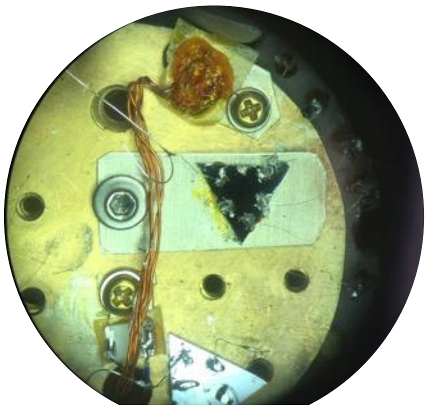
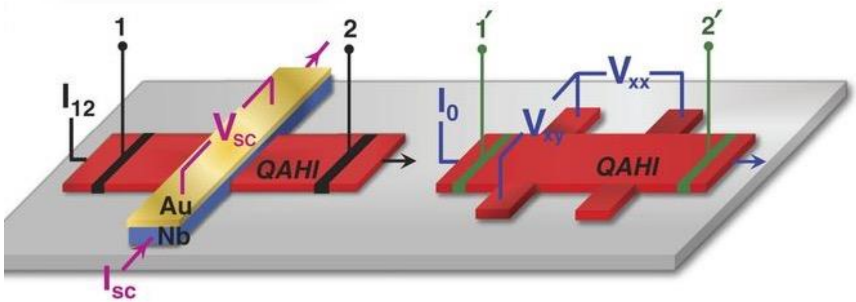
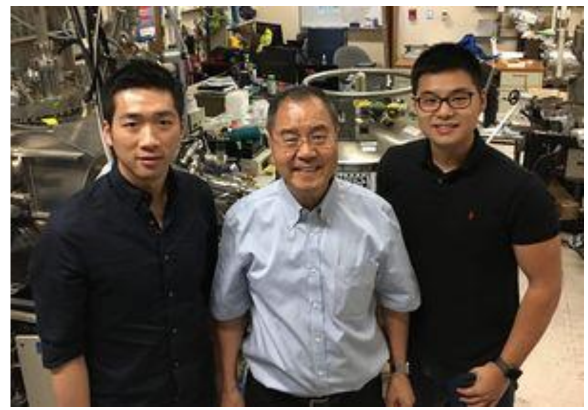
Evidence for chiral Majorana edge modes in a topological heterostructure





Prof. Kang L. Wang (UCLA) middle



Qinling He (left)

Prof. S.C. Zhang (Stanford)

& Kai Liu (UCD)

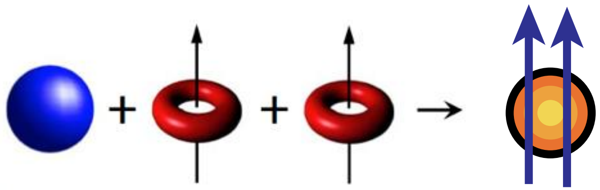
Qing Lin He, Lei Pan, Alexander L. Stern, Edward Burks, Xiaoyu Che, Gen Yin, Jing Wang, Biao Lian, Quan Zhou, Eun Sang Choi, Koichi Murata, Xufeng Kou, Tianxiao Nie, Qiming Shao, Yabin Fan, Shou-Cheng Zhang, Kai Liu, Jing Xia, Kang L. Wang

Jing Xia, UC Irvine

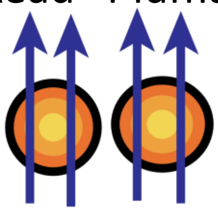
May 7th, 2018 @ CAS Topological Workshop

Lesson from v =5/2 non-Abelian FQHE

Composite Fermion (CF) =
1 electron + 2 flux quanta
(zero effective B field at v =5/2!)

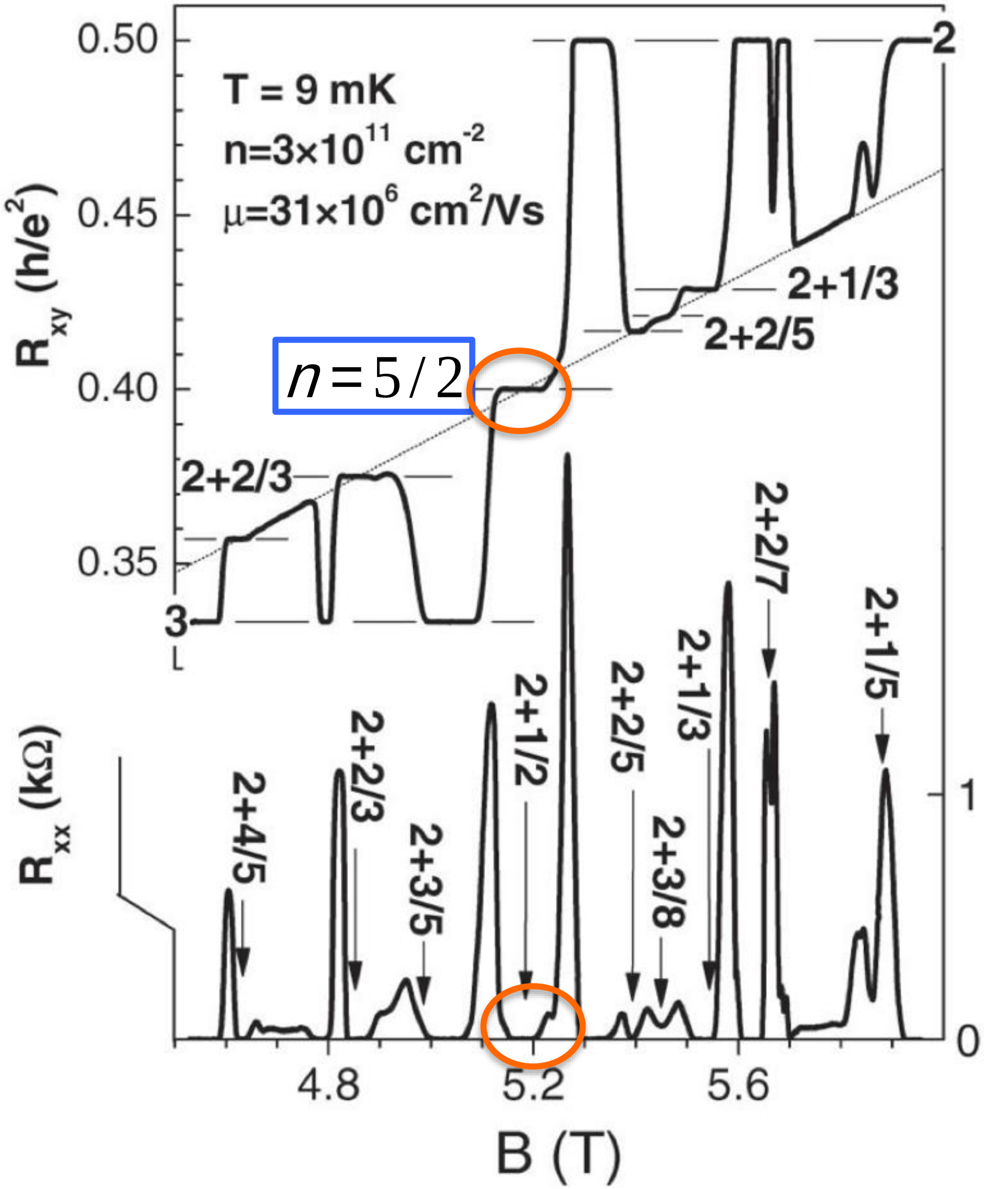


Moore-Read "Pfaffian" state

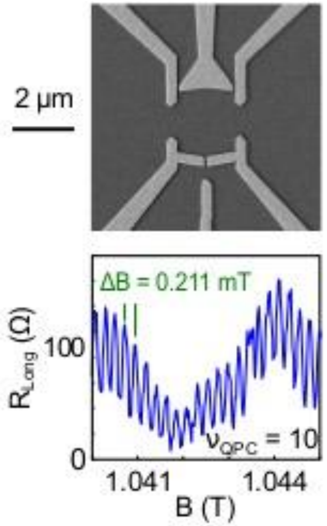


Chiral "p-wave" superconductor
of composite Fermions

Can we get rid of the high magnetic field?



"Artificial" 5/2 state w/o magnetic field



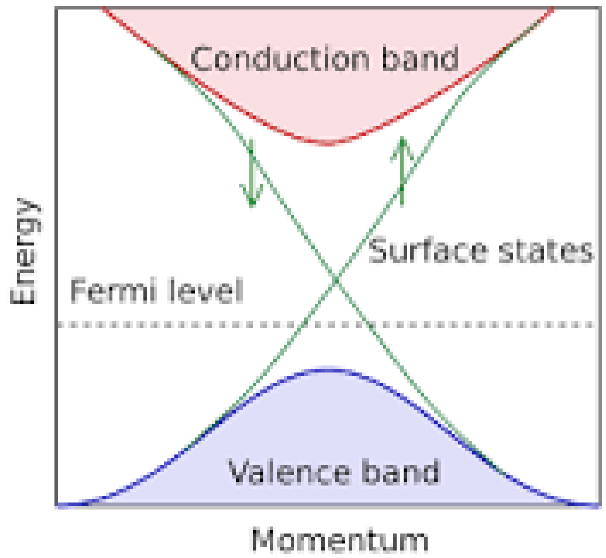
5/2 FQHE state is very hard to achieve and very hard to work with.

