SAND2019-6588C

Search for Majorana Particles in Dirac Semimetal Cd_3As_2

Wei Pan

Sandia National Labs

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Why Quantum Computer?

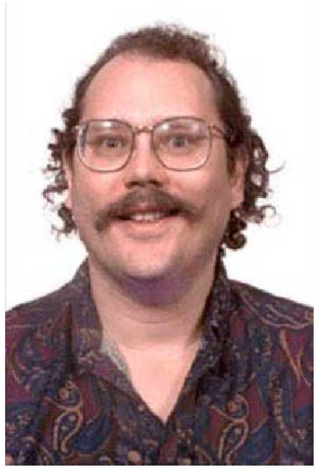
Quantum computer (QC) can

“… solve problems that classical computers cannot crack....”

(News: Q&A article in Nature)

Modern encryption is based on the assumption that it is impossible to prime-factorize a large digit number within a reasonable time frame.

Peter Shor



Classical computer: Factorizing a 200-digit RSA-200 semiprime required **75 CPU-years** (Wikipedia).

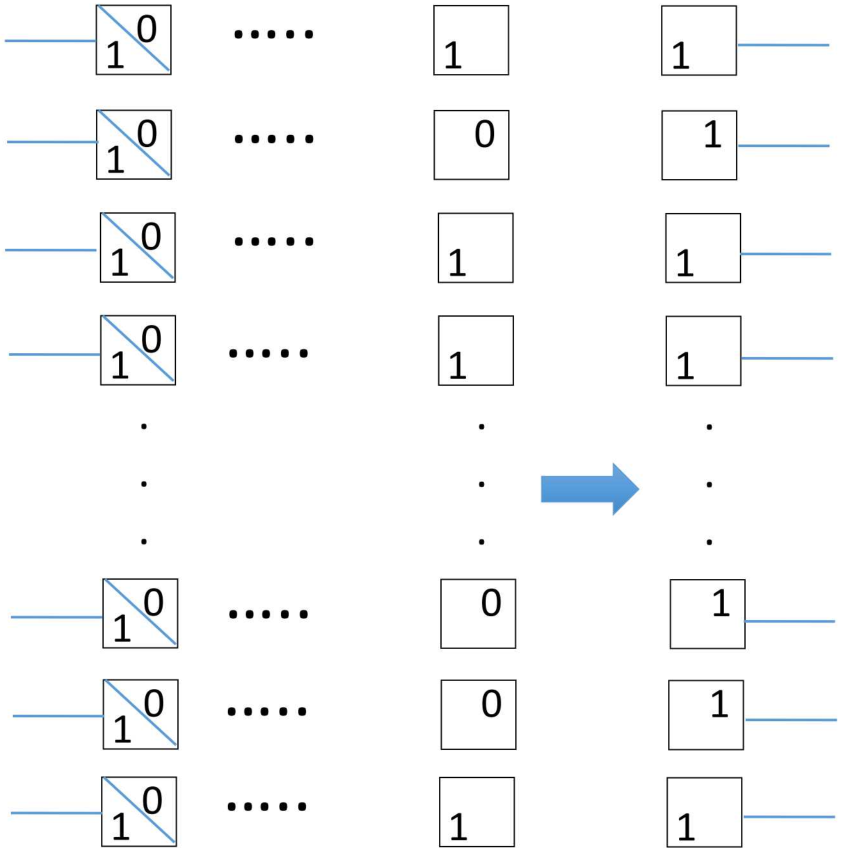
Peter Shor in 1994, algorithm for prime factorization

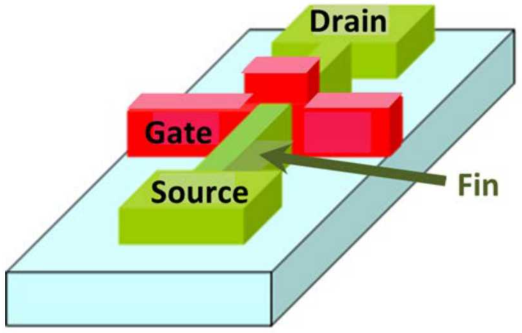
using a *quantum computer*

A 300-digit number can be prime-factorized in a few hours!

Issues with quantum computation

- large error rate
- many extra bits for error correction





However, this is extremely difficult, if not **impossible**, to implement many extra quantum bits!

Feature | Computing | Hardware

15 Nov 2018 | 16:00 GMT

The Case Against Quantum Computing

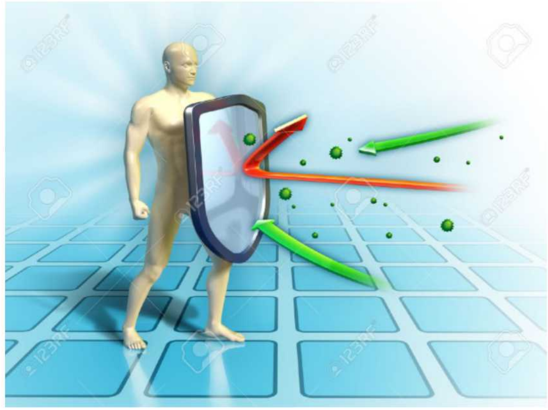
The proposed strategy relies on manipulating with high precision an unimaginably huge number of variables

By **Mikhail Dyakonov**

To repeat: A useful quantum computer *needs to process a set of continuous parameters that is larger than the number of subatomic particles in the observable universe.*

Topological quantum computation to rescue

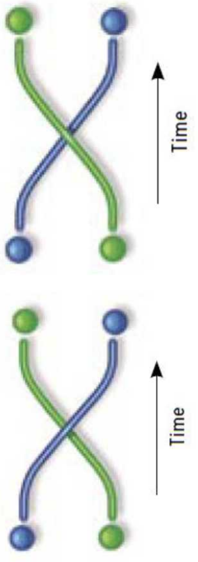
- global operation of braiding Majorana fermions, thus robust against local decoherence processes.

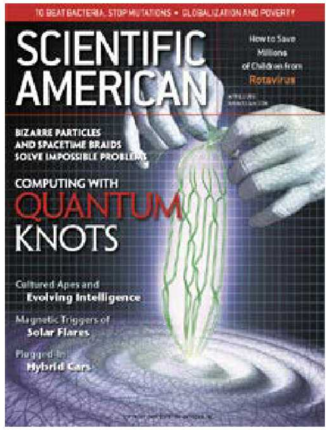


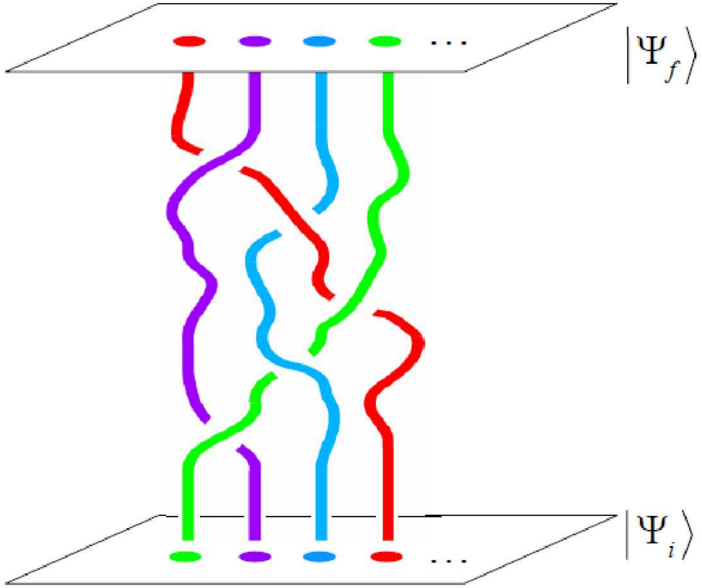
- topological quantum computation: error rate < 10^{-30}.

qubit 0

qubit 1







However….

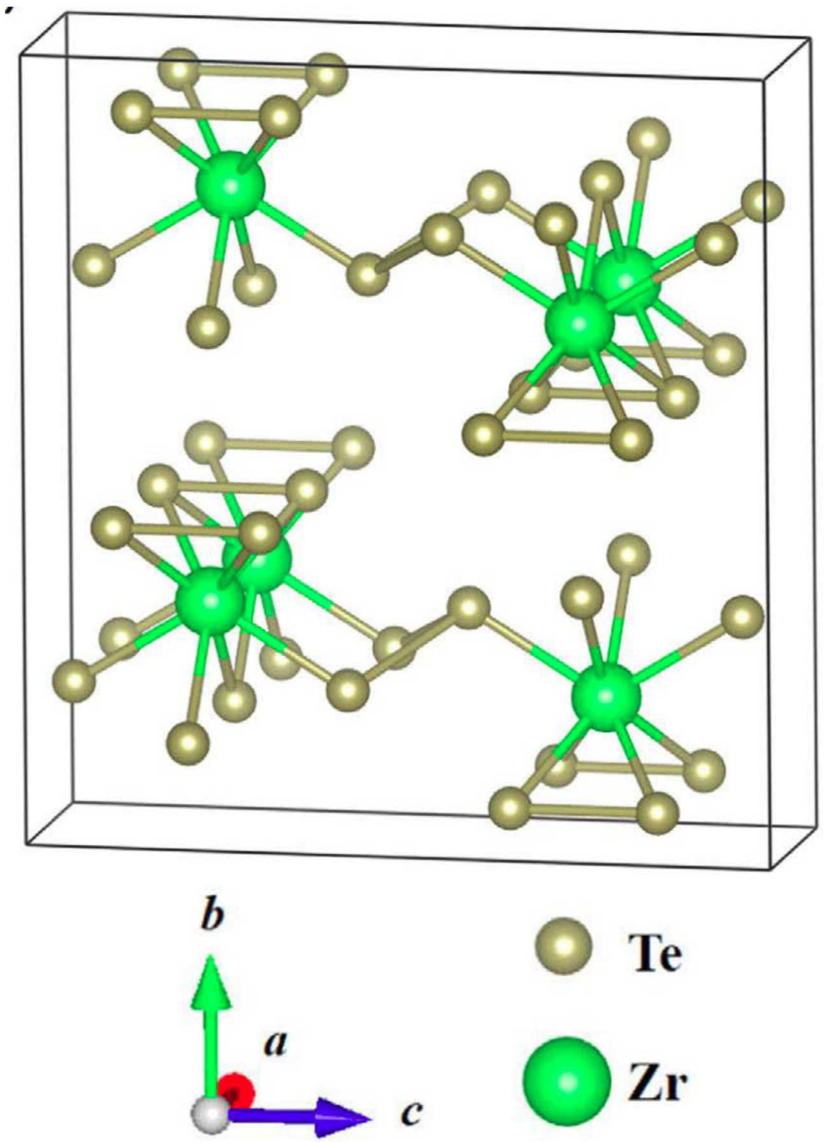
Existence of Majorana fermions has not been confirmed yet!

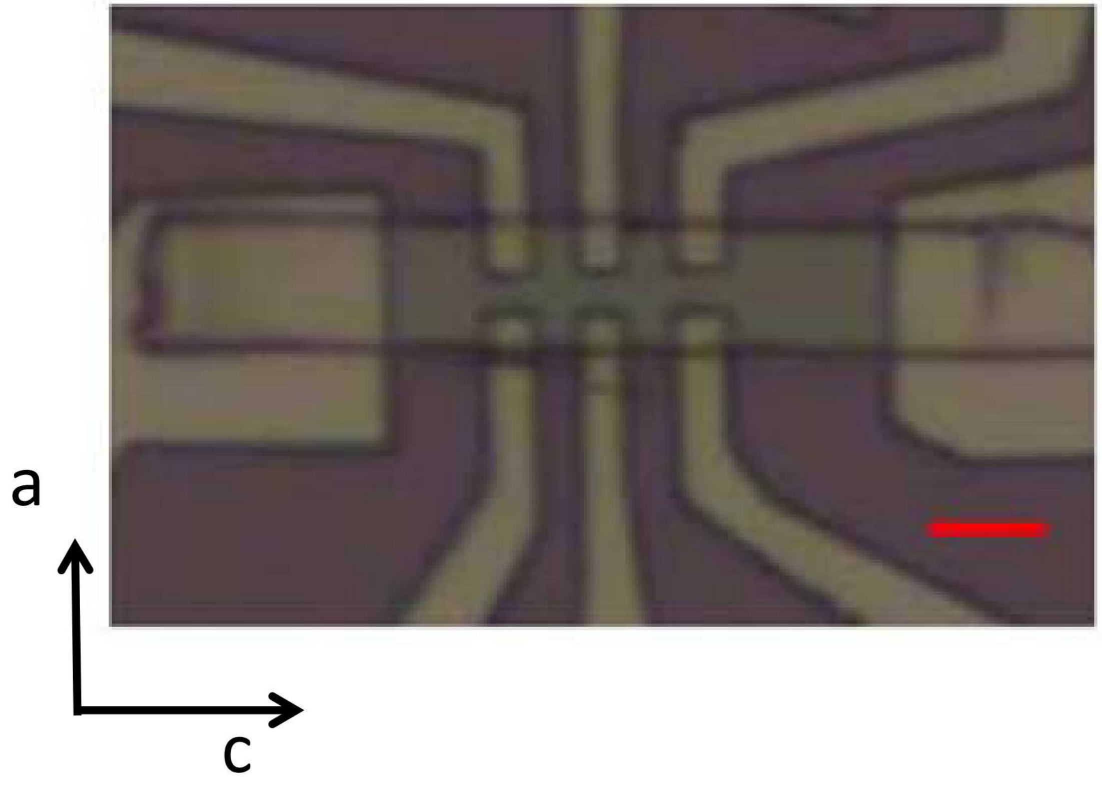
Topological quantum materials project at Sandia

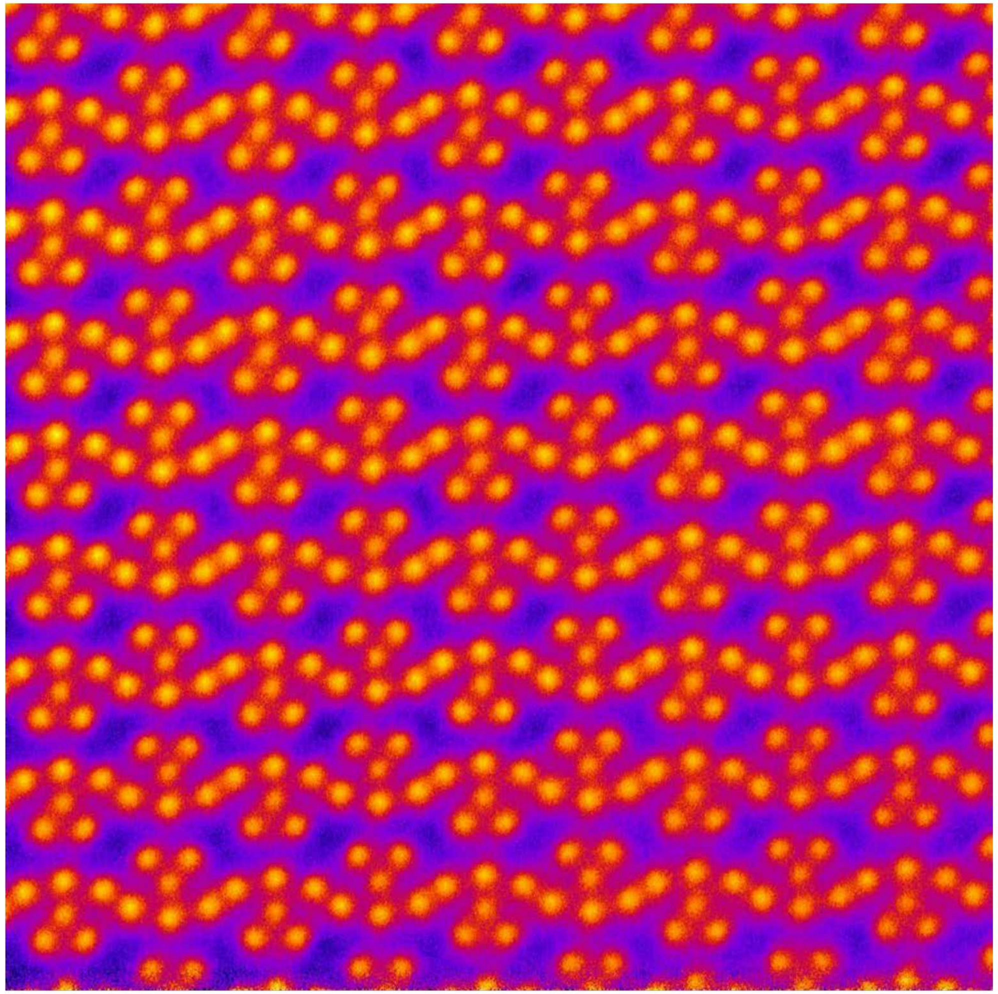
- S.R. Lee, P.A. Sharma, A.L. Lima-Sharma, W. Pan, and T.M. Nenoff, CHEMISTRY OF MATERIALS (2019).
- D.L. Medlin, N. Yang, C.D. Spataru, L.M. Hale, and Y. Mishin, Nature Communications (2019).

- F. Zhang and W. Pan, Nature Materials (2018).
- G. Kunakova, L. Galletti, S. Charpentier, J. Andzane, D. Erts, F. Leonard, C.D. Spataru, T. Bauch, and F. Lombardi, Nanoscale (2018).
- W. Yu, W. Pan, D. Medlin, M.A. Rodriguez, S.R. Lee, Z.-q. Bao, and F. Zhang, Phys. Rev. Lett. (2018).
- F. Leonard, W. Yu, K.C. Collins, D.L. Medlin, J.D. Sugar, A.A. Talin, and W. Pan, ACS Applied Materials & Interfaces (2018).

