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Novel electronic transport in topological semimetals

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Supervisor: Wei Pan

10/04/2017

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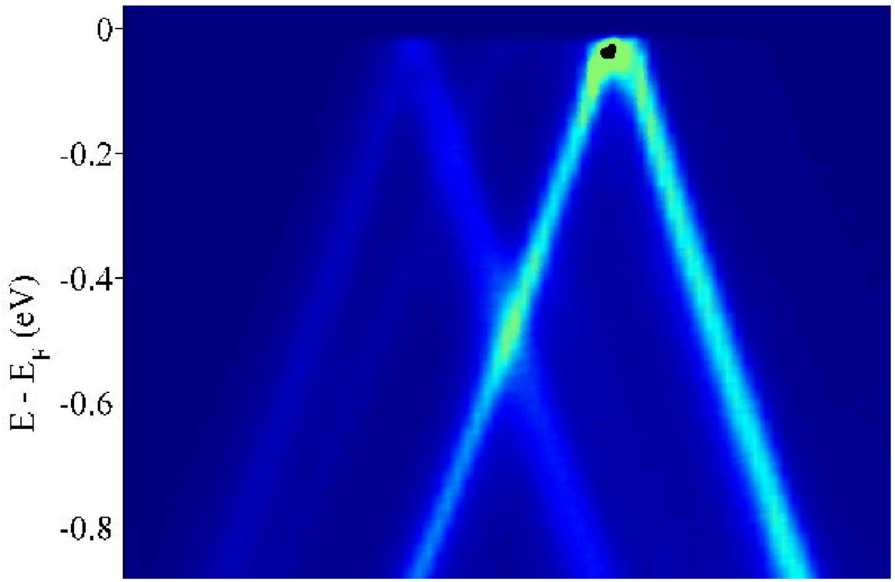
Outline

- Introduction
- Transport properties of $ZrTe_5$
- Transport measurement of Cd_3As_2
- Josephson supercurrents in Cd_3As_2
- Summary

Dirac Materials

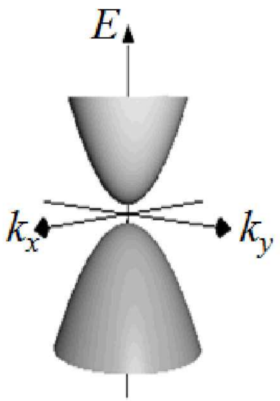
linear energy band: massless Dirac fermions



ARPES– multilayer epitaxial graphene

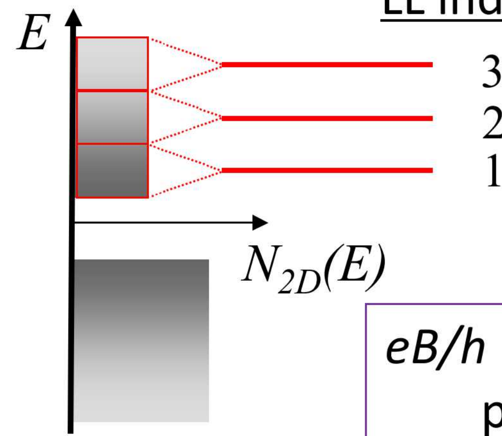
Sprinkle, M. *et al. Physical Review Letters* **103**, 226803 (2009)

Landau levels



GaAs

LL index (n)



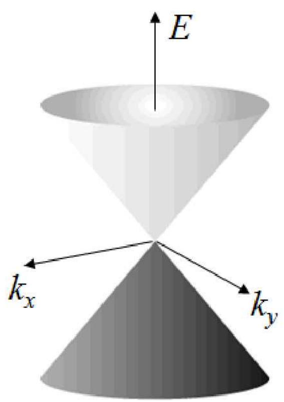
eB/h per LL
per spin

LL energies

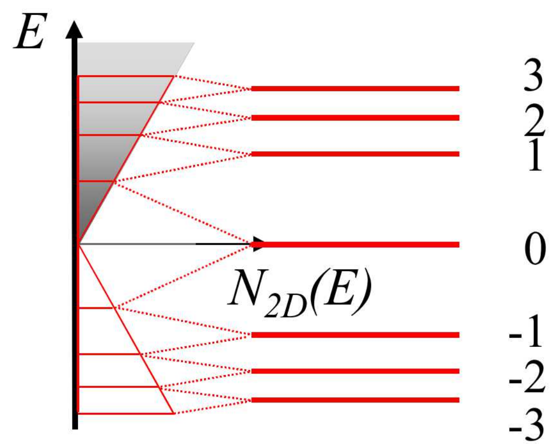
$$E_n = (n + 1/2)\hbar\omega_c$$

$$\omega_c = \frac{eB}{m^*}$$

linear in *B*-field



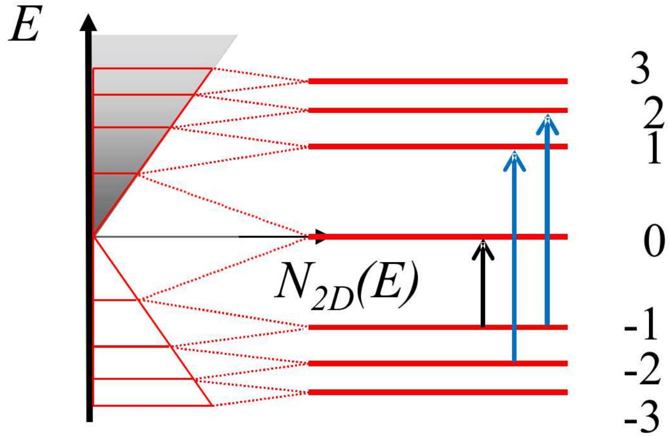
Graphene



$$E_n = \pm\sqrt{2e\hbar c^2 |n| B}$$

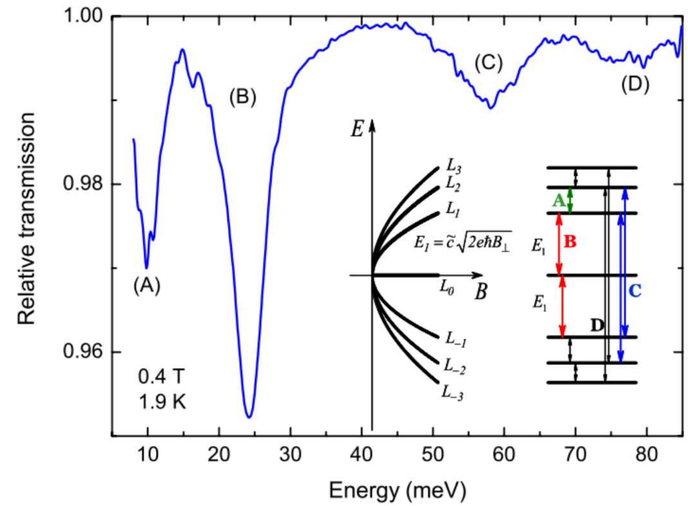
energies depend on $\sqrt{B}$

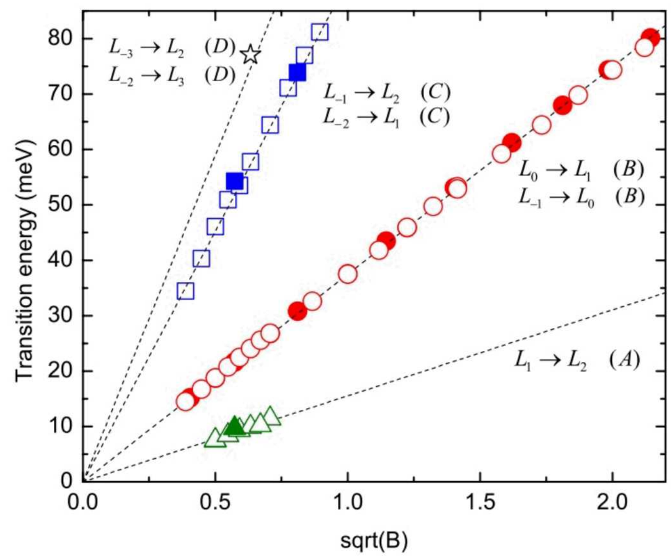
Magneto-infrared Spectroscopy



$$\Delta E_{n_1,\,n_2} = \sqrt{2e\hbar\tilde{c}^2 B}\times\left(\sqrt{|n_2|}\pm\sqrt{|n_1|}\right)$$

energies depend on $\sqrt{n}$ and $\sqrt{B}$!





M. L. Sadowski *et al.*, Phys. Rev. Lett. **97**, 266405 (2006)

Outline

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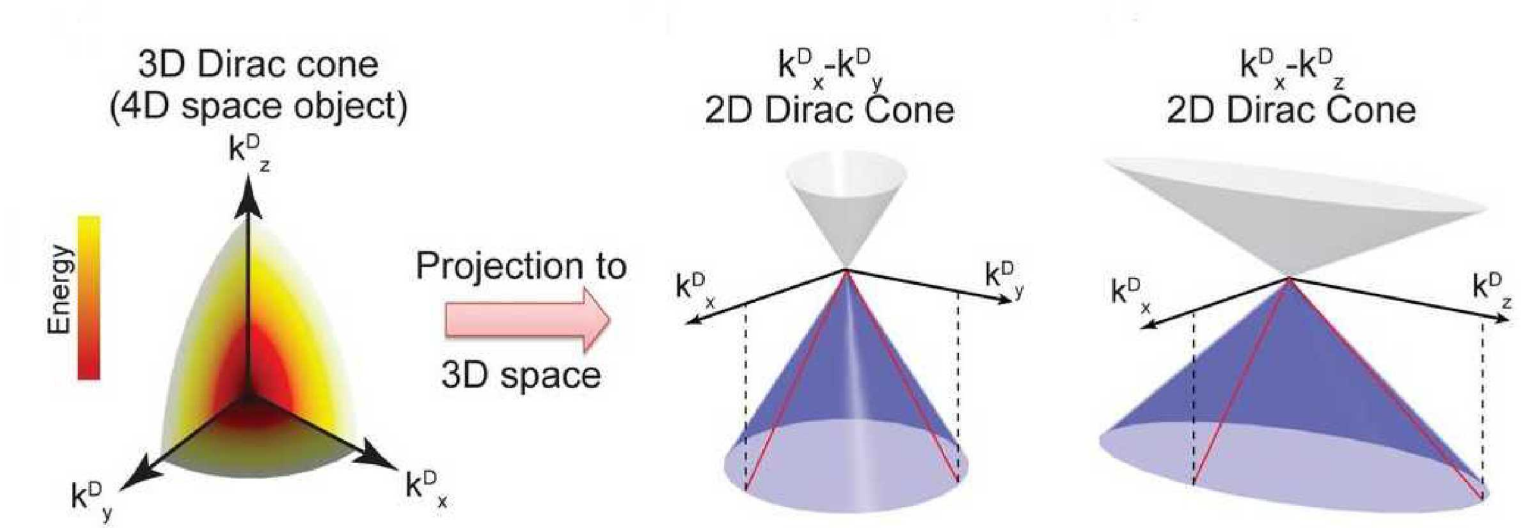
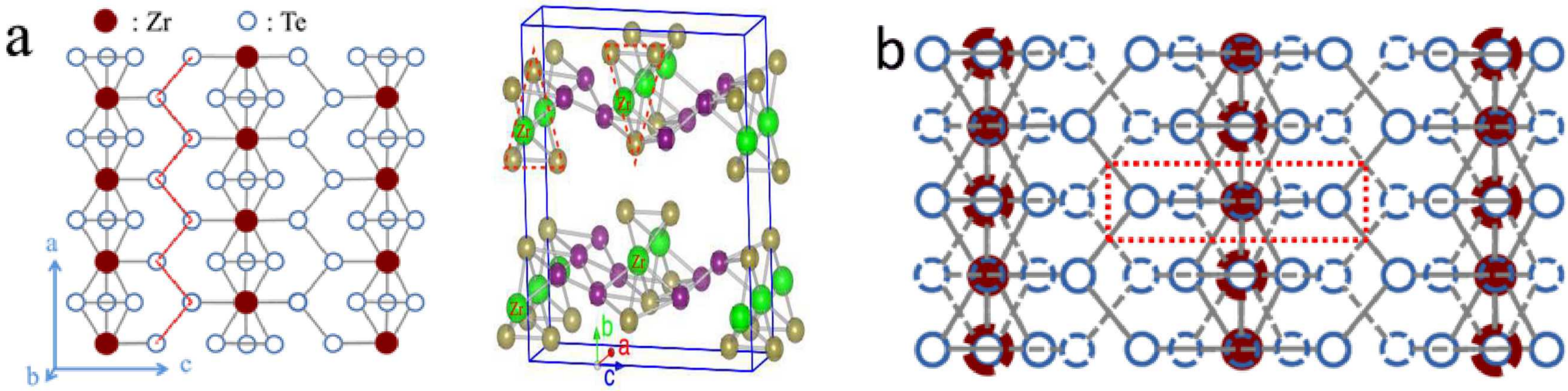
- Transport measurement of $ZrTe_5$
- Transport measurement of Cd_3As_2
- Induced superconductivity in Cd_3As_2