5/2 FQHE state is essentially:

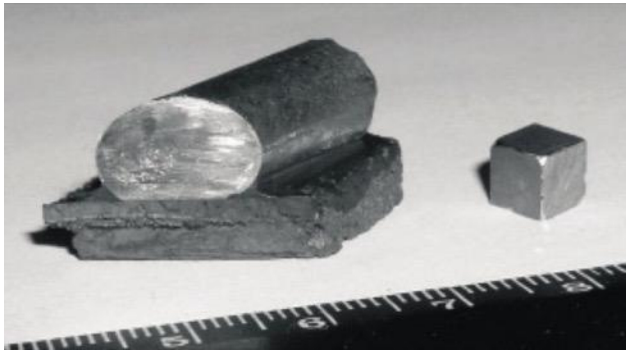
a "superconductor" of composite Fermions in

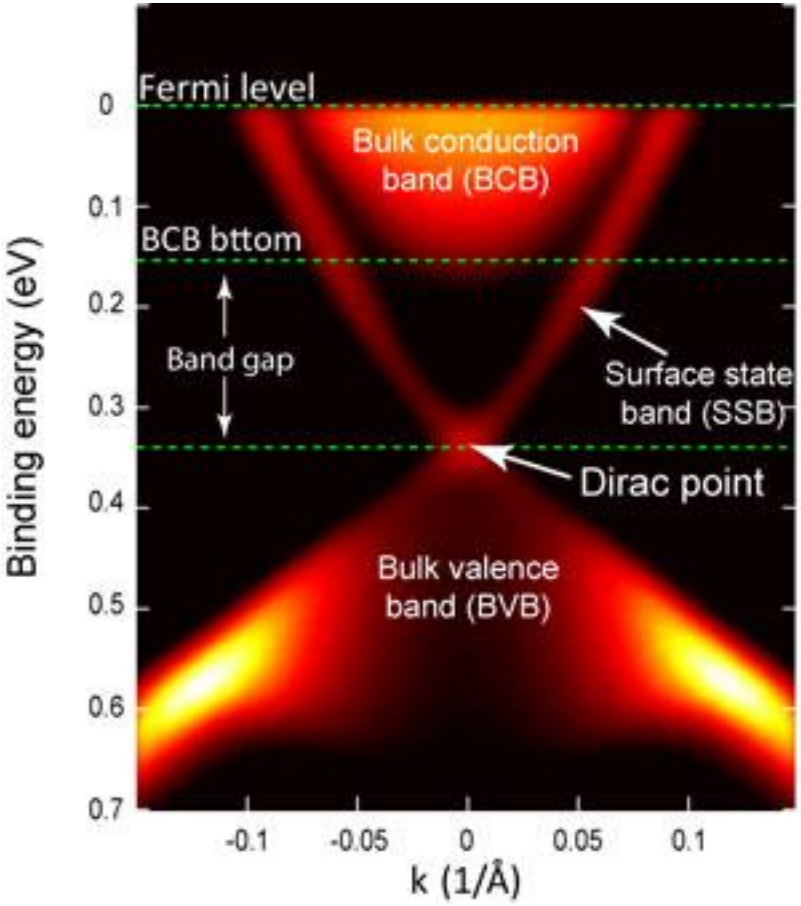
FQHE at high magnetic field

Topological Insulator



Bismuth telluride (Bi_2Te_3)

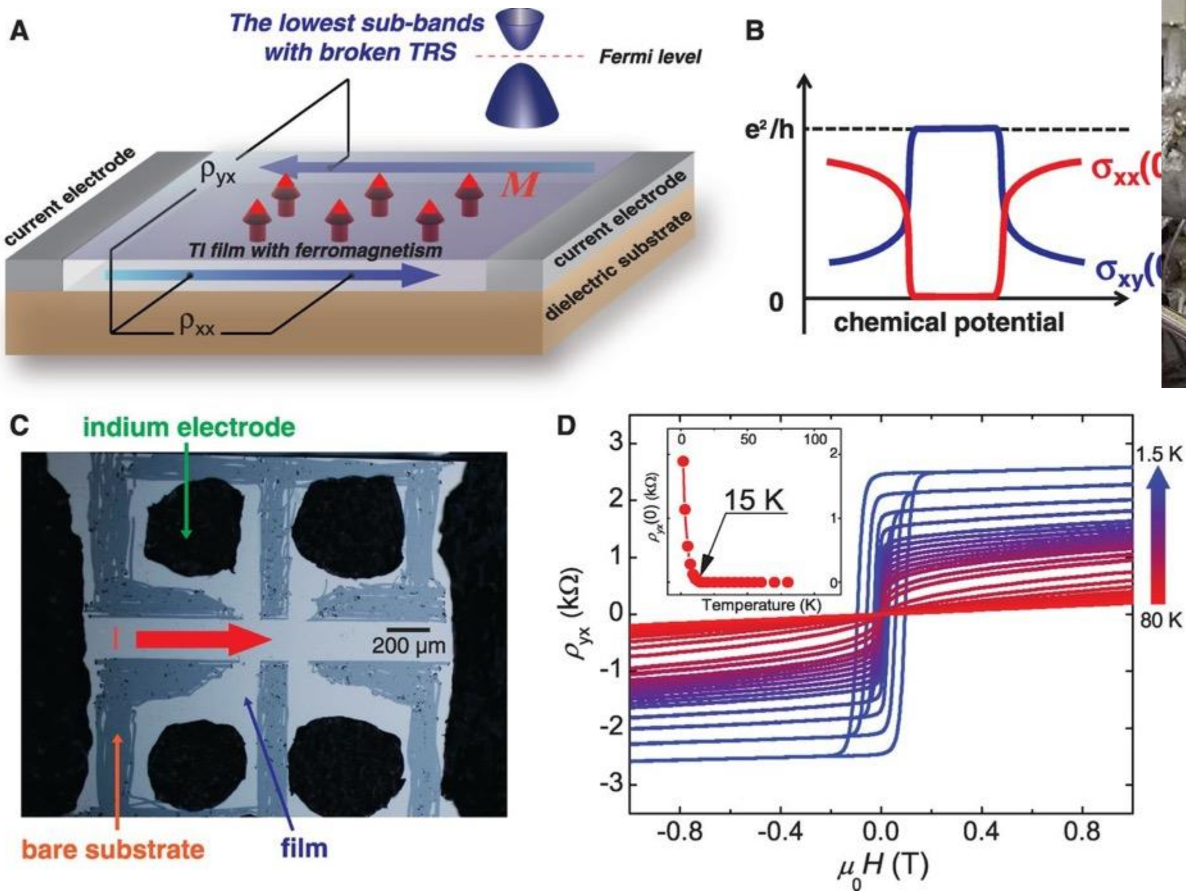


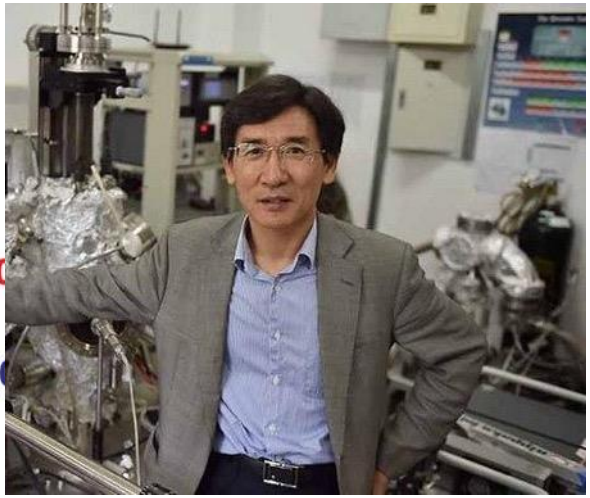


A review, see:
Xiao-Liang Qi and Shou-Cheng Zhang
Rev. Mod. Phys. 83, 1057

Quantum Anomalous Hall effect

Adding magnetic dopants: a “quantum Hall state” without magnetic field!





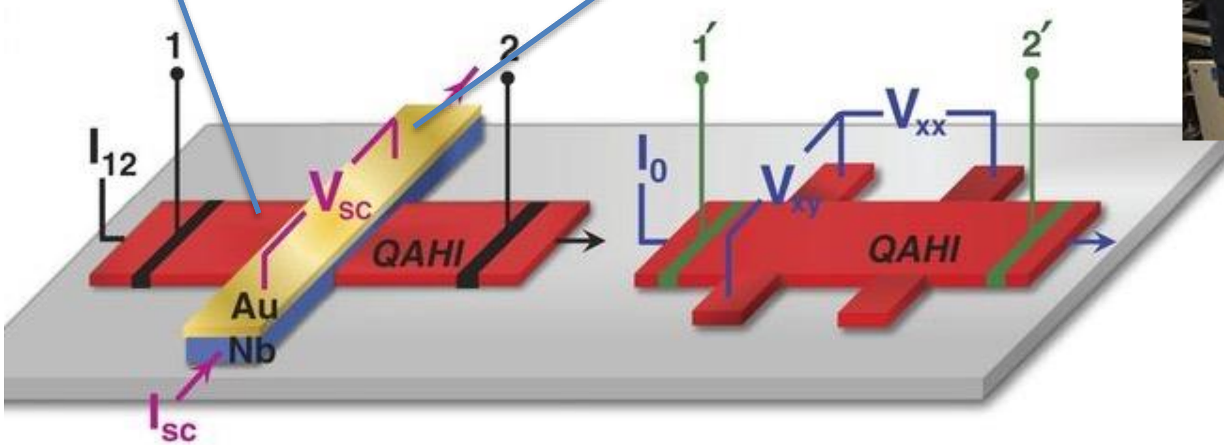
Discovery of the Quantum Anomalous Hall effect

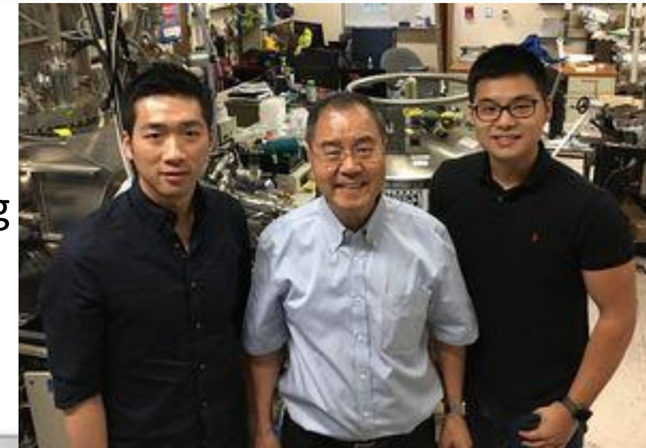
Qi-Kun Xue group, Science 340, 167 (2013)

Adding “superconductor”

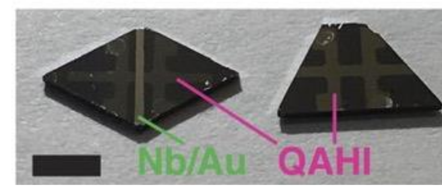
Quantum Anomalous Hall sample:
$(Cr_{0.12}Bi_{0.26}Sb_{0.62})_2Te_3$ (6 nm thick)

Nb for superconducting proximity effect





Prof. Kang L. Wang group, UCLA



REPORT

Chiral Majorana fermion modes in a quantum anomalous Hall insulator–superconductor structure

