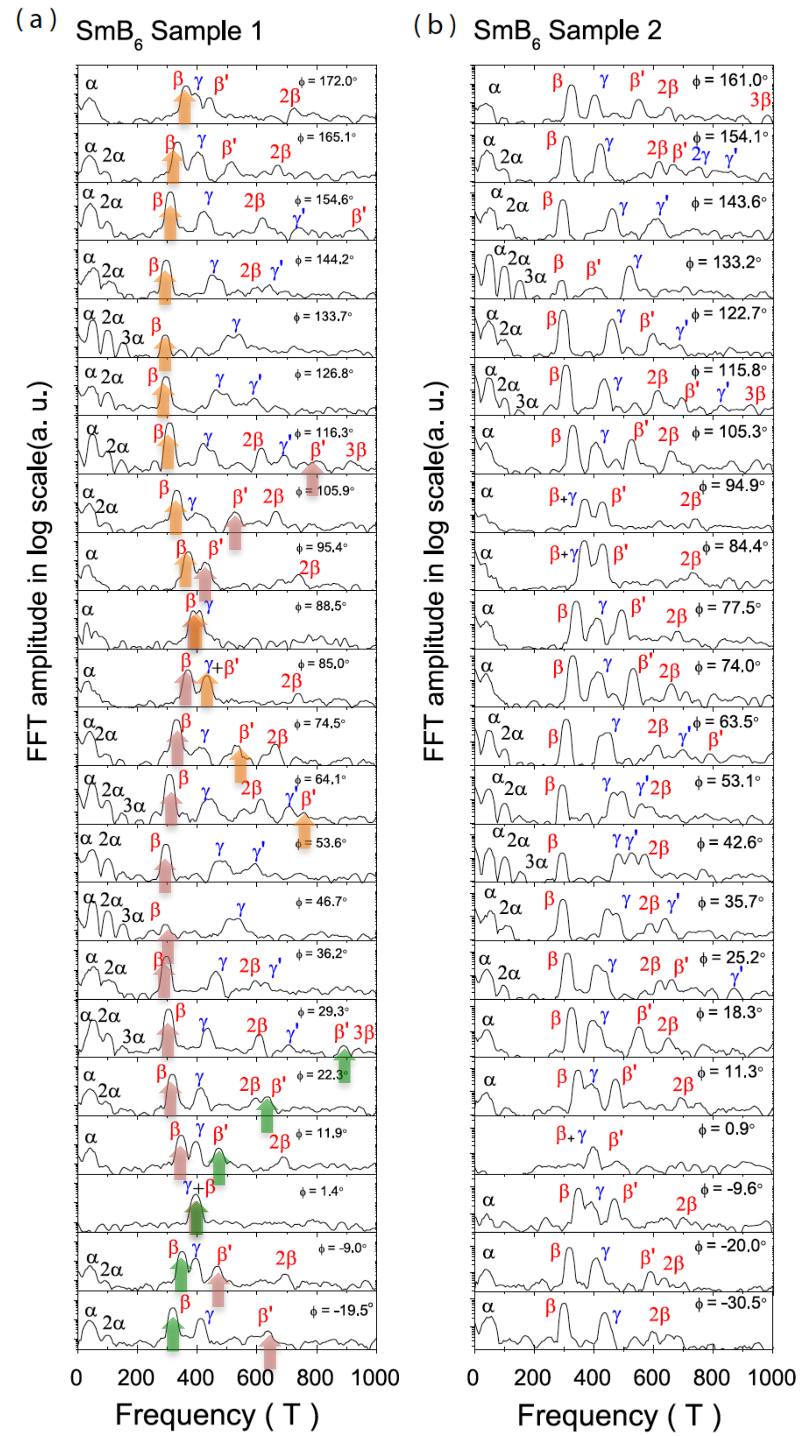

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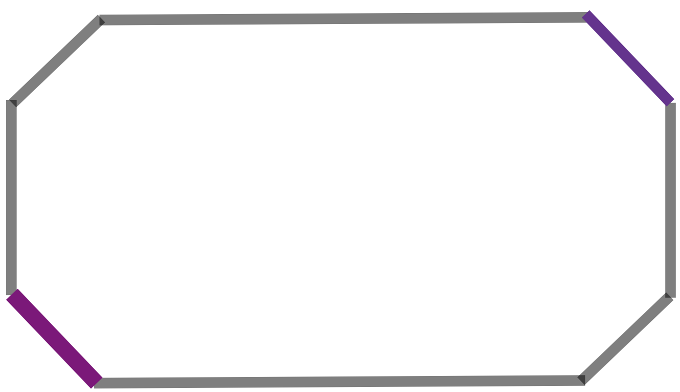