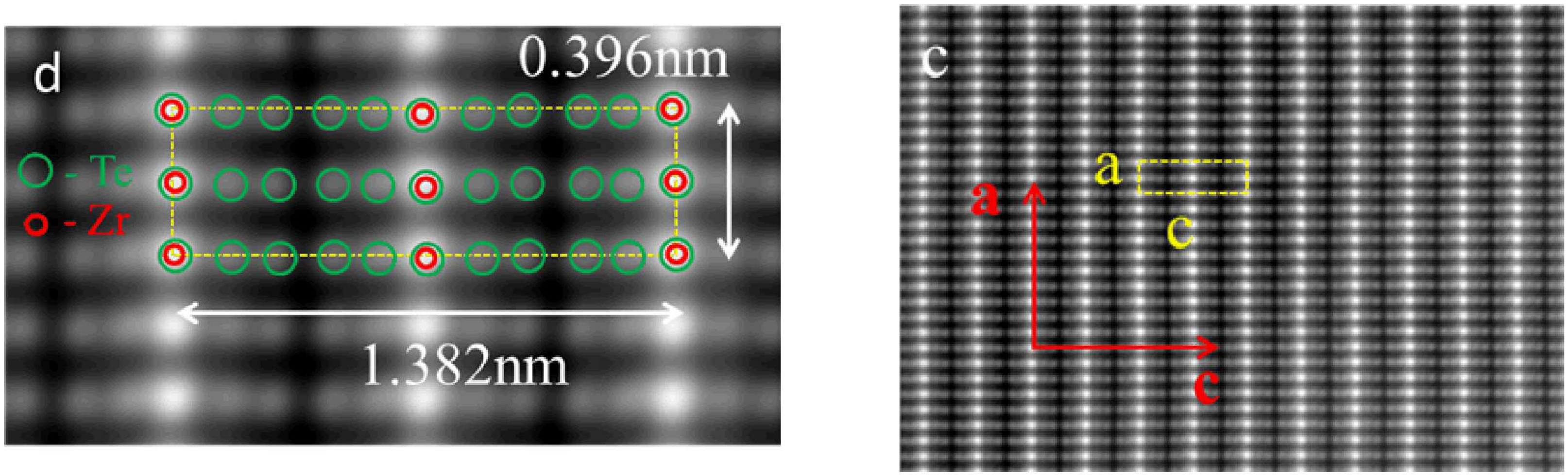
3D Topological Dirac Semimetal



Wang, Z. *et al.* Dirac semimetal and topological phase transitions in A_3Bi (A = Na, K, Rb). *Physical Review B* 85, 195320 (2012).

ZrTe$_5$ Crystal Structure





W. Yu, *et al. Scientific Reports,* **6**,35357 (2016)

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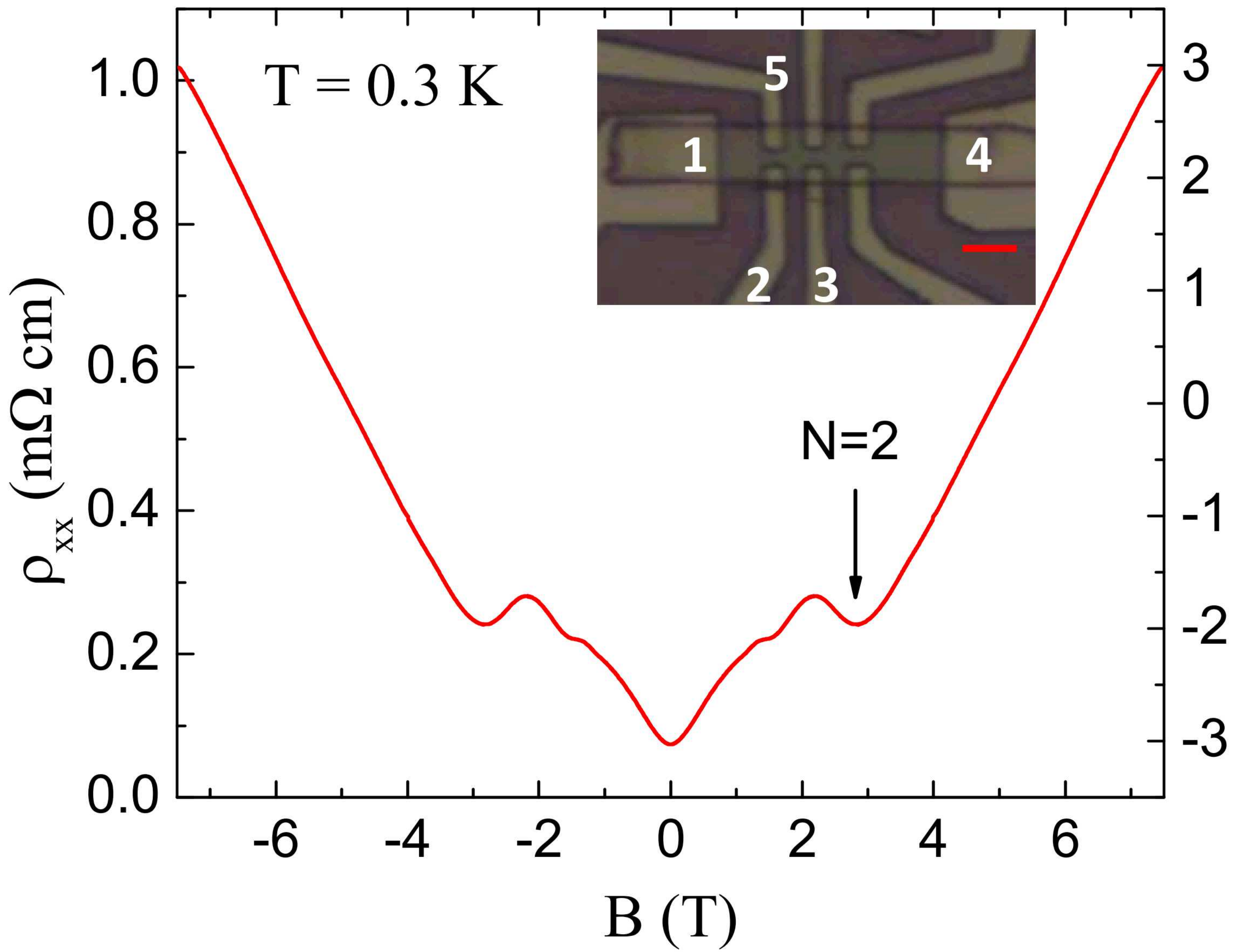
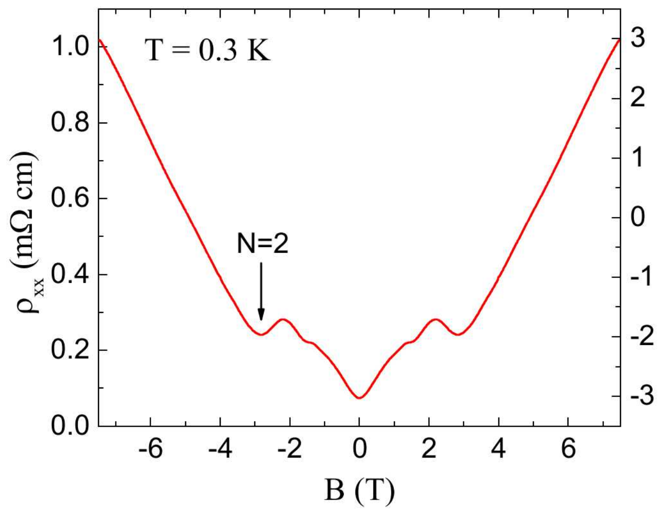
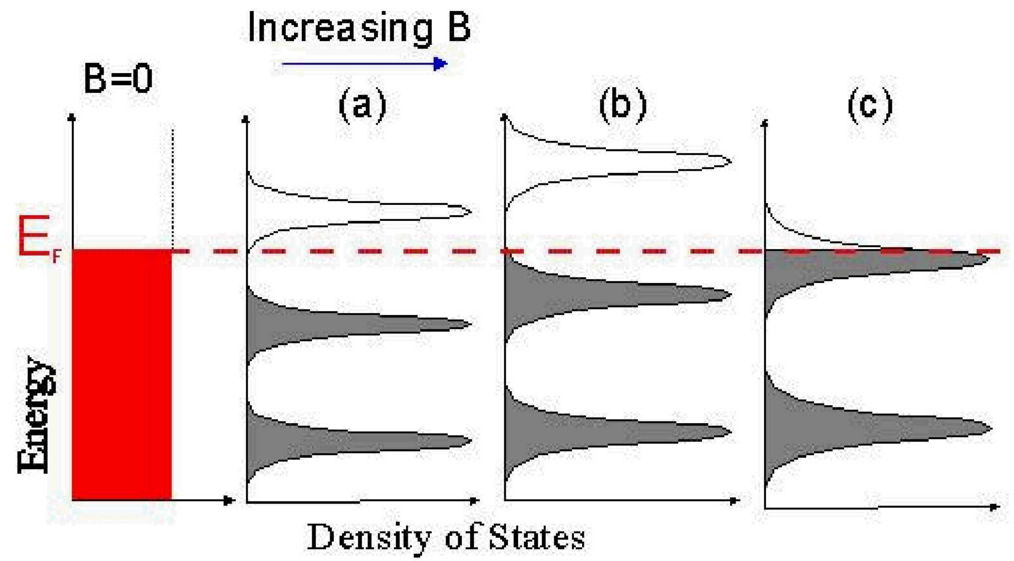
Transport measurement of $ZrTe_5$



Shubnikov-de Haas Oscillations



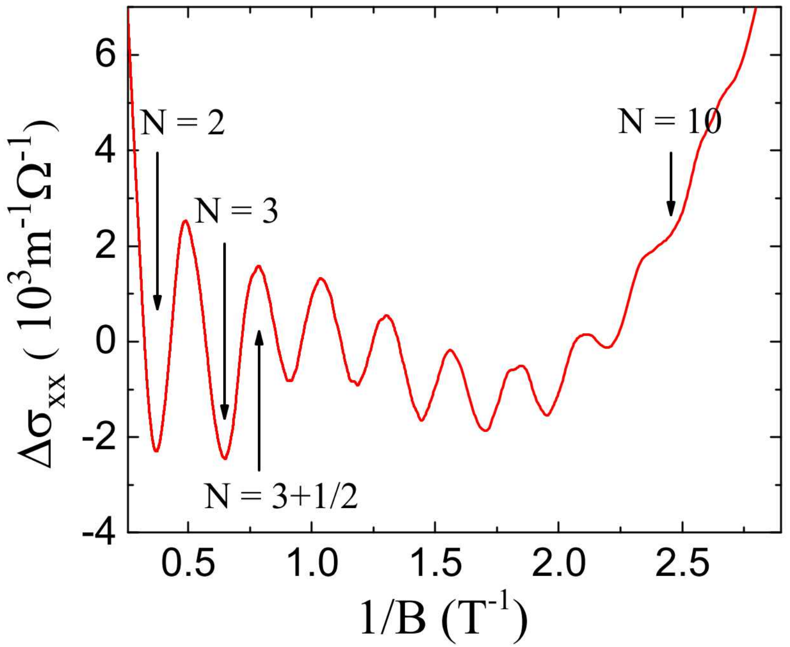


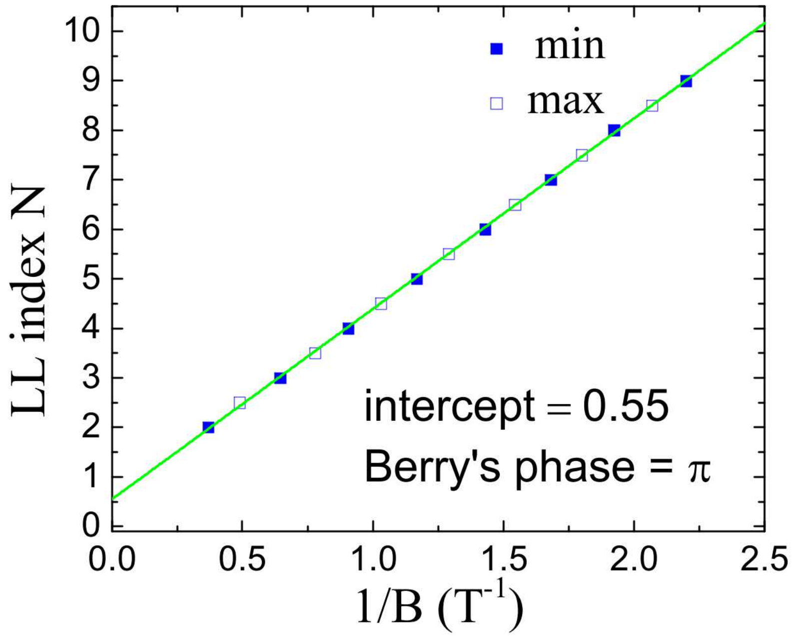
$$S_F \frac{\hbar}{eB} = 2\pi(\mathrm{N}+\gamma) = 2\pi\left(\mathrm{N}+\frac{1}{2}-\frac{\varphi_B}{2\pi}\right)$$