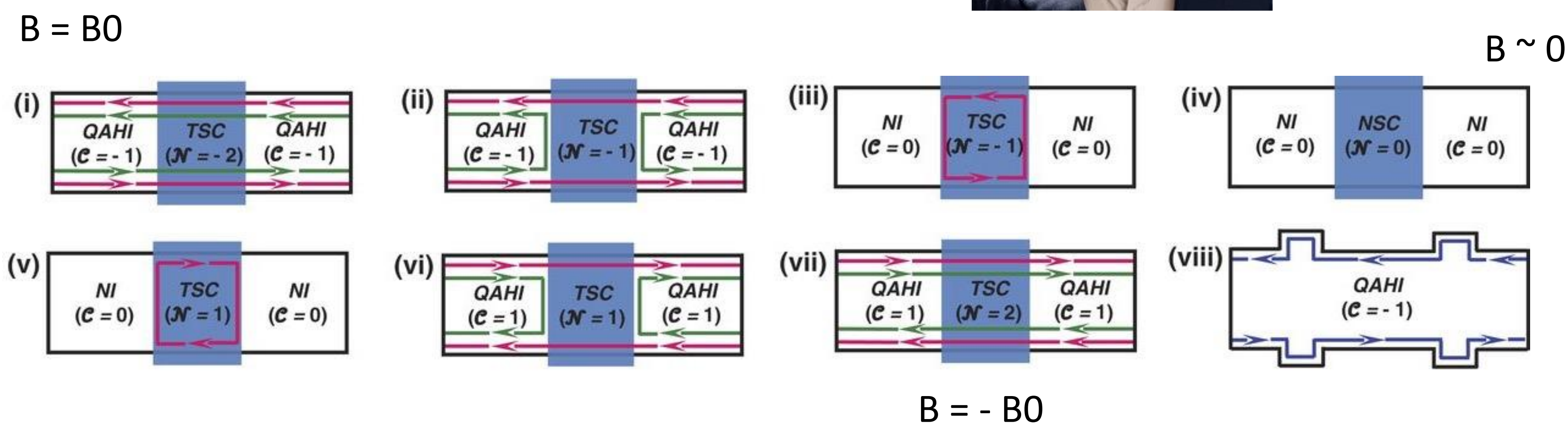
Qing Lin He[1,*,†], Lei Pan[1,†], Alexander L. Stern[3], Edward C. Burks[4], Xiaoyu Che[1], Gen Yin[1], Jing Wang[5,6], Biao Lian[6], Quan Zhou[6], Eun Sang Choi[7], Koichi Murata[1], Xufeng Kou[1,8,*], Zhijie Chen[4], Tianxiao Nie[1], Qiming Shao[1], Yabin Fan[1], Shou-Cheng Zhang[6,*], Kai Liu[4], Jing Xia[3], Kang L. Wang[1,2,*]

Science
Vol 357, Issue 6348
21 July 2017

A Chiral TSC

The quantum numbers (hence the chiral Majorana edge modes (CMEM)) of this artificially created chiral TSC (Topological Superconductor) can be tuned by a small magnetic field.

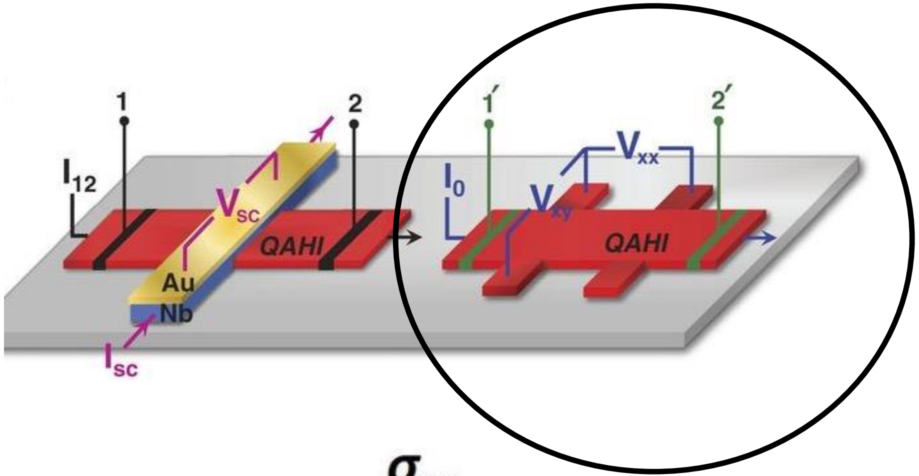
Prof. S.C. Zhang (Stanford)

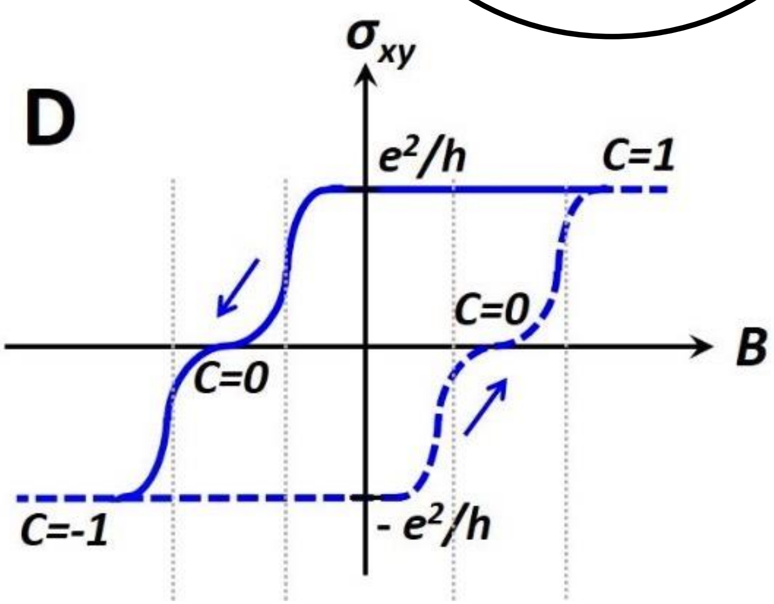


C:	Chern number	N:	# of Chiral edge states
QAHI:	Quantum Anomalous Hall (C odd)	TSC:	Topological Superconductor (N odd)
NI:	Normal Insulator (C = even)	NSC:	Normal Superconductor (N even)

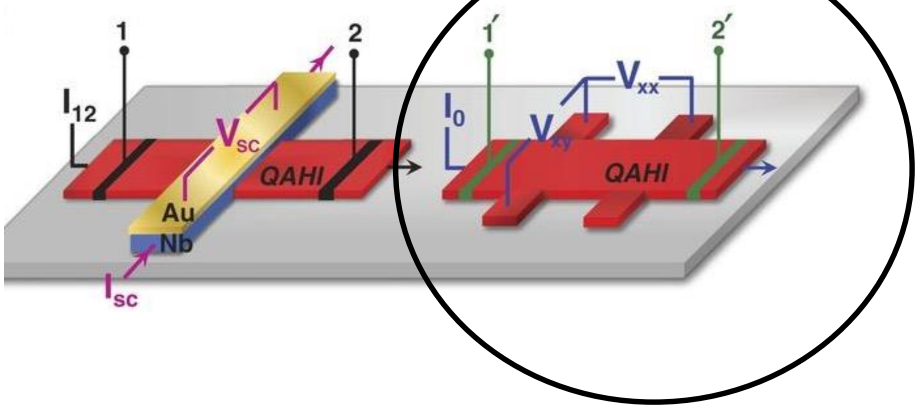
How to measure the C number?