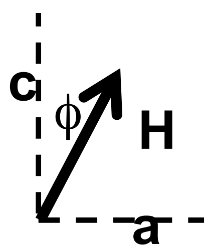

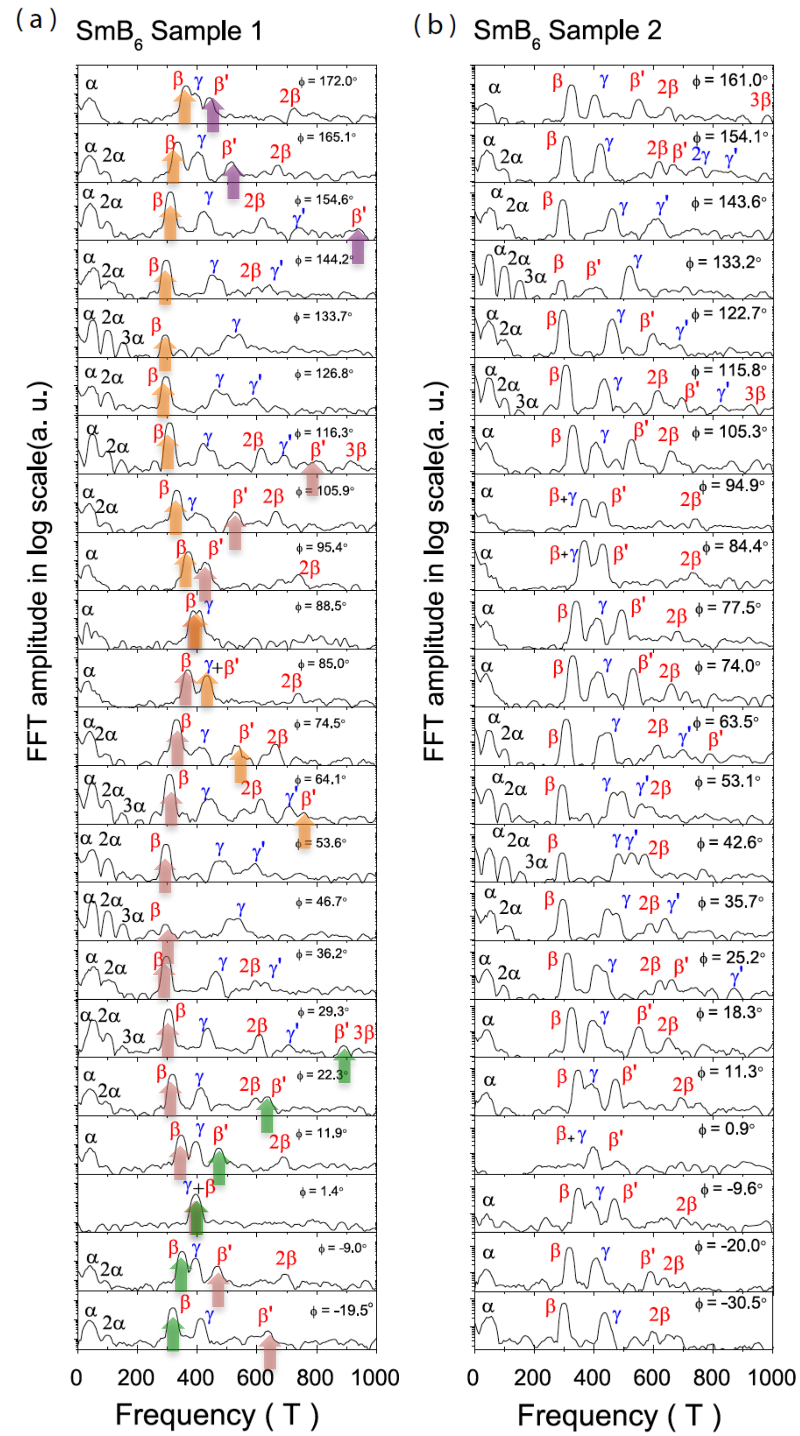

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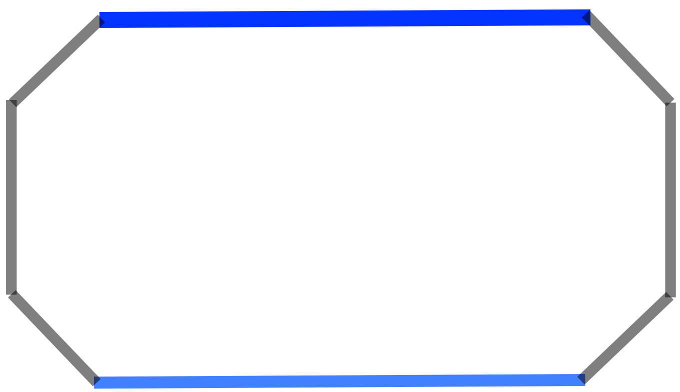
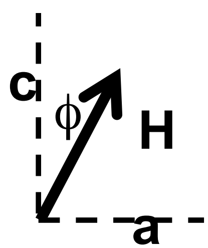
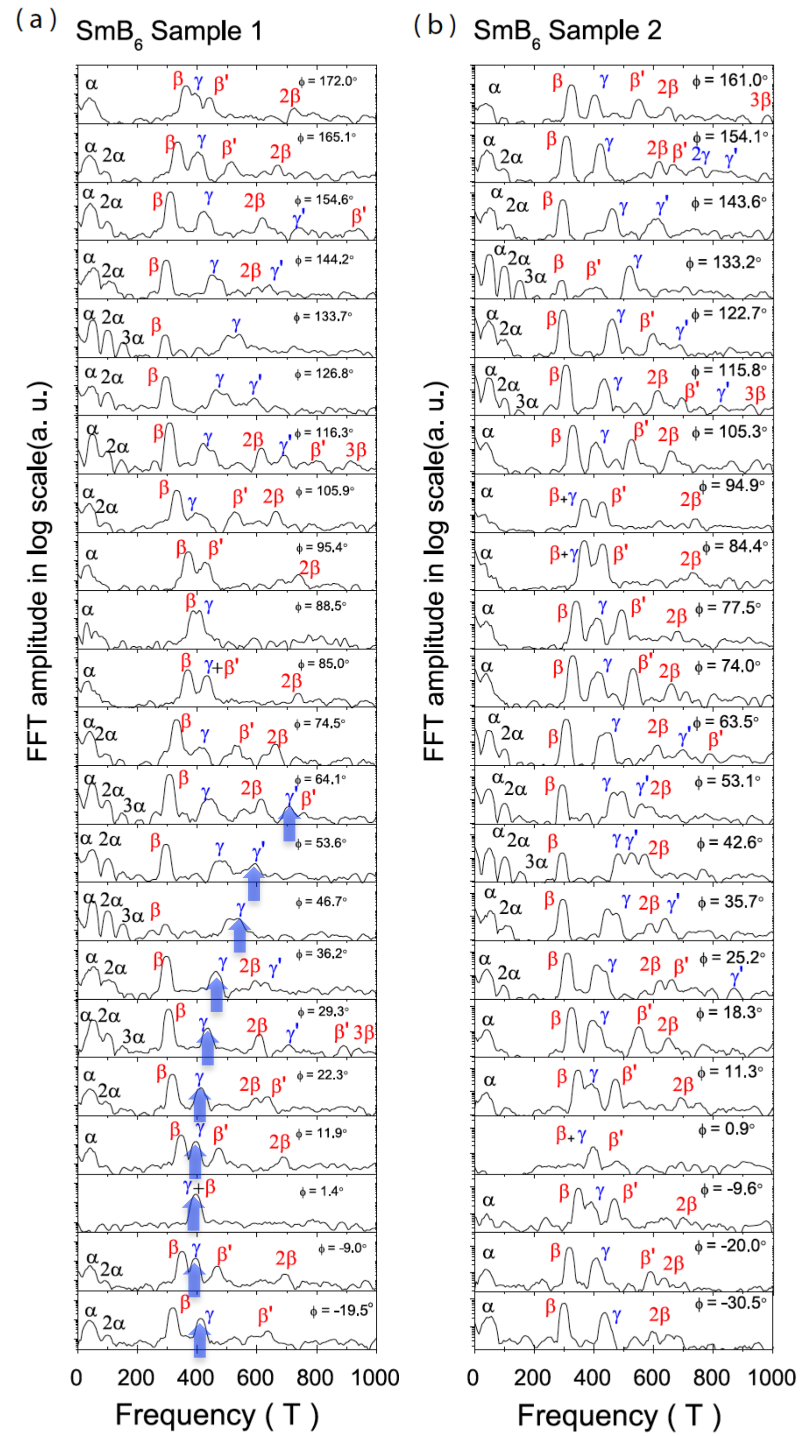
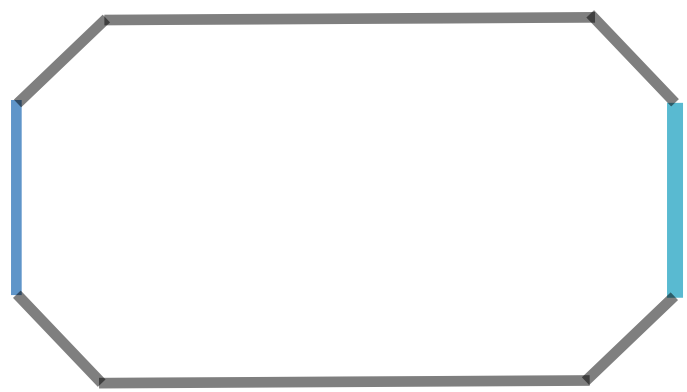
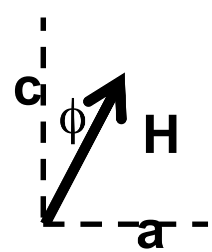


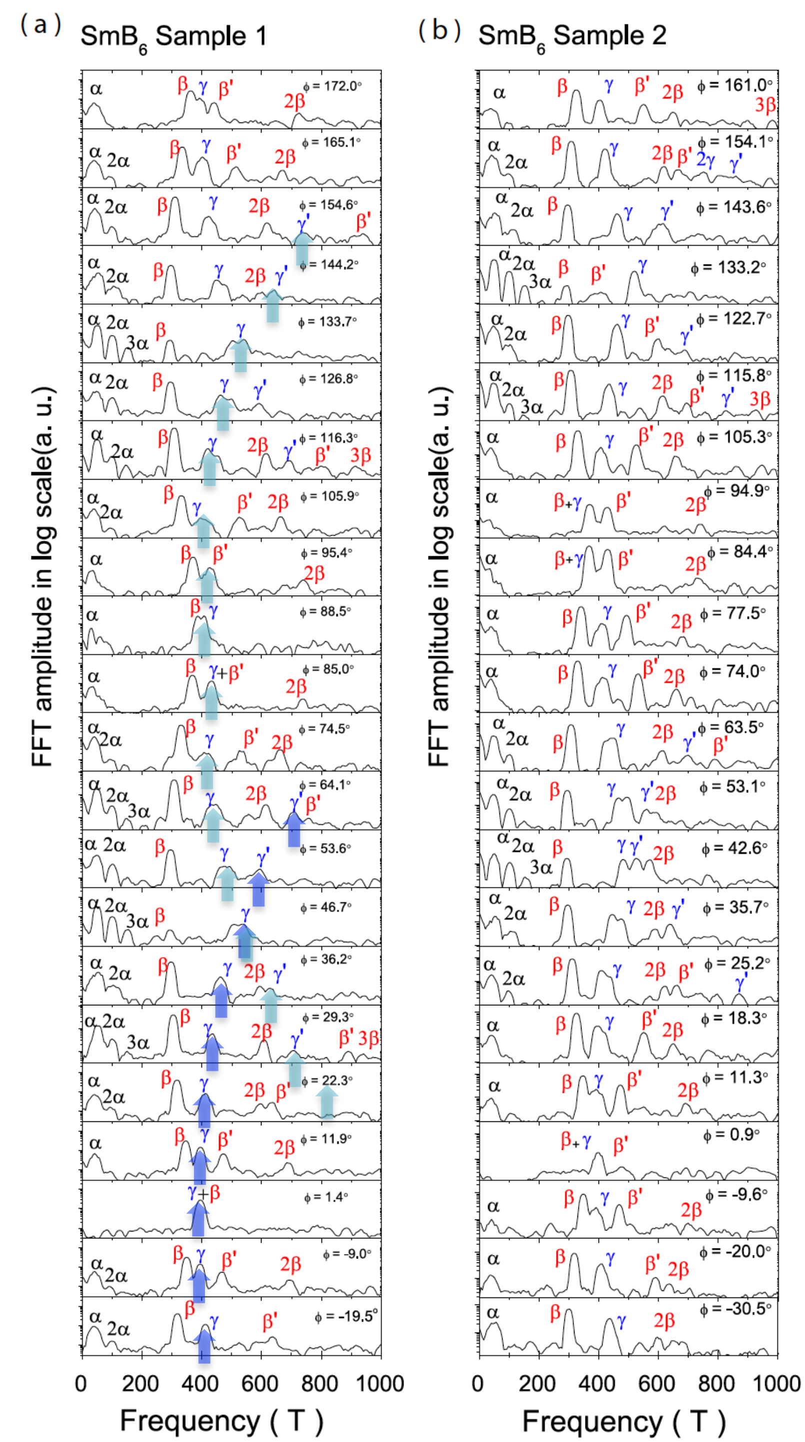




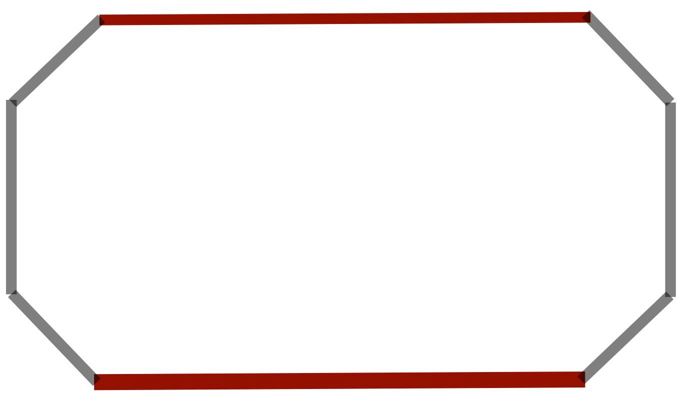
FFT in logarithmic scale helps track F vs. angle