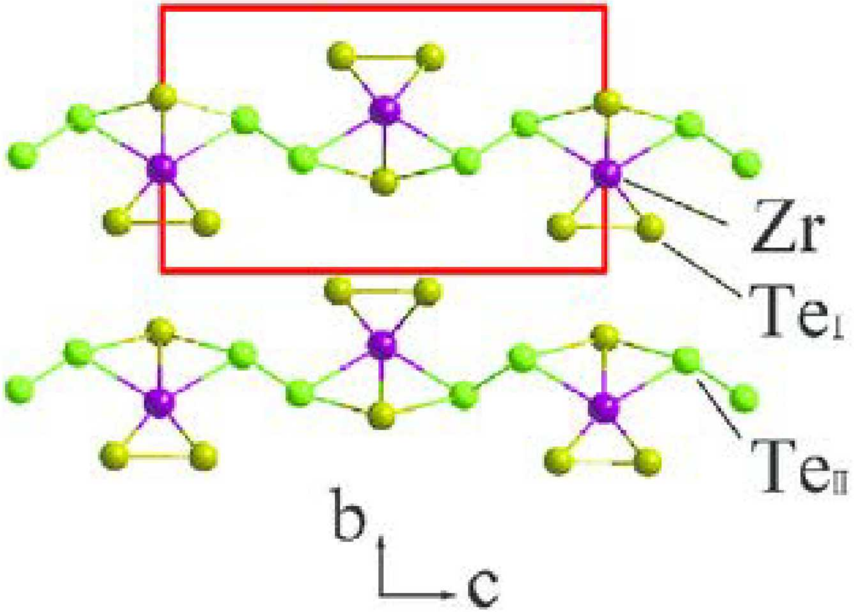
$ZrTe_5$

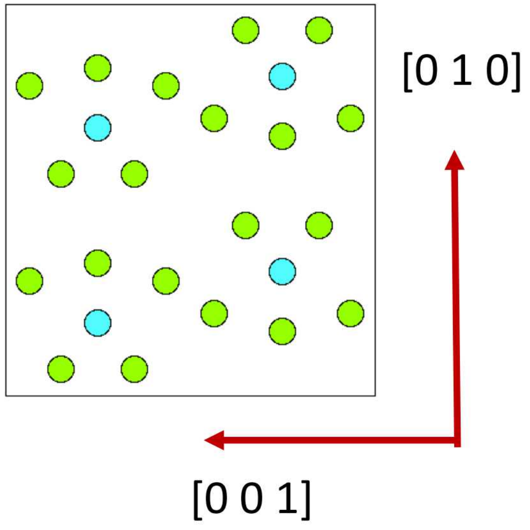


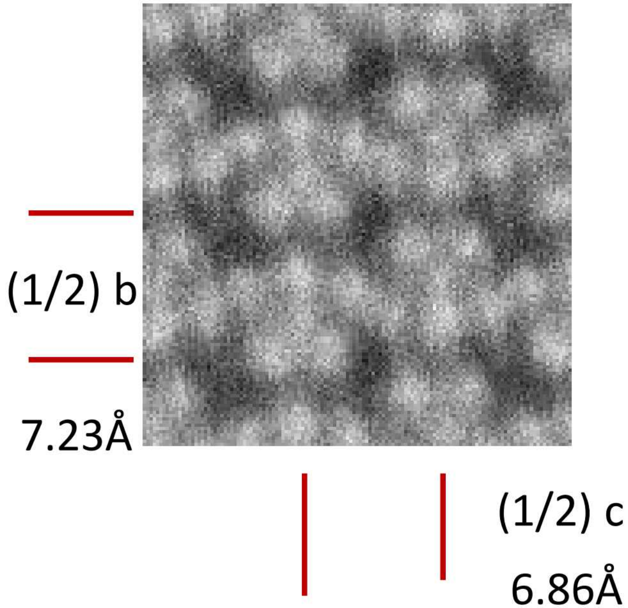




(D. Medlin) 1 nm







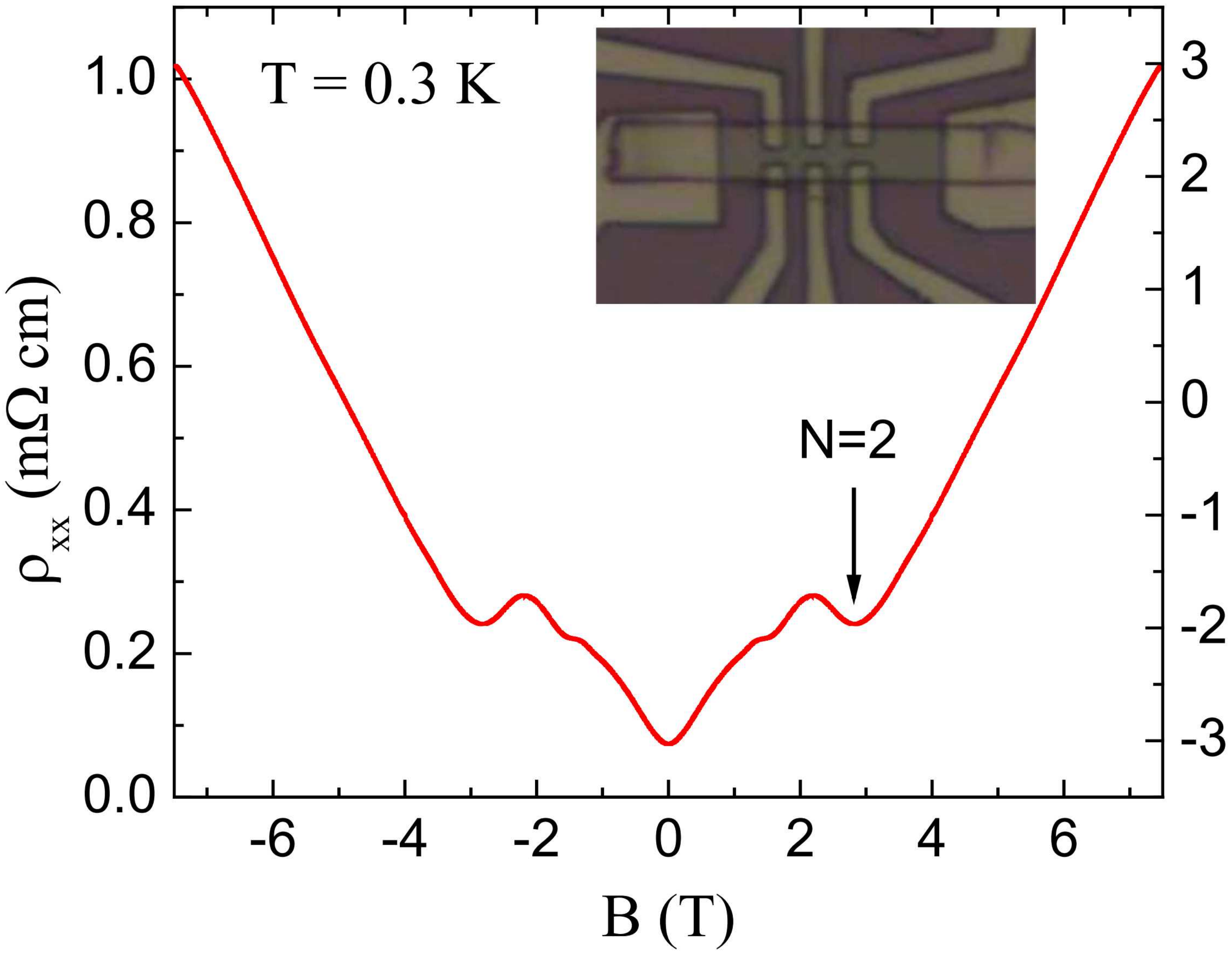
b=14.46 Å, c=13.72Å

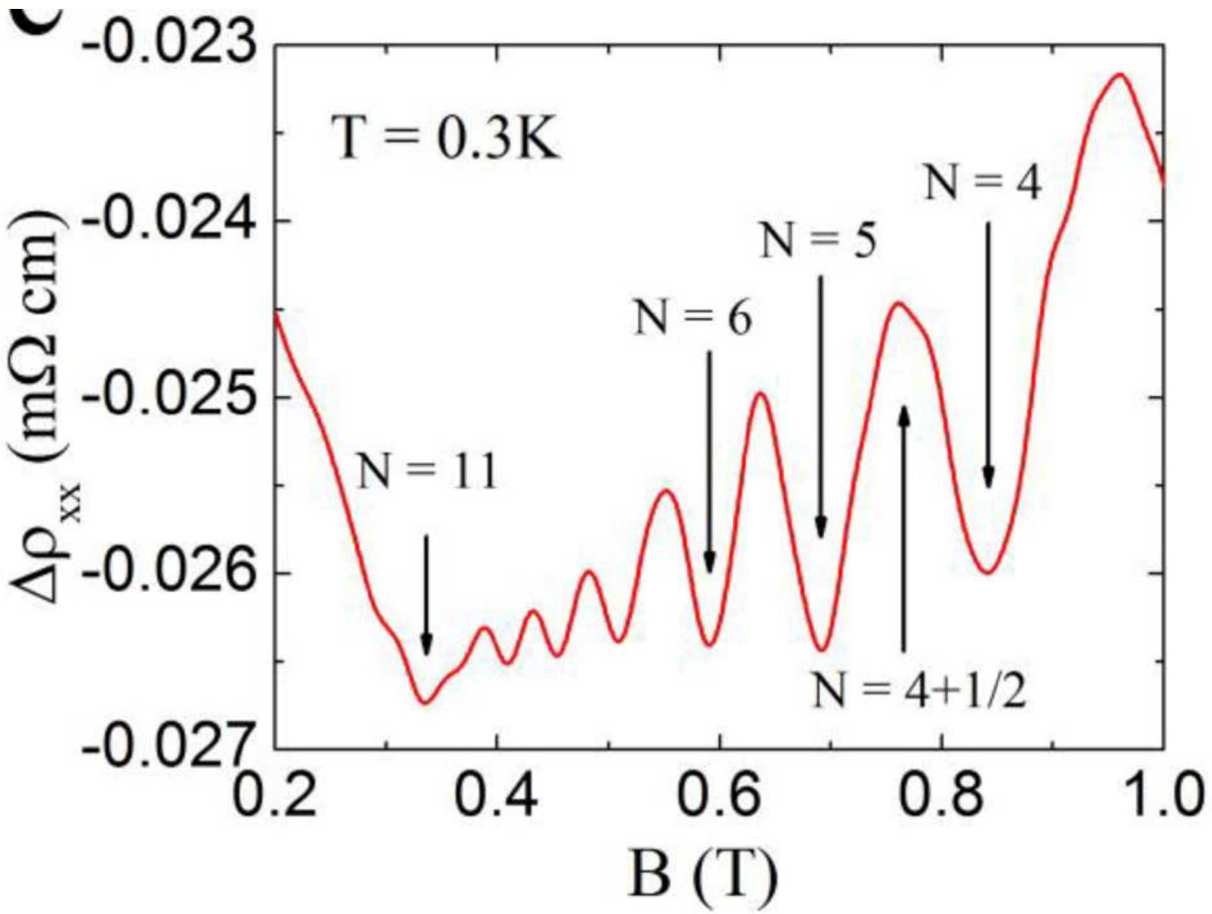
Spacegroup: Cmcm (#63)