QAHI

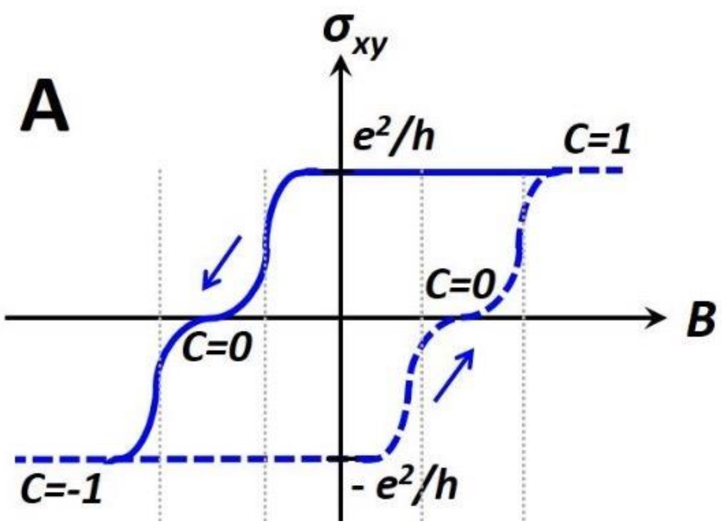




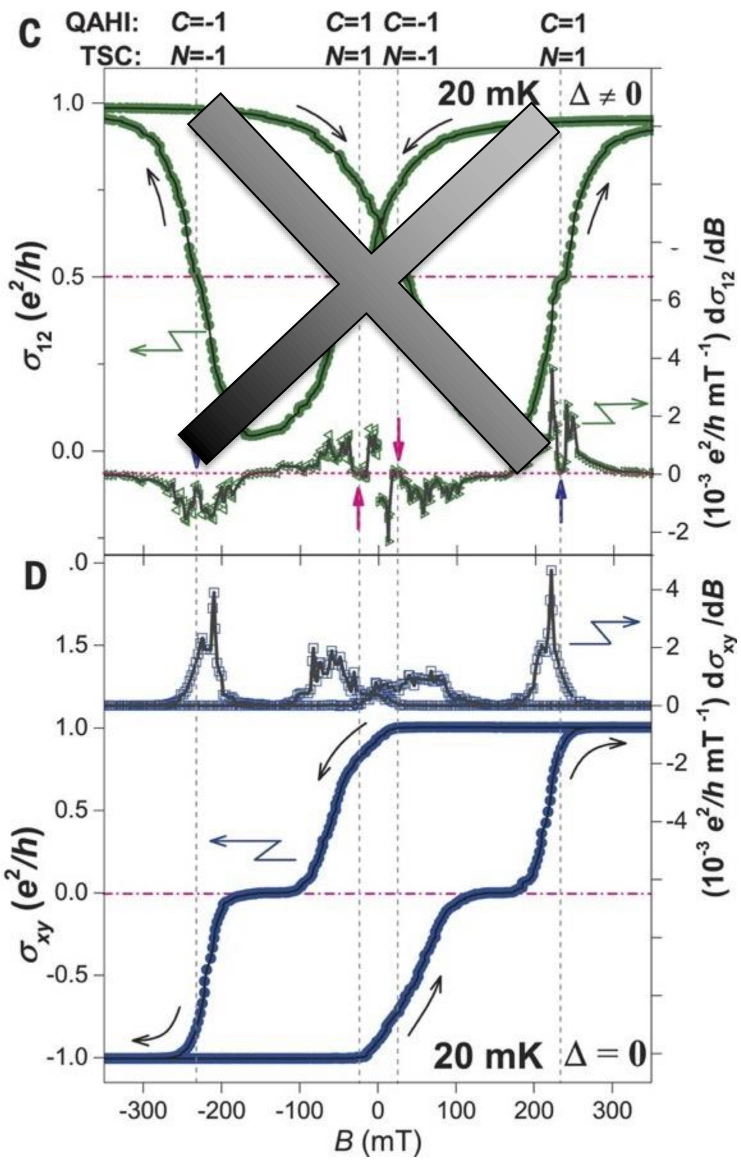
Experiment



1
2
1′
2′
I_{12}
V_{sc}
QAHI
Au
Nb
I_{sc}
I_0
V_{xx}
V_{xy}
QAHI

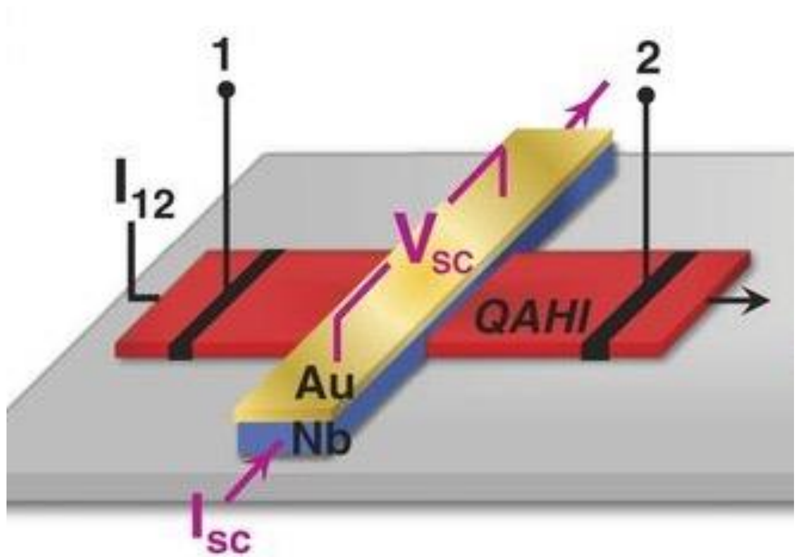


A
σ_{xy}
e^2/h
C=1
C=0
C=0
B
C=-1
$-e^2/h$



C
QAHI: C=-1 C=1 C=-1 C=1
TSC: N=-1 N=1 N=-1 N=1
20 mK $\Delta \neq 0$
σ_{12} (e^2/h)
(10^{-3} e^2/h mT^{-1}) $d\sigma_{12}/dB$
D
σ_{xy} (e^2/h)
(10^{-3} e^2/h mT^{-1}) $d\sigma_{xy}/dB$
20 mK $\Delta = 0$
B (mT)

Now make the middle part SC.

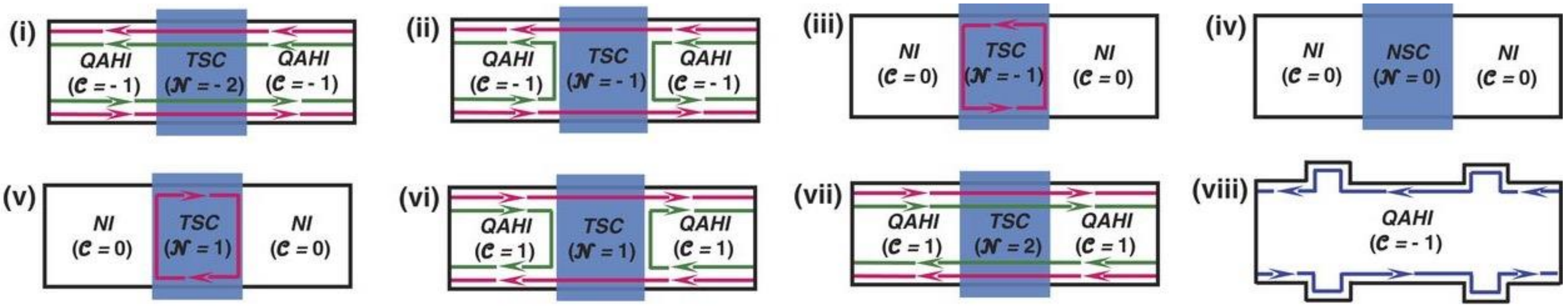


Adding superconductor

It is important to break inversion symmetry so that top and bottom SC gap are different.

B = B0

B ~ 0



B = - B0

C:	Chern number	N:	total Chern number
QAHI:	Quantum Anomalous Hall (C odd)	TSC:	Topological Superconductor (N odd)
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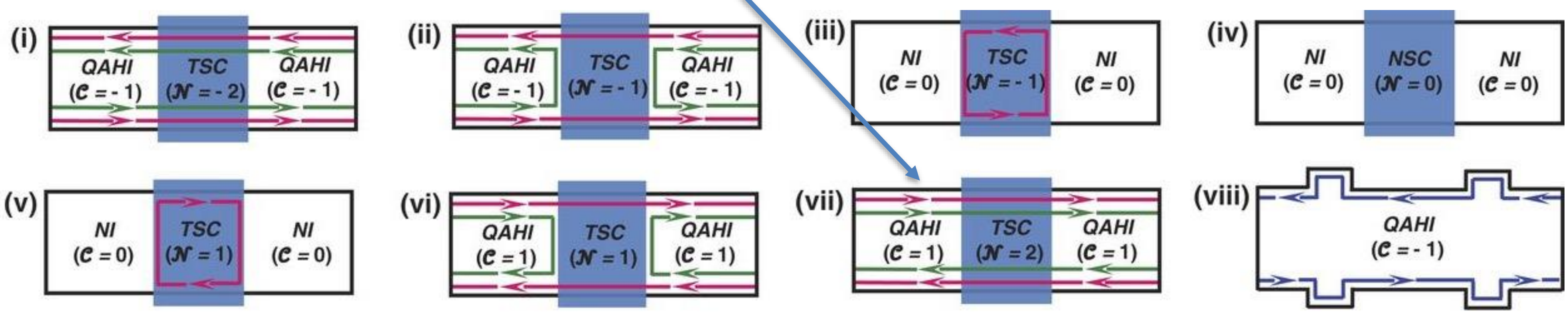
A Chiral TSC

It is important to break inversion symmetry so that top and bottom SC gap are different.

Two CMEM, topologically equivalent to 1 QH chiral edge

B = B0

B ~ 0



B = - B0

C:	Chern number
QAHI:	Quantum Anomalous Hall (C odd)
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NSC:	Normal Superconductor (N even)

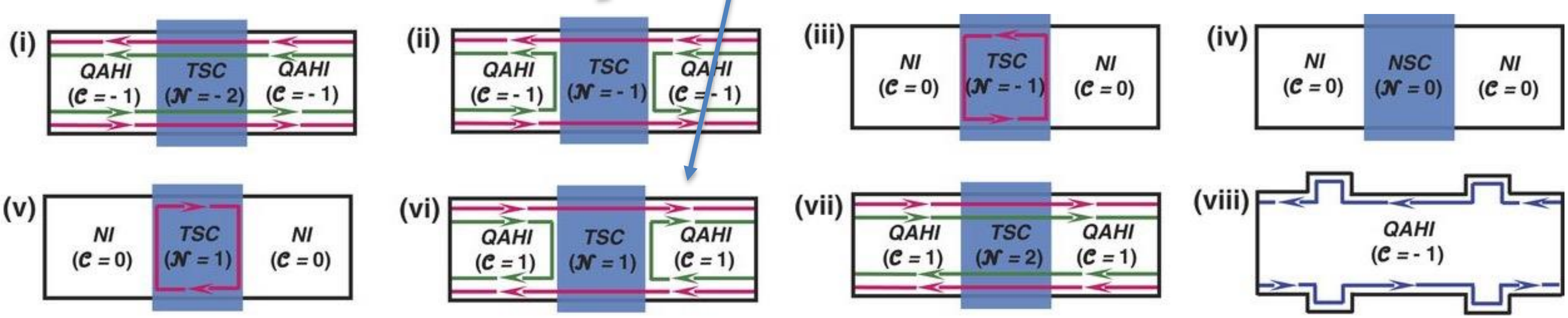
A Chiral TSC

It is important to break inversion symmetry so that top and bottom SC gap are different.

One CMEM in TSC vanishes, N=1; thus one CMEM in QAHI is reflected.

B = B0

B ~ 0



B = - B0

C:	Chern number	N:	total Chern number
QAHI:	Quantum Anomalous Hall (C odd)	TSC:	Topological Superconductor (N odd)
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A Chiral TSC