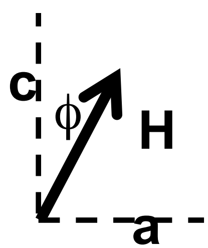


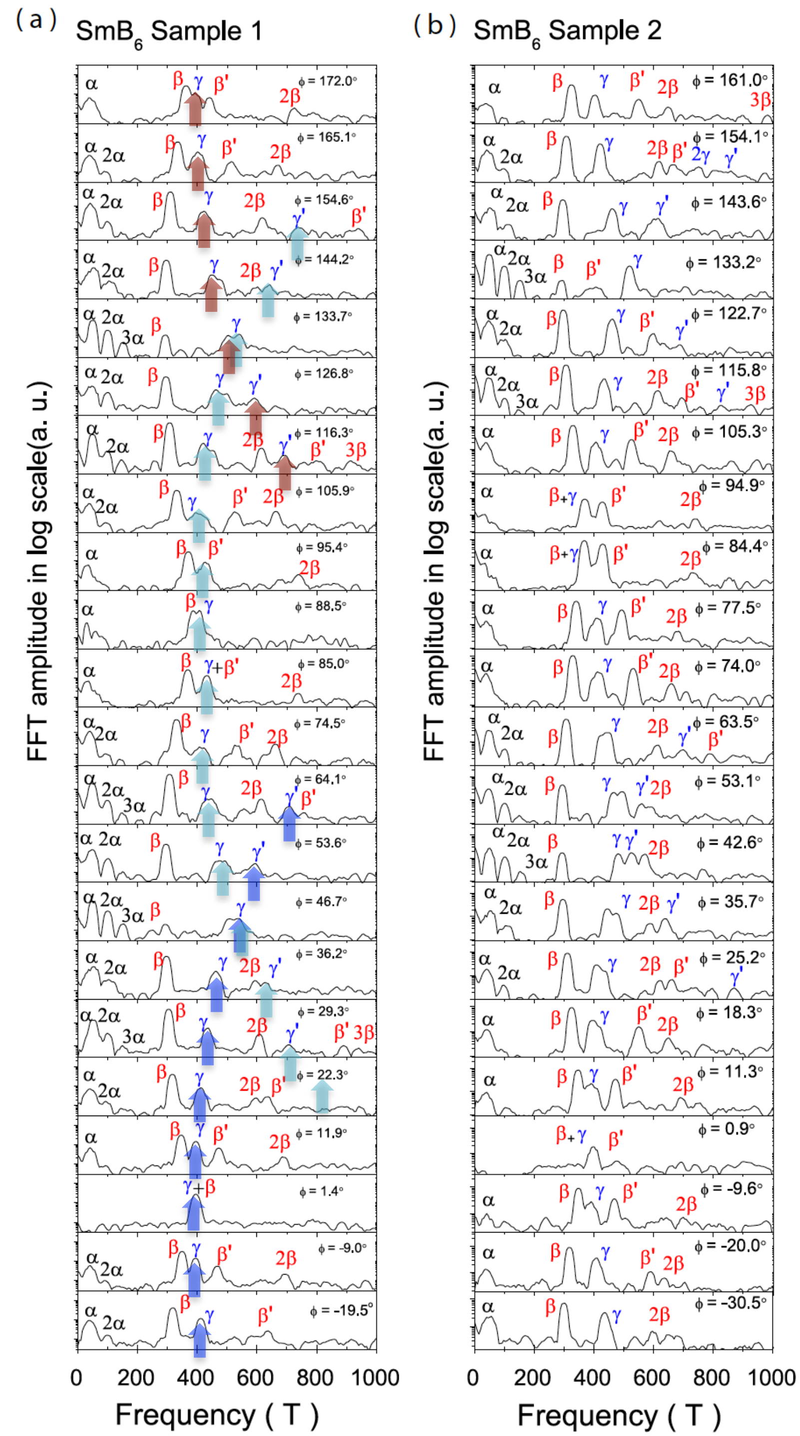




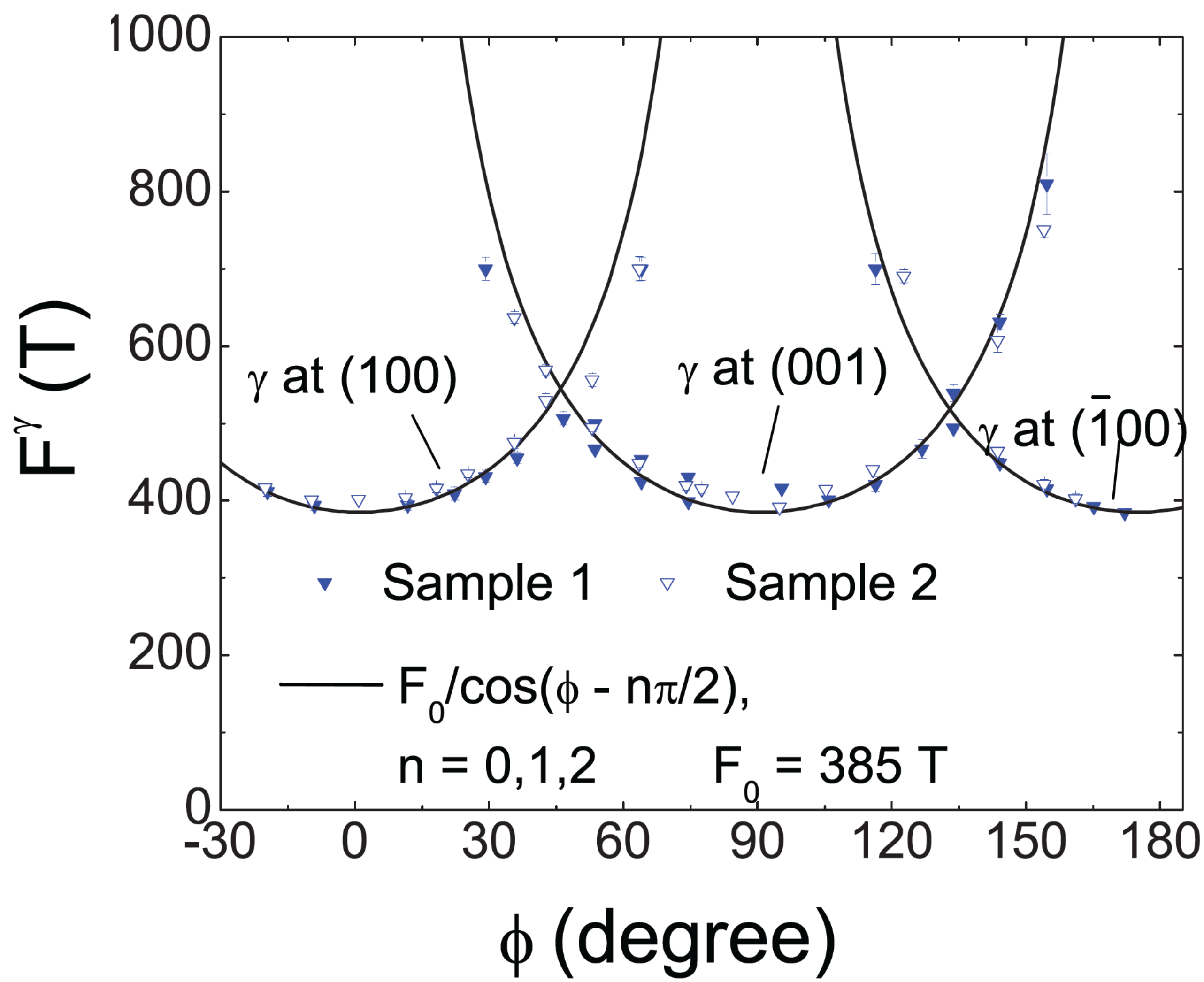
FFT in logarithmic scale helps track F vs. angle