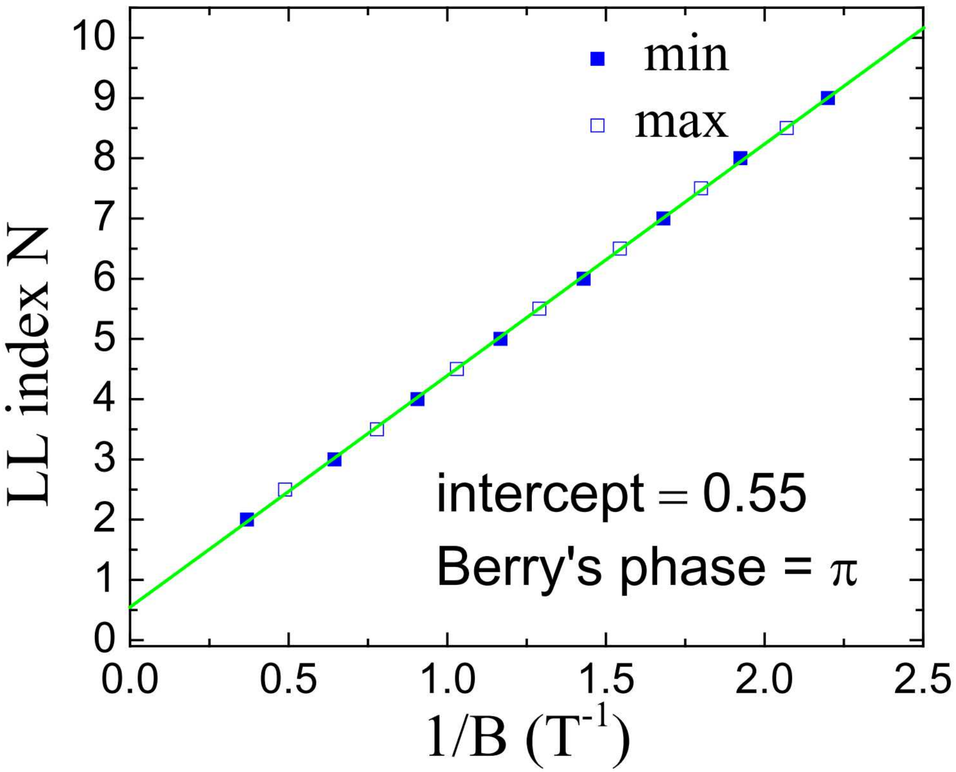
a=3.9875Å, b=14.530Å, c=13.724Å

H. Fjellvåg, A. Kjekshus, Solid State Communications, 60 (2) (1986) 91-93

Quantum oscillations in ZrTe5



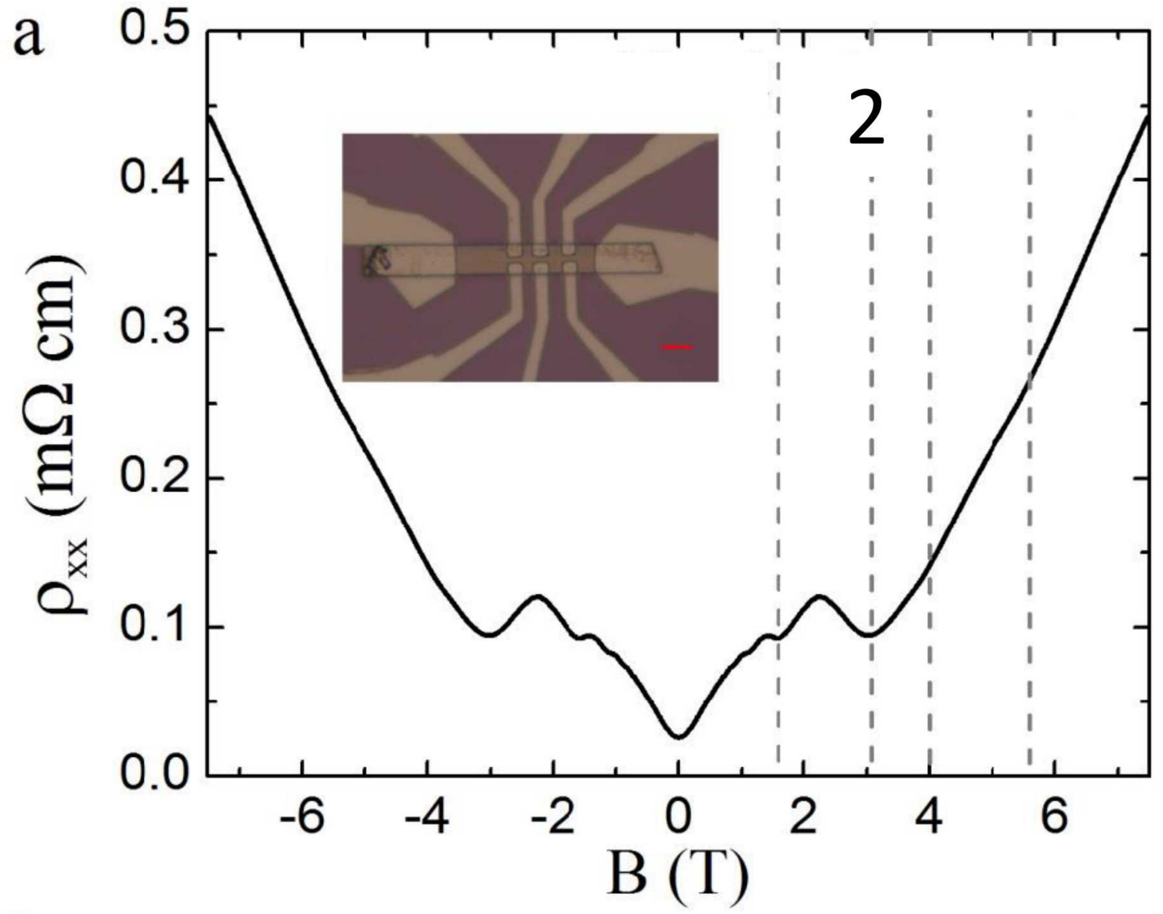


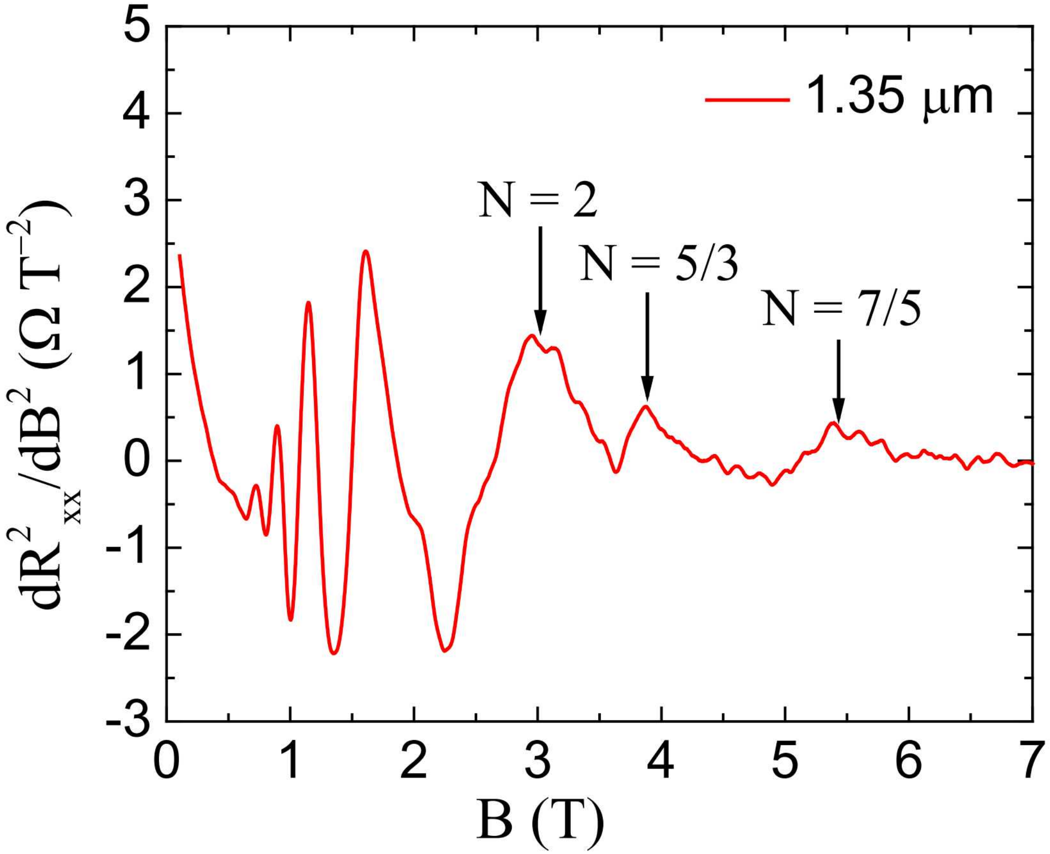


1. $\mu_q = 1/\mathrm{B} = 2.5 \times 10^4\ \mathrm{cm^2 V^{-1} s^{-1}}$

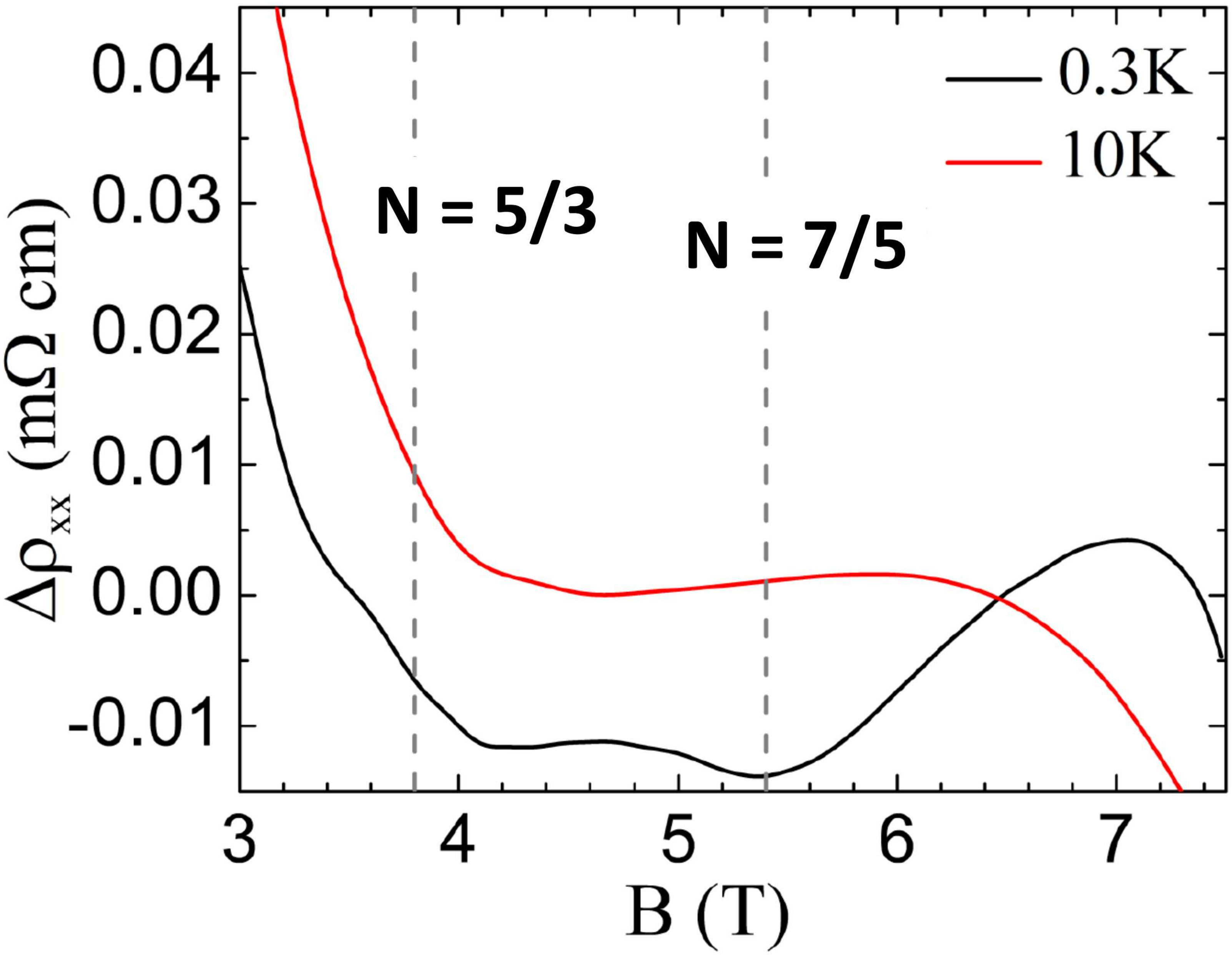
2. $n^{\mathrm{SdH}} = \frac{2e}{h}\frac{\mathrm{N}}{1/B} = 1.86 \times 10^{11}\ \mathrm{cm^{-2}}$

Quantum Oscillations at Fractional Landau levels



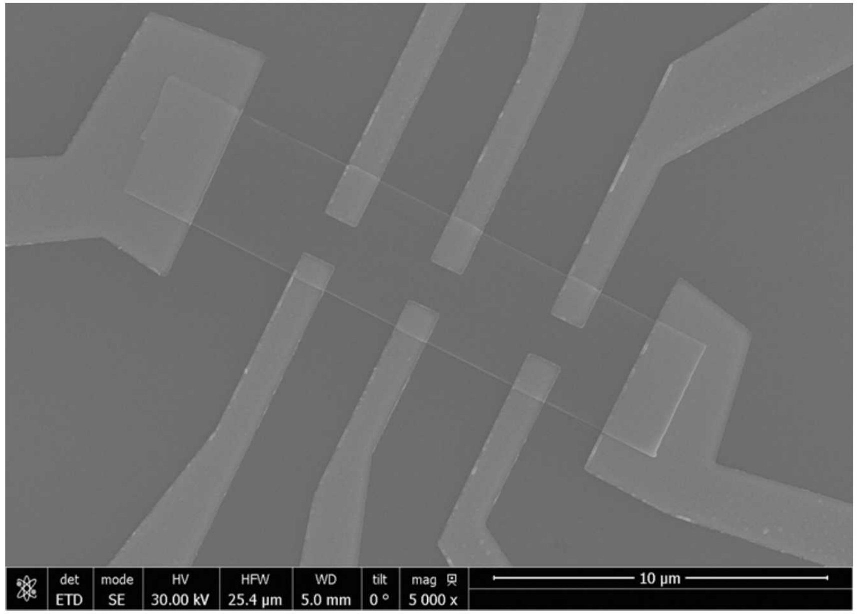


W. Yu, Y. Jiang, J. Yang, Z.L. Dun, H.D. Zhou, Z. Jiang, P. Lu, and W. Pan, Scientific Reports (2016).

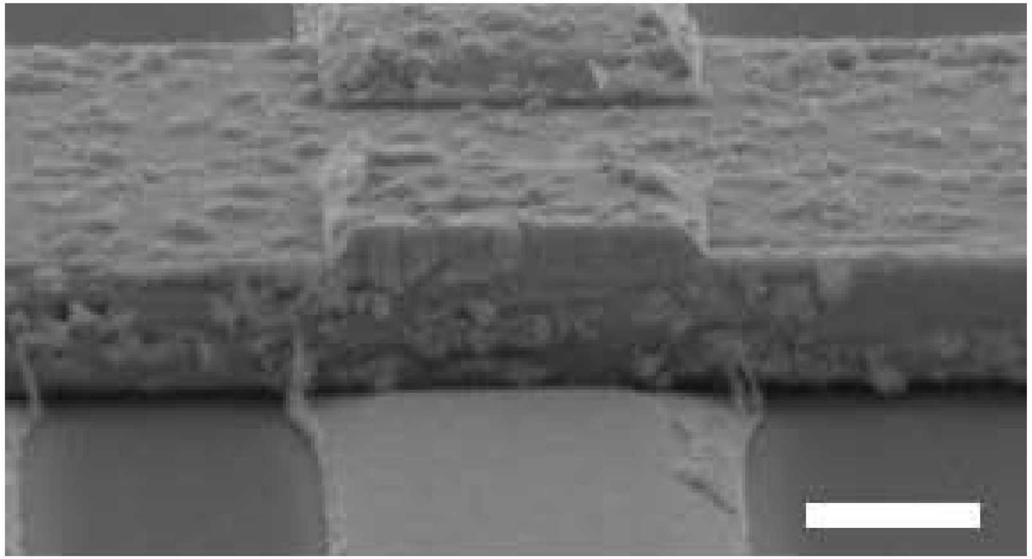


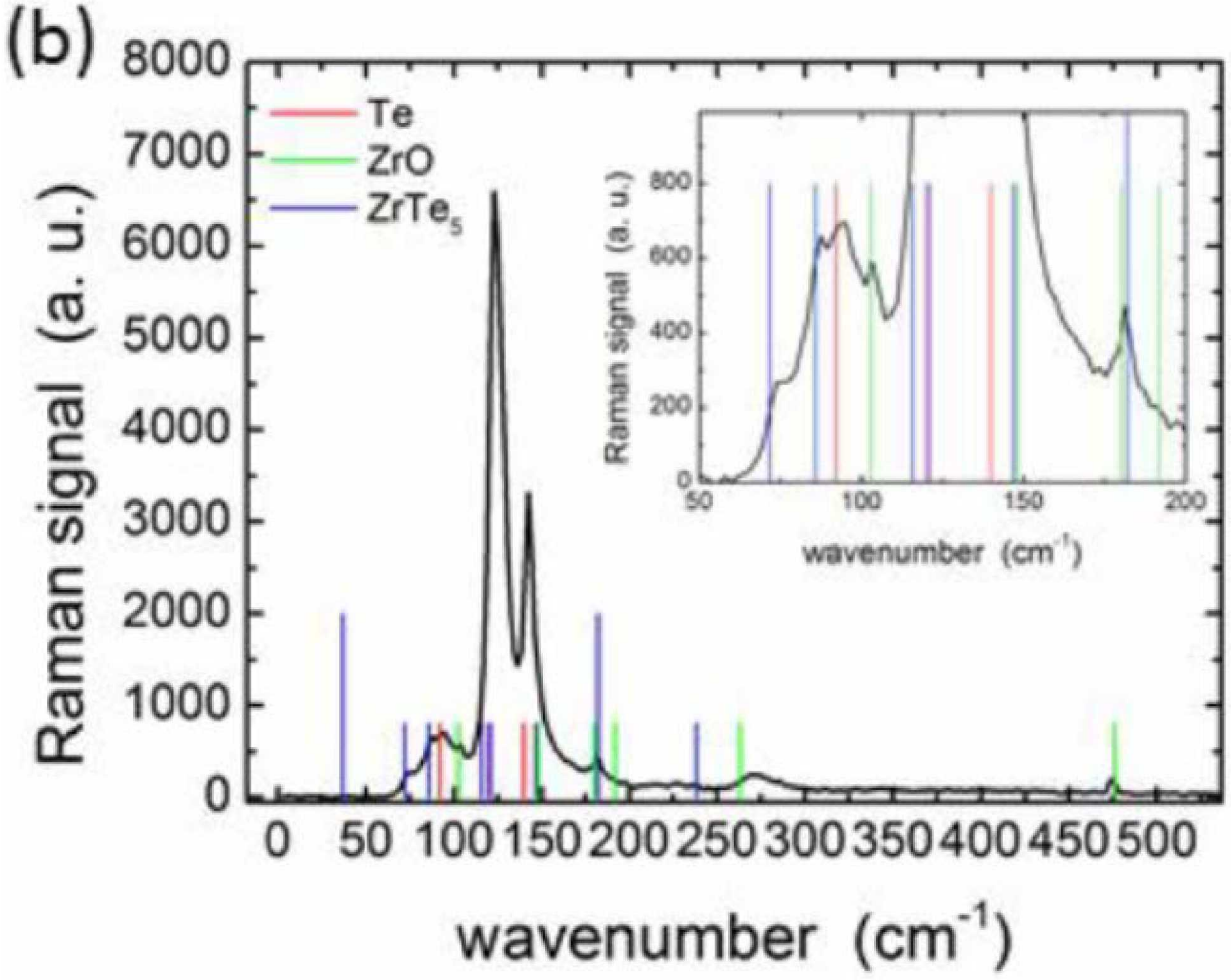
W. Yu, Y. Jiang, J. Yang, Z.L. Dun, H.D. Zhou, Z. Jiang, P. Lu, and W. Pan, Scientific Reports (2016).

freshly fabricated device



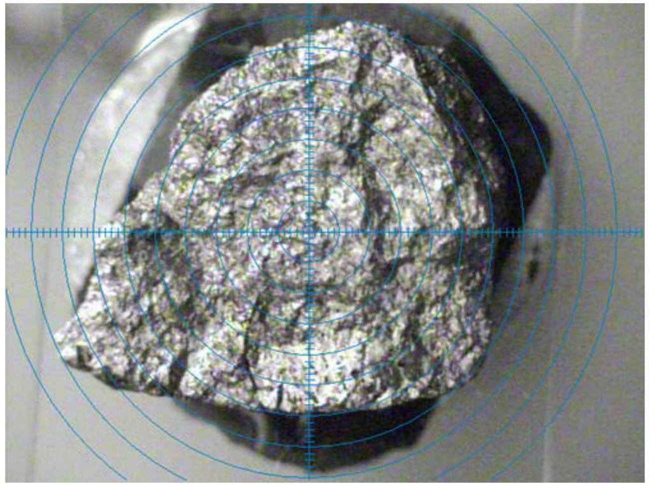
after a few days in air



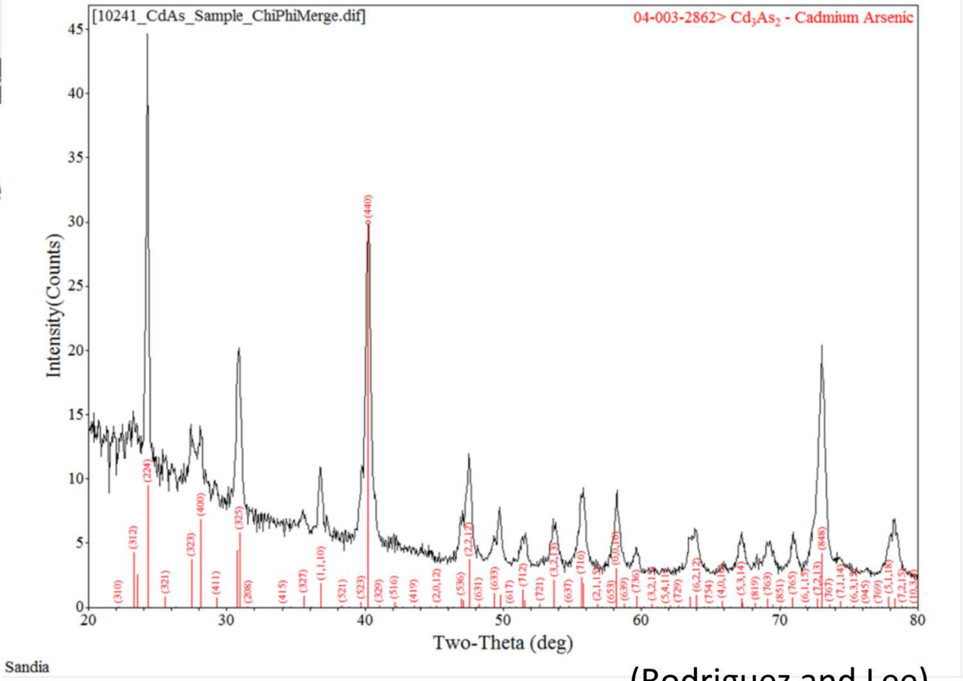


Dirac semimetal Cd_3As_2

air stable, and can be purchased from a commercial company



All of the observed diffraction maxima correspond with expected reflections for single-phase Cd3As2

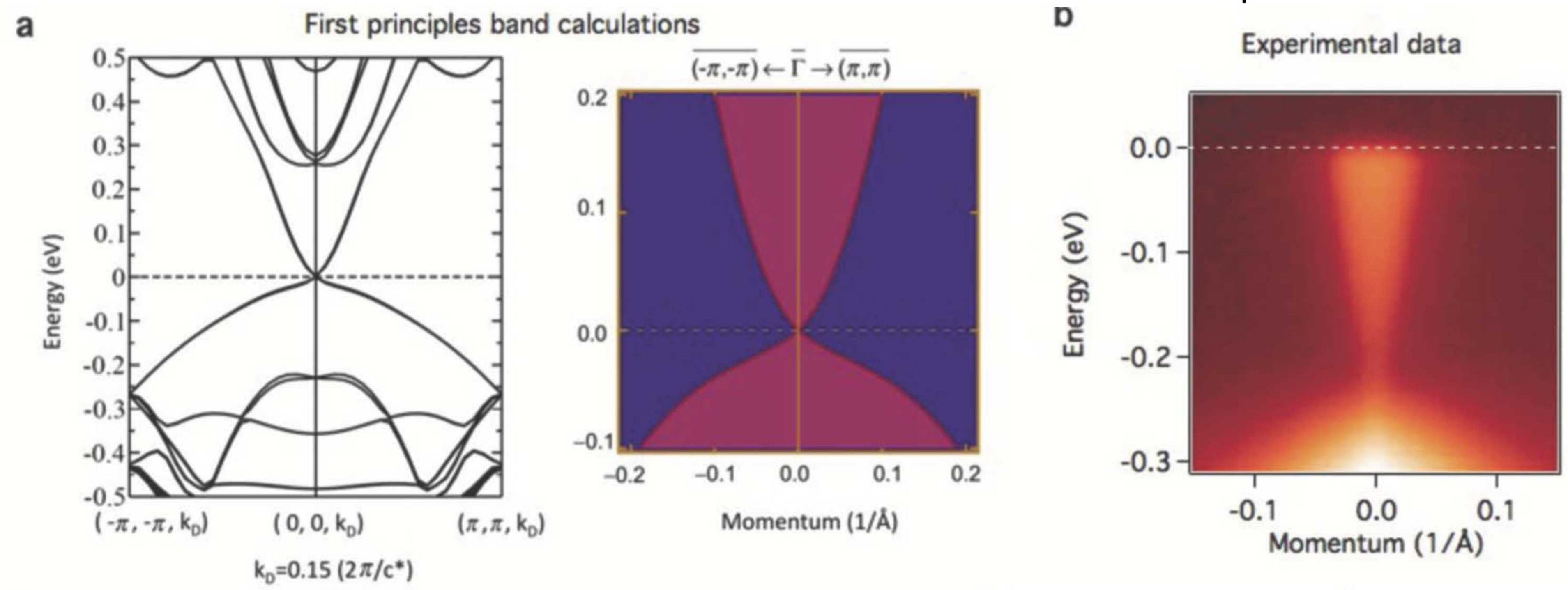


(Rodriguez and Lee)

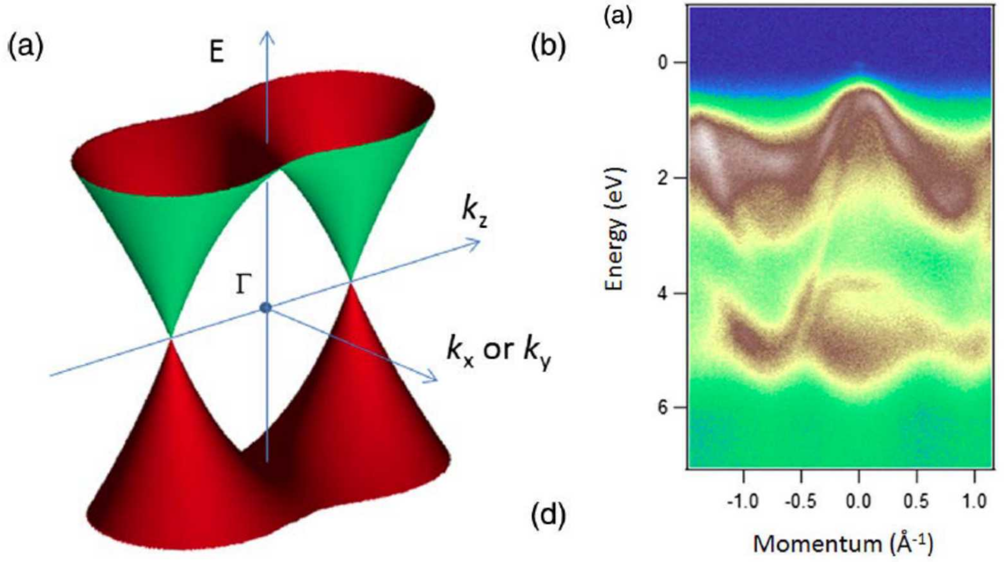
Wang et al. Three-dimensional Dirac semimetal and quantum transport in Cd3As2. Phys. Rev. B 88, 125427 (2013).