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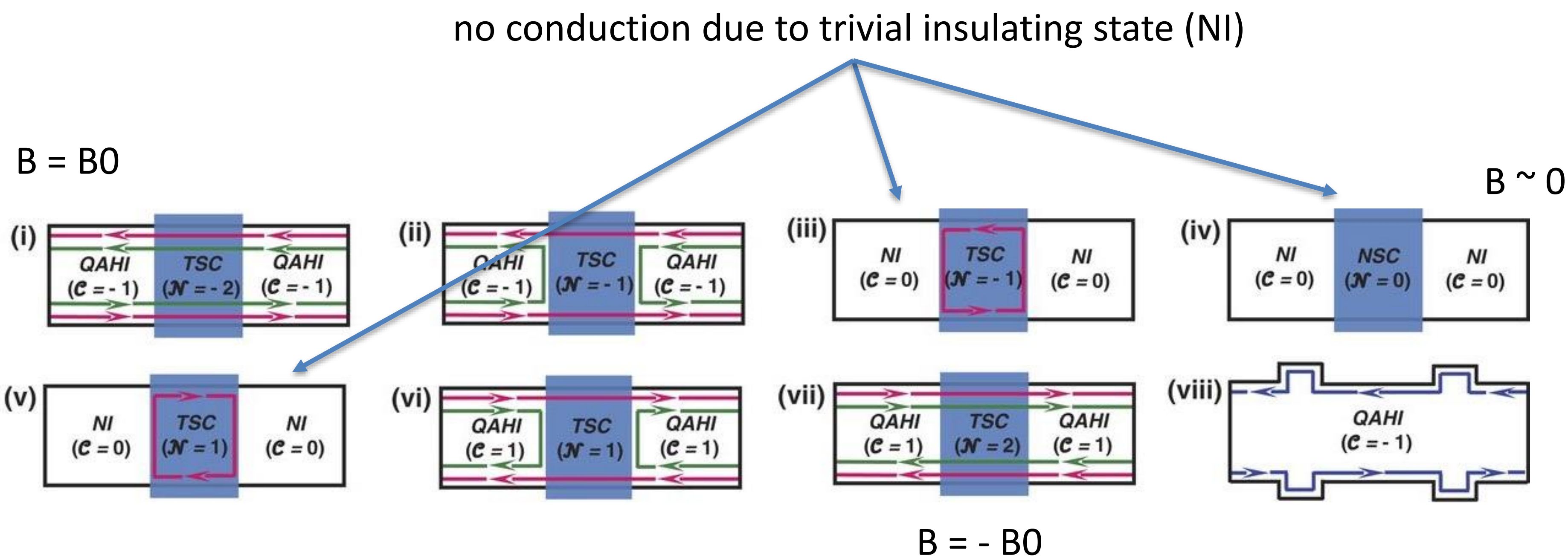
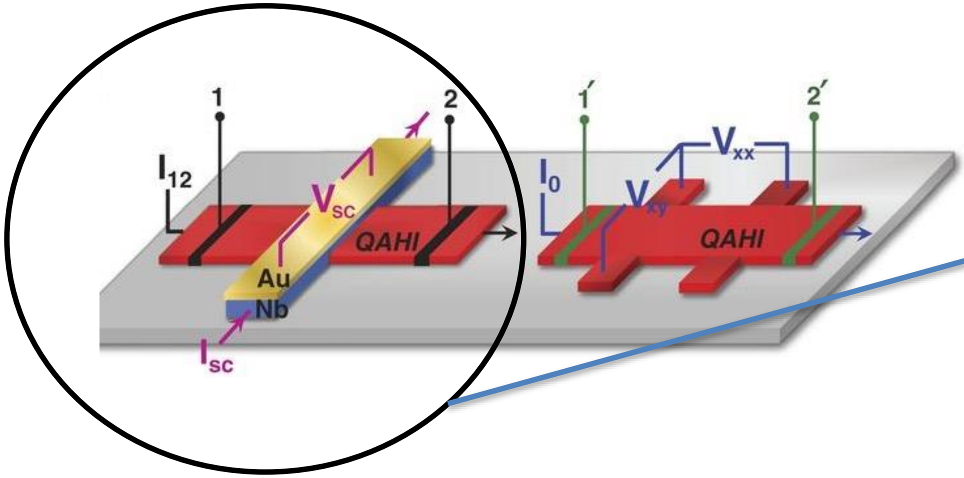
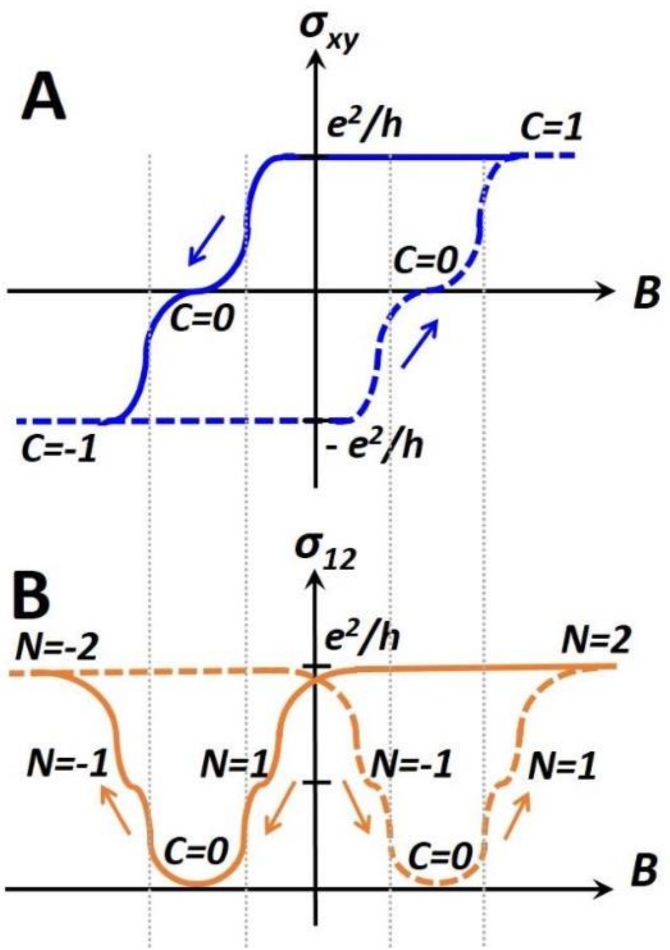


C:	Chern number	N:	total Chern number
QAHI:	Quantum Anomalous Hall (C odd)	TSC:	Topological Superconductor (N odd)
NI:	Normal Insulator (C = even)	NSC:	Normal Superconductor (N even)

How do we know the N number?

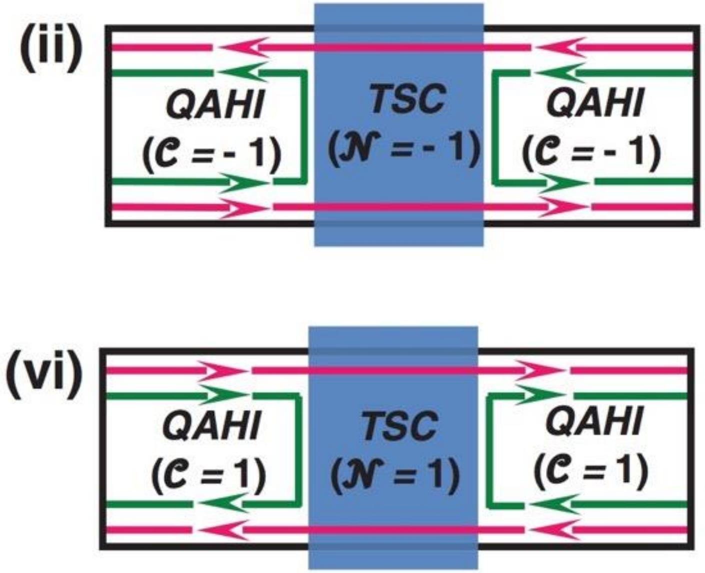


If the middle is SC

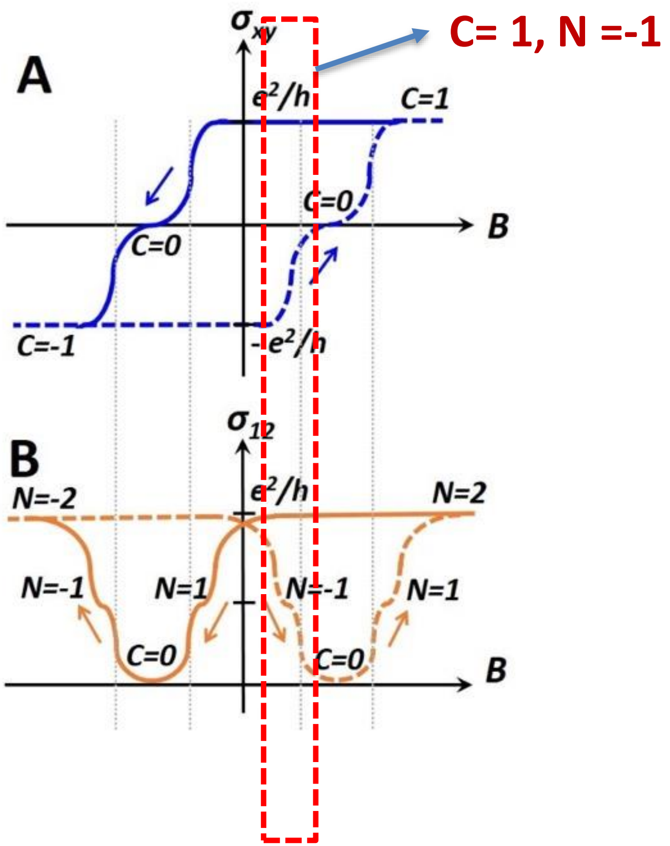


In the middle of the QAHI bar, the proximity to an s-wave super-conductor drives the QAHI into a superconducting regime, where a finite superconducting pairing amplitude is induced to the surface of the QAHI.

A Chiral TSC



If the middle is SC

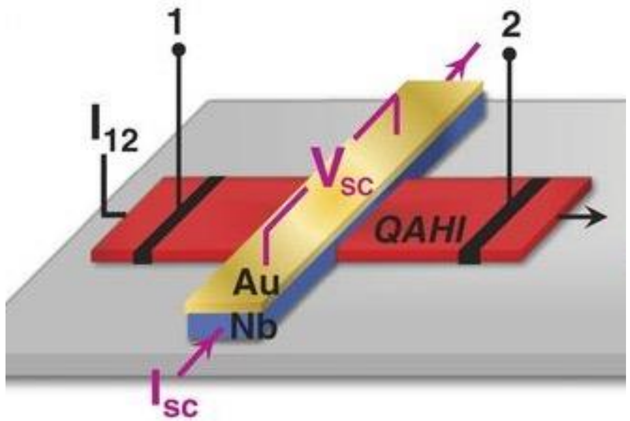


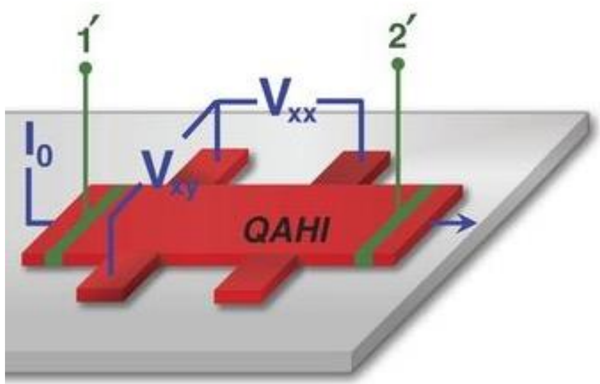
The single Chiral Majorana state ($N = \pm 1$) during the reversal of the magnetization (e.g. near zero magnetic field)

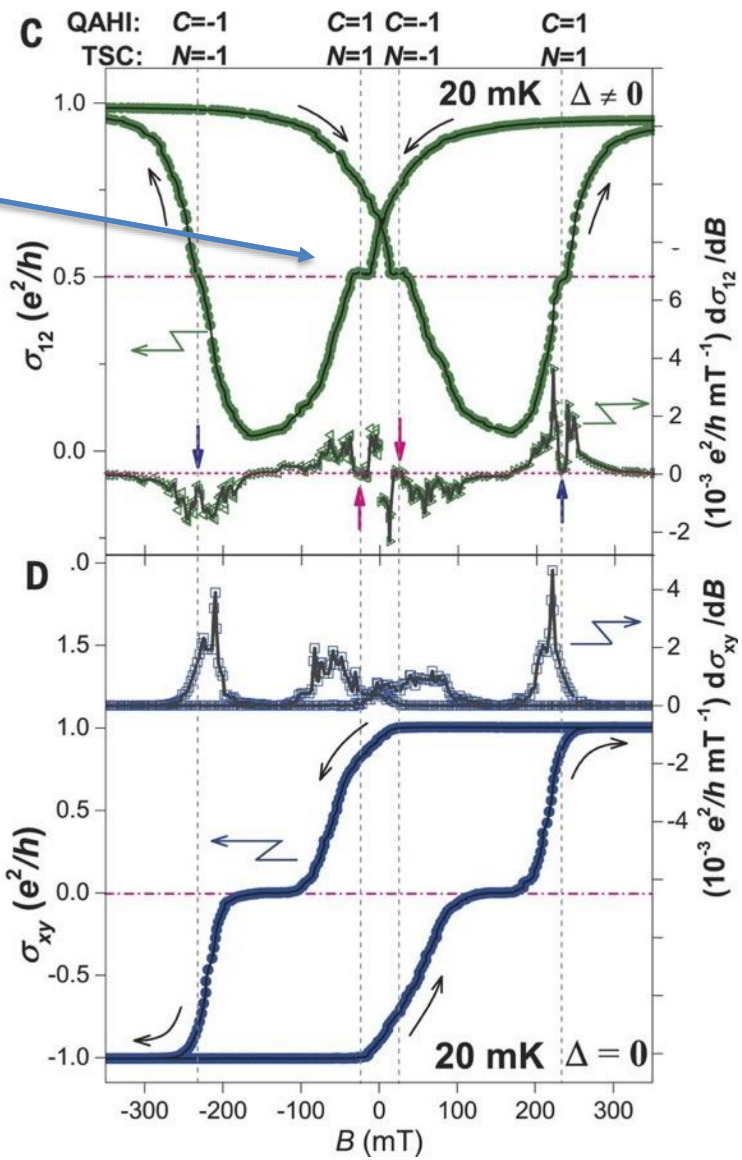
Unlike QHE or QAHE or any known topological state, it would feature a half-integer longitudinal conductance plateau (0.5 e^2/h)