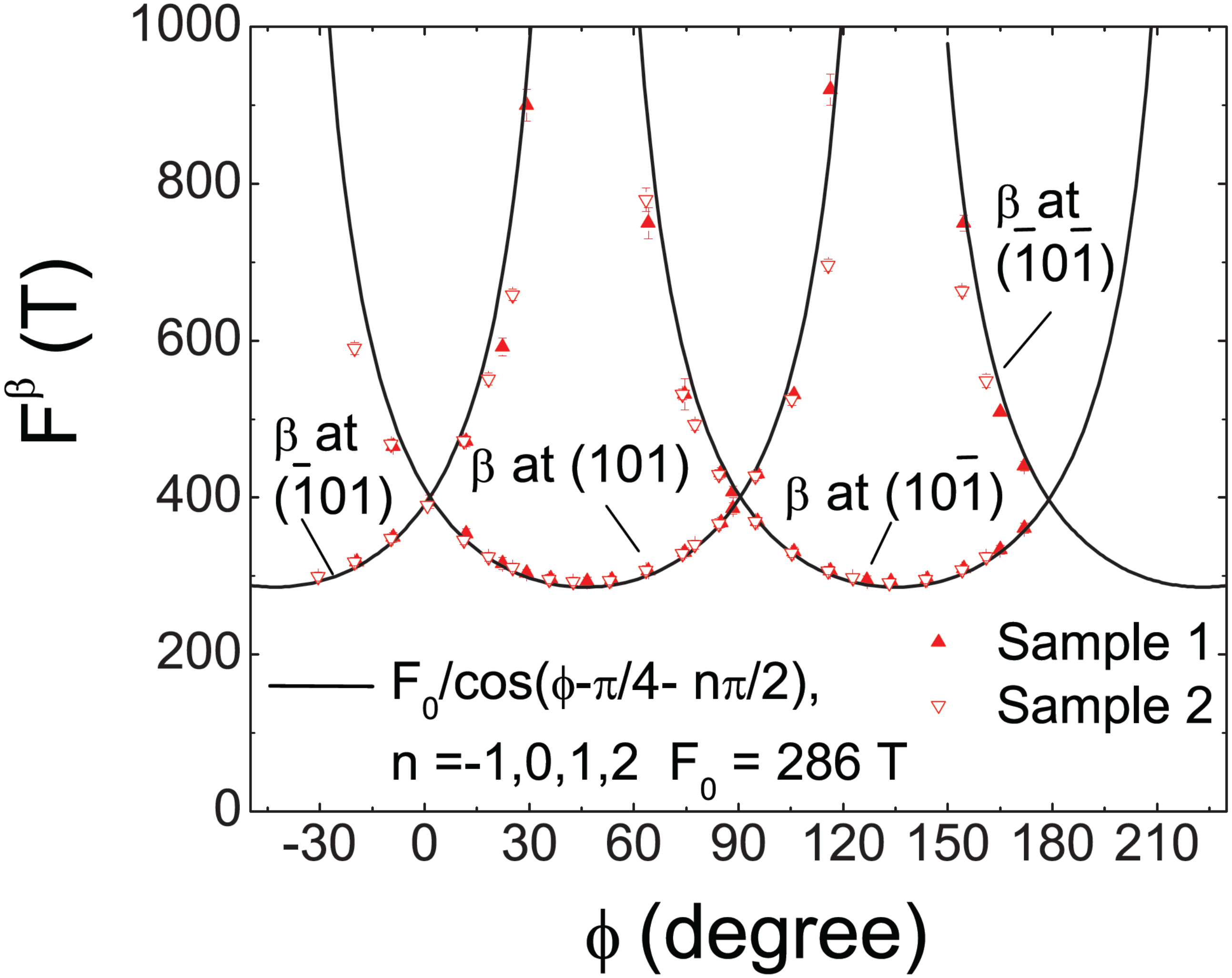


Two-dimensional γ pocket on (100) plane



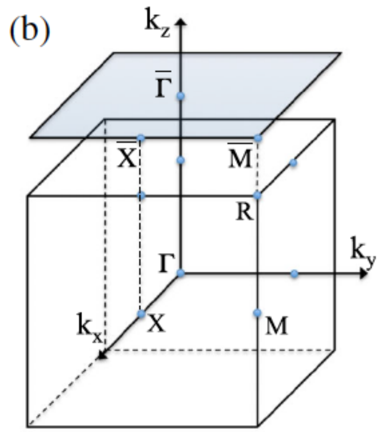
G. Li, *et al. Science 2014*

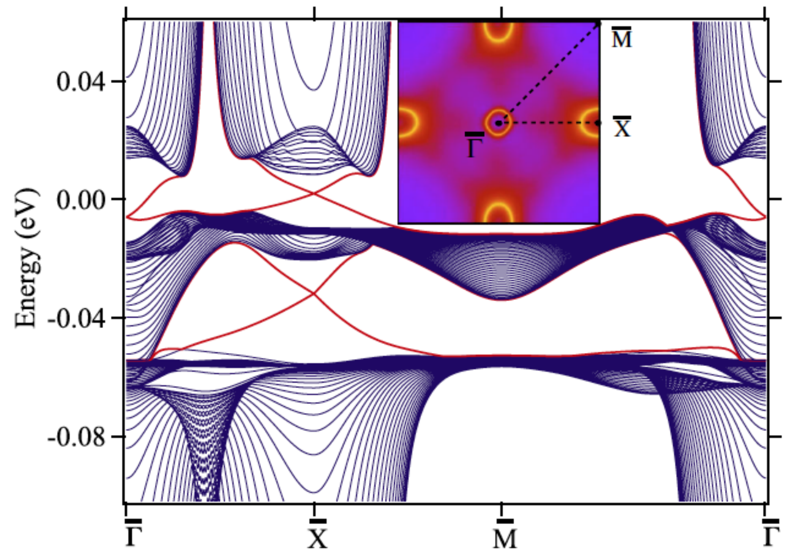
Two-dimensional β pocket on (101)