Conventional materials: $\varphi_B = 0$

Dirac materials: $\varphi_B = \pi$

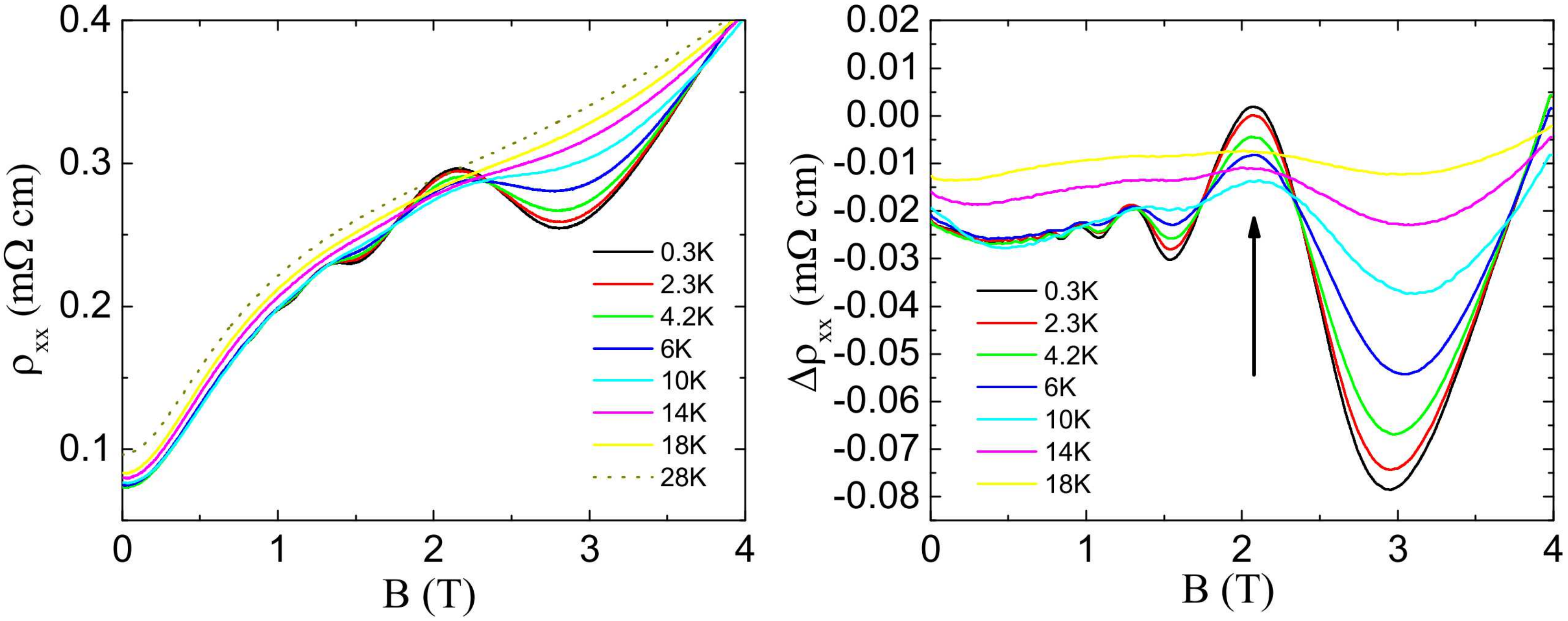
Shubnikov-de Haas Oscillations



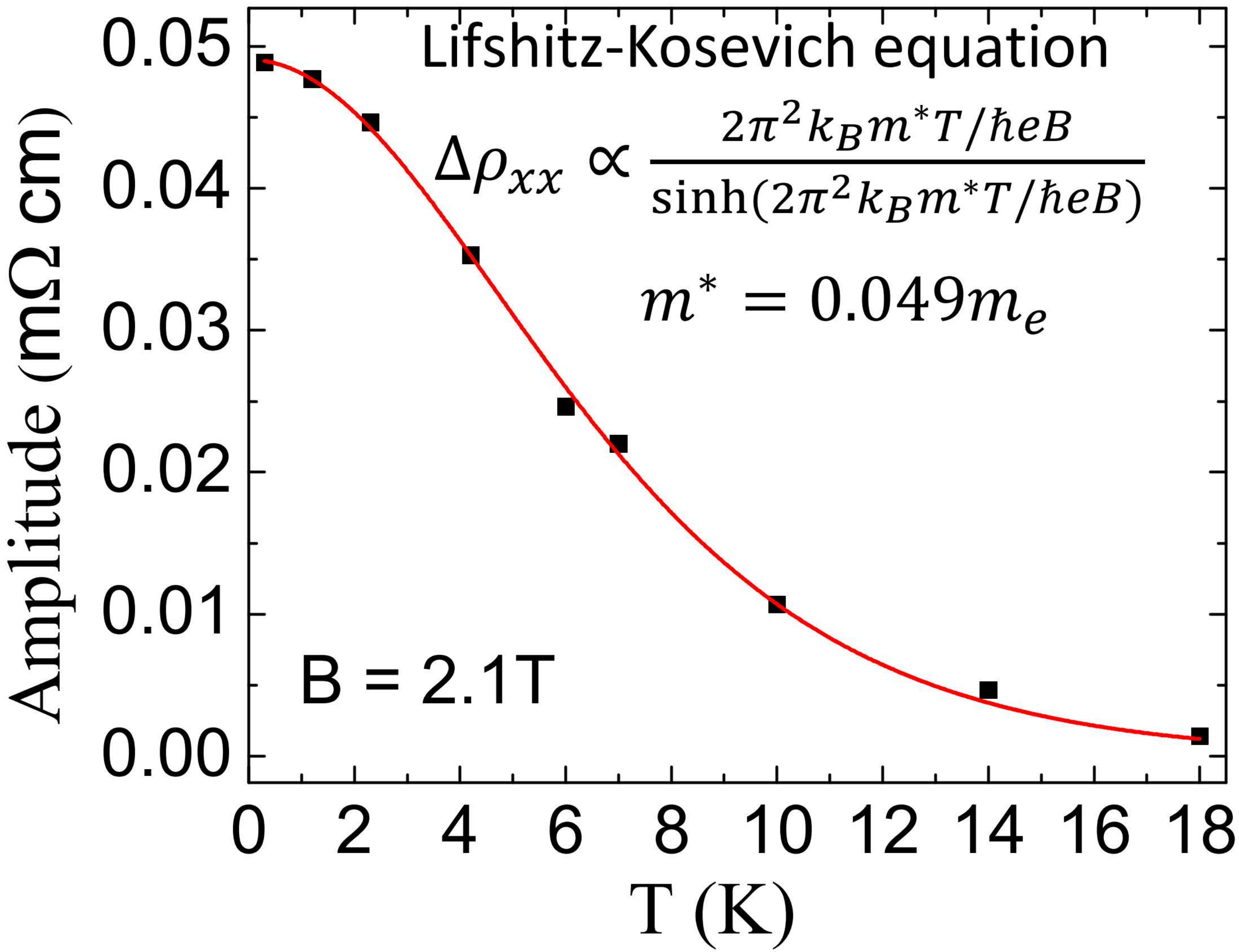


1. $\sigma_{xx} = \rho_{xx}/(\rho_{xx}^2 + \rho_{xy}^2)$
2. $\mu_q = 1/B = 2.5 \times 10^4\ cm^2V^{-1}s^{-1}$
3. $n^{SdH} = \frac{2e}{h}\frac{N}{1/B} = 1.86 \times 10^{11}\ cm^{-2}$

Temperature Dependence

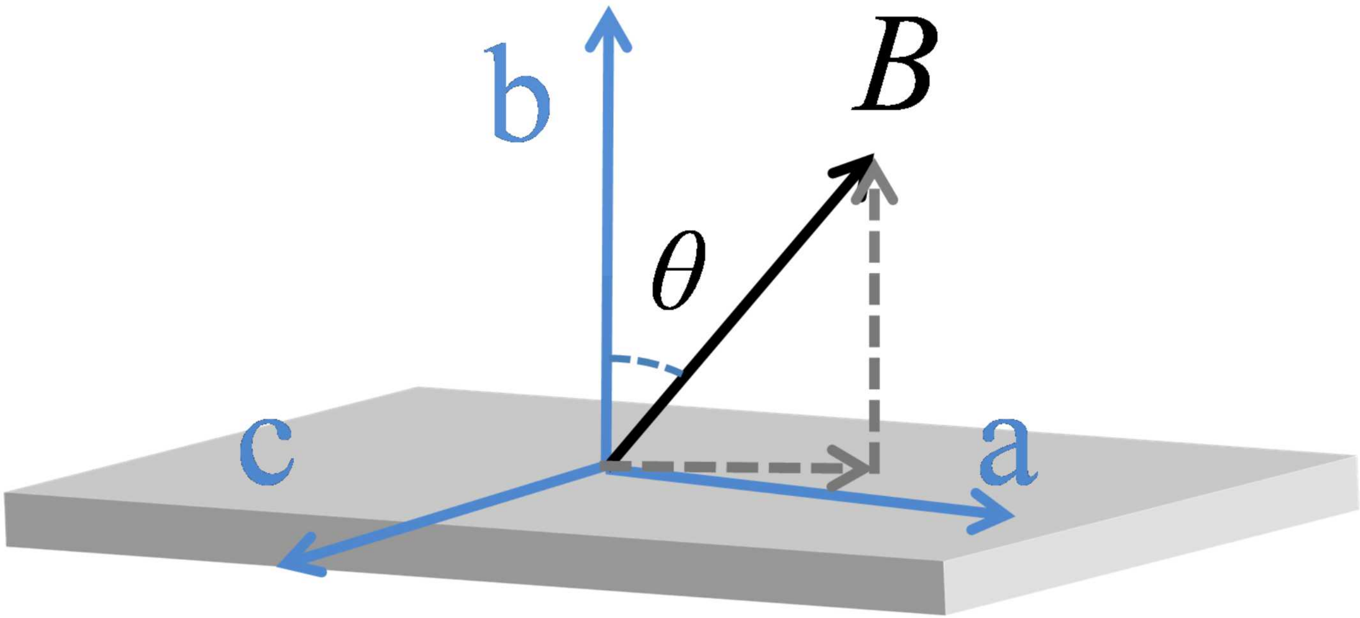


Effective Mass



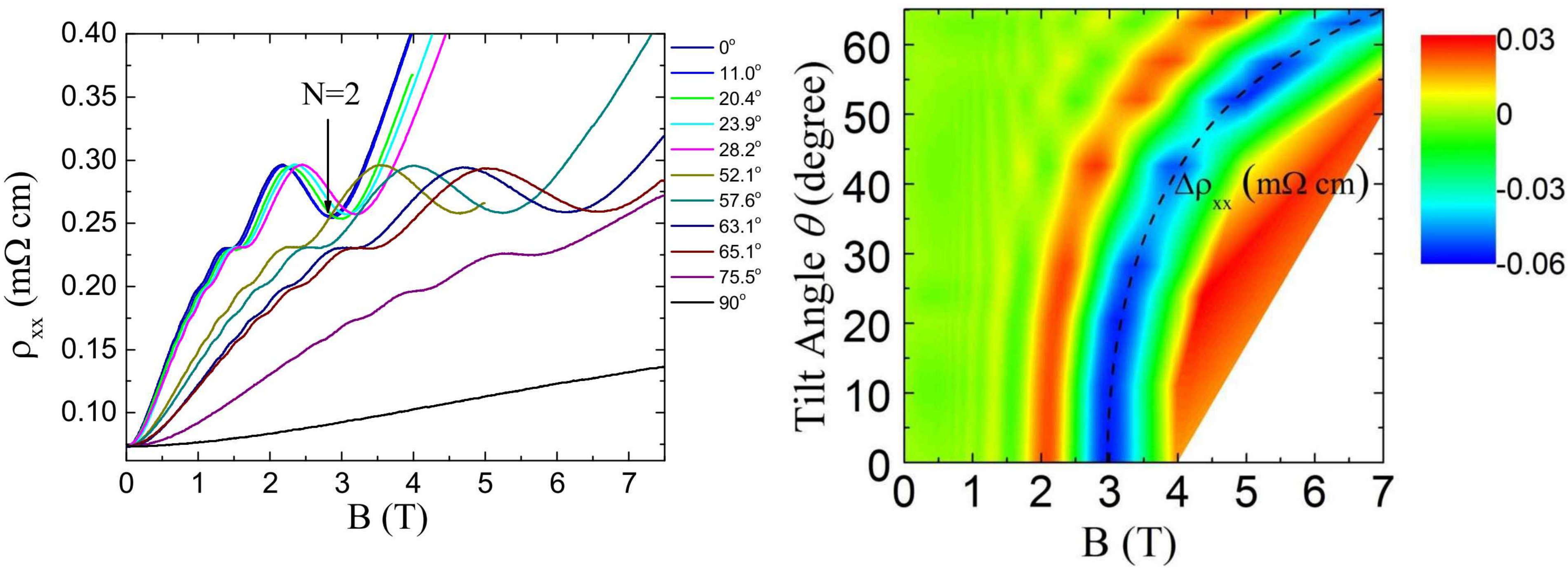
Novoselov, K. S. *et al.* *Nature* **438**, 197-200 (2005).