The “smoking gun”: 0.5 plateau

Longitudinal conductance between terminal 1 and 2 would feature a half-integer plateau (0.5 e^2/h) near magnetic reversal.



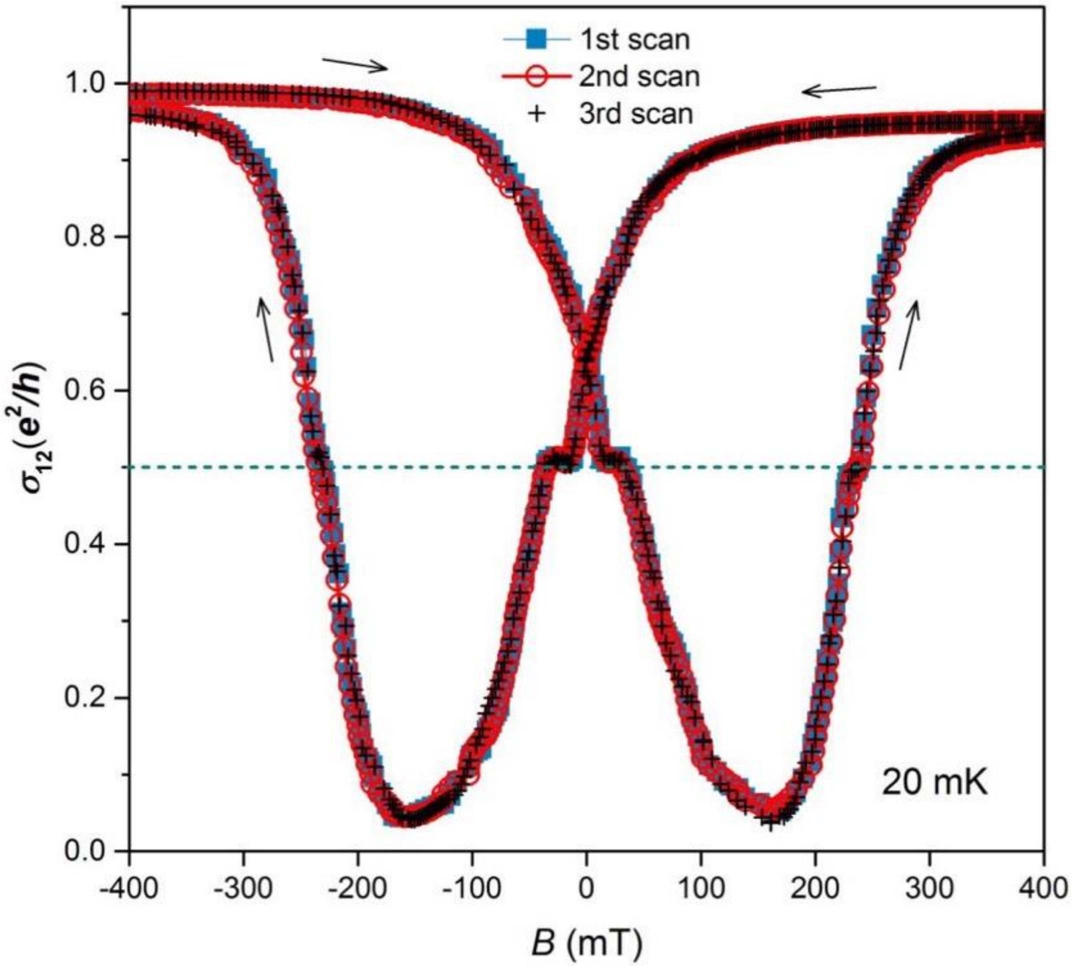




Sigma_xy of nearby QAHI sample w/o SC

Repeatability

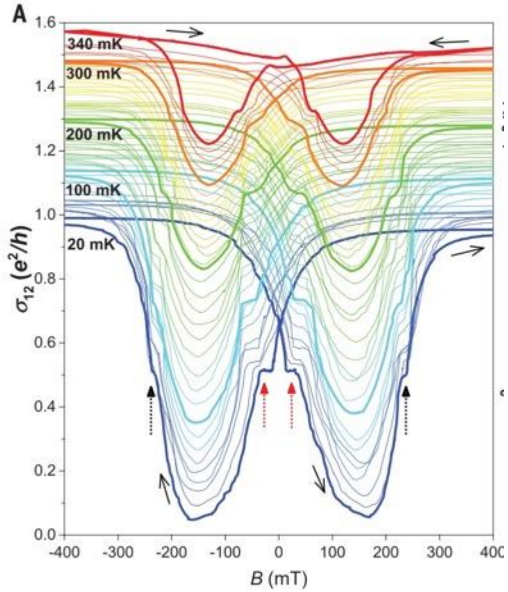
#1 device



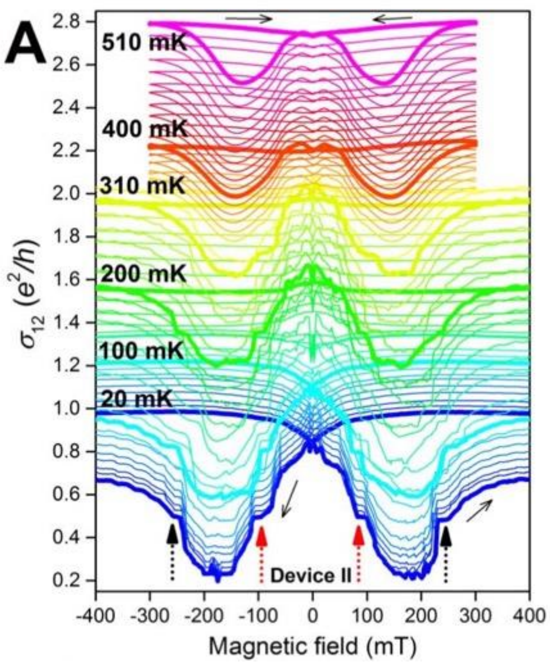
Repeatability

3 devices separated by months.

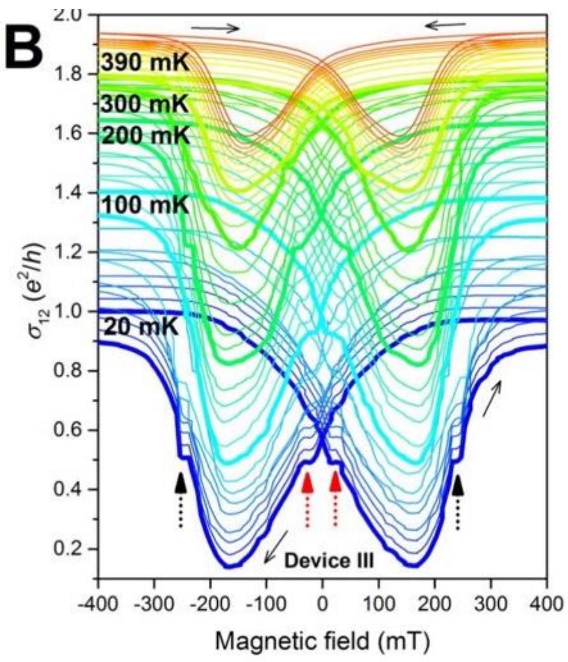
#1 device



#2 device



#3 device



- Is this directly related to topological Qubit?

- Maybe a much complicated construction is needed. However it is close to Ettore Majorana’s original idea…

Notes on Ettore Majorana (disappeared 1938)

1) This Majorana fermion propagating edge state satisfies the propagating wave equation originally proposed by Ettore Majorana, which was intended to describe neutrinos.

Dirac equation
$$\begin{aligned}(E + \vec{p}\cdot\vec{\sigma})\chi - m\varphi = 0 \\ (E - \vec{p}\cdot\vec{\sigma})\varphi - m\chi = 0\end{aligned}$$

Majorana equation
$$\begin{aligned}(E + \vec{p}\cdot\vec{\sigma})\chi - im_a\sigma_2\chi^* = 0 \\ (E - \vec{p}\cdot\vec{\sigma})\varphi - im_b\sigma_2\varphi^* = 0\end{aligned}$$

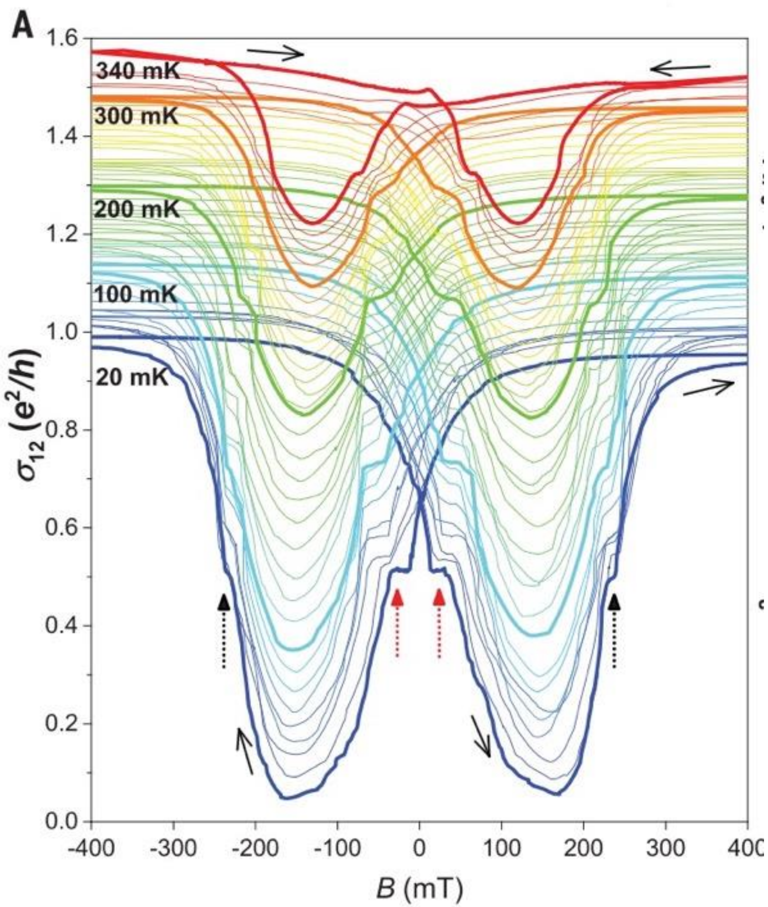
2) The fundamental aspects of the Majorana fermion modes and their non-Abelian braiding properties can be potentially used for topologically protected (fault-tolerant) quantum computation.