G. Li, *et al. Science 2014*

Advanced Calculation shows possible surface state on the 100 cleavage plane

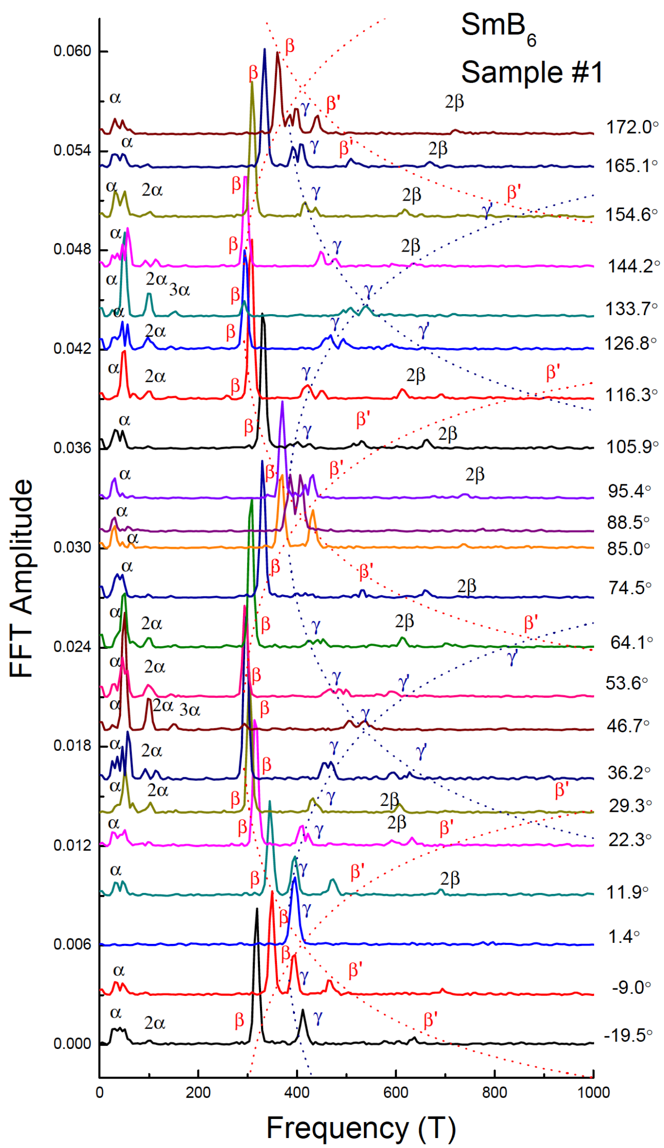


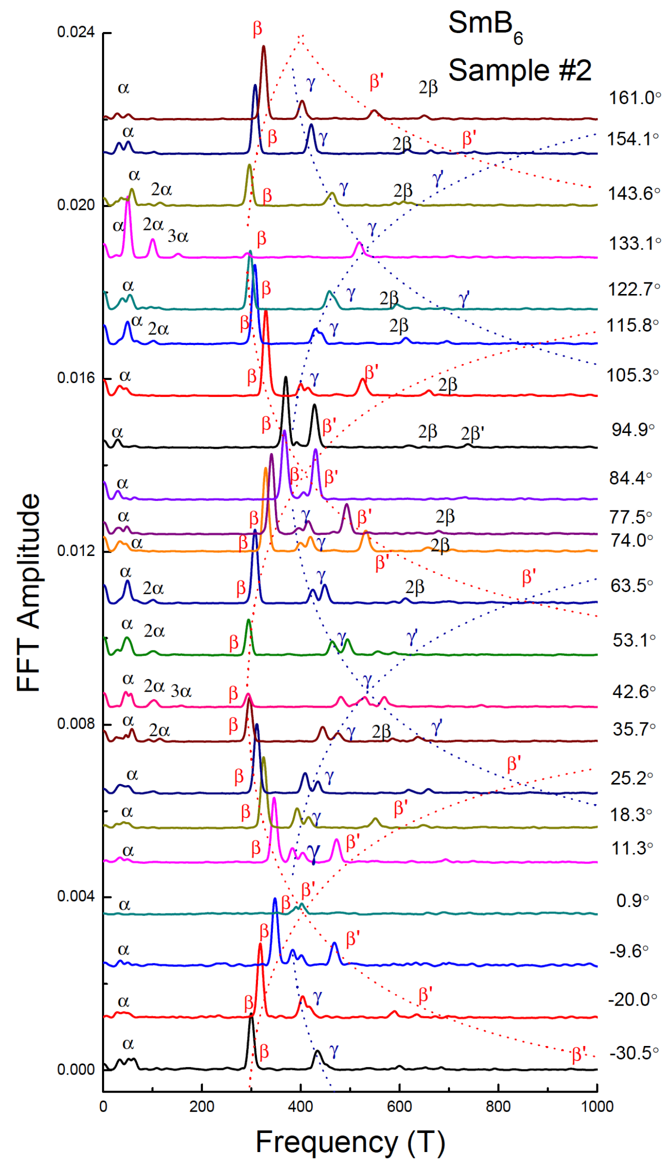


3 Dirac Cones, 2 Fermi Surface Areas

Lu, *et al. PRL (2013)*

Track the angular dependence of the frequency

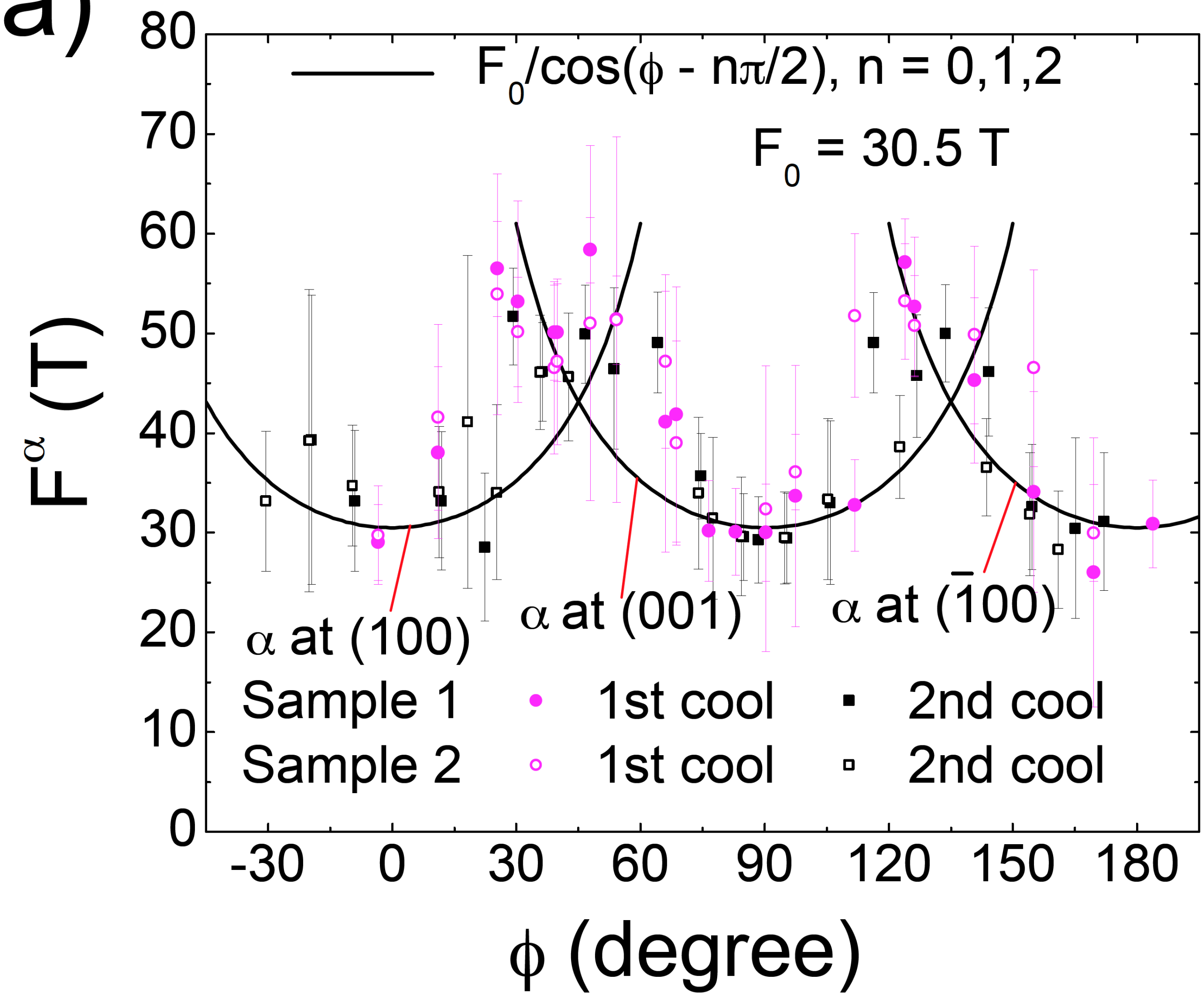




~ 10 degree between each trace

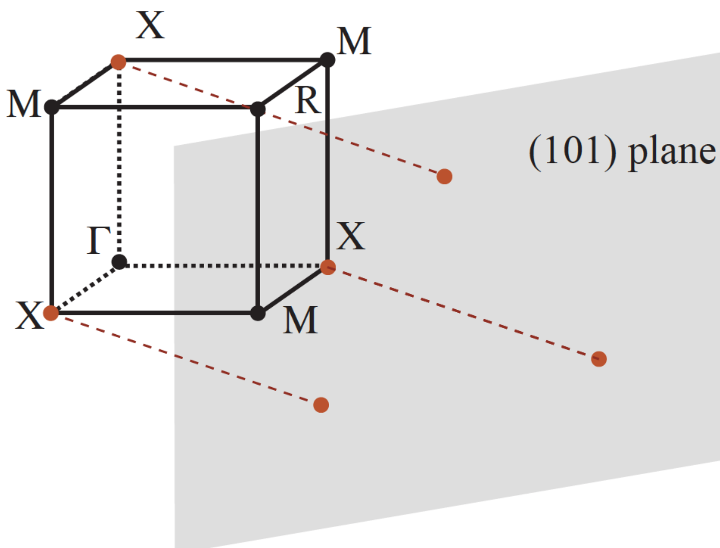
Two-dimensional α pocket on (100) plane

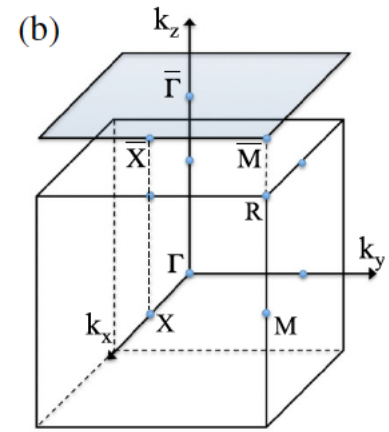
(a)