Angular-dependent Measurement



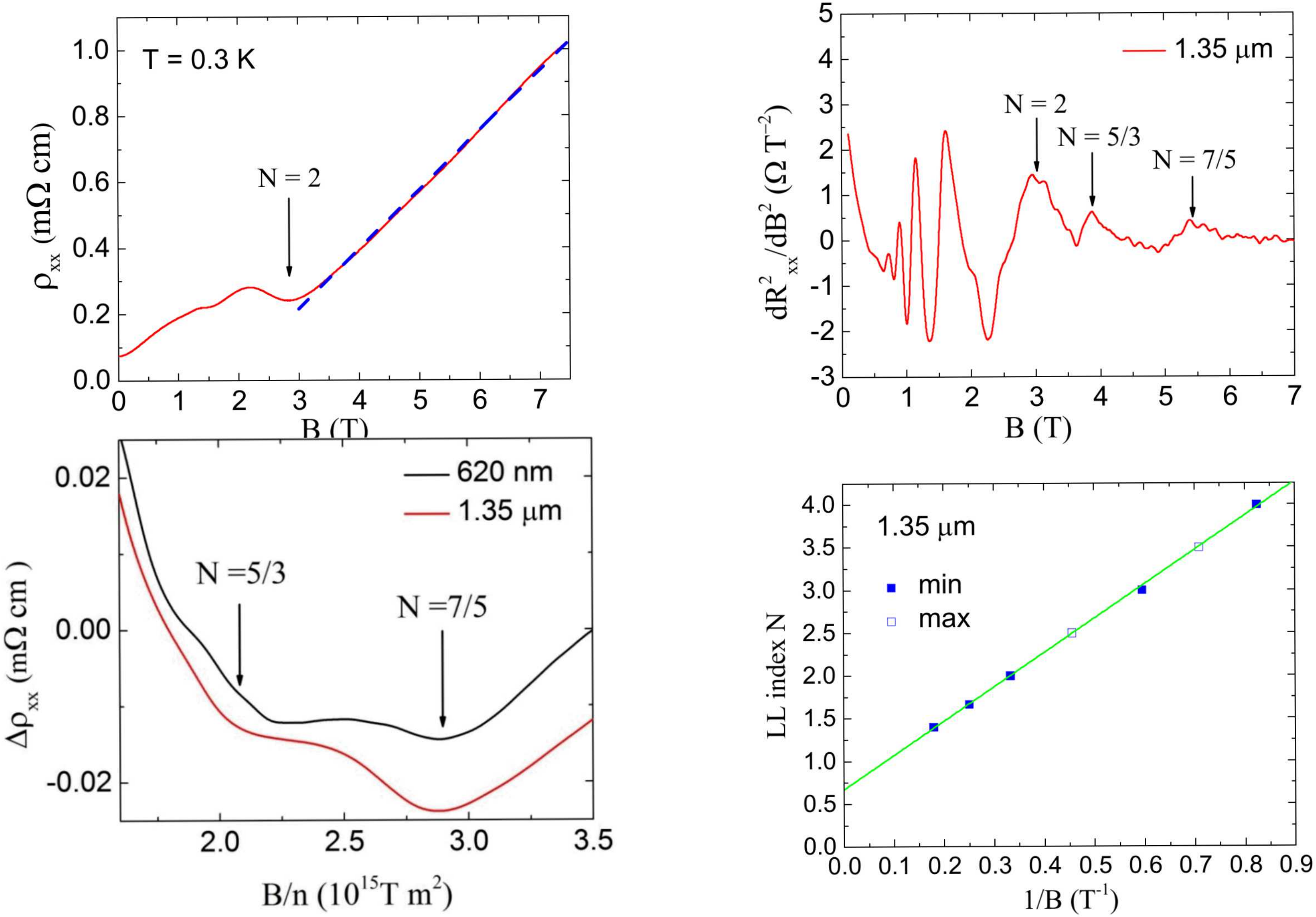
$$B\perp = B * \cos(\theta)$$

Angular-dependent Measurement



$$B(\theta) = B(\theta = 0°)/\cos(\theta)$$

Fractional Quantum Oscillations



Summary I

- High resolution STEM image of $ZrTe_5$ for the first time
- Magneto-transport measurement:
  - ✓ ρ_{xx} shows linear magnetic field dependence in high magnetic field
  - ✓ Non-trivial π Berry's phase- Dirac fermions
  - ✓ Angular dependence measurement shows 2D nature of Dirac fermions
  - ✓ Quantum oscillations at fractional Landau level indices

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- **Transport measurement of Cd_3As_2**
- Josephson supercurrents in Cd_3As_2
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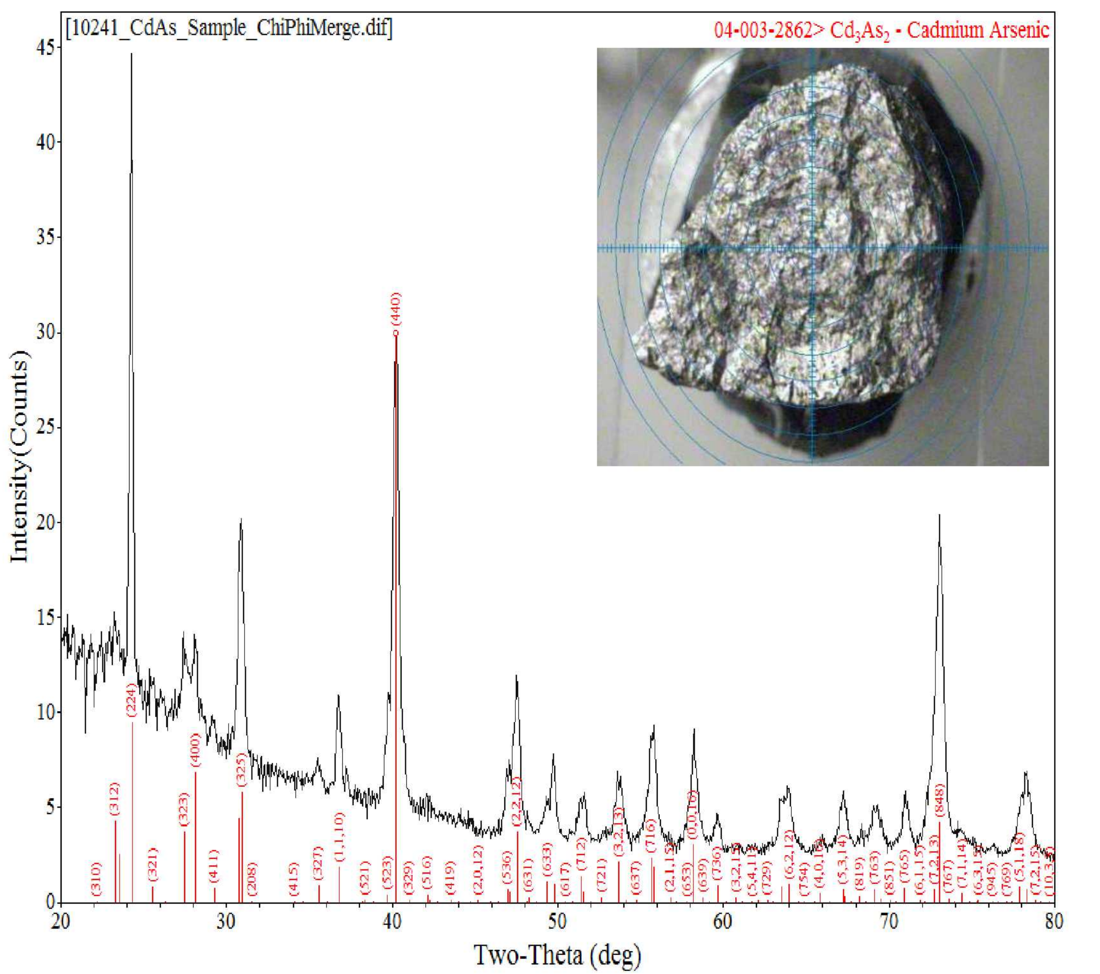
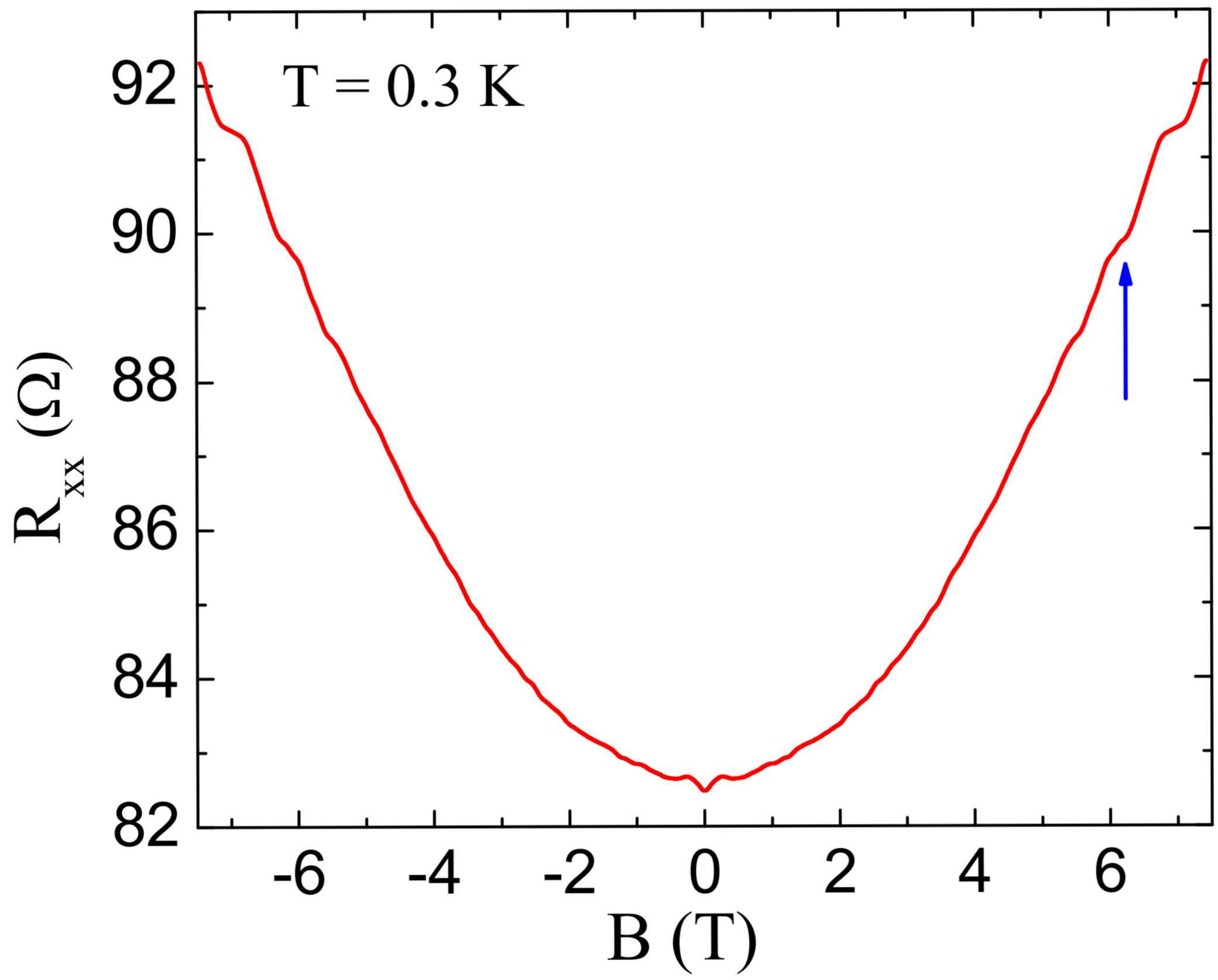
X-ray Diffraction