Cd_3As_2 is a 3D Dirac semimetal, protected by the C4 symmetry and spin-orbit coupling.

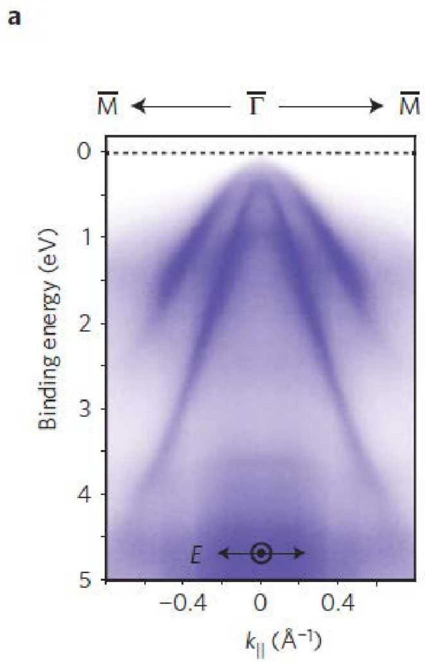
Neupane et al Nature Commun. 5, 3786 (2014).

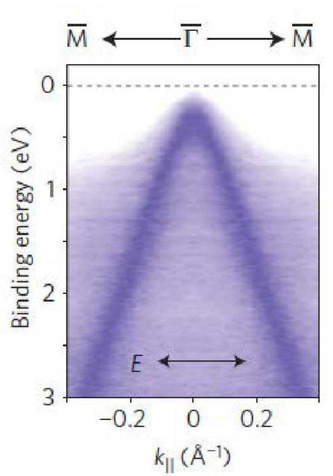


Borisen et al, PRL 113, 027603 (2014)

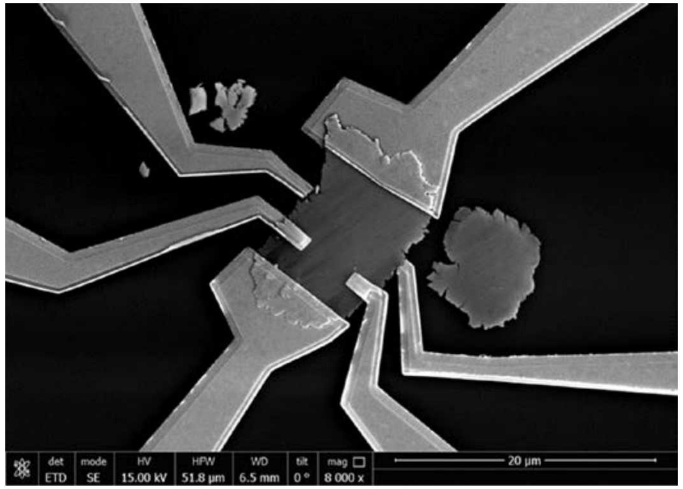


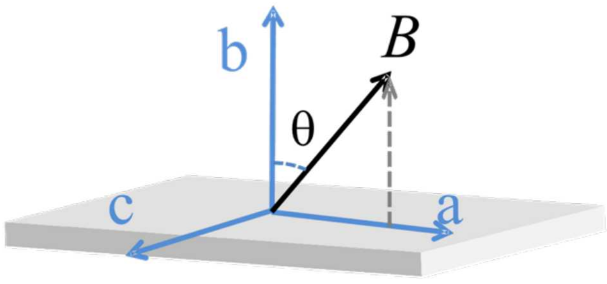
Liu et al, Nature Mat. 13, 677 (2014).



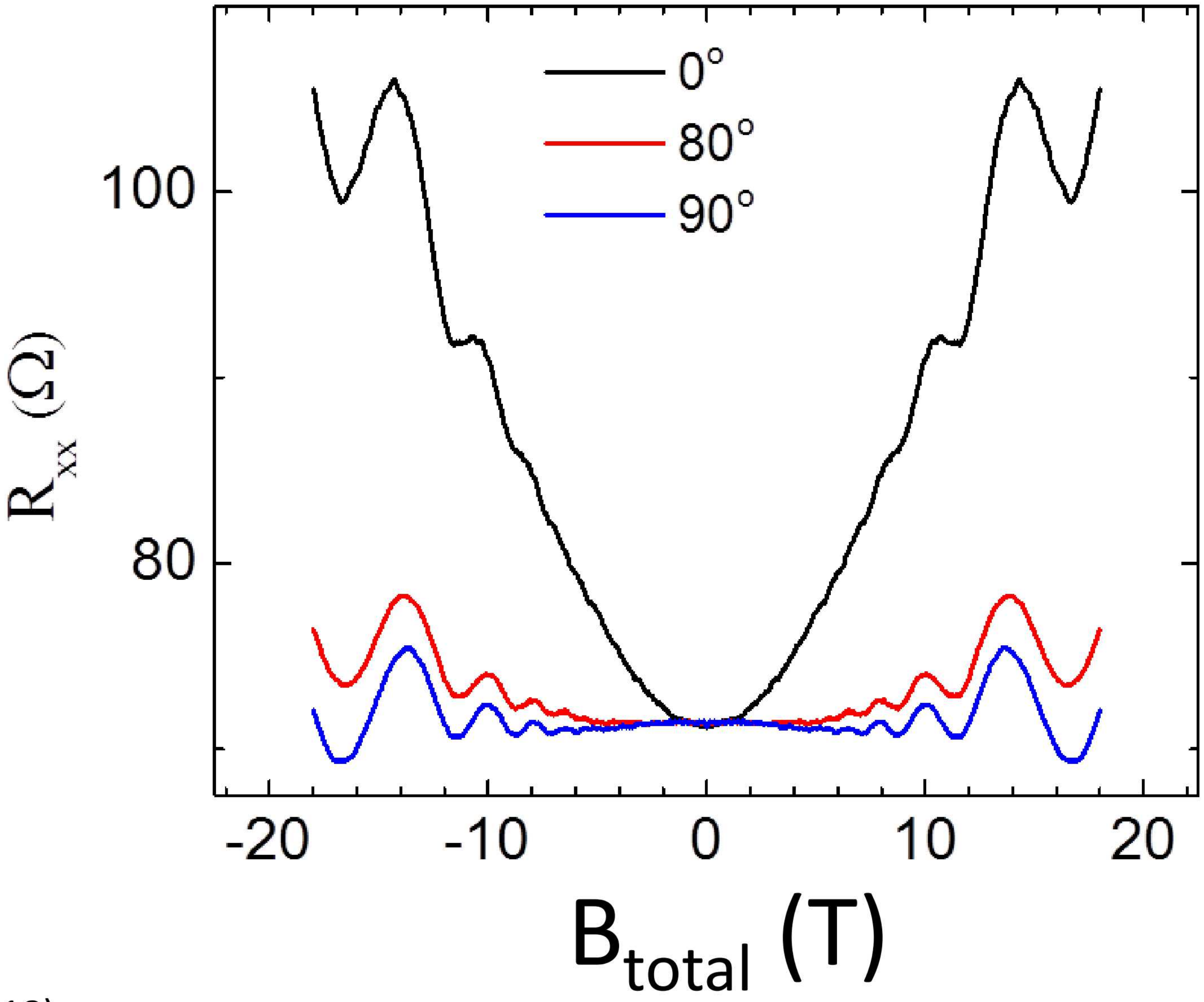


3D nature

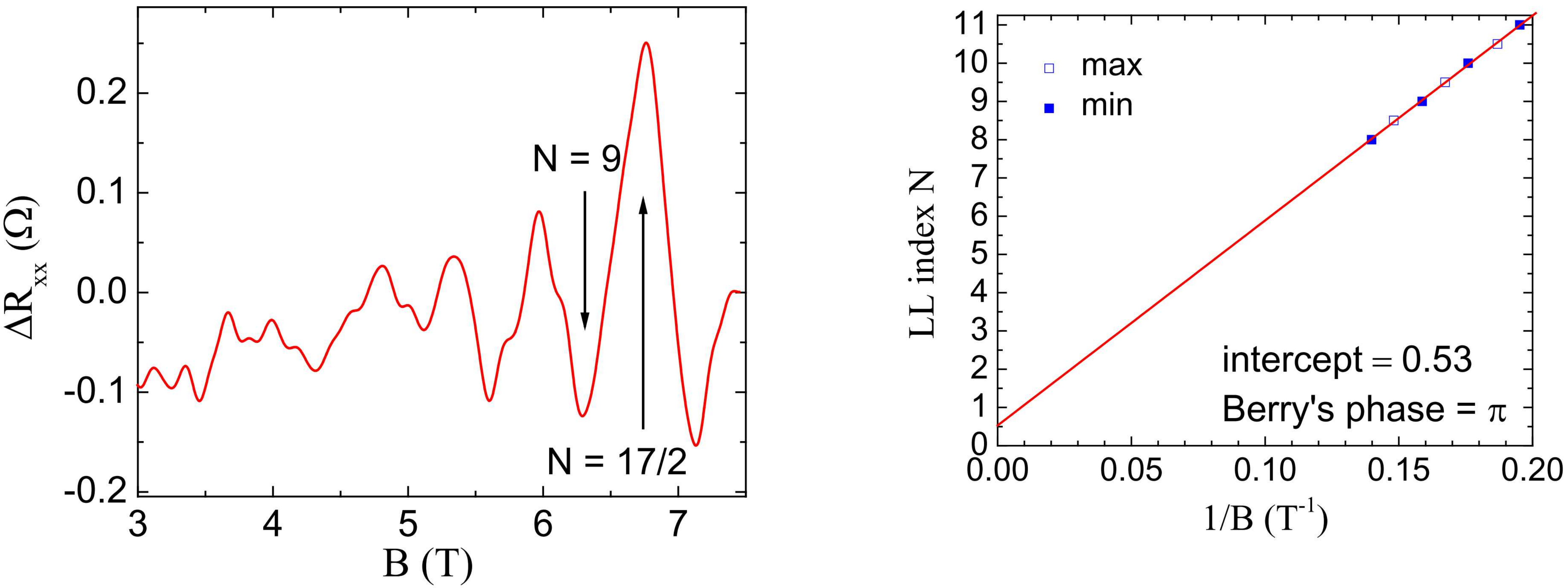




$B\perp = B * \cos(\theta)$



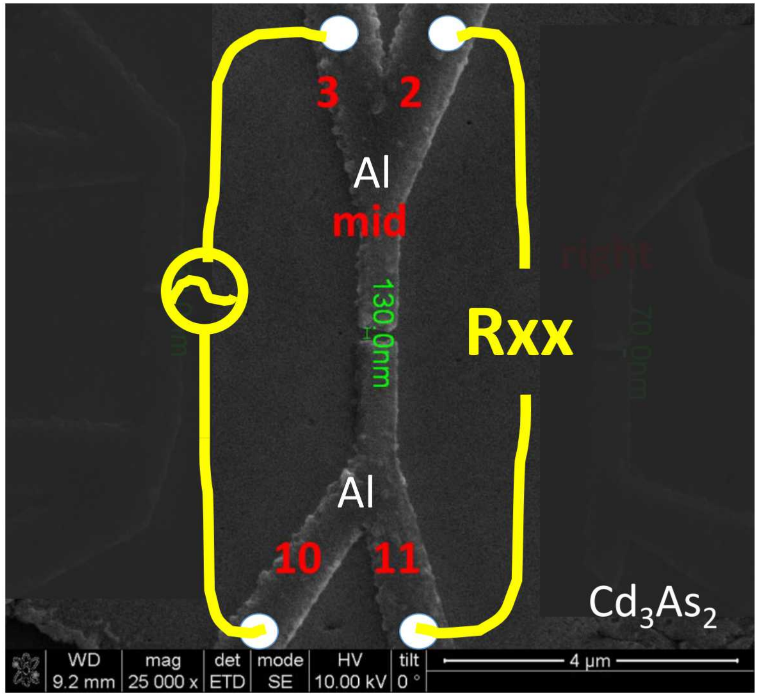
Yu, Pan et al, PRL (2018)



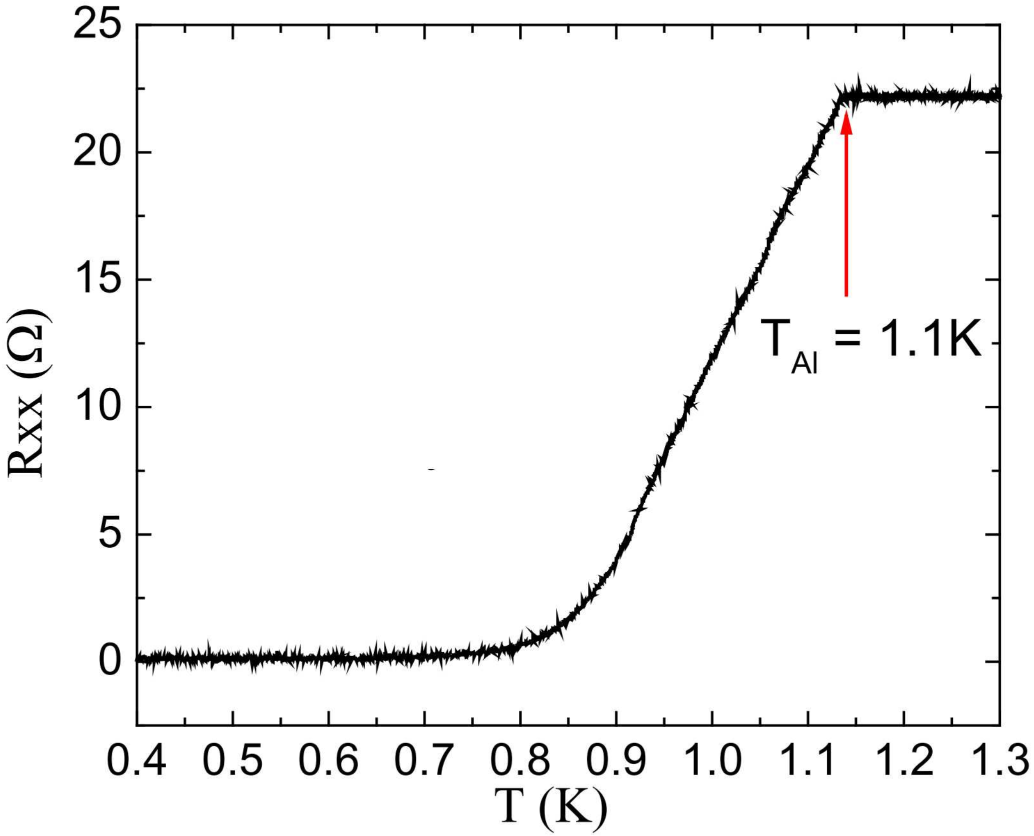
N = 9
N = 17/2
ΔR_xx (Ω)
B (T)
max
min
LL index N
intercept = 0.53
Berry's phase = π
1/B (T^-1)

Proximity induced superconductivity in Cd_3As_2

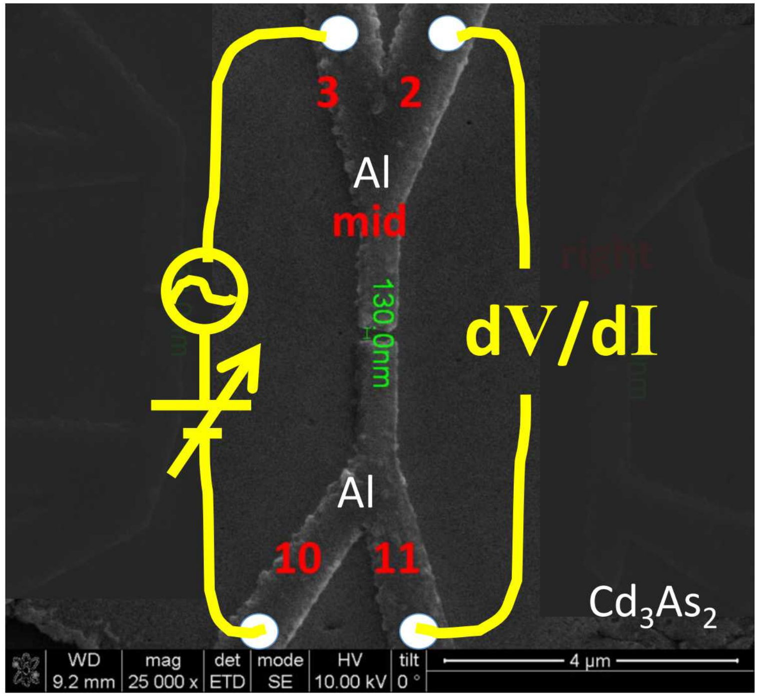
(W. Yu, W. Pan, D.L. Medlin, M.A. Rodriguez, S.R. Lee, Z.Q. Bao, F. Zhang, Phys. Rev. Lett, 2018)