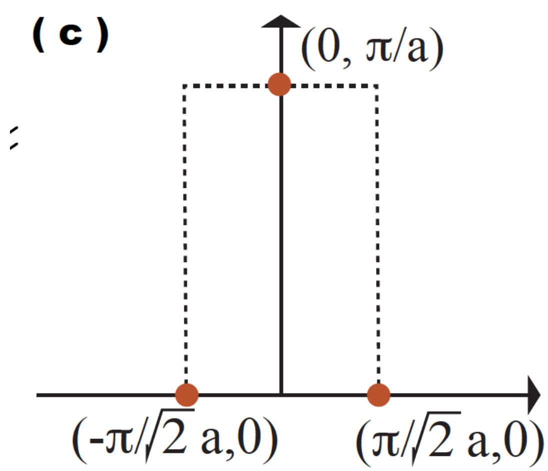


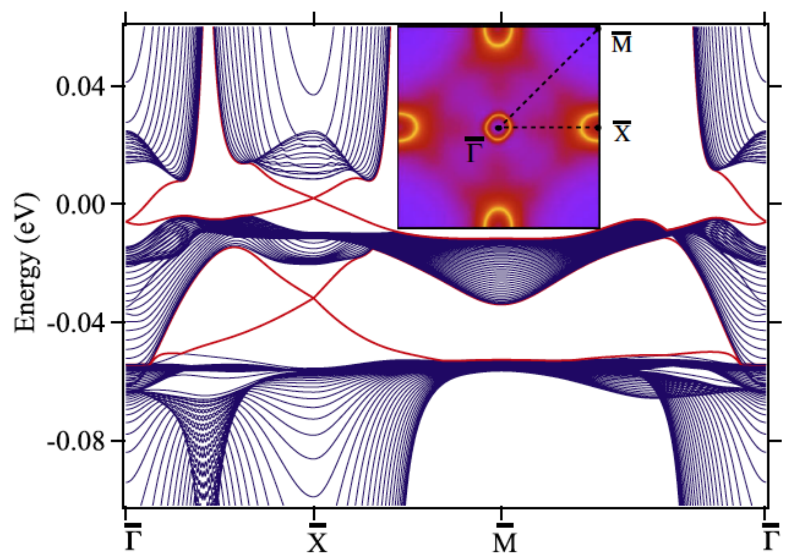
G. Li, *et al. Science 2014*

Surface states





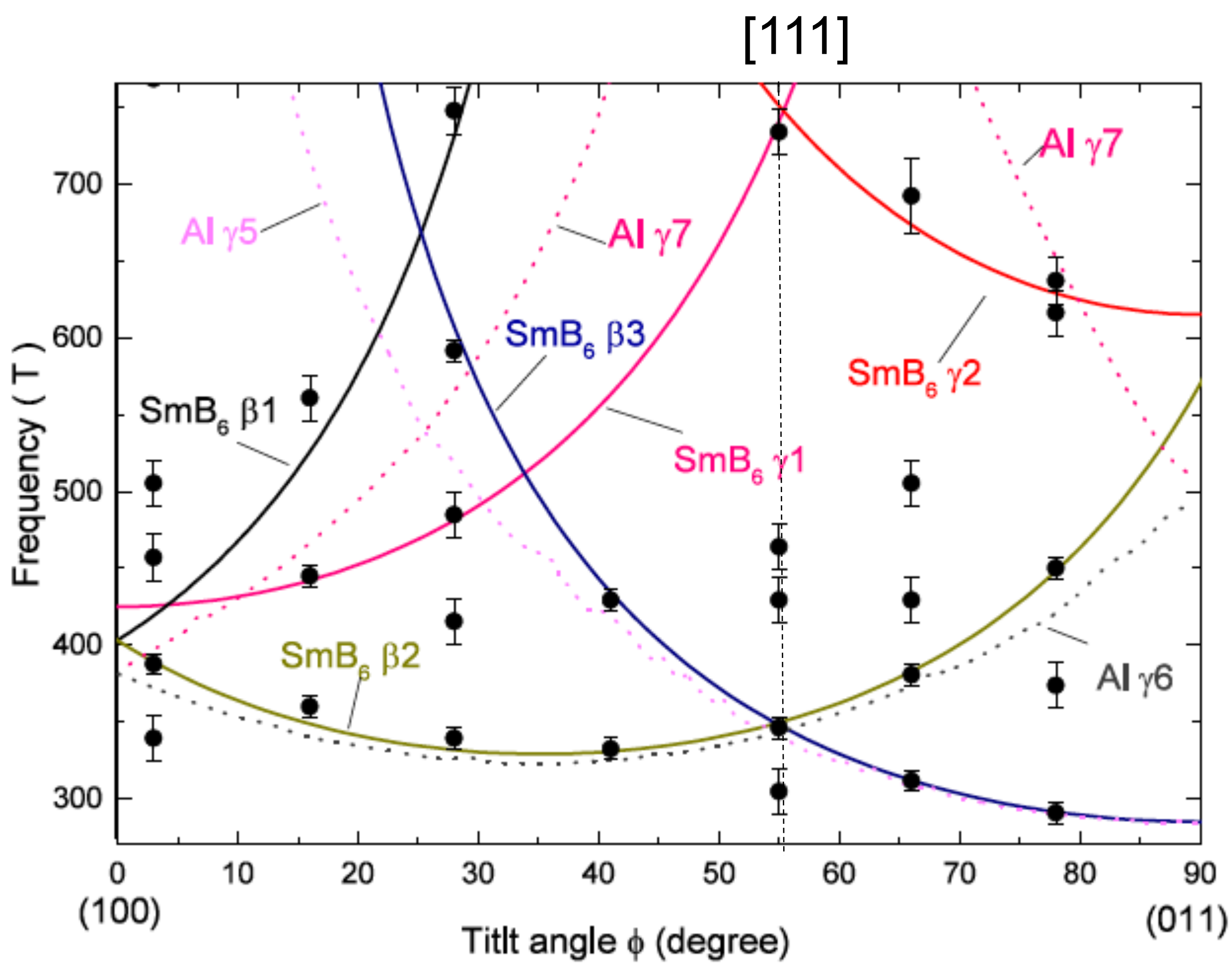




G. Li, *et al. Science 2014*

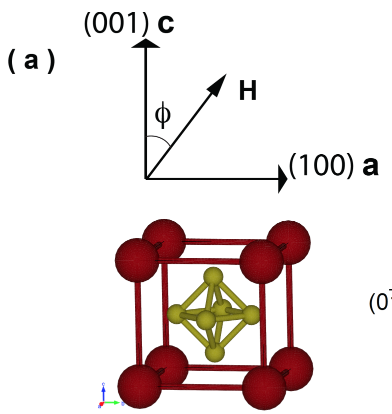
Lu, *et al. PRL (2013)*

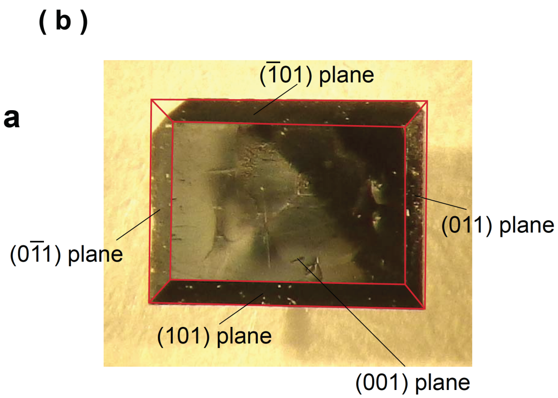
2D nature rotating from 100 axis to 011 axis