a = 1.2680(2) nm and c = 2.5308(6) nm

H. Yi *et al*, Scientific Reports 4, 6106 (2014)
R. Sankar *et al*, Scientific Reports 5, 12966 (2015)

Magnetoresistance of Cd_3As_2



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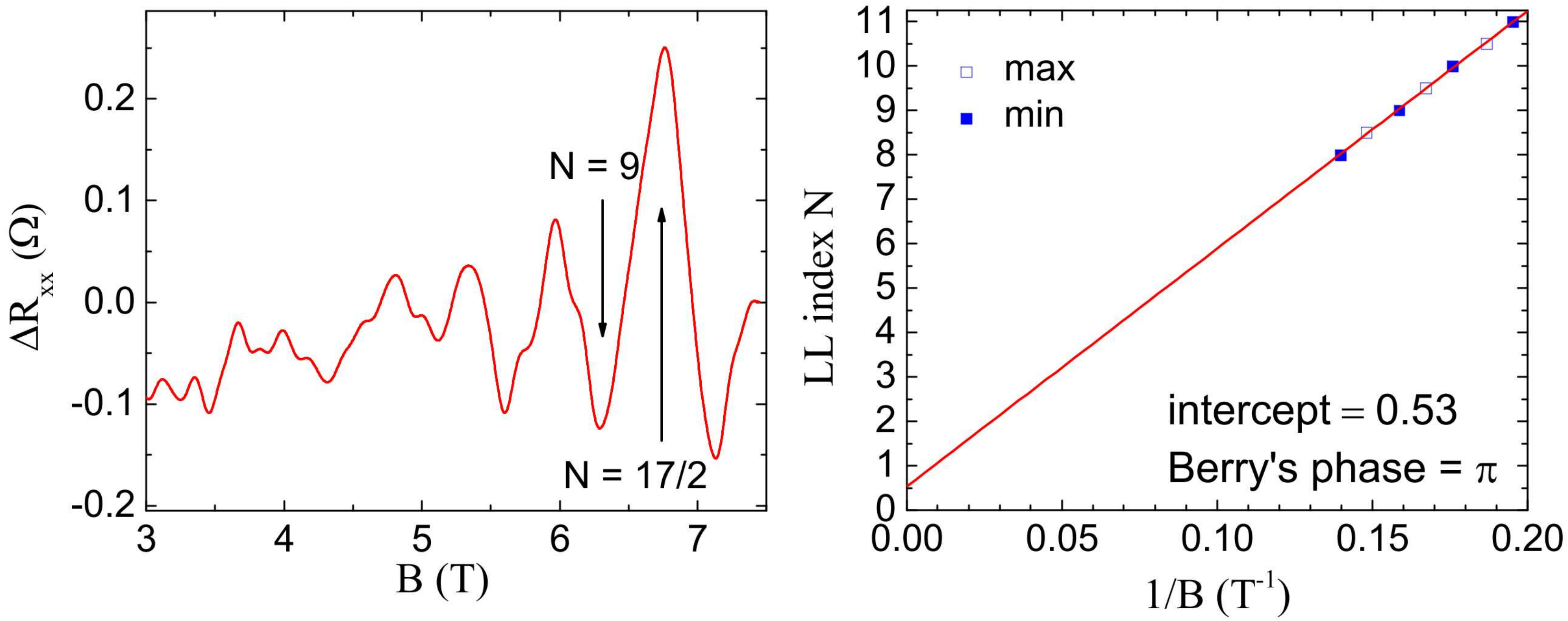
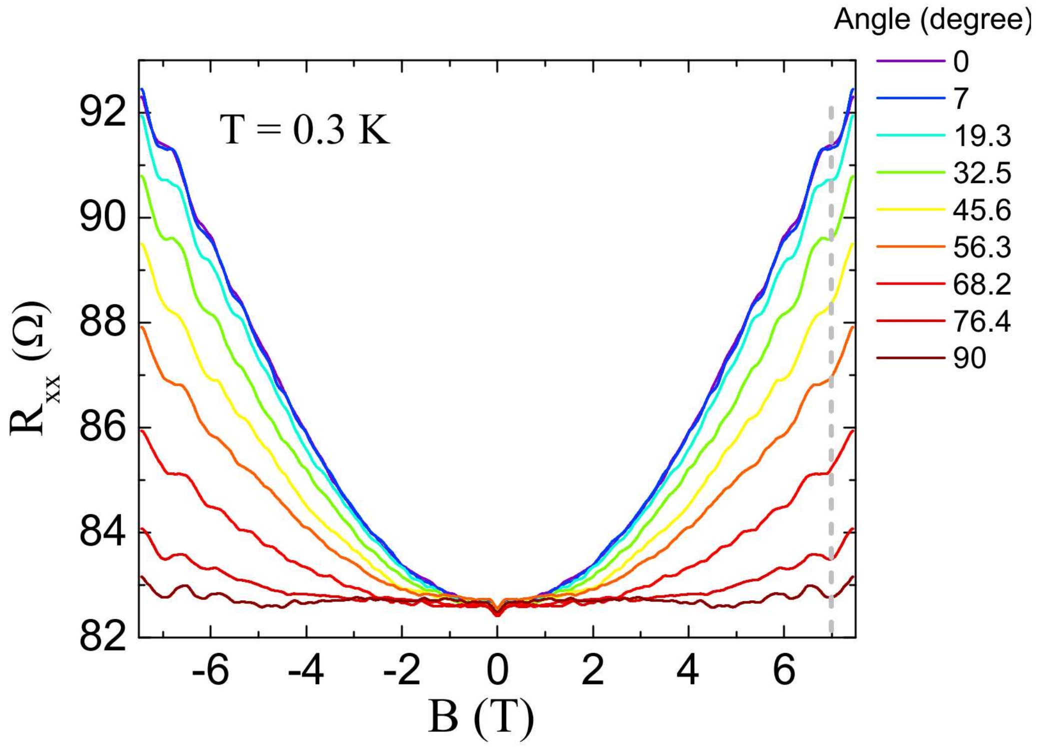
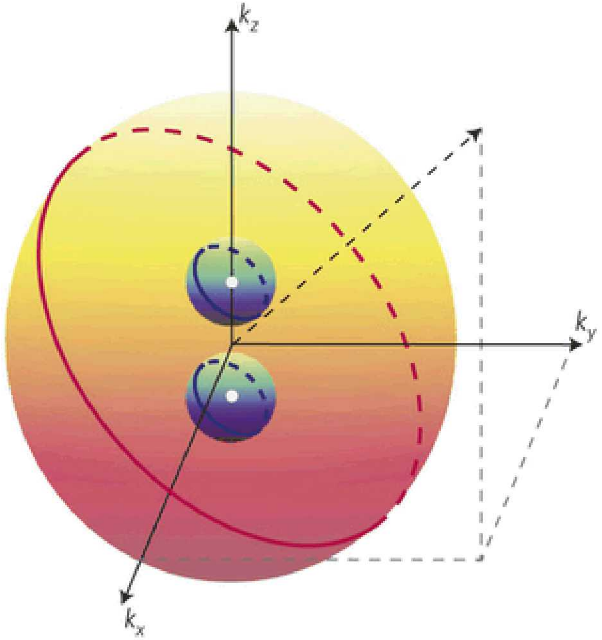
SdH oscillations



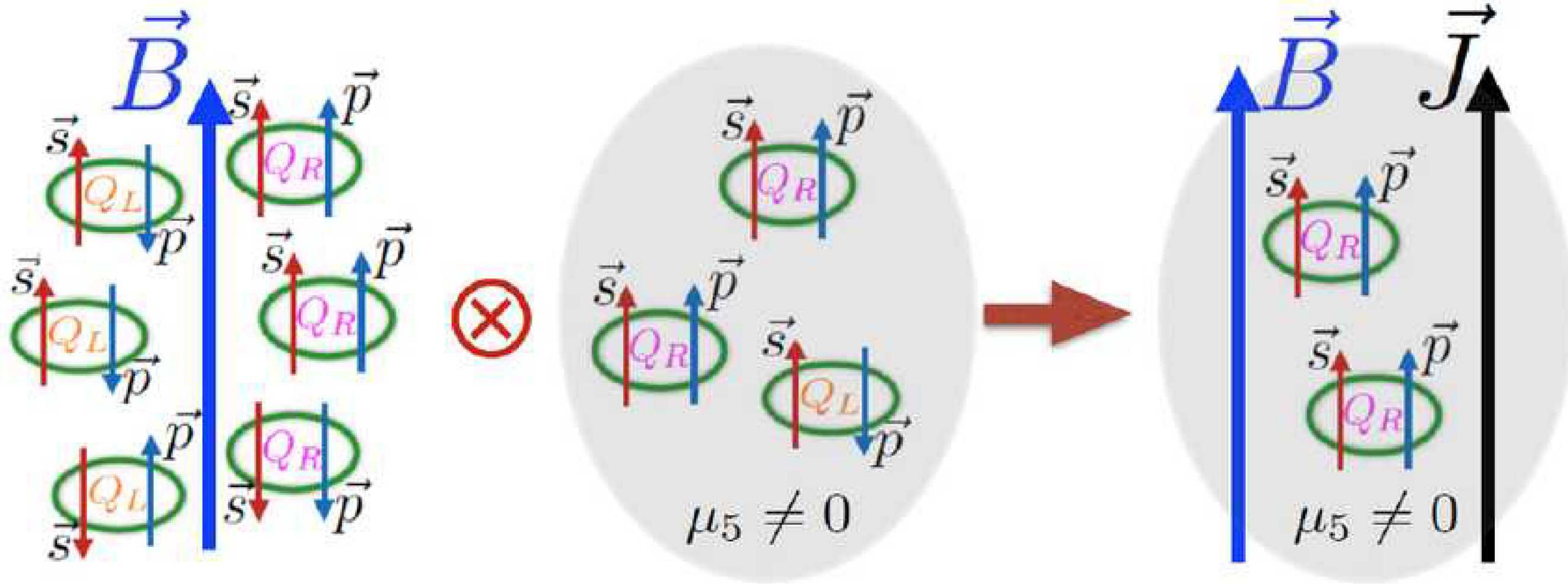
Angular-dependent Measurement





Borisenko, S *et al.* Physical Review Letters **113**, 027603 (2014)