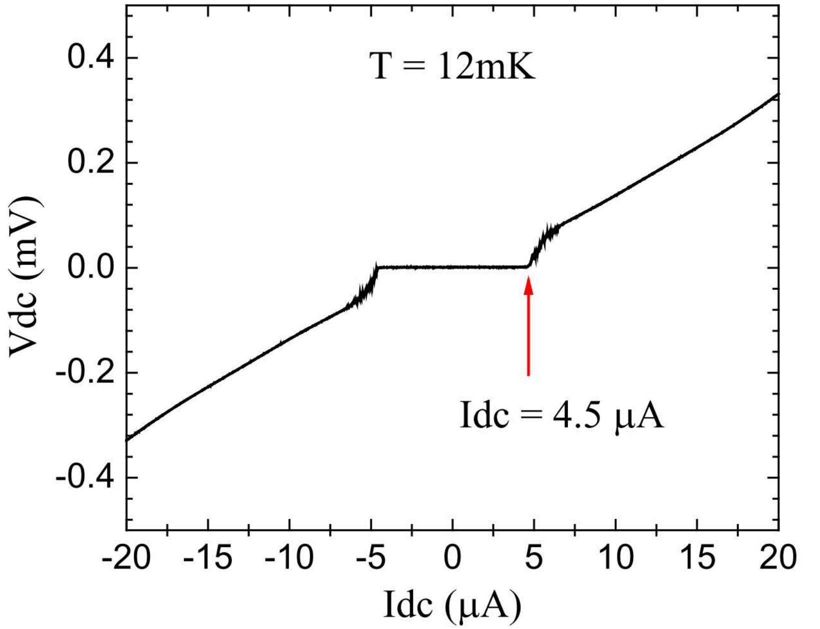


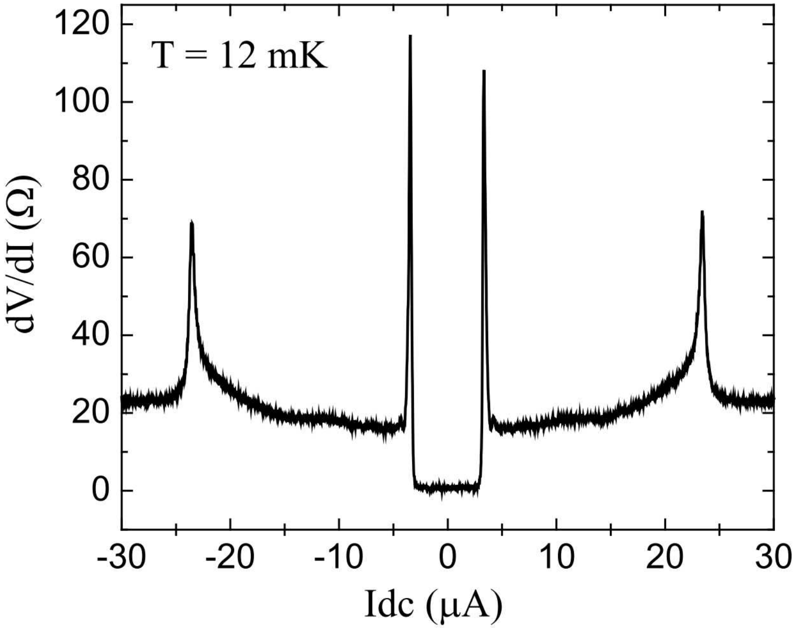
3
2
Al
mid
Rxx
Al
10
11
Cd3As2
WD 9.2 mm
mag 25 000 x
det ETD
mode SE
HV 10.00 kV
tilt 0 °
4 µm

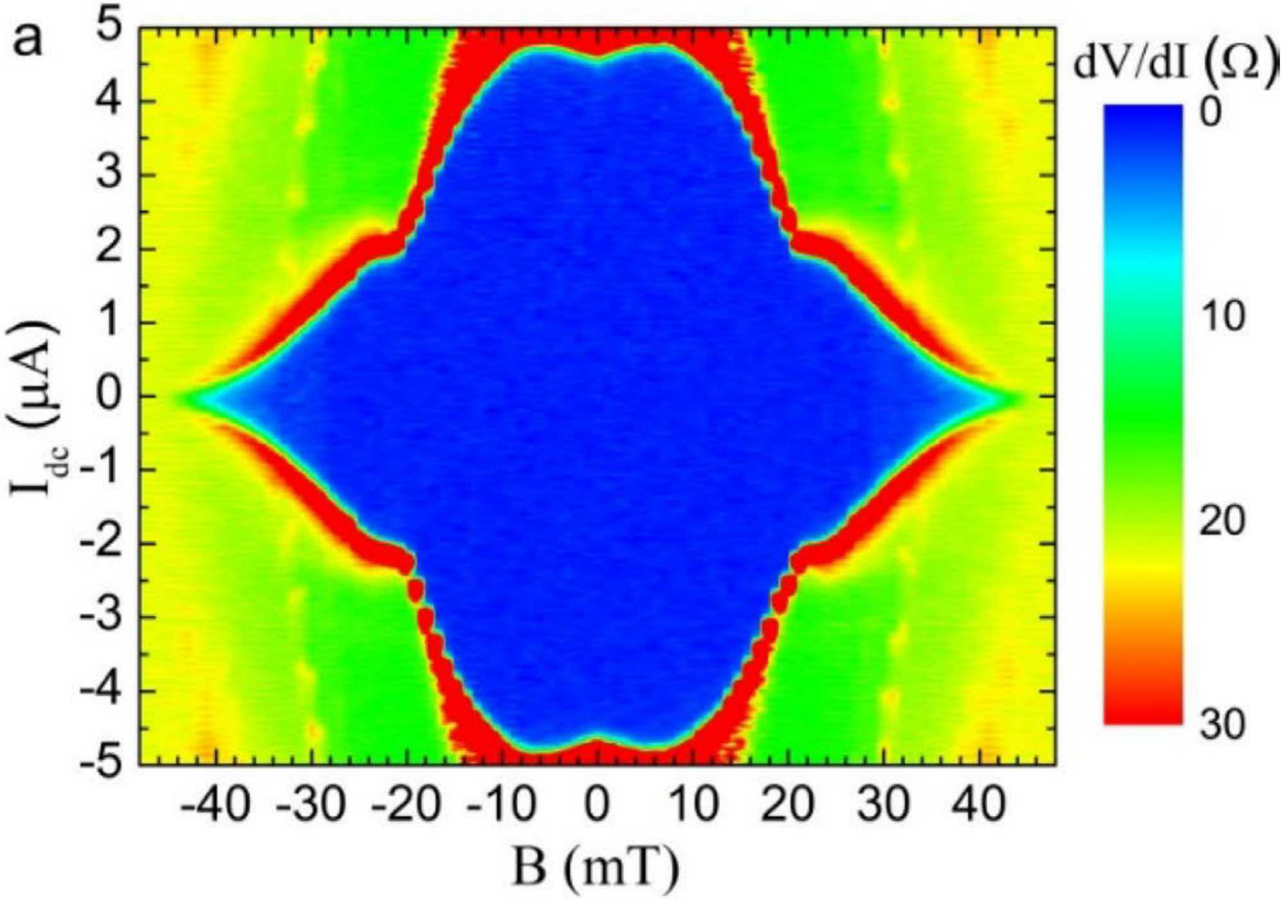


Rxx (Ω)
T (K)
T_Al = 1.1K
25
20
15
10
5
0
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3

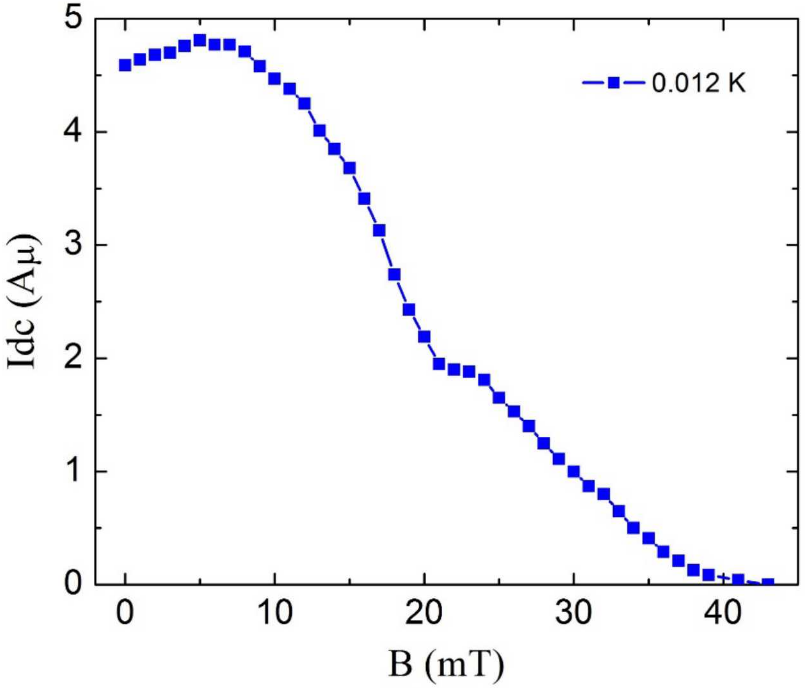

3
2
Al
mid
130.0nm
dV/dI
Al
10
11
Cd_3As_2
WD 9.2 mm
mag 25 000 x
det ETD
mode SE
HV 10.00 kV
tilt 0 °
4 μm


T = 12mK
Vdc (mV)
Idc = 4.5 μA
Idc (μA)
0.4
0.2
0.0
-0.2
-0.4
-20
-15
-10
-5
0
5
10
15
20

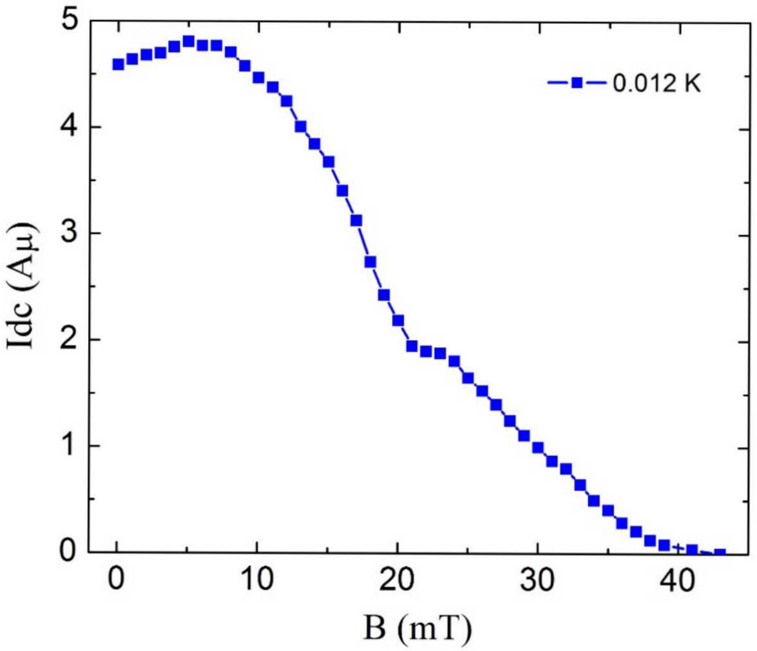

T = 12 mK
dV/dI (Ω)
Idc (μA)
120
100
80
60
40
20
0
-30
-20
-10
0
10
20
30

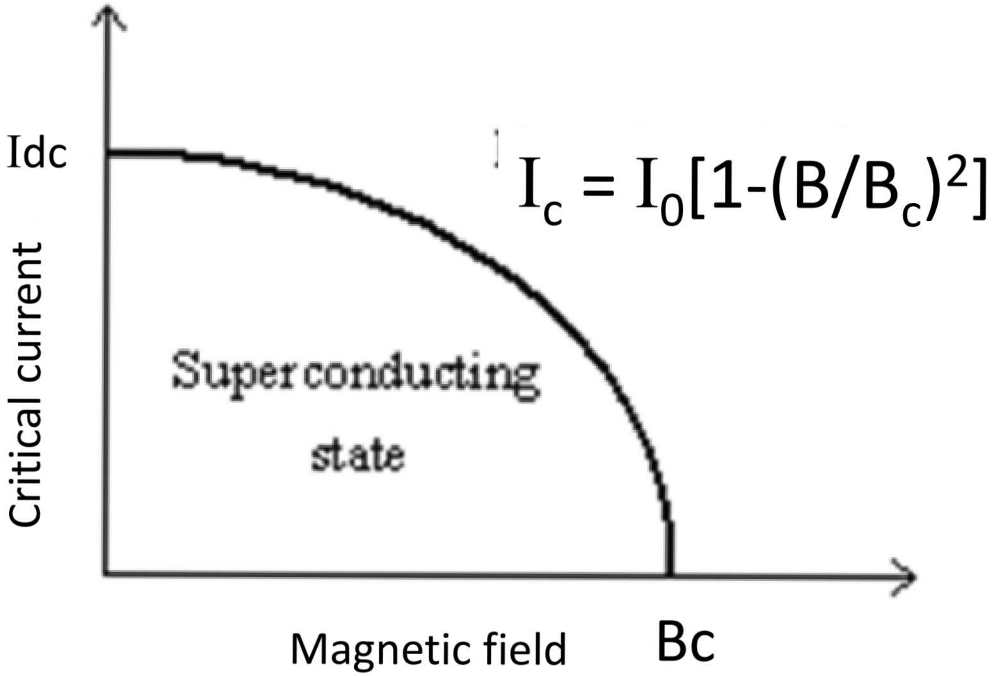


a
dV/dI (Ω)
0
10
20
30
5
4
3
2
1
0
-1
-2
-3
-4
-5
I_{dc} (μA)
-40 -30 -20 -10 0 10 20 30 40
B (mT)

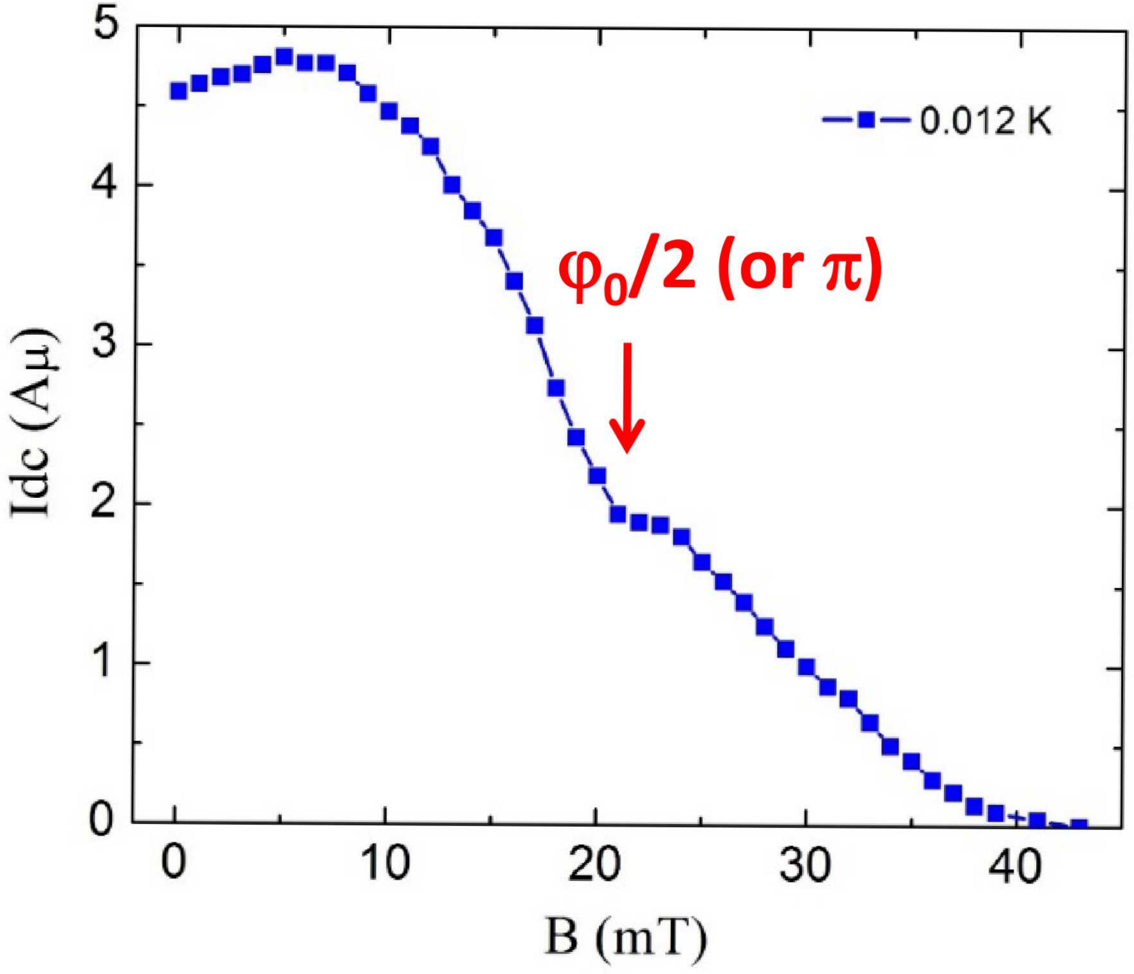


0.012 K
Idc (Aμ)
5
4
3
2
1
0
0 10 20 30 40
B (mT)


0.012 K
Idc (Aμ)
B (mT)
0
10
20
30
40
1
2
3
4
5


Idc
$I_c = I_0[1-(B/B_c)^2]$
Critical current
Super conducting state
Magnetic field
Bc

π anomaly

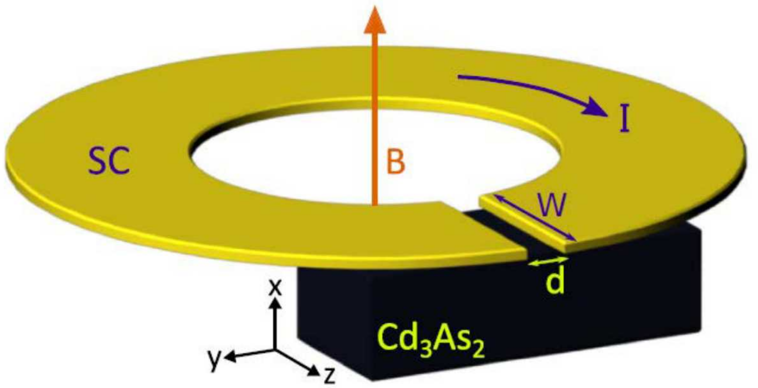


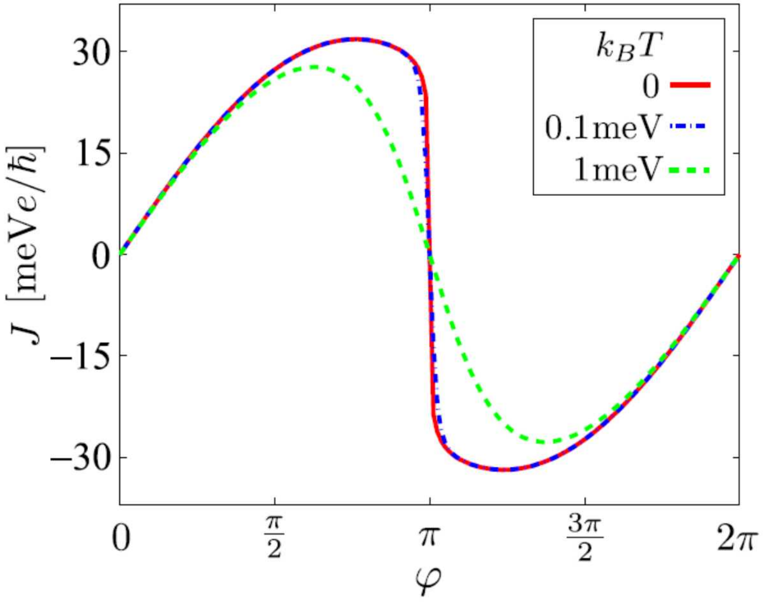
Yu, Pan et al, PRL (2018)