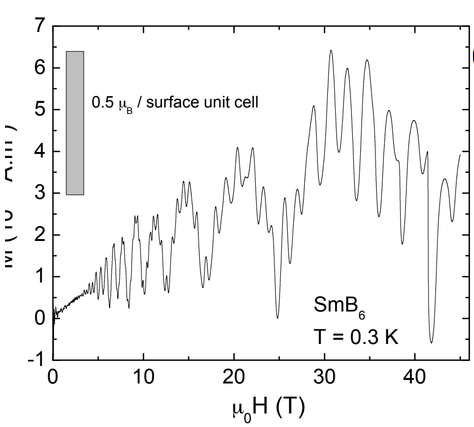


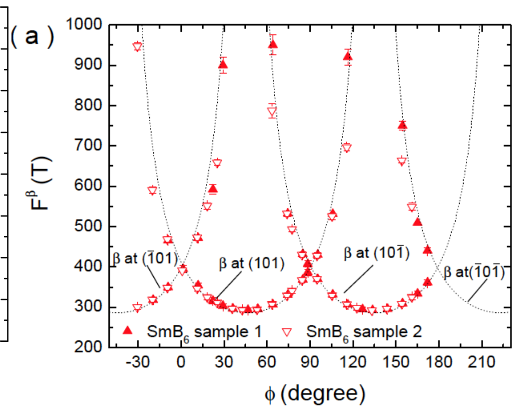
G. Li, *et al. Science 2014*

Topological Kondo insulators SmB_6







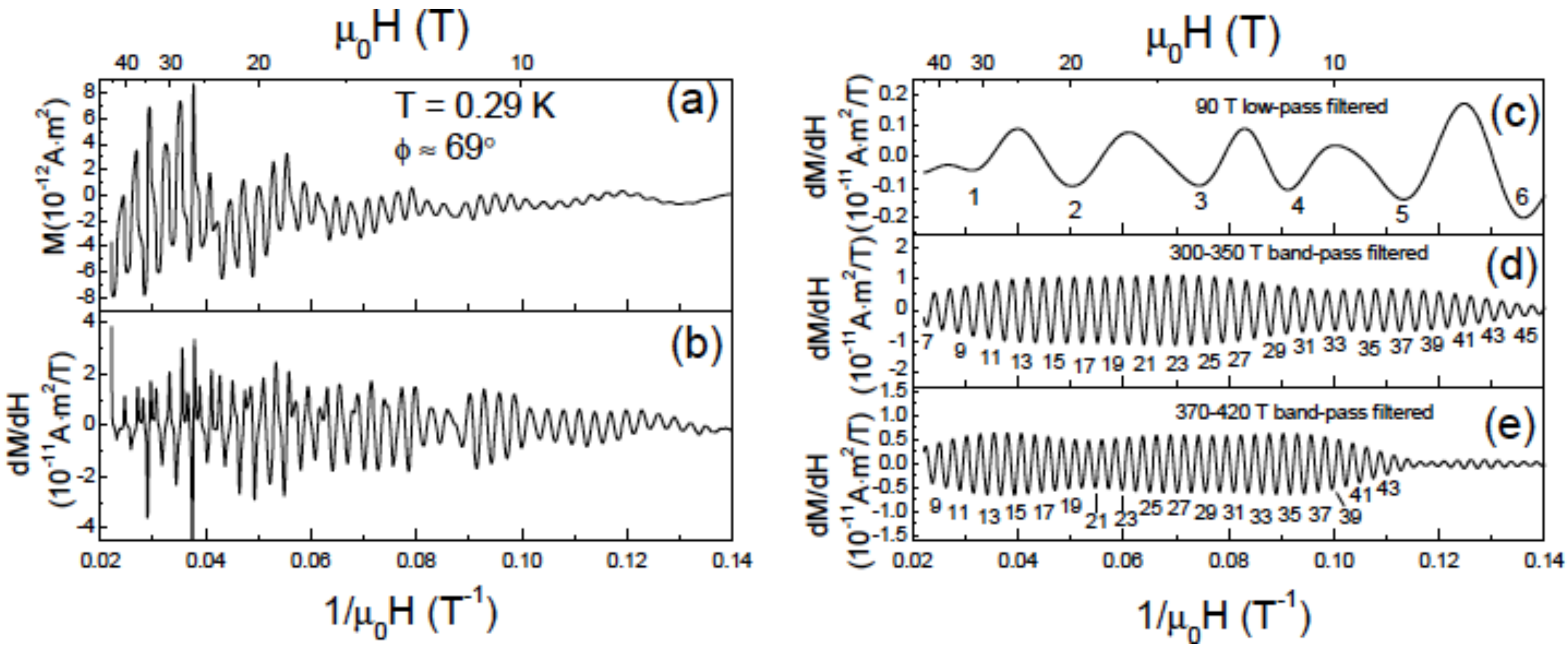


1. **WHY?** Kondo Insulator SmB_6

2. **HOW?** Torque magnetometry

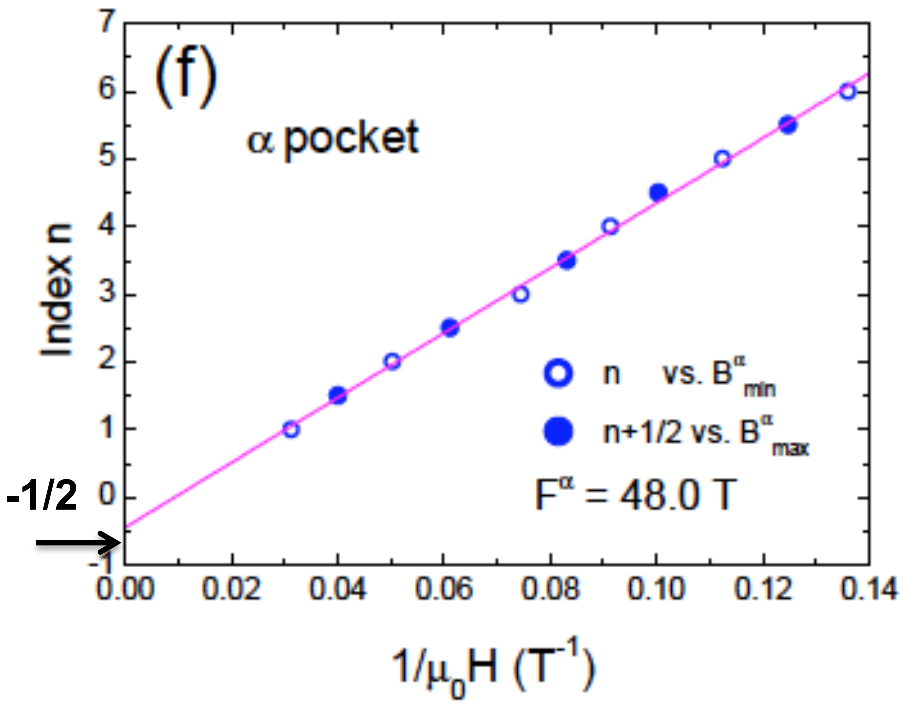
3. **Result?**
   - Quantum oscillations in **M**
   - 2 dimensional surface state F ~ 1 /cos (angle)
   - **Landau Levels index plots → -1/2 Berry phase factor for Dirac dispersion**
   - Heavy Mass observed in Floating-zone samples

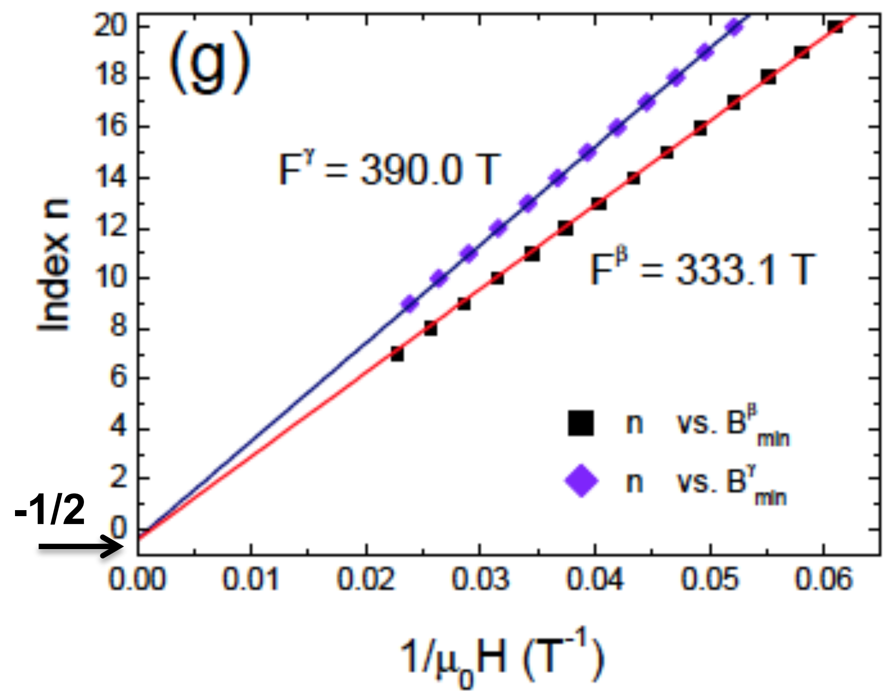
Resolving Landau Levels



G. Li, *et al. Science 2014*

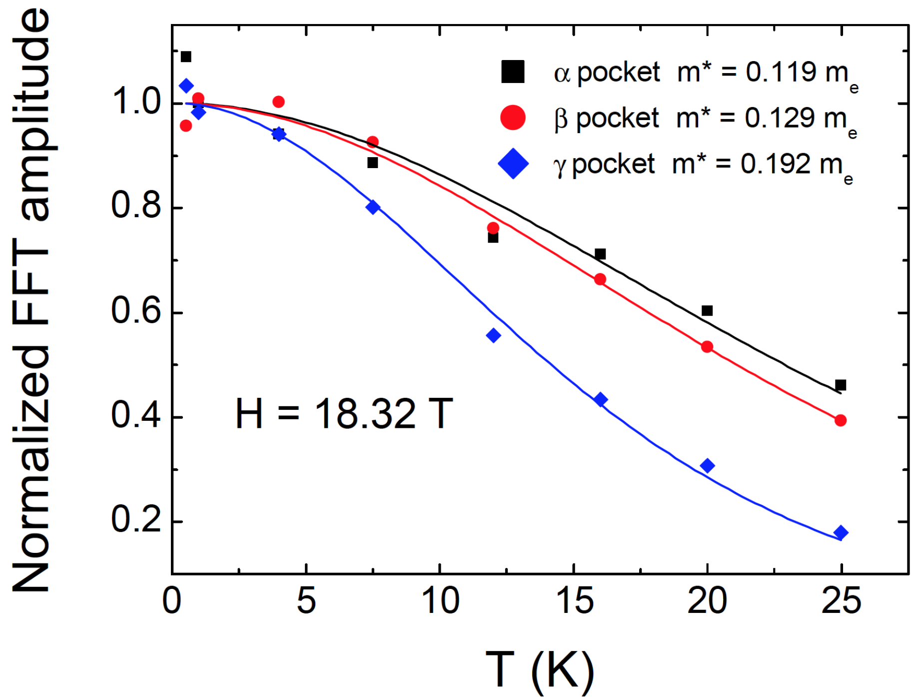
Index plot → -1/2 at infinite H limit

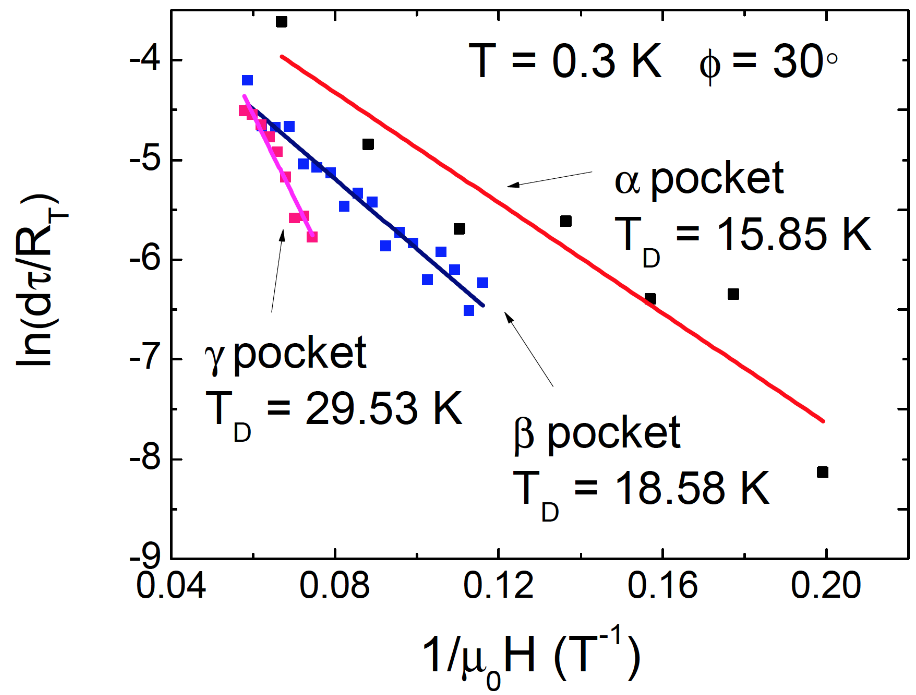




G. Li, *et al. Science 2014*

Open question: Light effective mass





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Open question: Large Fermi Velocity