Chiral magnetic effect



$$\mu_5 \equiv (\mu_R - \mu_L)/2$$

$$\vec{J}_{\mathrm{CME}} = \frac{e^2}{2\pi^2}\, \mu_5\, \vec{B}$$

$$\mu_5 \propto \vec{E} \cdot \vec{B}$$

$$\sigma_{\mathrm{CME}} \propto B^2$$

D. E. Kharzeev, *et al. Progress in Particle and Nuclear Physics*, **88**, 2016

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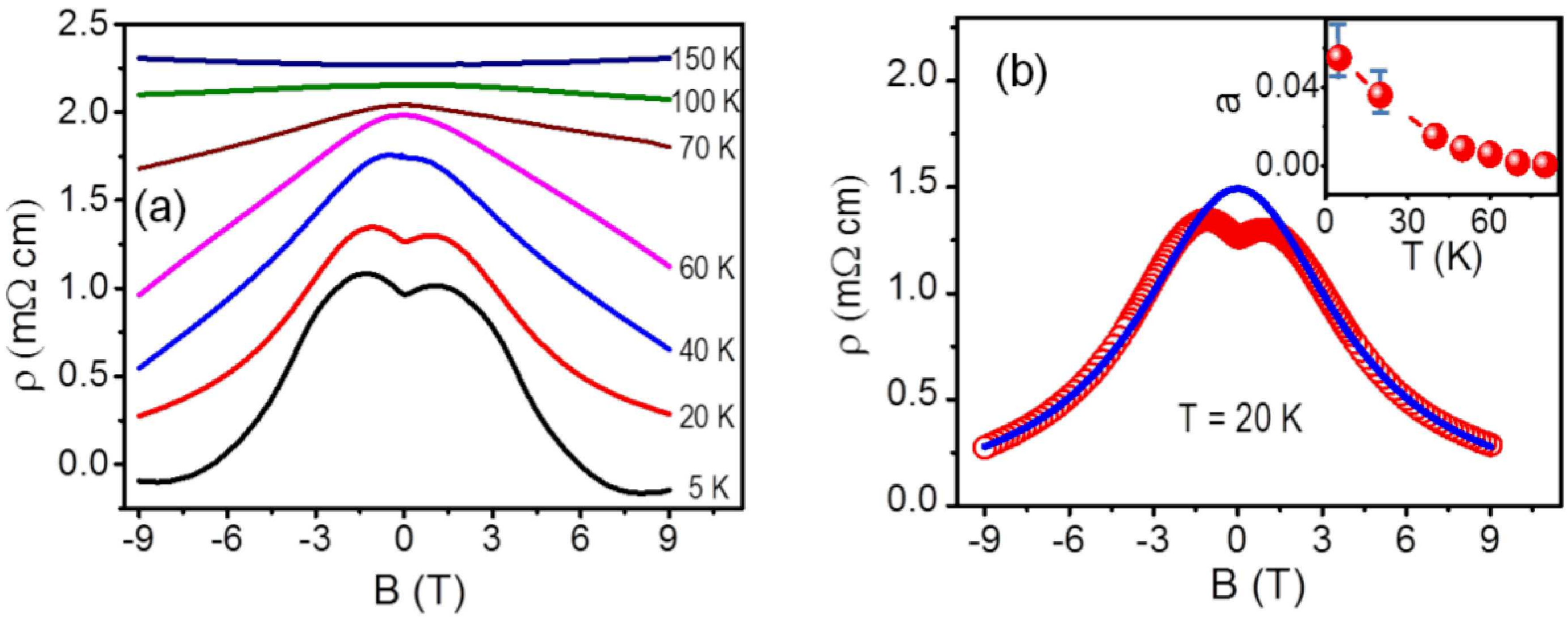
Chiral magnetic effect in $ZrTe_5$



$$\sigma_{\mathrm{CME}} = \sigma_0 + a(T)B^2$$

❖ Li, Q. *et al. Nat. Phys.* (2016).

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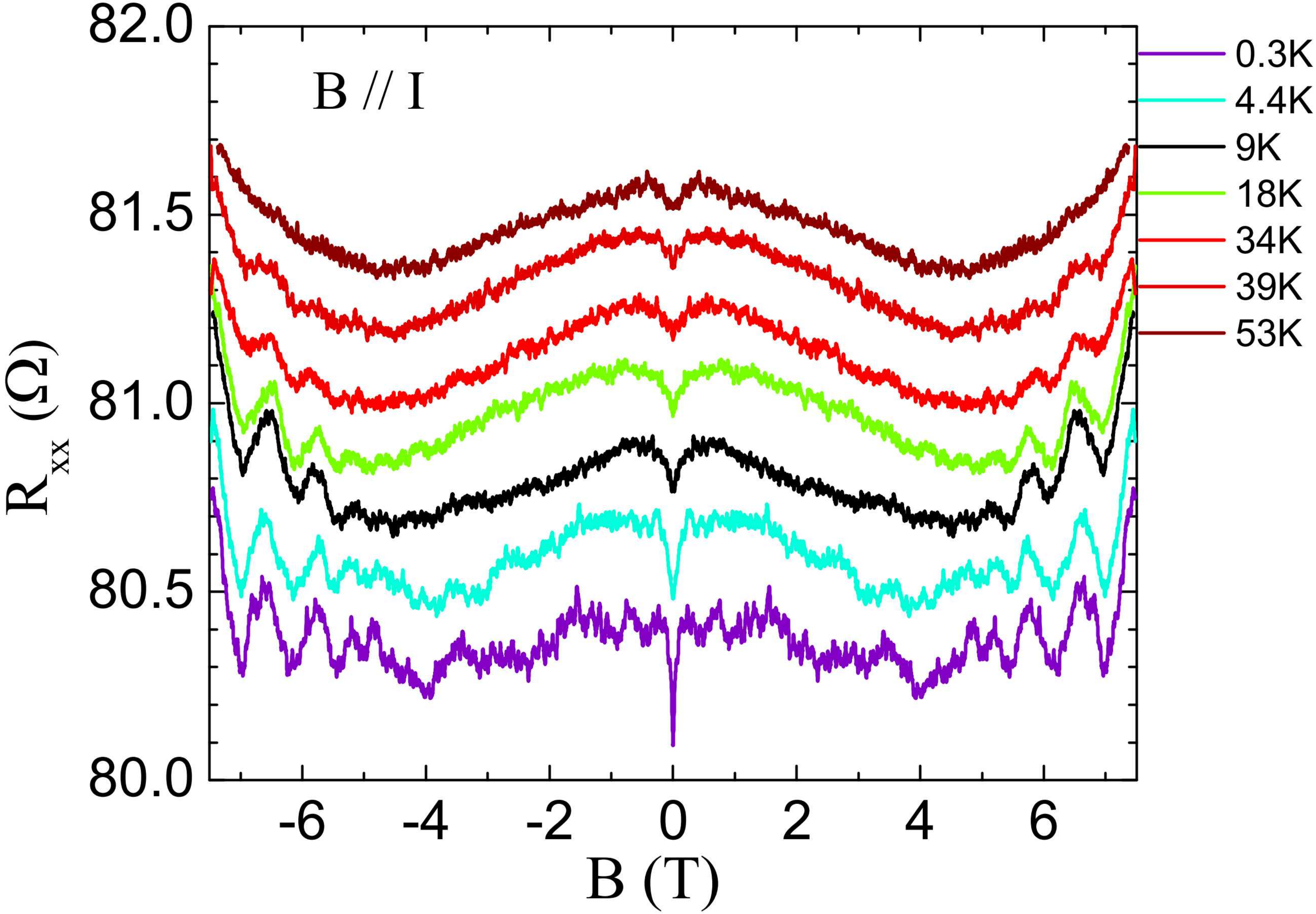
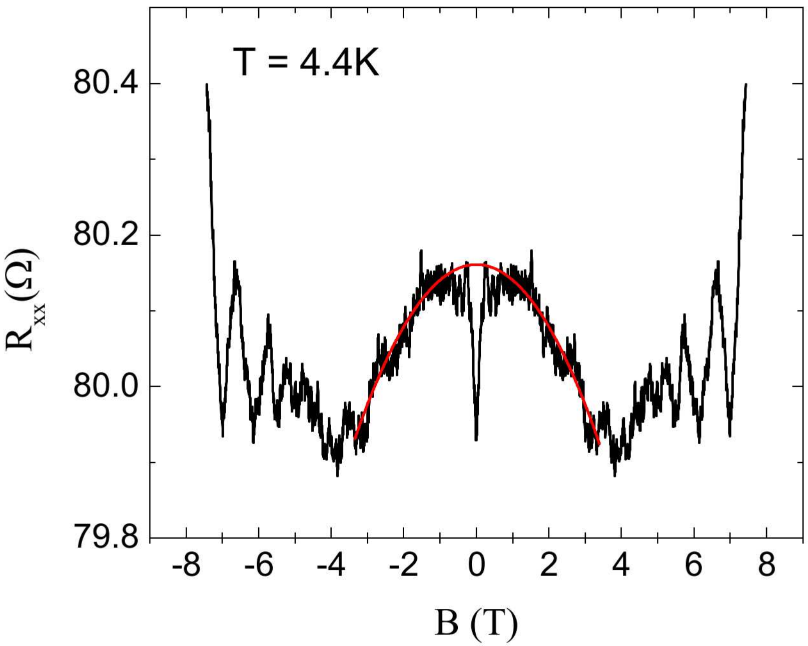
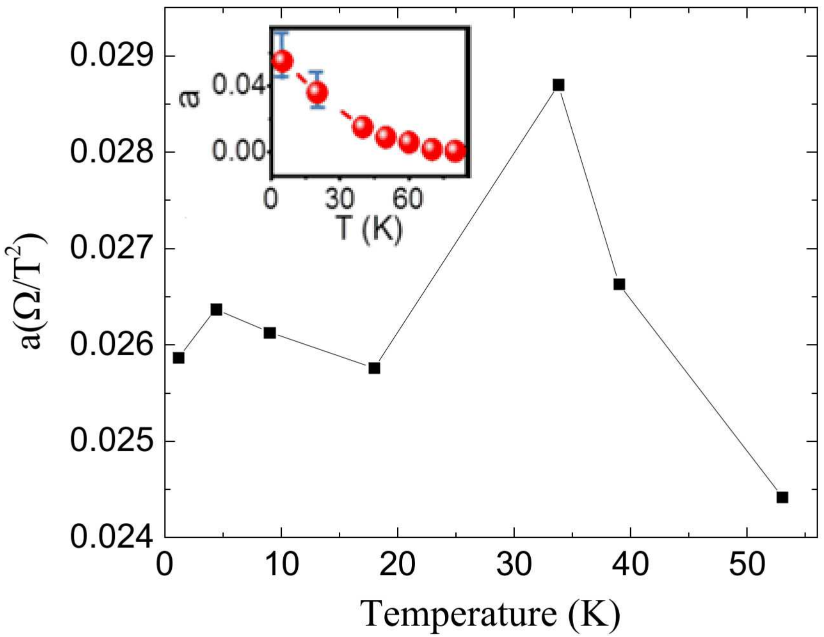
Chiral magnetic effect in Cd_3As_2



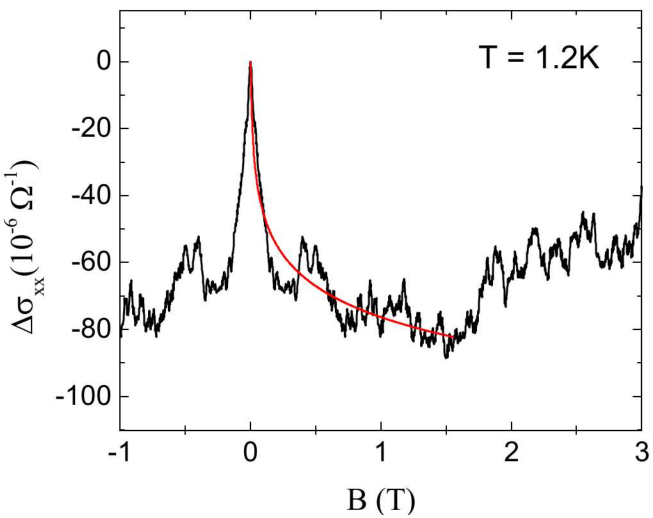
Chiral magnetic effect in Cd_3As_2

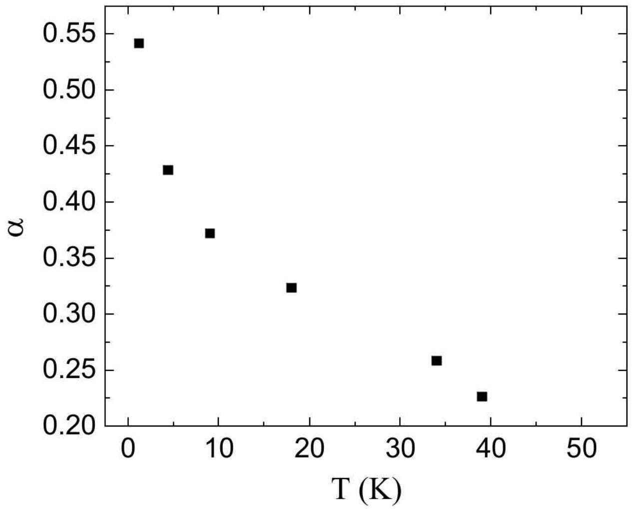




$$\sigma_{\mathrm{CME}} = \sigma_0 + a(T)B^2$$

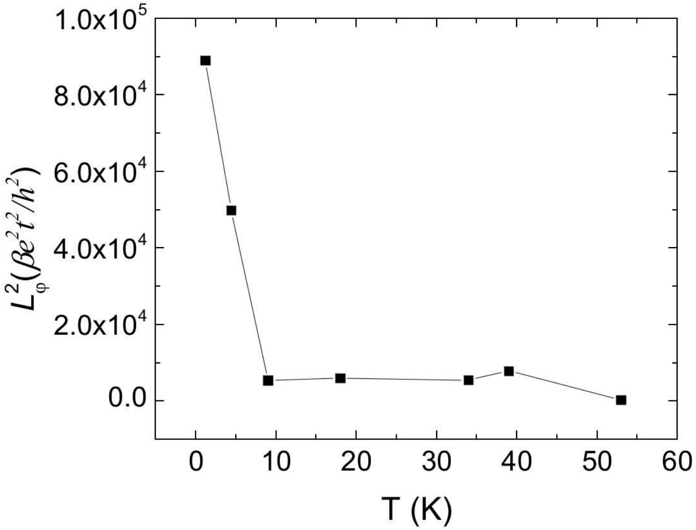
Weak anti-localization





$$\Delta\sigma_{||}(B) \cong \alpha\frac{-e^2}{2\pi^2\hbar}\ ln\left(1 + \beta\frac{et^2}{4\hbar B_\varphi}\ B^2\right)$$

$$B_\varphi = \hbar/\left(4eL_\varphi^2\right)$$



Conventional materials: $\alpha = -1$

Dirac materials: $\alpha = 0.5$

Zhao, B. *et al. Scientific Reports* **6**, 22377,(2016)