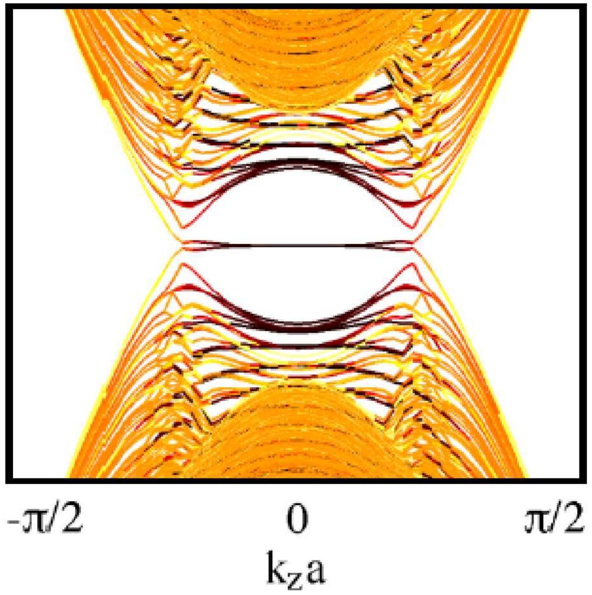
PHYSICAL REVIEW B **95**, 174505 (2017)

Josephson current signatures of Majorana flat bands on the surface of time-reversal-invariant Weyl and Dirac semimetals

Anffany Chen,[1,2] D. I. Pikulin,[1,2,3] and M. Franz[1,2]

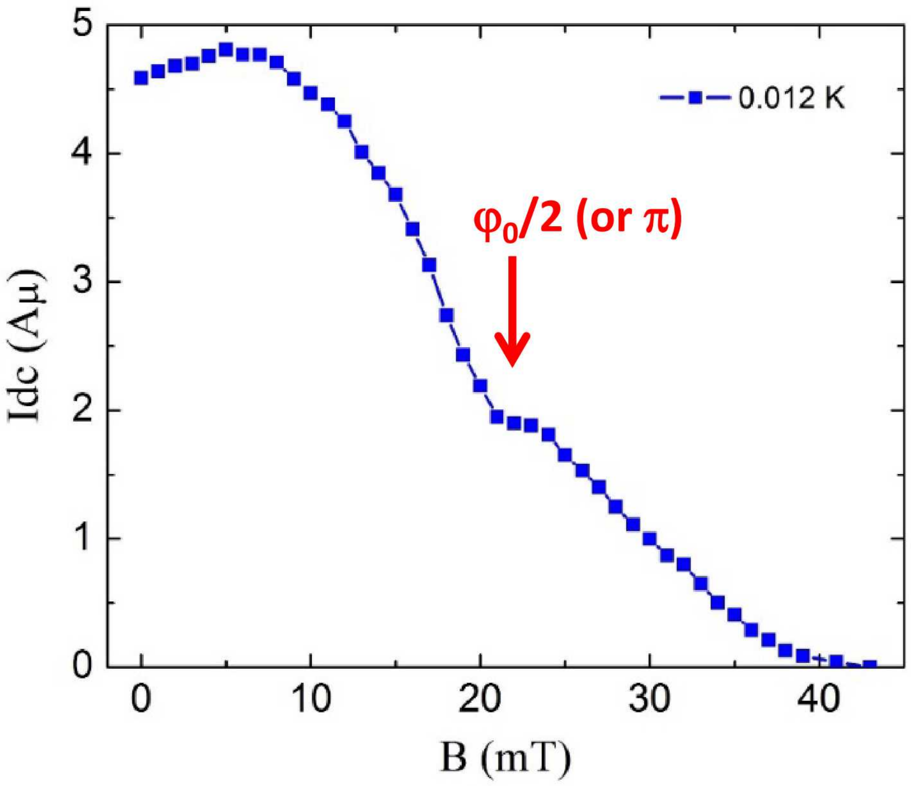


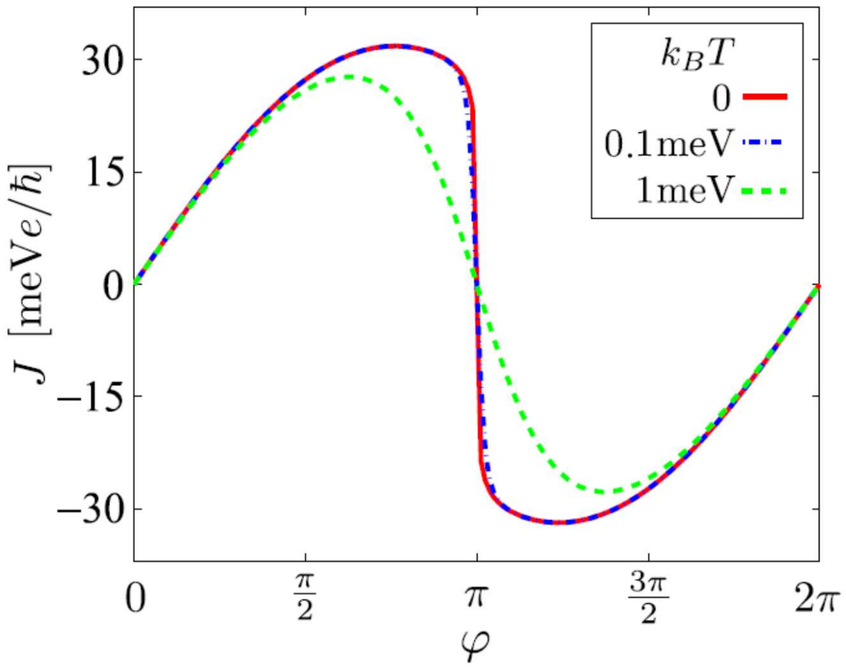




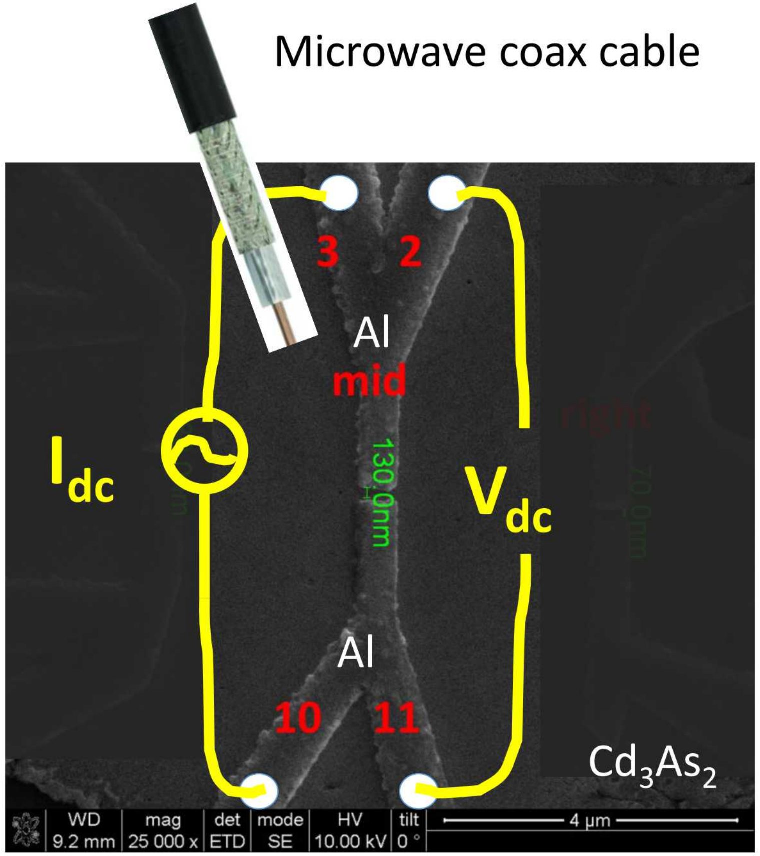
Majorana flat bands

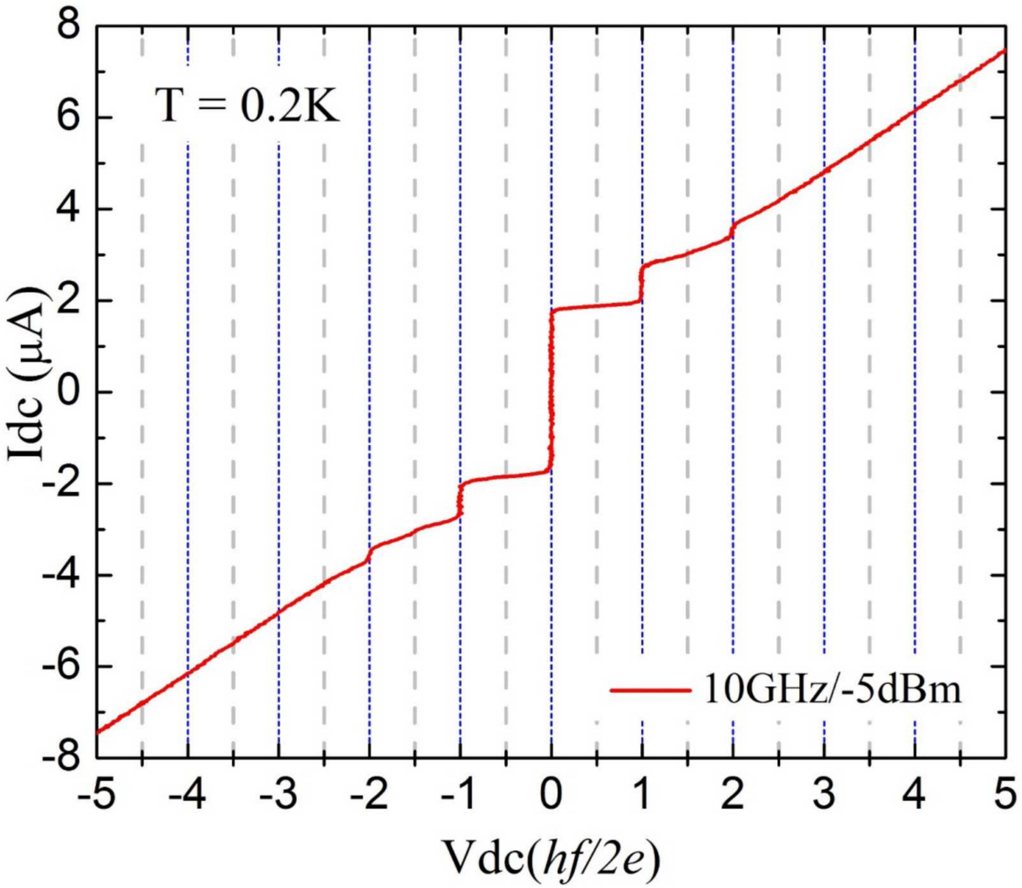
Formation of Majorana flat bands





AC Measurements

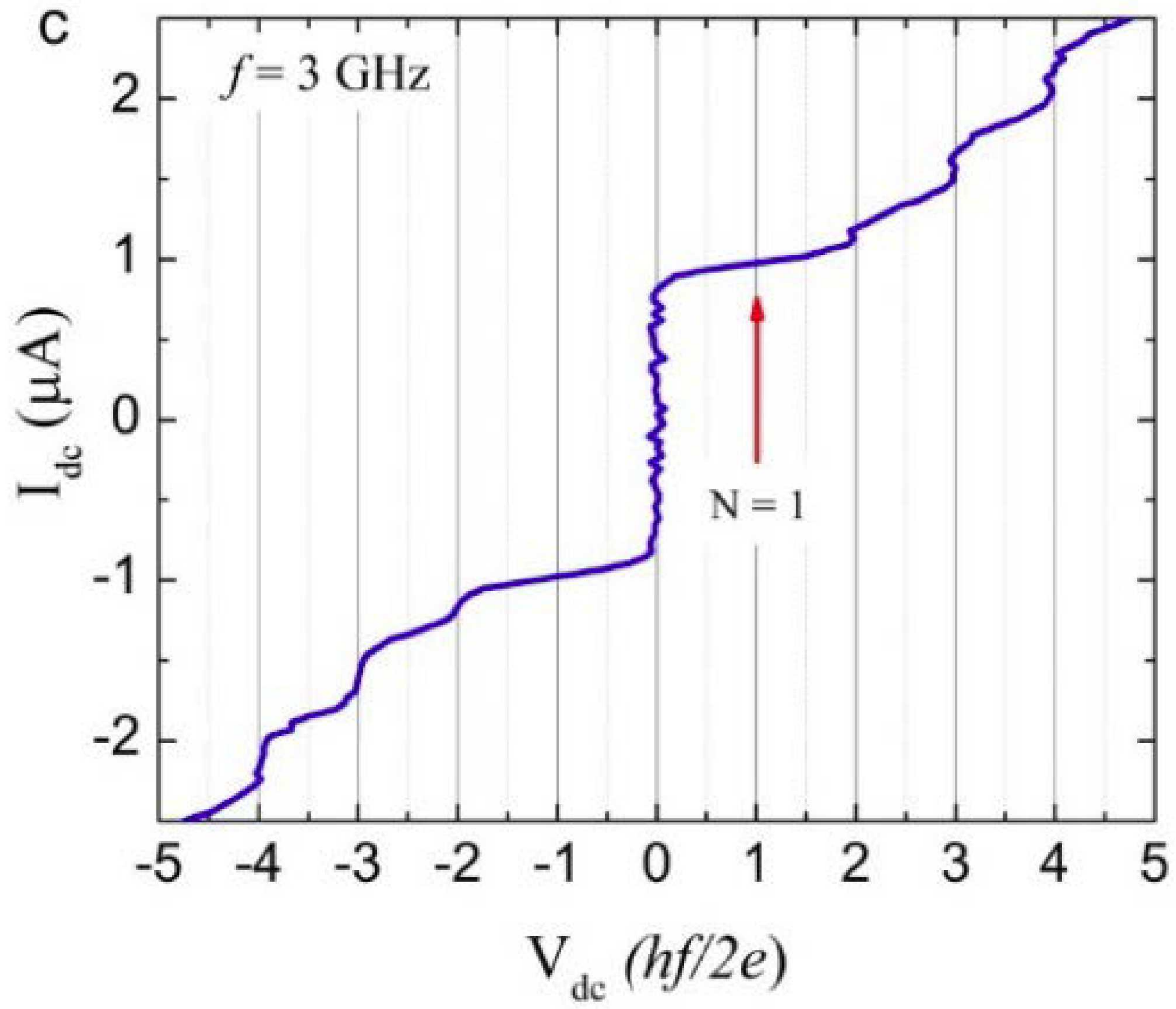




Shapiro steps:

$$V_n = nhf/2e$$

N = +/- 1 Shapiro steps missing



news & views

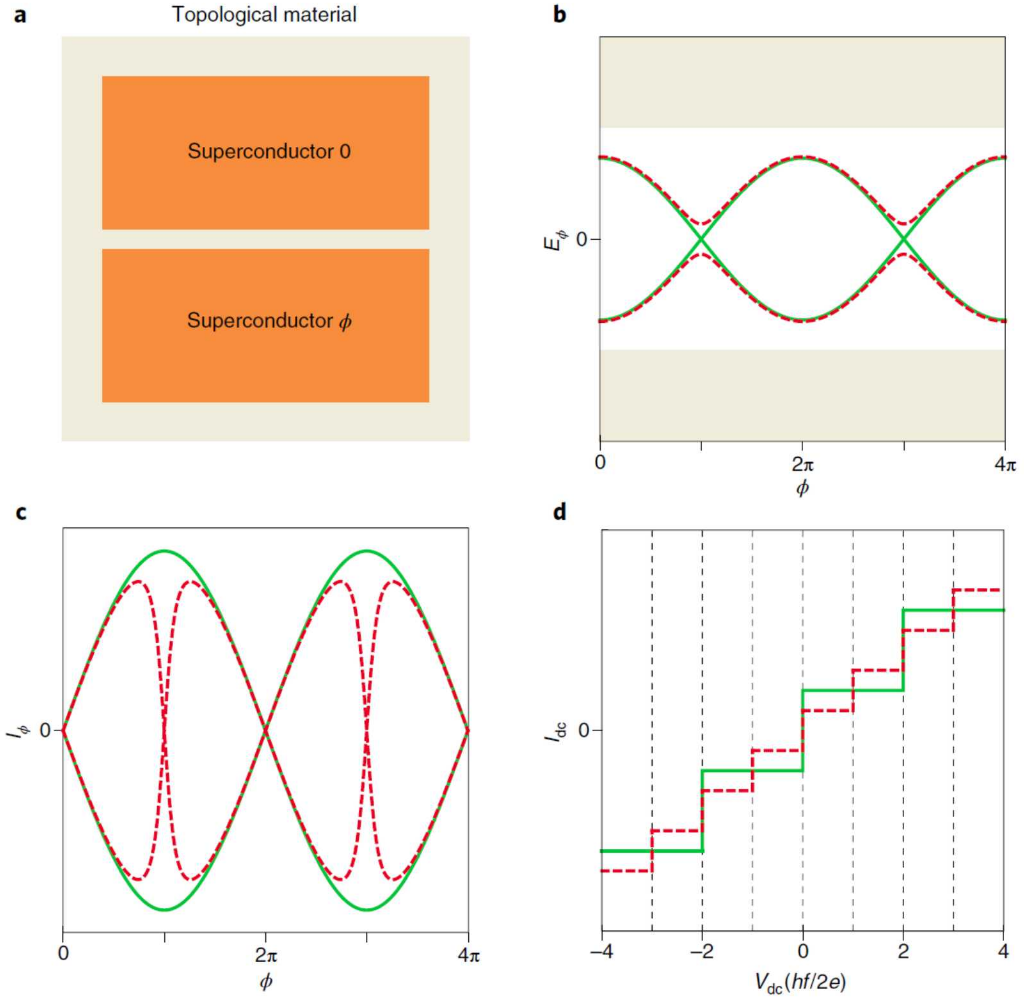
FRACTIONAL JOSEPHSON EFFECT

A missing step is a key step

Zhang and Pan, Nature Materials 17, 851–852 (2018)

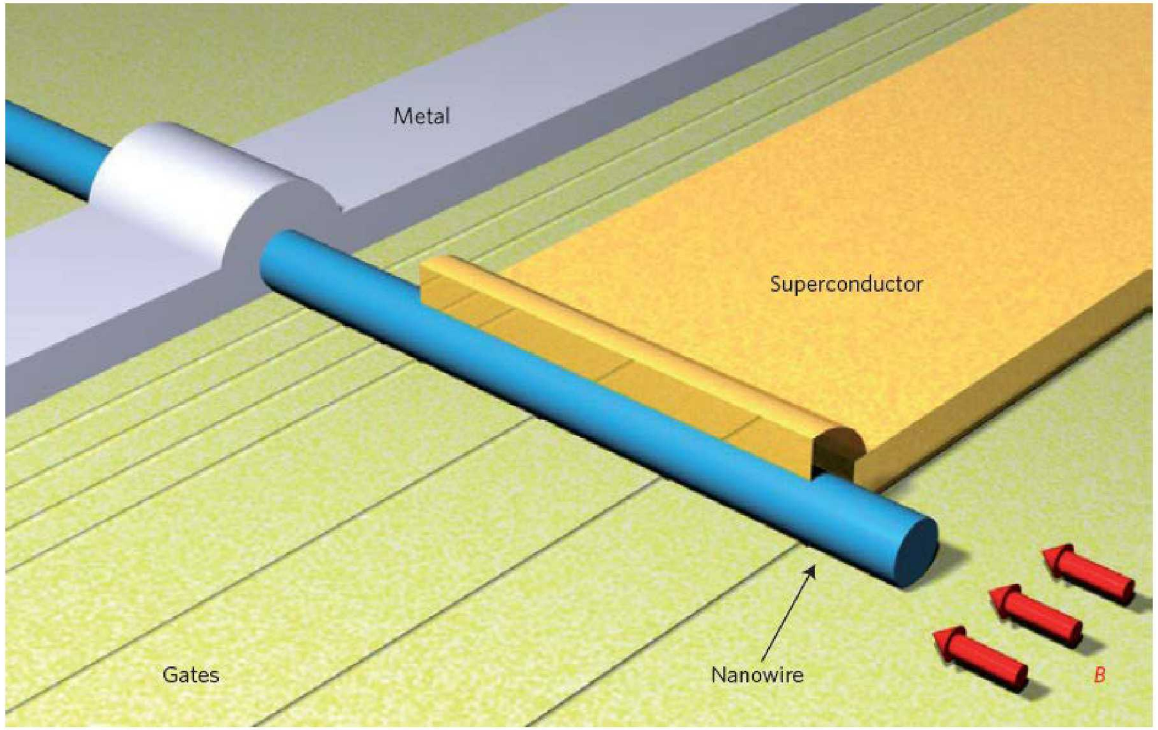
Physicists are searching for superconducting materials that can host Majoranas. New evidence for these elusive particles is provided by missing Shapiro steps in a Josephson effect mediated by an accidental Dirac semimetal.