	α	β	γ
F (T)	29.3±4	292 ±5	383 ± 5
Crystalline Surface Origin	(1 0 0)	(1 0 1)	(1 0 0)
k_F (nm^{-1})	0.28 ± 0.04	0.941 ± 0.008	1.08 ± 0.01
$\frac{m}{m_e}$	0.119 ± 0.007	0.129 ± 0.004	0.192 ± 0.005
v_F (10^5 m s^{-1})	2.9 ± 0.4	8.45 ± 0.33	6.50 ± 0.21
l (nm)	22 ± 8	55 ± 7	27 ± 4
μ ($\times 10^3 \mathrm{cm}^2$/V s)	1.2 ± 0.6	0.89 ± 0.12	0.38 ± 0.06
$k_F l$	6.2 ± 3.1	52 ± 7	29 ± 4
δ	-0.45 ± 0.07	-0.44 ± 0.06	-0.32 ± 0.07

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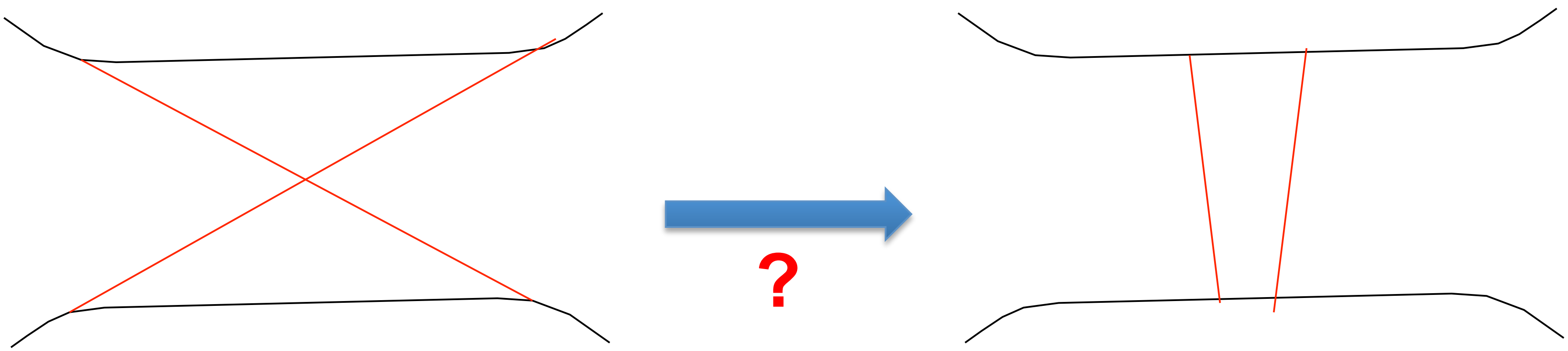
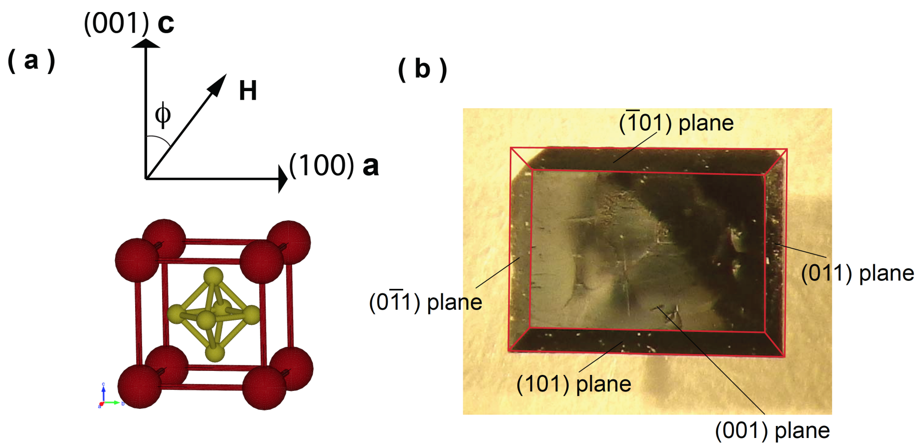
Open question: Large Fermi Velocity



Polar surface at 100 ? But non-polar on 101 surface

Interaction driven renormalization?

Topological Kondo insulators SmB_6



1. **WHY?** Kondo Insulator SmB_6
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   - Quantum oscillations in **M**
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     -1/2 Berry phase factor for
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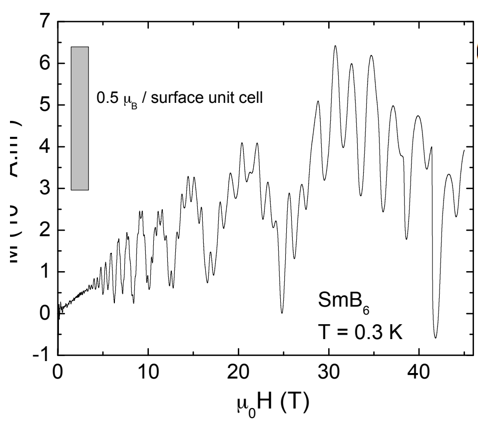
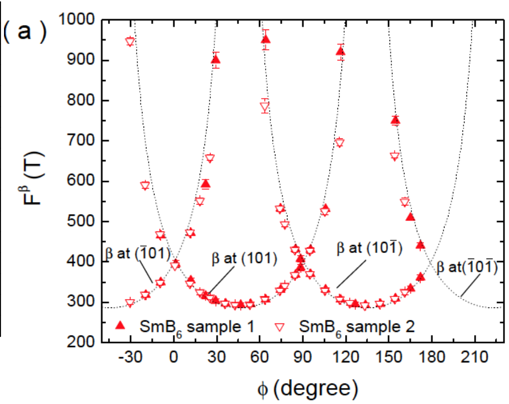
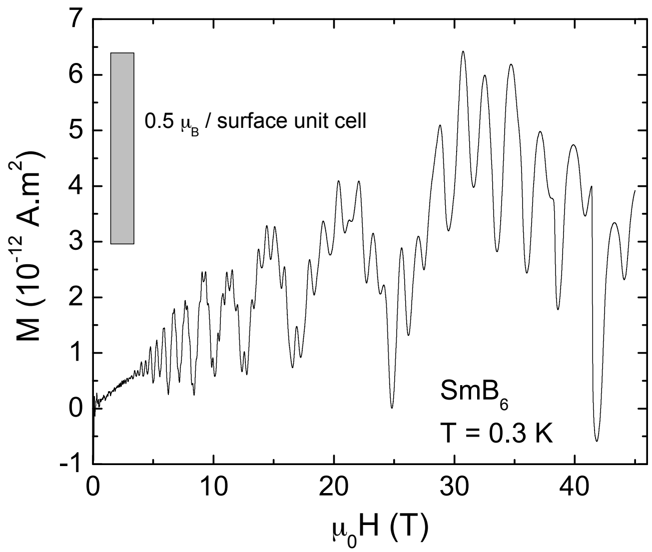
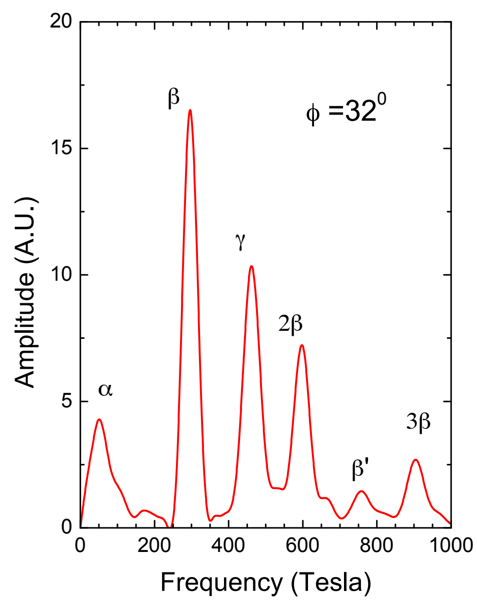
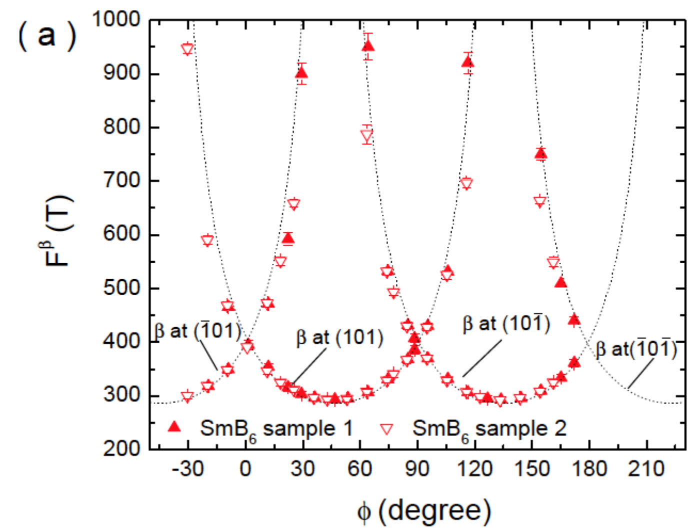




Conclusion
Surface states resolved at Kondo Insulator SmB_6







- Quantum oscillations in magnetization
- 2D surface state FS areas: 1 on (101) surface, 2 on (100) surface