On March 25, 1938, he disappeared under mysterious circumstances while going by ship from Palermo to Naples.

Why mK temperature?

Tc of QAHI materials = 29 K
Tc of Nb superconductor = 9 K

Why are we stuck at 20 mK?

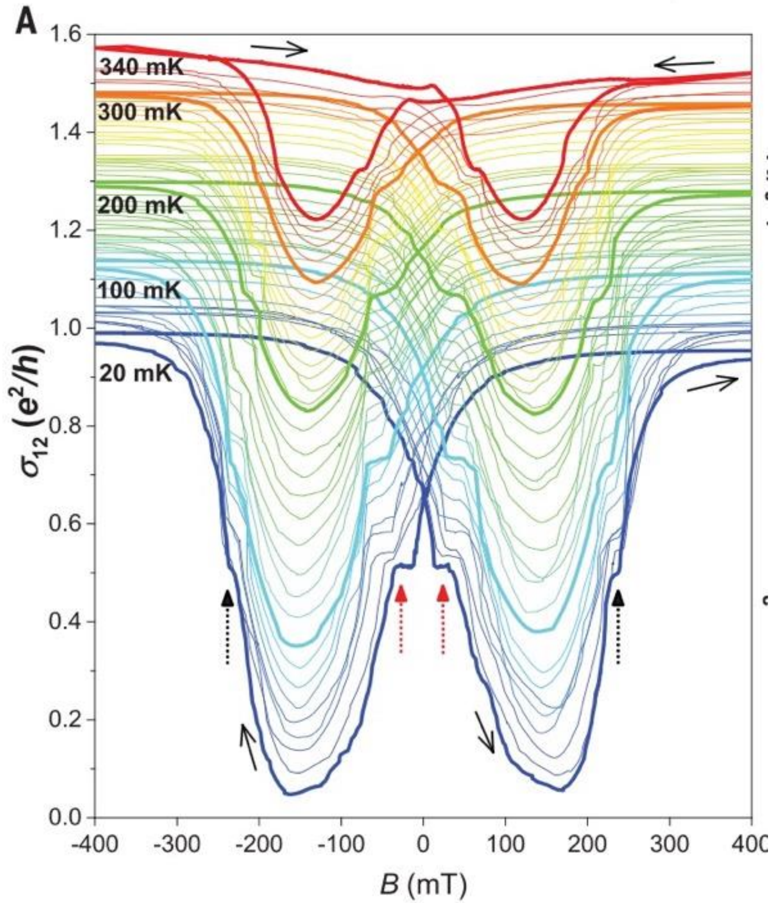


Why mK temperature?

Tc of QAHI materials = 29 K
Tc of Nb superconductor = 9 K

Why are we stuck at 20 mK?

Strange magnetism in QAHI. We looked into this using combined transport and magnetic imaging (Sagnac interferometer microscope.)



Summary

- A single Majorana edge mode is discovered in a topological superconductor structure.
- The mode is describe by the Majorana propagation equation and “maybe” useful for topological quantum computing.
- It is the instability of small FM region that kills QAHE. More uniform samples may reach QAHE at ~20 K.

Another potential candidate for Majorana edge state:

Exotic Superconductivity in Bi/Ni bilayer

Artificially engineered superconductor

Can we engineer some exotic superconductor?

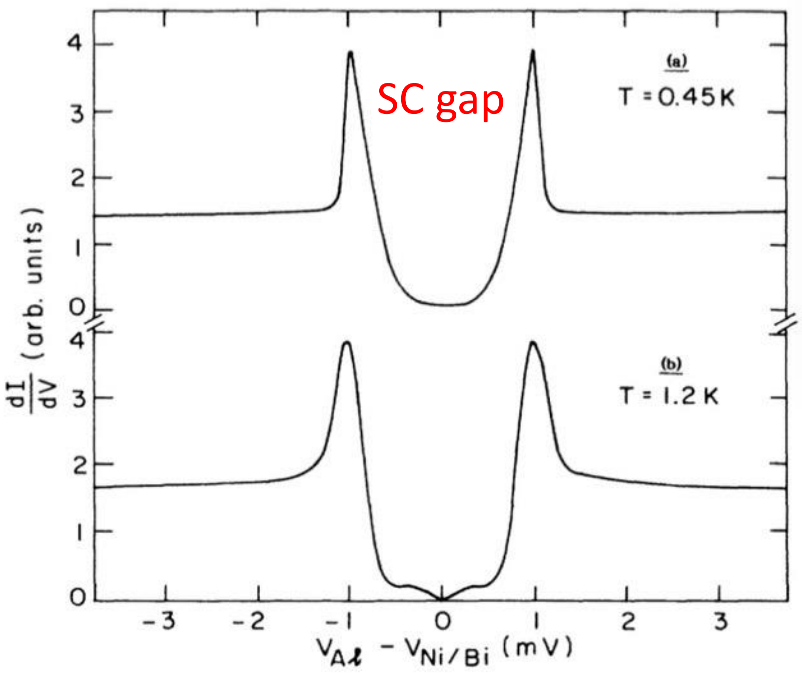


FIG. 1. Tunnel conductance plotted as a function of applied bias for two $Al/Al_2O_3/Ni/Bi$ tunnel junctions with Ni/Bi of 4/800 (a) and 10/85 (b) showing superconductivity at the Ni/Bi and Al with the Al_2O_3.

PHYSICAL REVIEW B

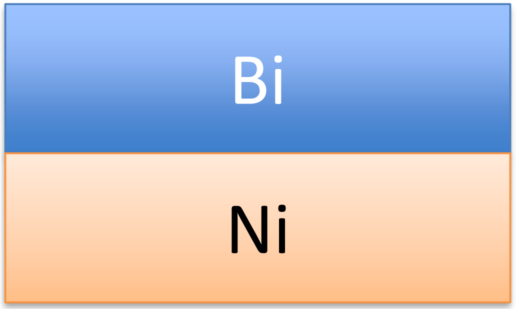
covering condensed matter and materials physics

Highlights Recent Accepted Authors Referees Search Press

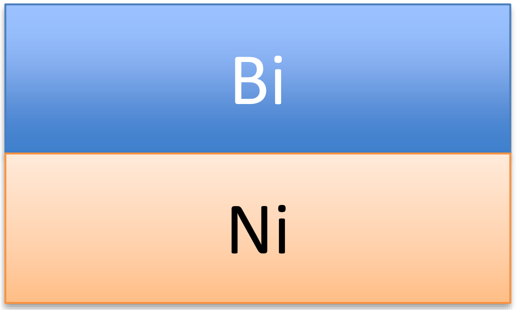
Superconducting phases of Bi and Ga induced by deposition on a Ni sublayer

J. S. Moodera and R. Meservey

Phys. Rev. B **42**, 179 – Published 1 July 1990



The nature of Bi/Ni superconductor?

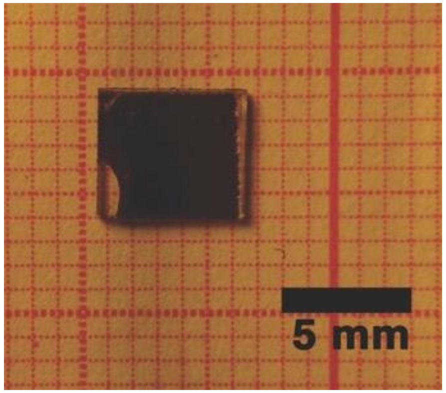


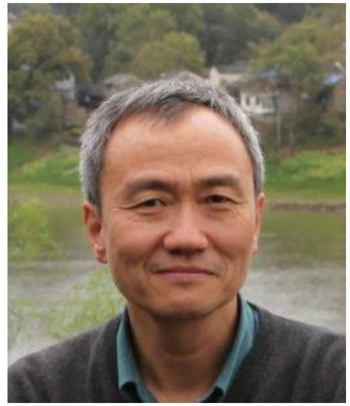
The superconductivity seems to be exotic:
Ni is a ferromagnet
Bi is a semimetal

Moodera sample was made by sputtering
Uncertainties on Bi thickness, Ni thickness, Bi/Ni interface....

Need better sample and new probes to understand this superconducting state...

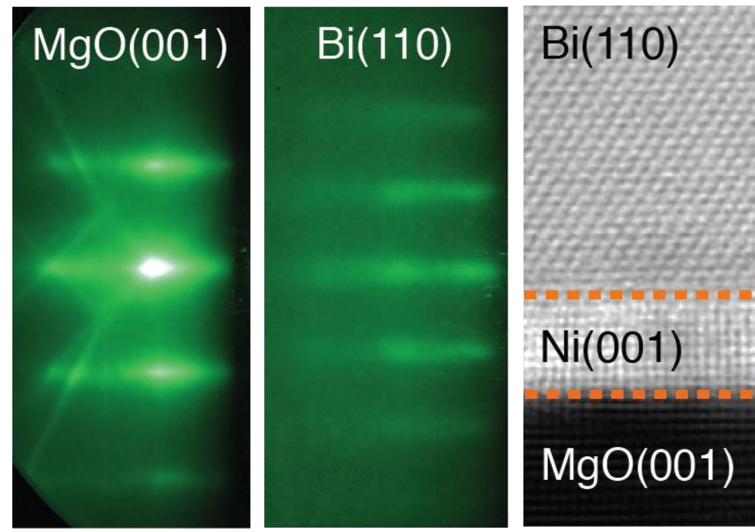
What is the nature of SC in Bi/Ni?