Summary II

- Non-trivial π Berry's phase in Cd_3As_2
- Angular-dependent measurement shows spherical Fermi surface
- Abnormal Chiral magnetic effect due to weak anti-location

Outline

- Introduction
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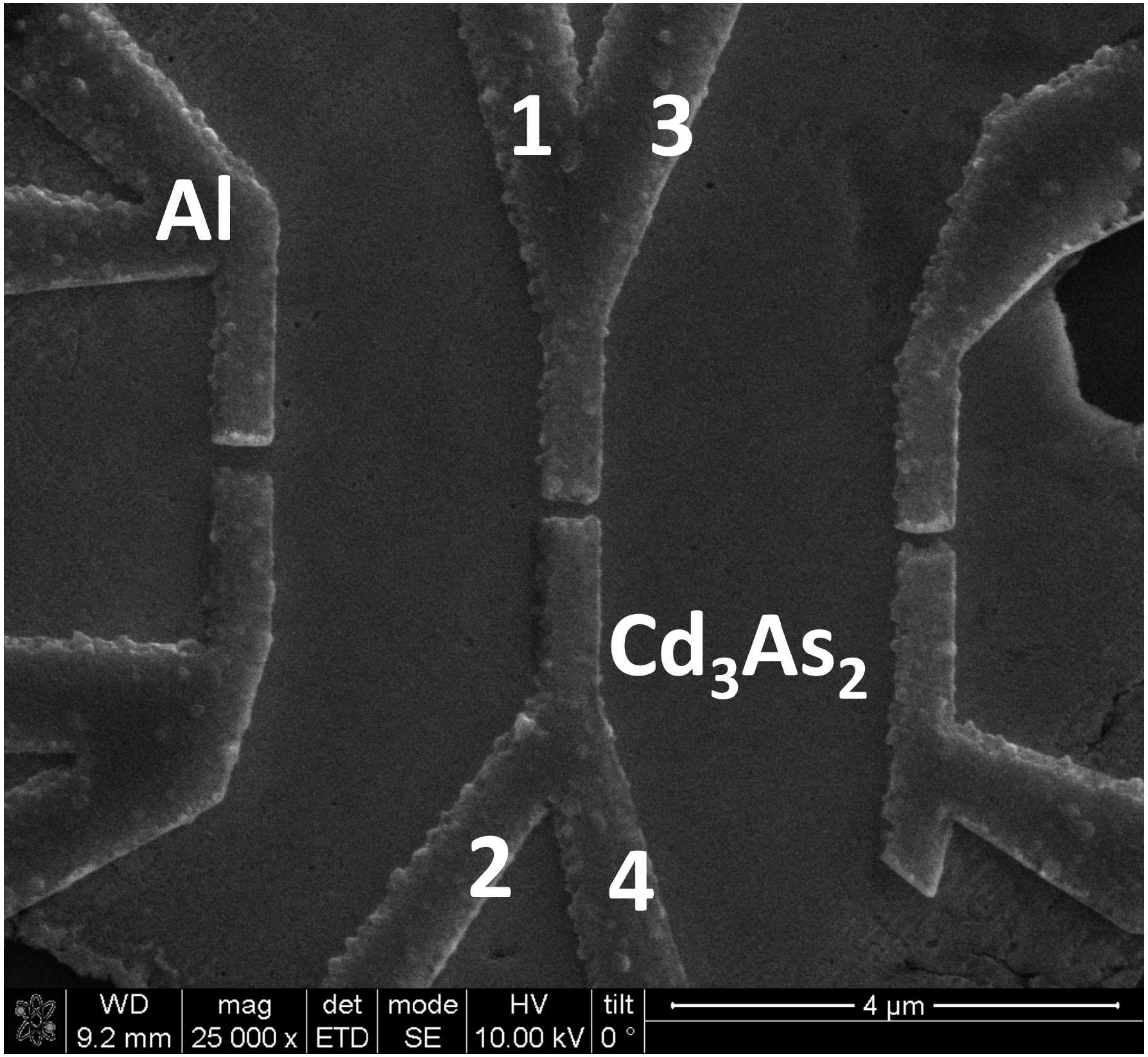
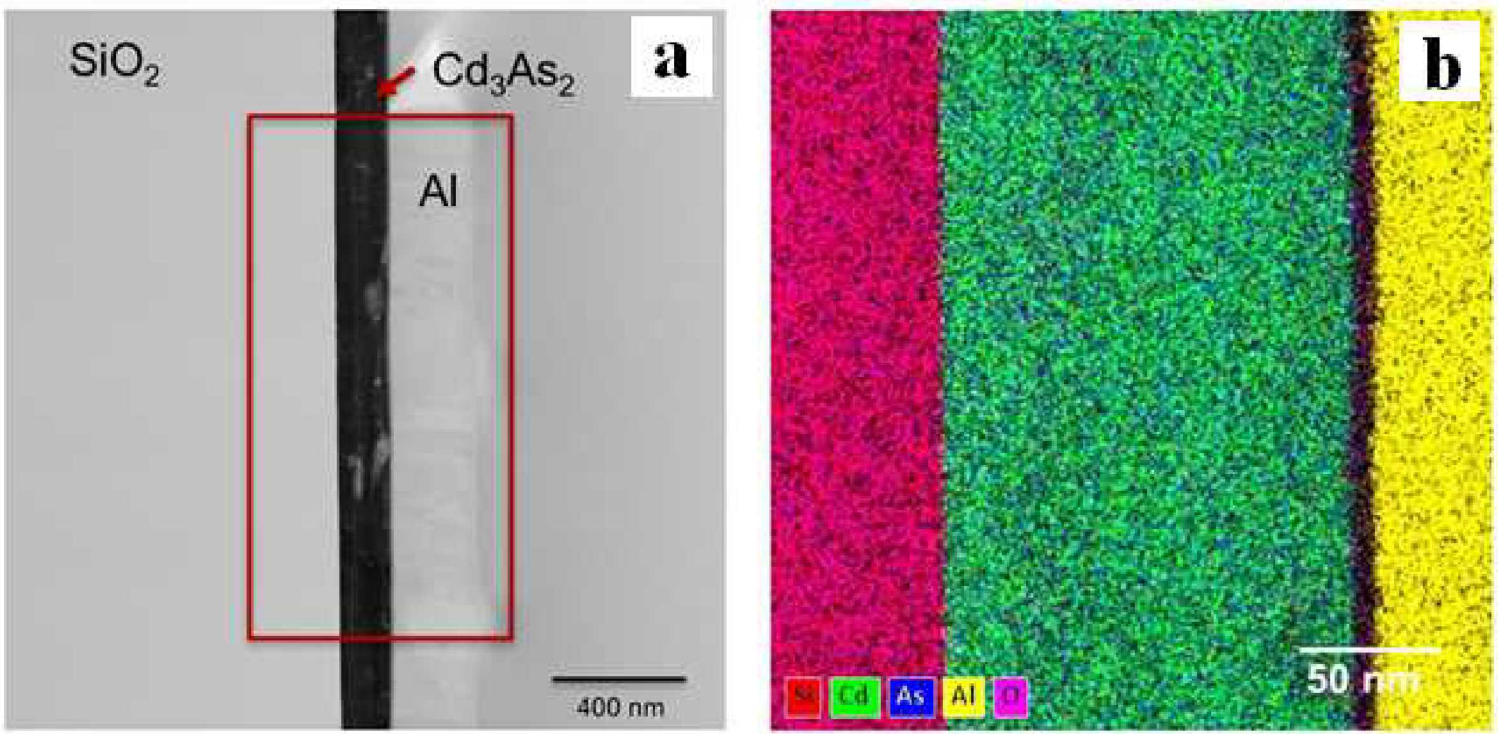
Al-Cd_3As_2-Al



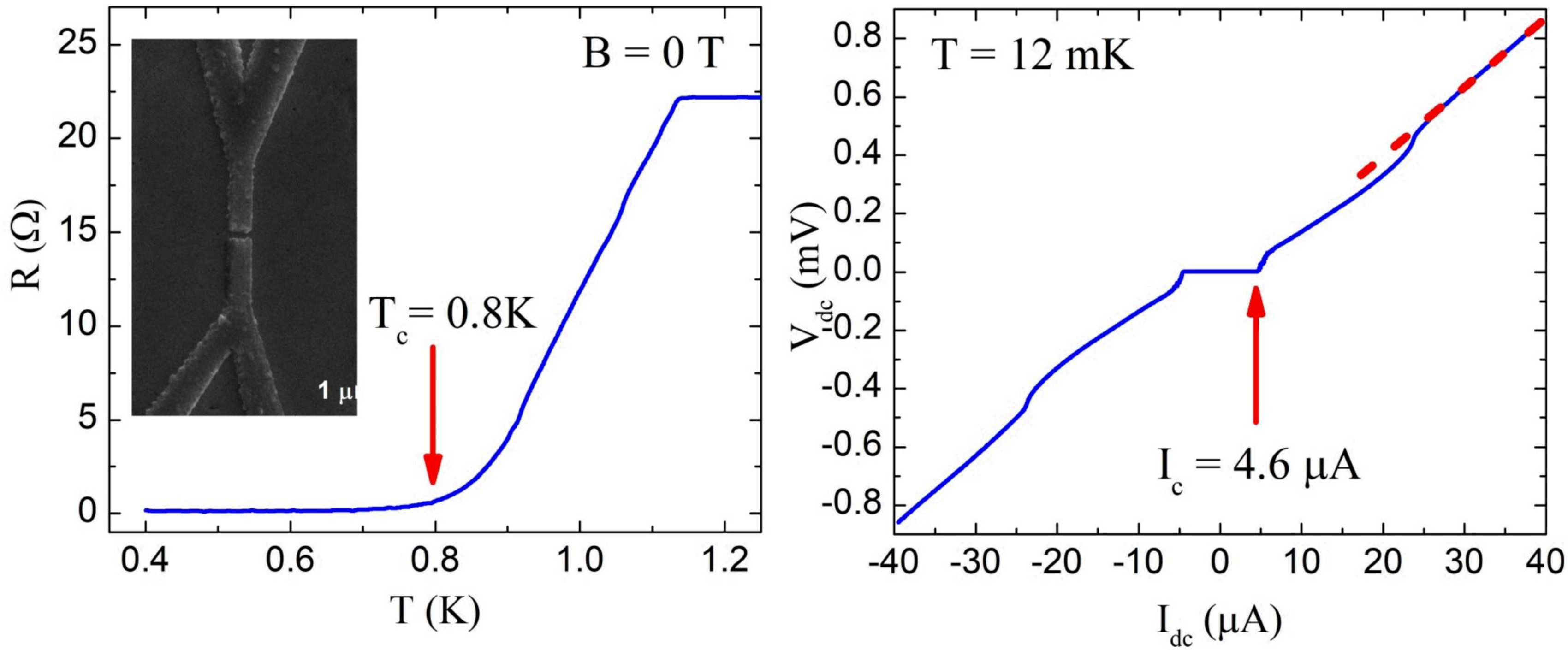
1
3
Al
Cd3As2
2
4
WD 9.2 mm
mag 25 000 x
det ETD
mode SE
HV 10.00 kV
tilt 0 °
4 μm