Fan Zhang and Wei Pan

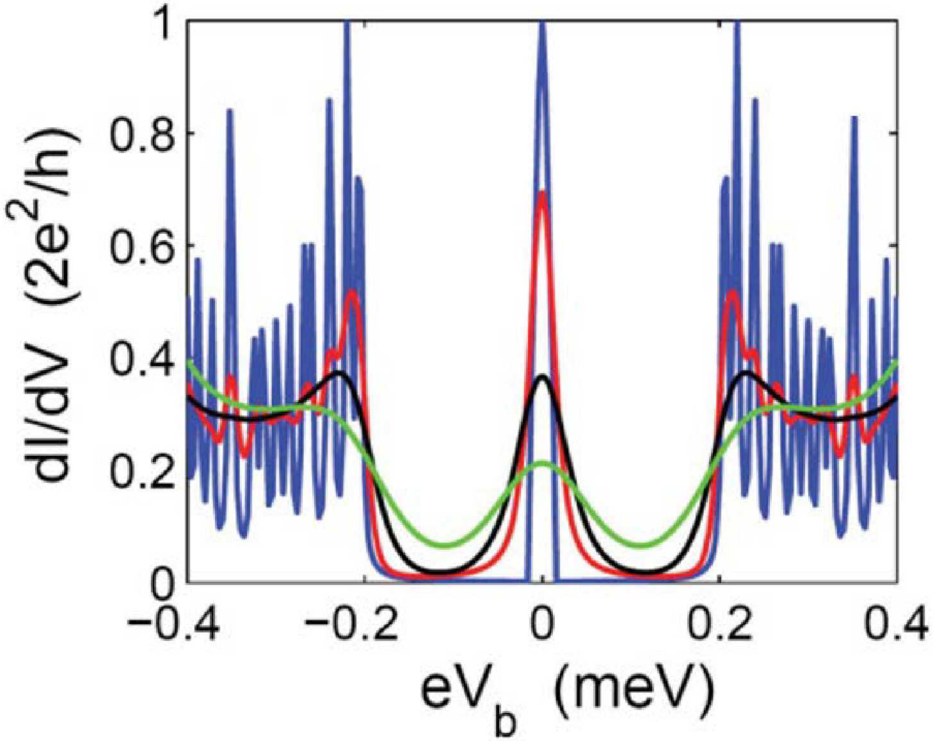


In the presence of Majorana particles, the current is 4π periodic, and only even Shapiro steps are visible.

Search for Majorana Zero modes: **zero bias peak**

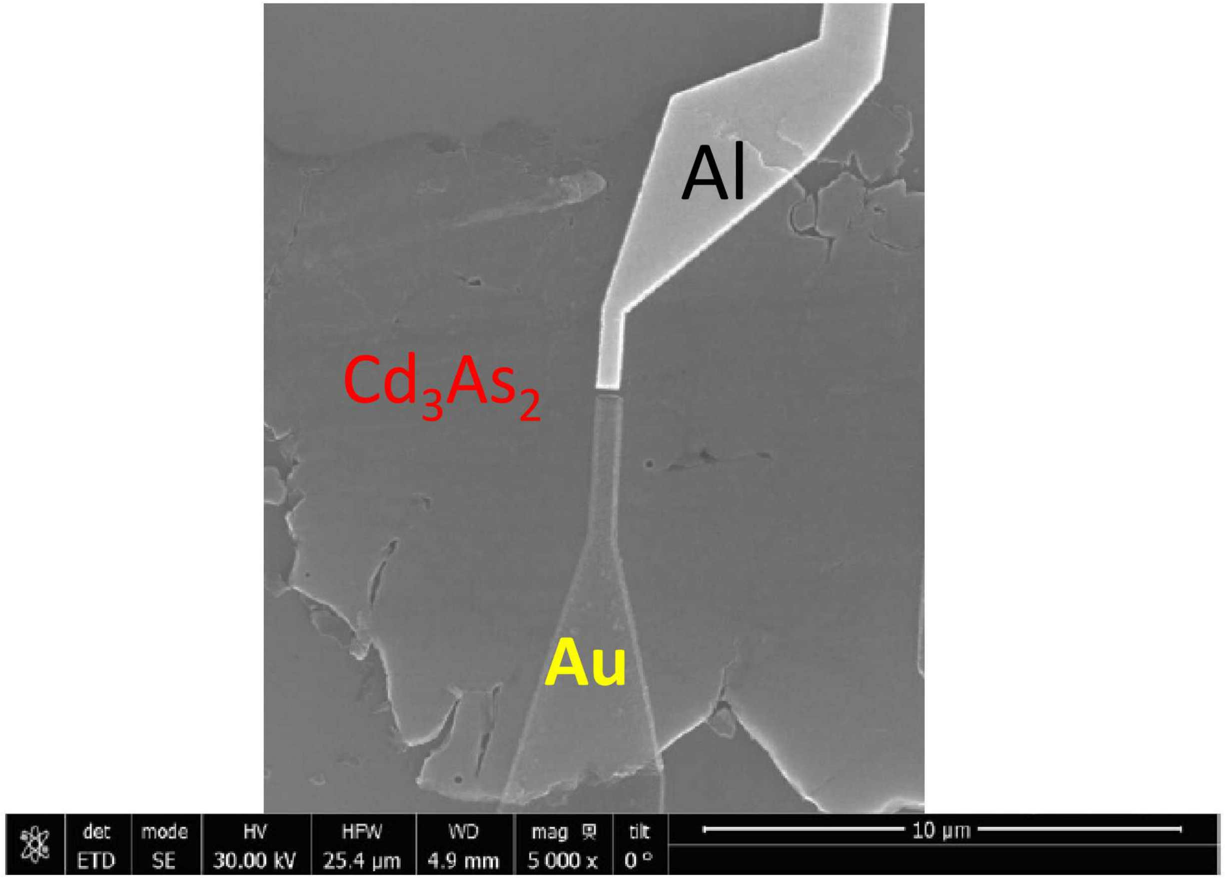


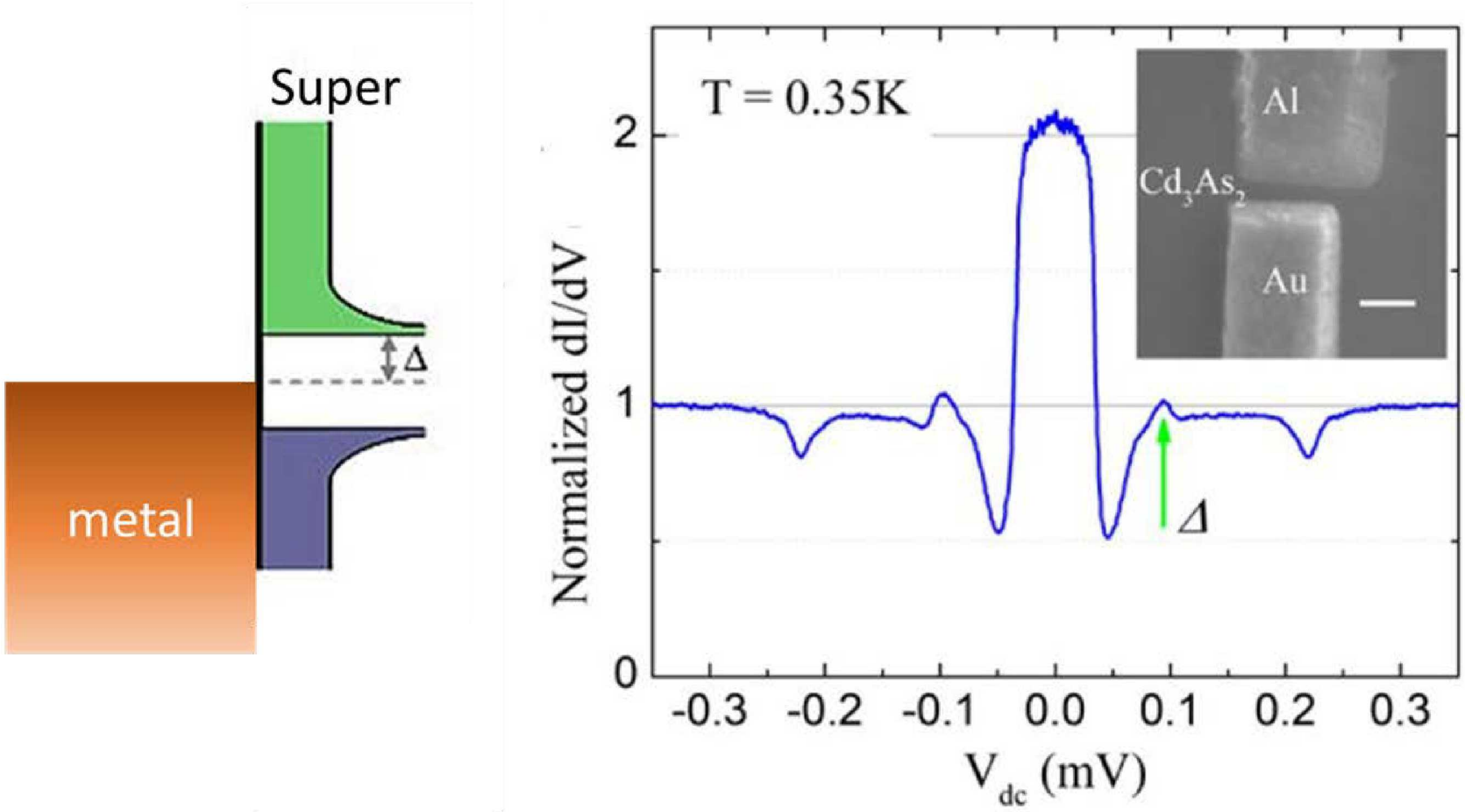
V Mourik et al, Science 336, 1003 (2012)



R.M. Lutchyn, J.D. Sau, and S. Das Sarma, PRL (2010)

Au-Cd_3As_2-Al tunnel junctions



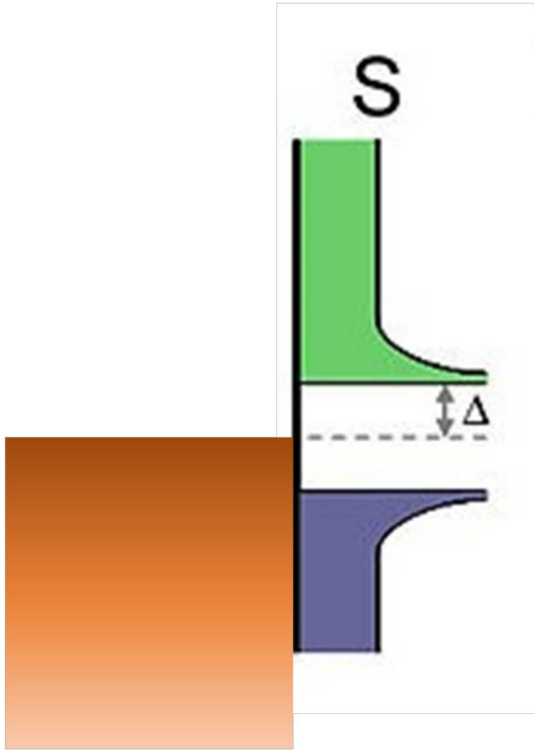

Super
Δ
metal
T = 0.35K
Al
Cd_3As_2
Au
Δ
Normalized dI/dV
V_{dc} (mV)
0
1
2
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3

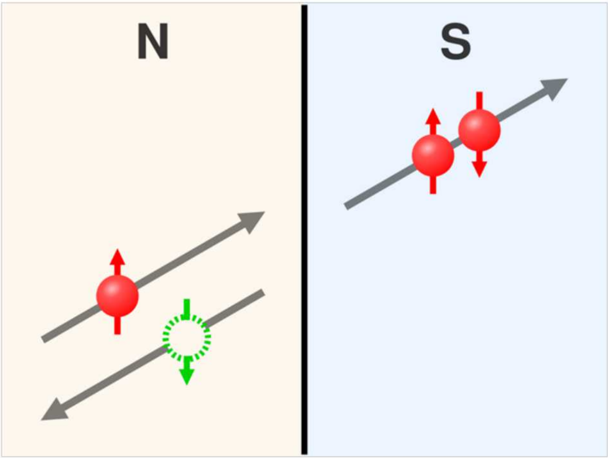
Andreev reflection

Metal + superconductor(SC) junction

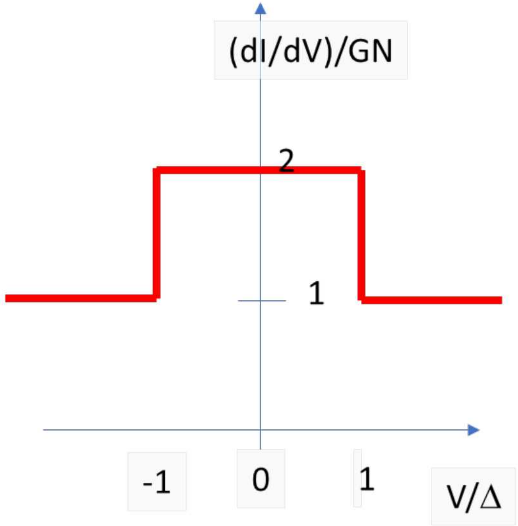
Assuming Andreev reflection:

Andreev reflection process involves an electron incident on the interface from the normal metal at energies less than the superconducting energy gap. The incident electron forms a Cooper pair in the superconductor with the retroreflection of a hole of opposite spin and velocity but equal momentum to the incident electron, as seen in the figure. (from wiki)

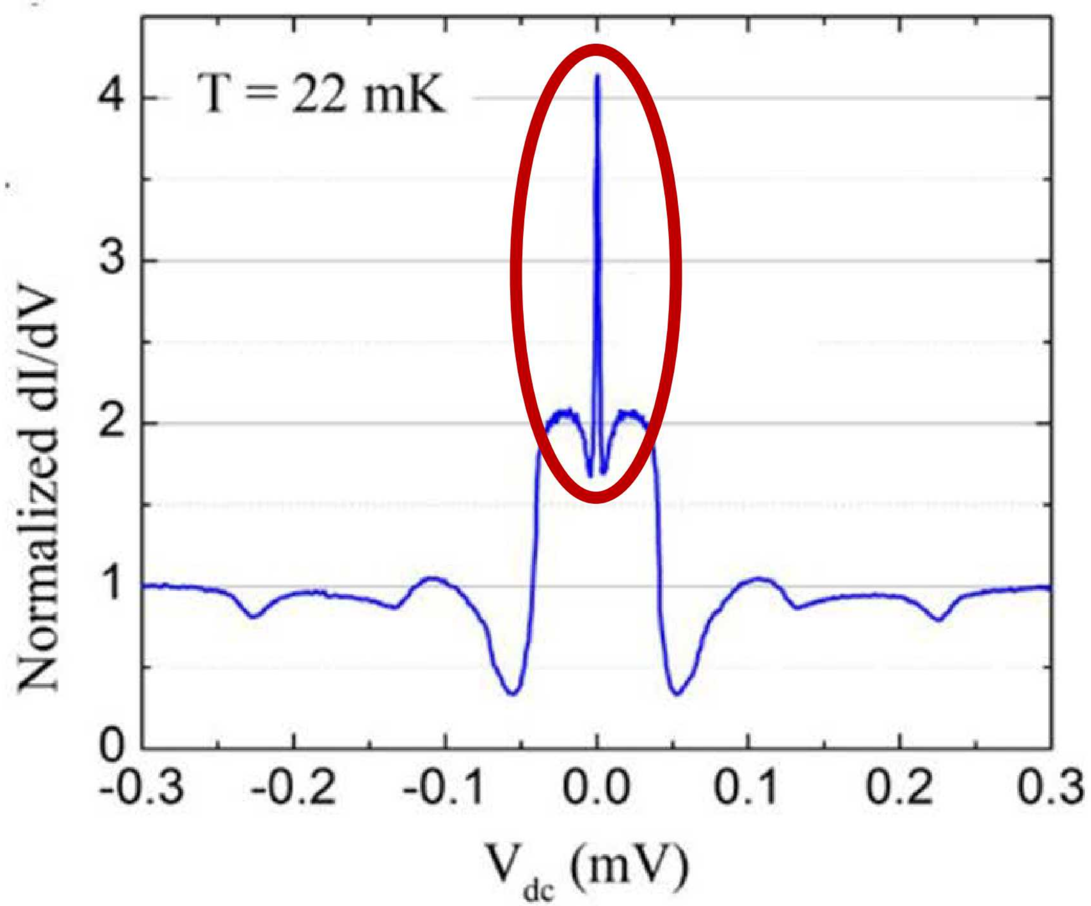




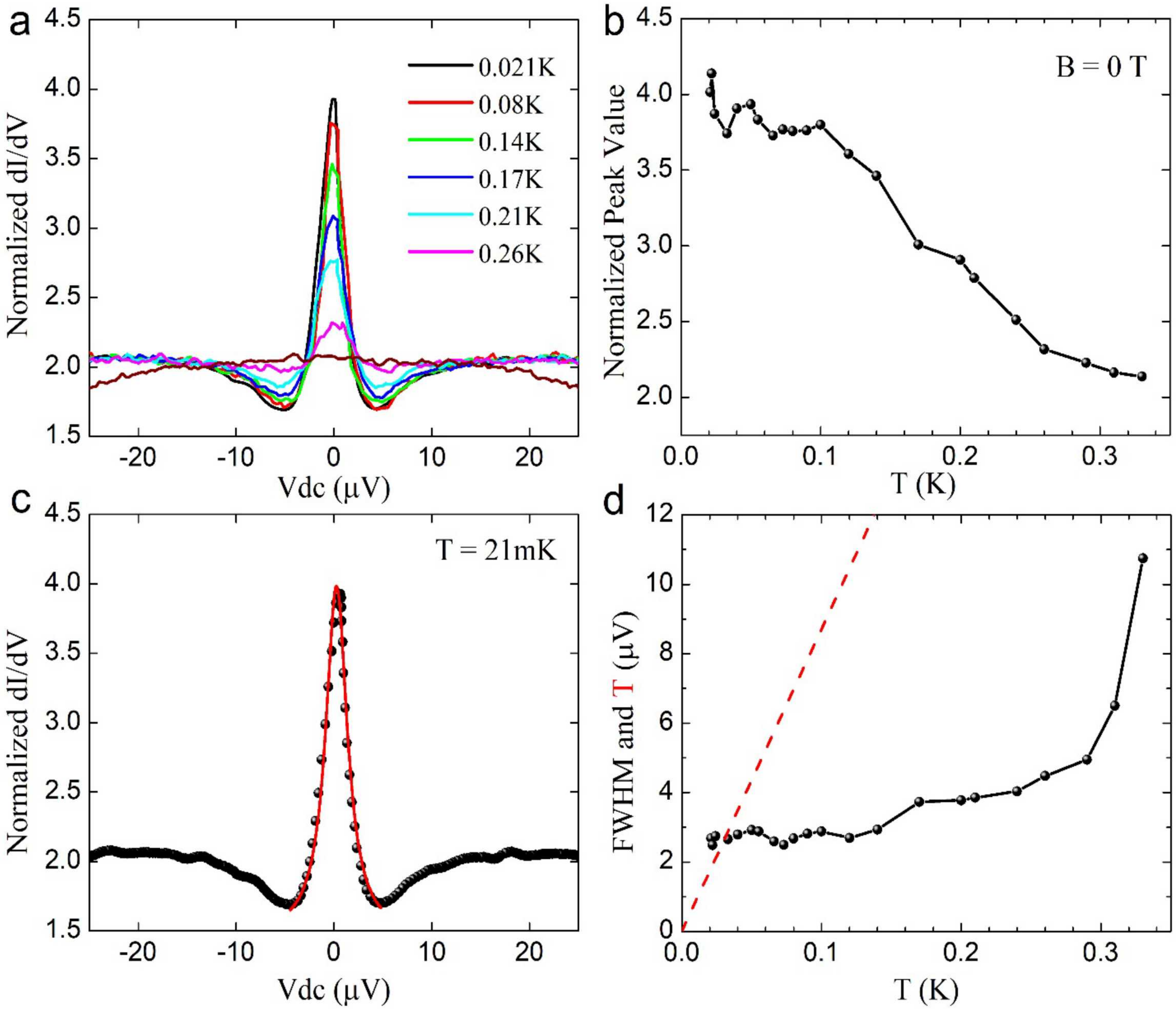
GN: normal state conductance



Because of Andreev reflection, there is a finite conductance even when V is smaller than Δ. Due to two conducting processes, electron tunneling from metal into SC and reflection of hole, the conductance actually is doubled.



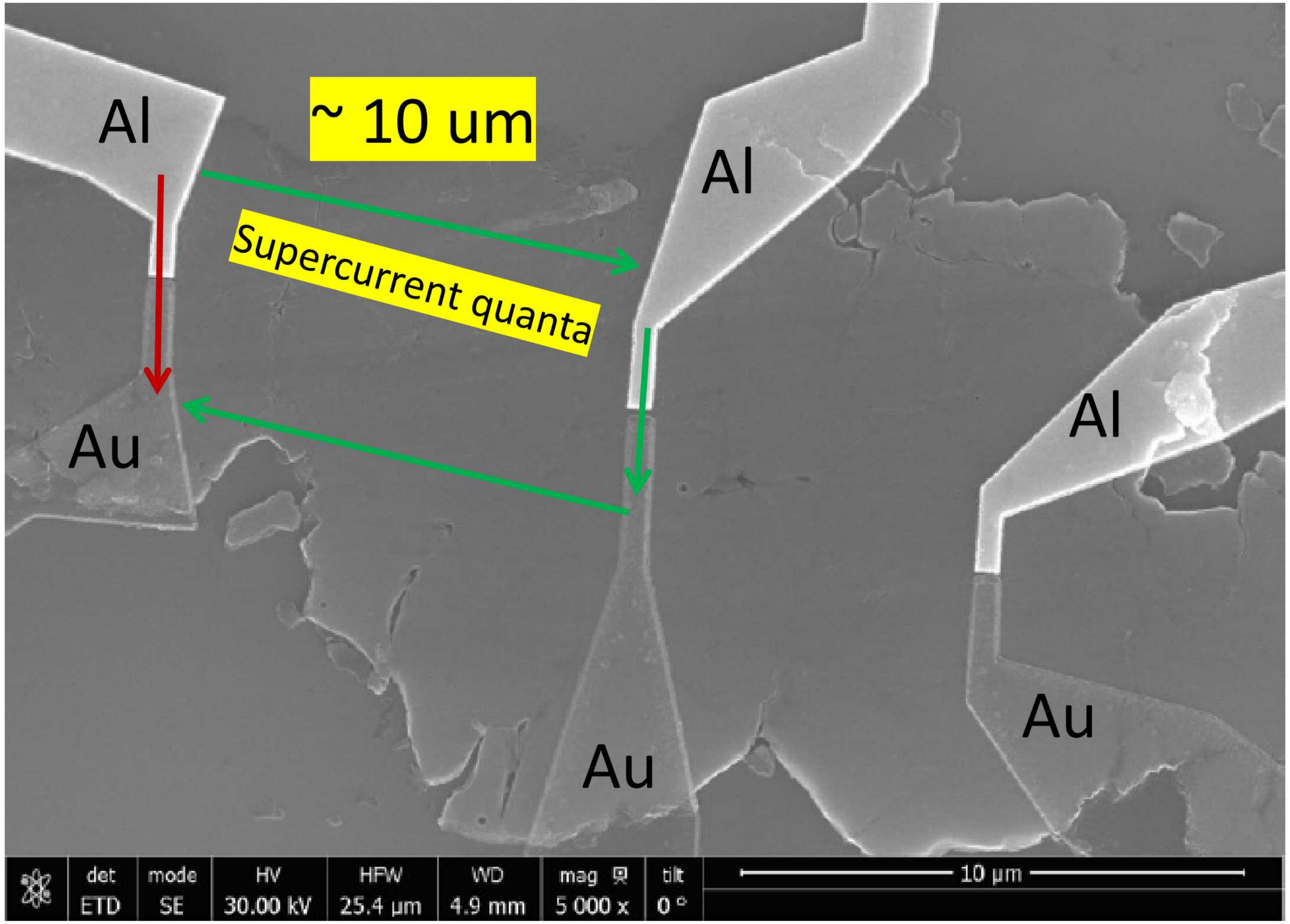
T = 22 mK
Normalized dI/dV
0
1
2
3
4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
V_{dc} (mV)

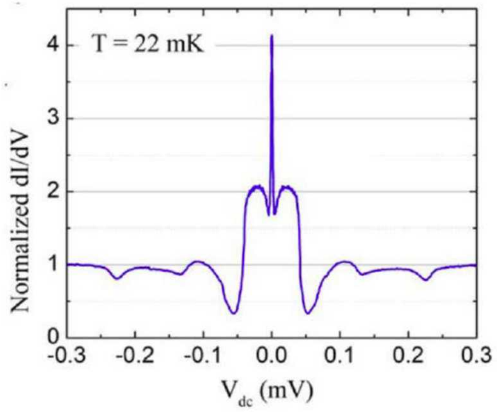


For MZMs:
FWHM ~ 3.5 $k_B T$

A possible Ivanchenko and Zil'berman (1968) origin

(JETP Lett. 8, 113 (1968))

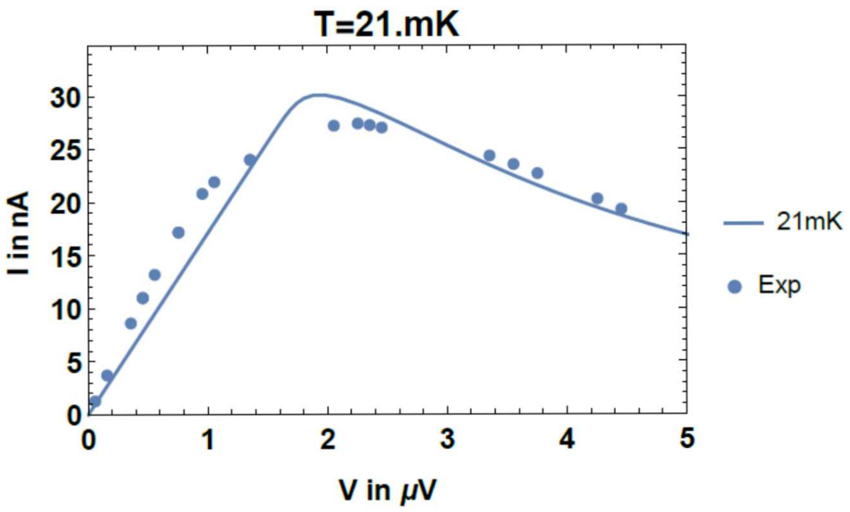


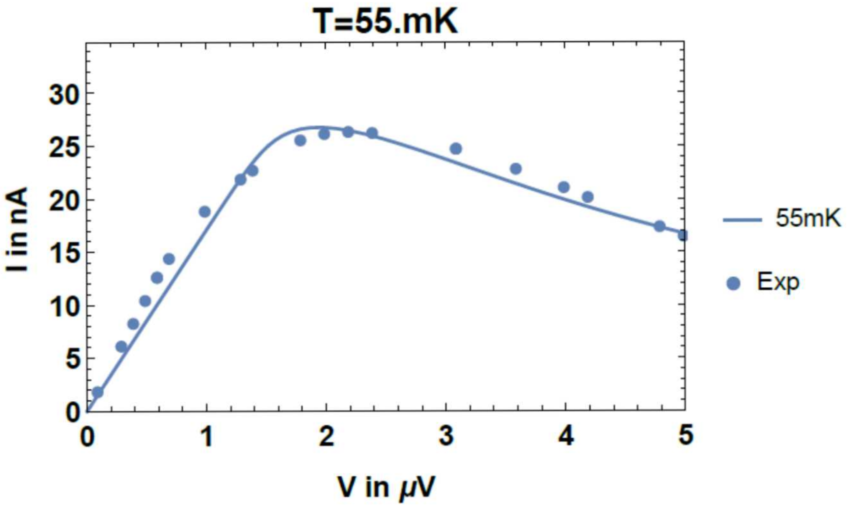


In collaboration with Dima Pikulin at Microsoft Station Q, and Rafael Haenel and Marcel Franz at UBC

Ivanchenko and Zil'berman 1968

$$I(V) \quad = \quad I_0 \mathrm{Im}\left[\frac{I_{1-2i\beta(V+R_2 I)\hbar/(2e(R_1+R_2))}\left(\beta\frac{\hbar}{2e}I_0\frac{\Delta(T)}{\Delta(0)}\right)}{I_{-2i\beta(V+R_2 I)\hbar/(2e(R_1+R_2))}\left(\beta\frac{\hbar}{2e}I_0\frac{\Delta(T)}{\Delta(0)}\right)}\right]$$





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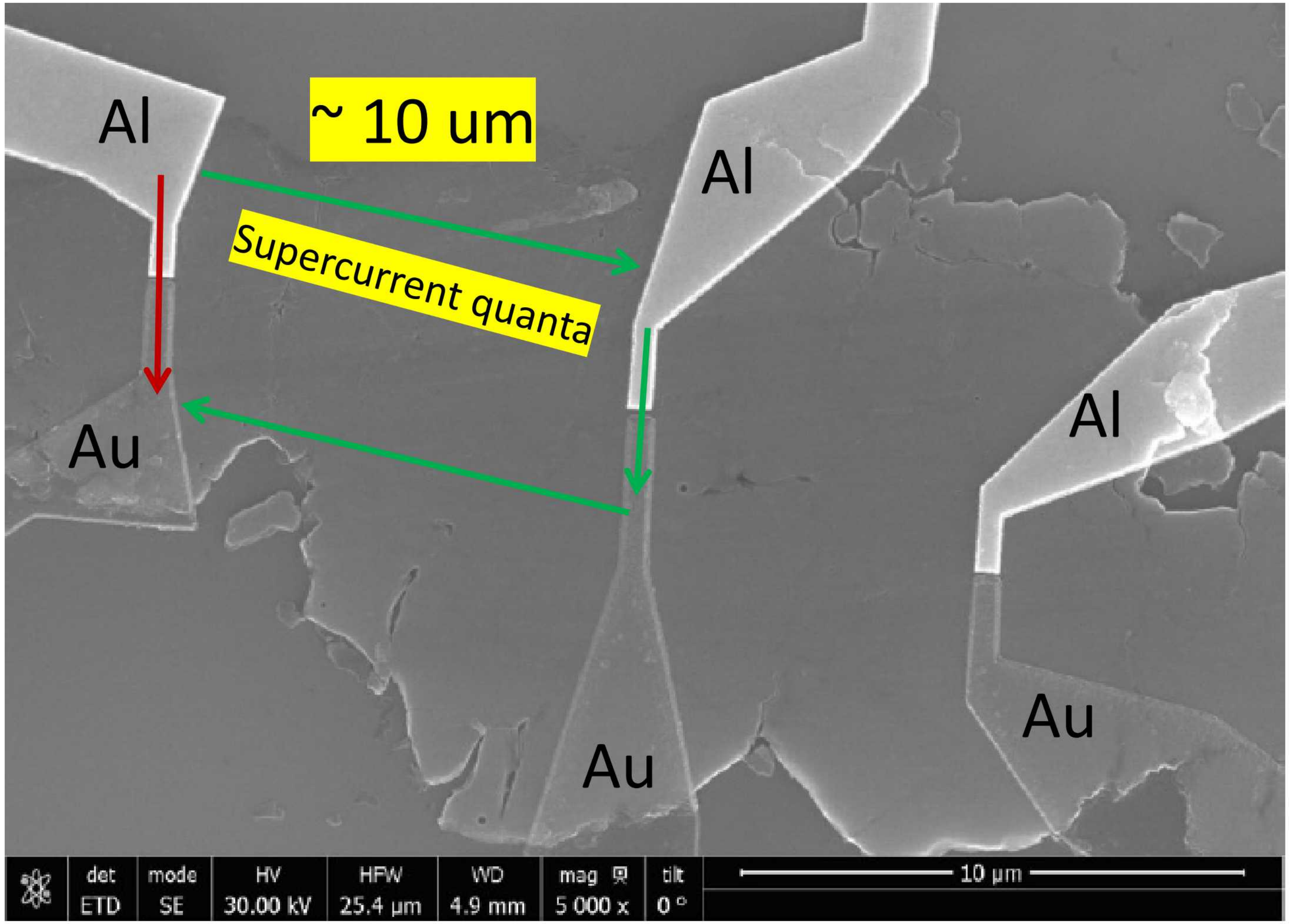
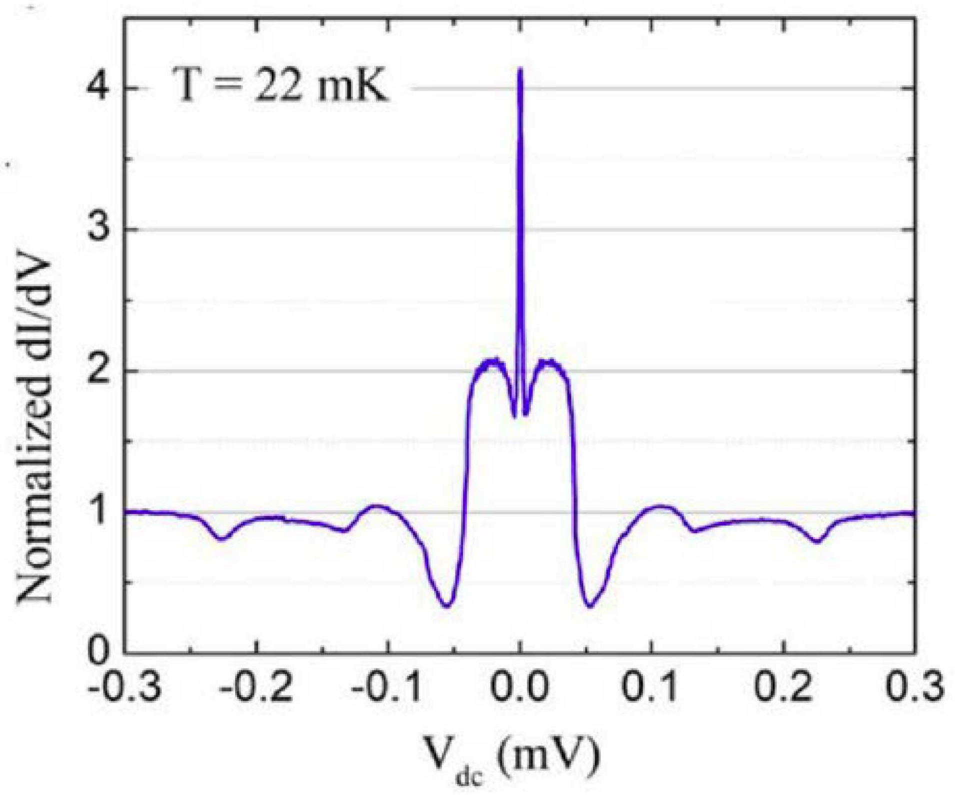


However, the phase coherence length of Cd_3As_2 ~ 0.6 um (obtained from weak anti-location fitting) is much less than 10 um!



The origin of the zero bias peak in our Au-Cd3As2-Al tunnel junctions remains puzzling !

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Thank you!