TEM Results



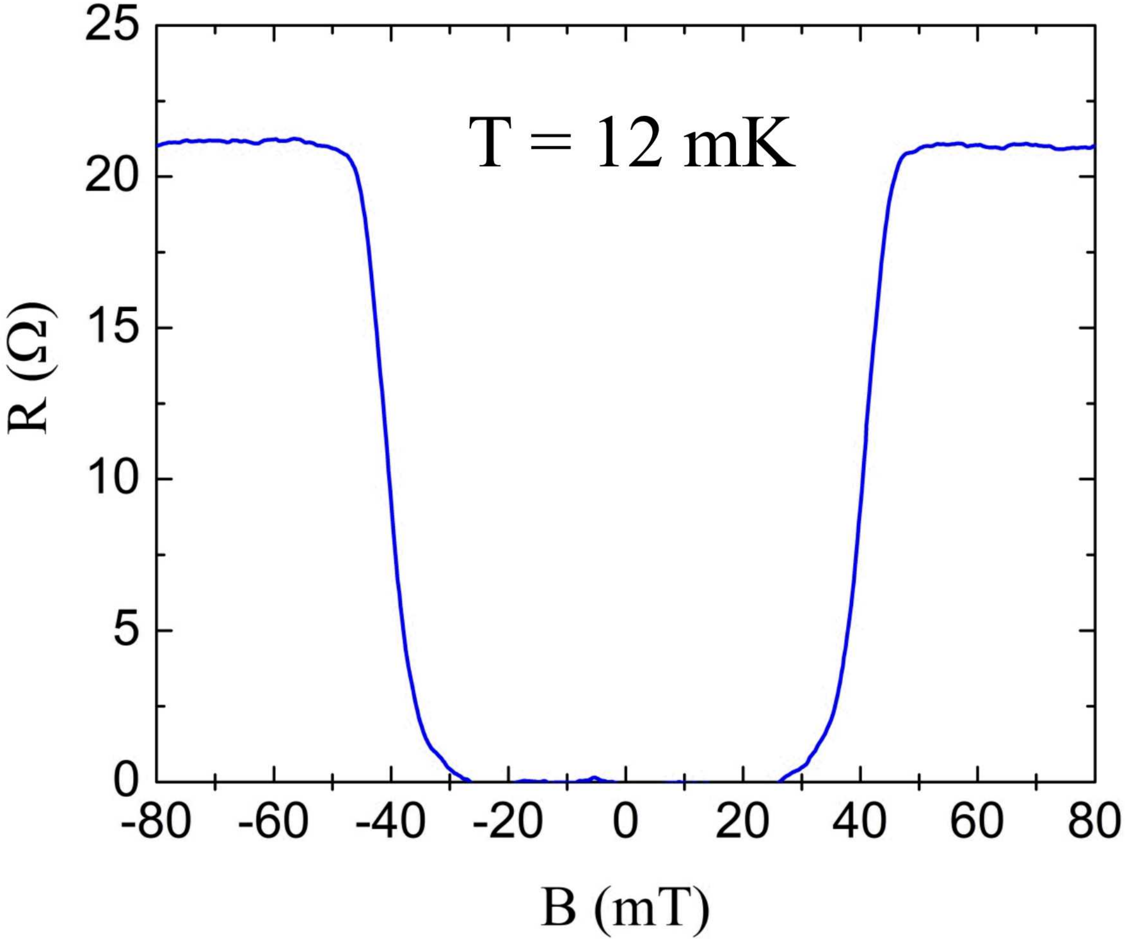
59% Cd and 41% As

Superconductivity

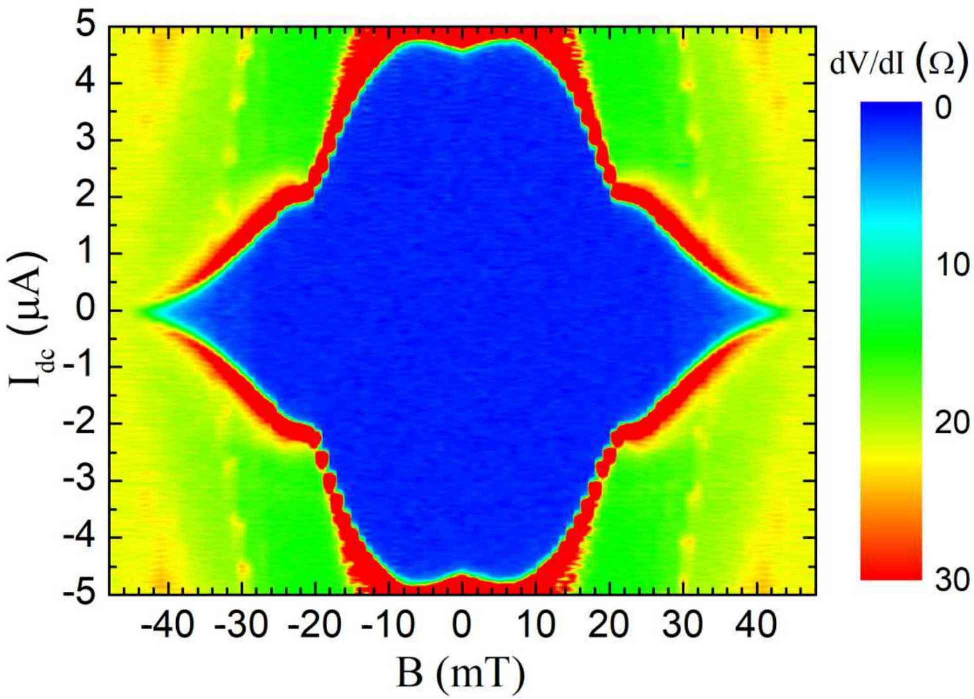


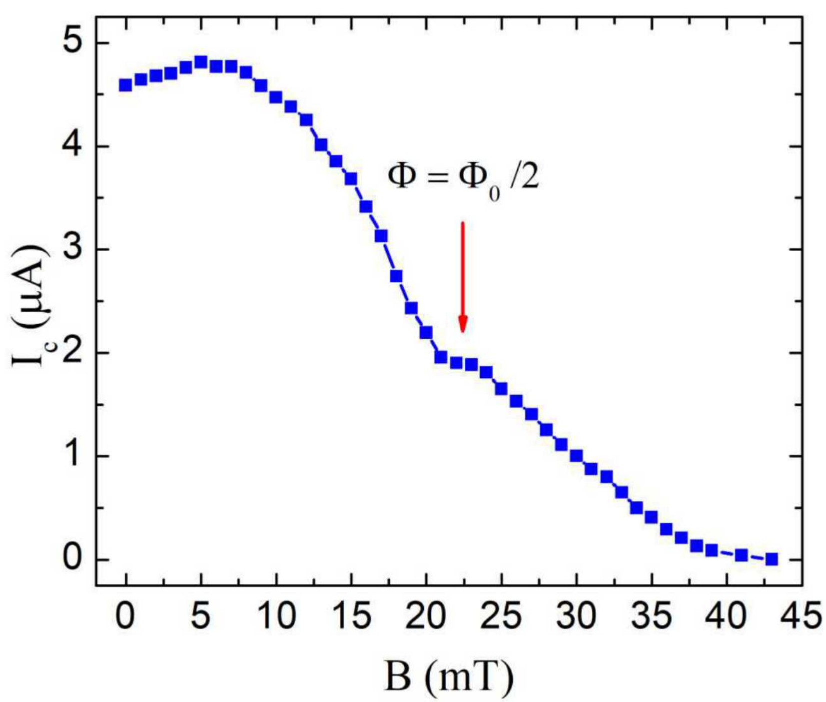
$\Delta = 1.76 k_B T_c = 120\ \mu\text{V}$ $\quad$ $I_c R_n \sim 110 \mu\text{V}, R_n = 23.8\ \Omega$

Field Dependence



π Periodic Supercurrent





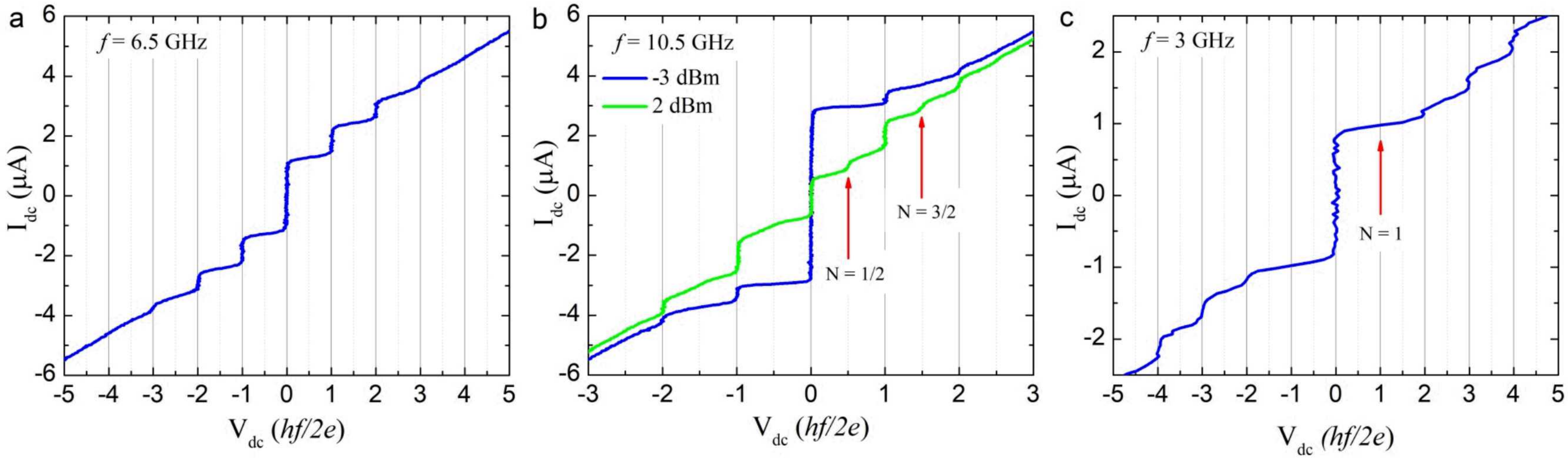
$$2\pi \text{ period: } B = \Phi_0/S_j \sim 46 \text{ mT}$$

$$S_j = 4.5\times10^{-14} \text{ m}^2$$

X. Shi, *et al*., J. Appl. Phys. 118, 133905 (2015)
J. Tiira, *et al.,* Nat. Commun. 8, 14984 (2017)
P. R. Wallace, phys. stat. sol. (b) 92, 49 (1979)

a.c. Josephson Effect

2π π 4π

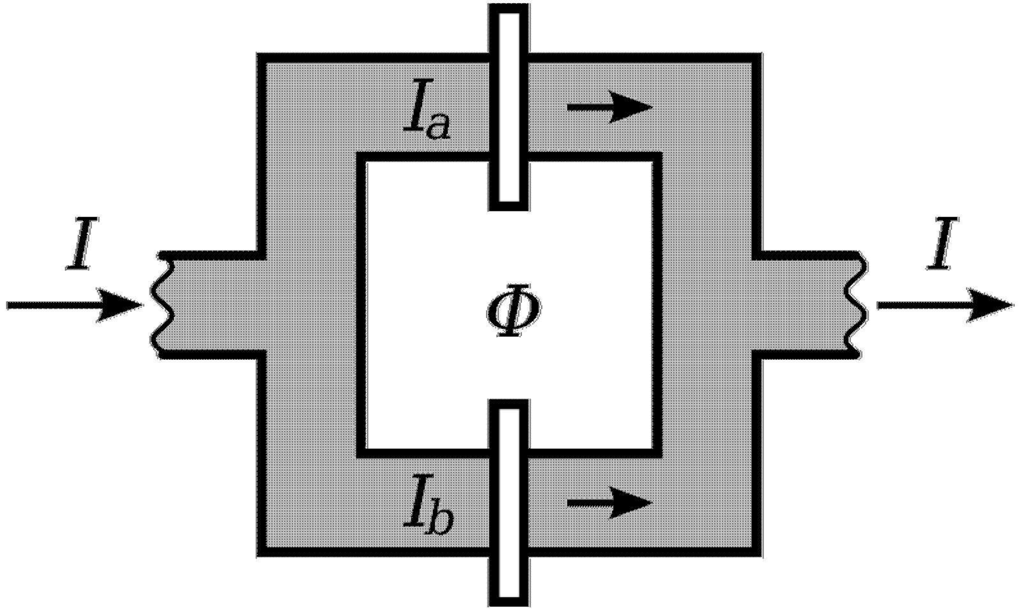


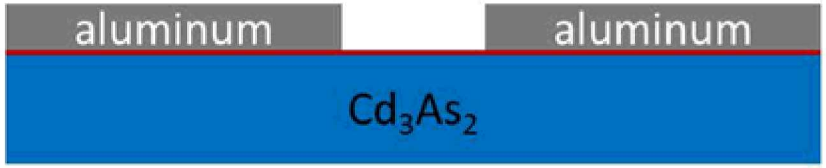
$$V_{dc} = N^{*}hf/2e$$

J. Wiedenmann, *et al.,* Nat. Commun. 7, 10303 (2016)
L.P. Rokhinson, *et al*., Nature Physics 8, 795-799 (2012)

Theoretical Model

SQUID





Summary III

- superconductor-Cd_3As_2-superconductor
- I_c enhancement by the magnetic field
- π period supercurrent and 4π period supercurrent

"π and 4π Josephson Effects Mediated by a Dirac Semimetal", arXiv:1801.04365

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Thanks!