Prof. Xiaofeng Jin (Fudan)

Today: High quality Bi/Ni samples with MBE



molecular beam epitaxy (MBE)

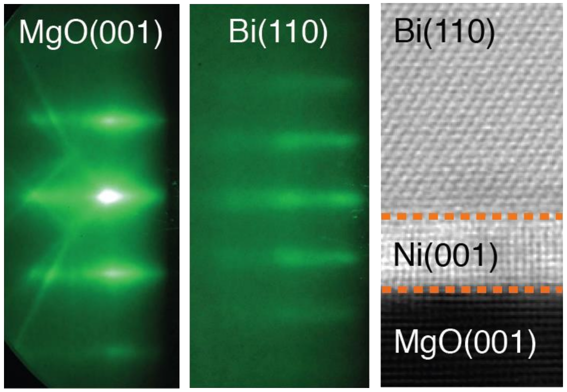
SCIENCE ADVANCES | RESEARCH ARTICLE

SUPERCONDUCTIVITY

Time-reversal symmetry-breaking superconductivity in epitaxial bismuth/nickel bilayers

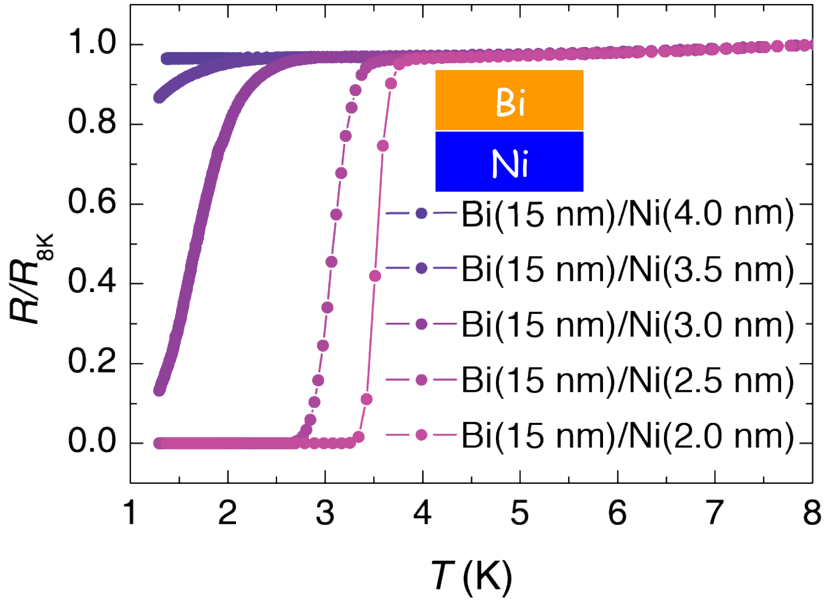
Xinxin Gong,[1,2] Mehdi Kargarian,[3] Alex Stern,[1] Di Yue,[2] Hexin Zhou,[2] Xiaofeng Jin,[2] Victor M. Galitski,[3] Victor M. Yakovenko,[3] Jing Xia[1*]

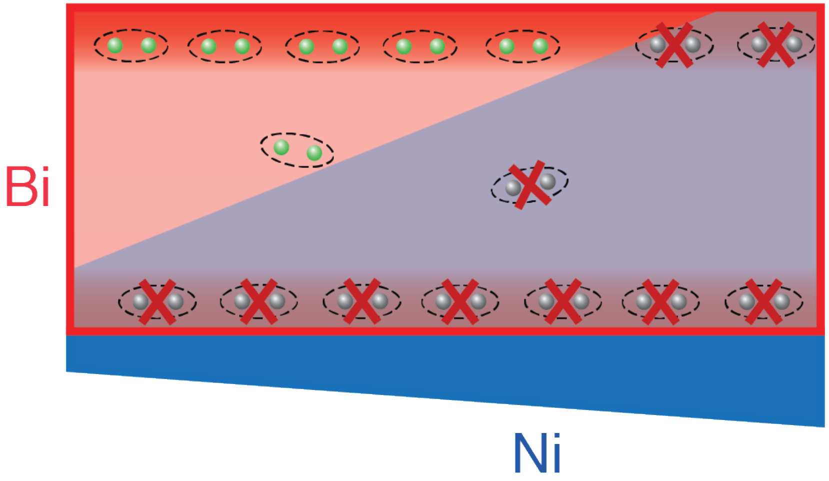
What is the nature of SC in Bi/Ni?



MBE High quality
Bi/Ni samples

Thicker Ni layer seems to suppress superconductivity.





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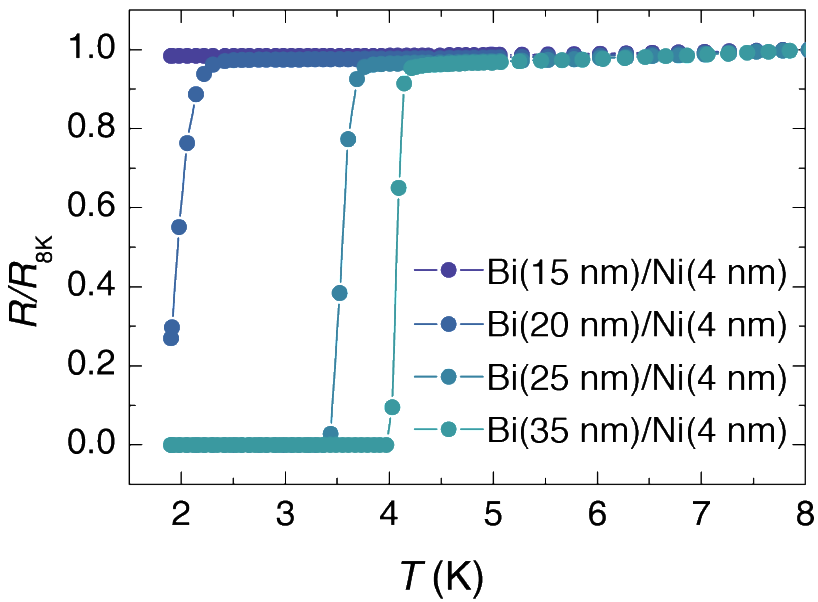
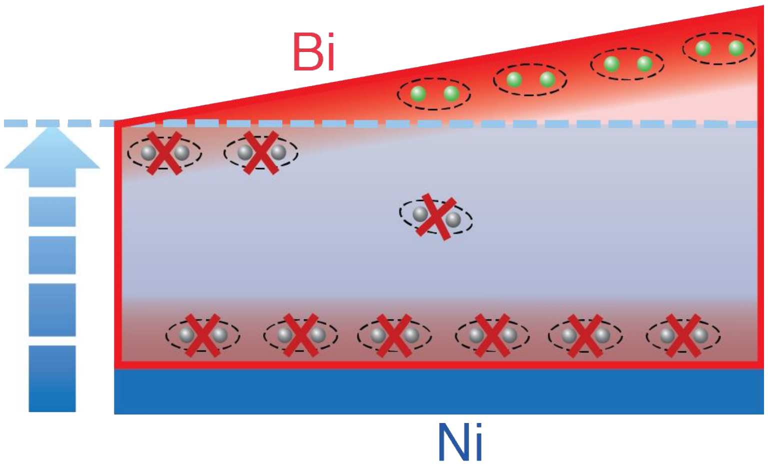
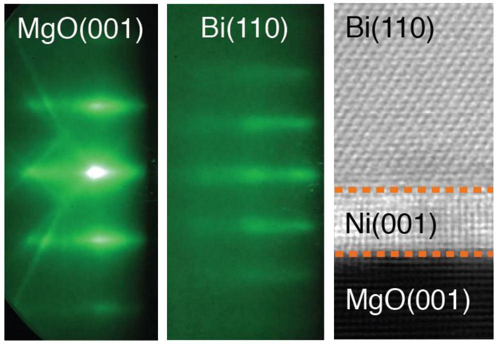
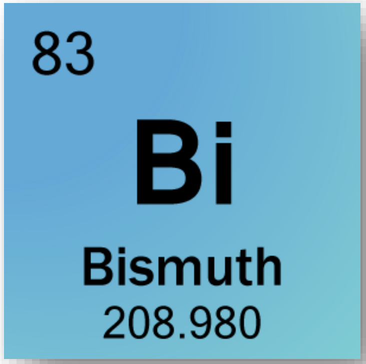




Thicker Bi seems to strengthen superconductivity.



The interesting case of Bi



Facts about Bi:

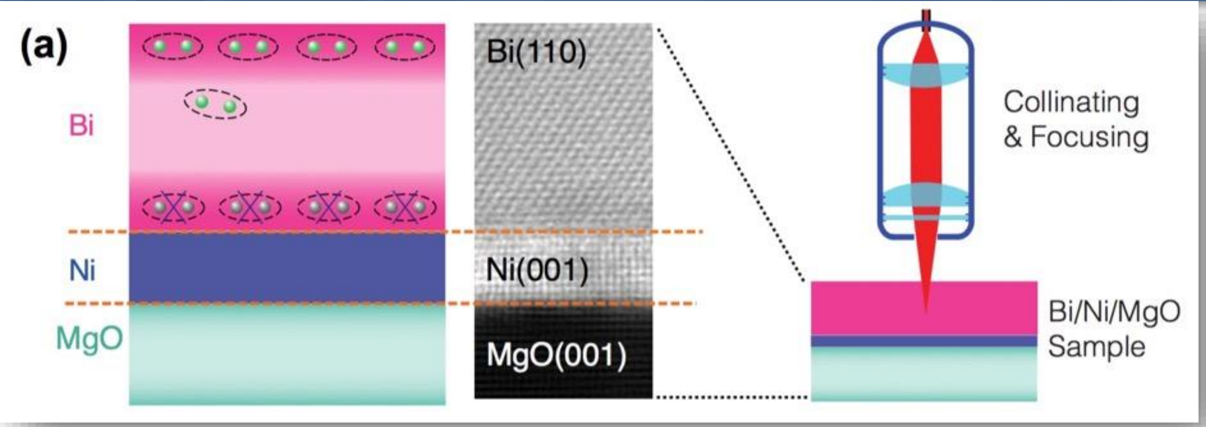
The heaviest nonradioactive element.

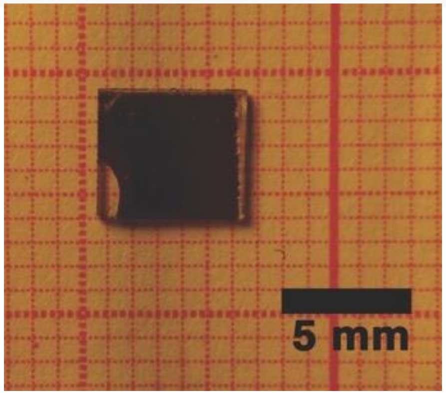
Normally a semimetal with extremely long mean free path.

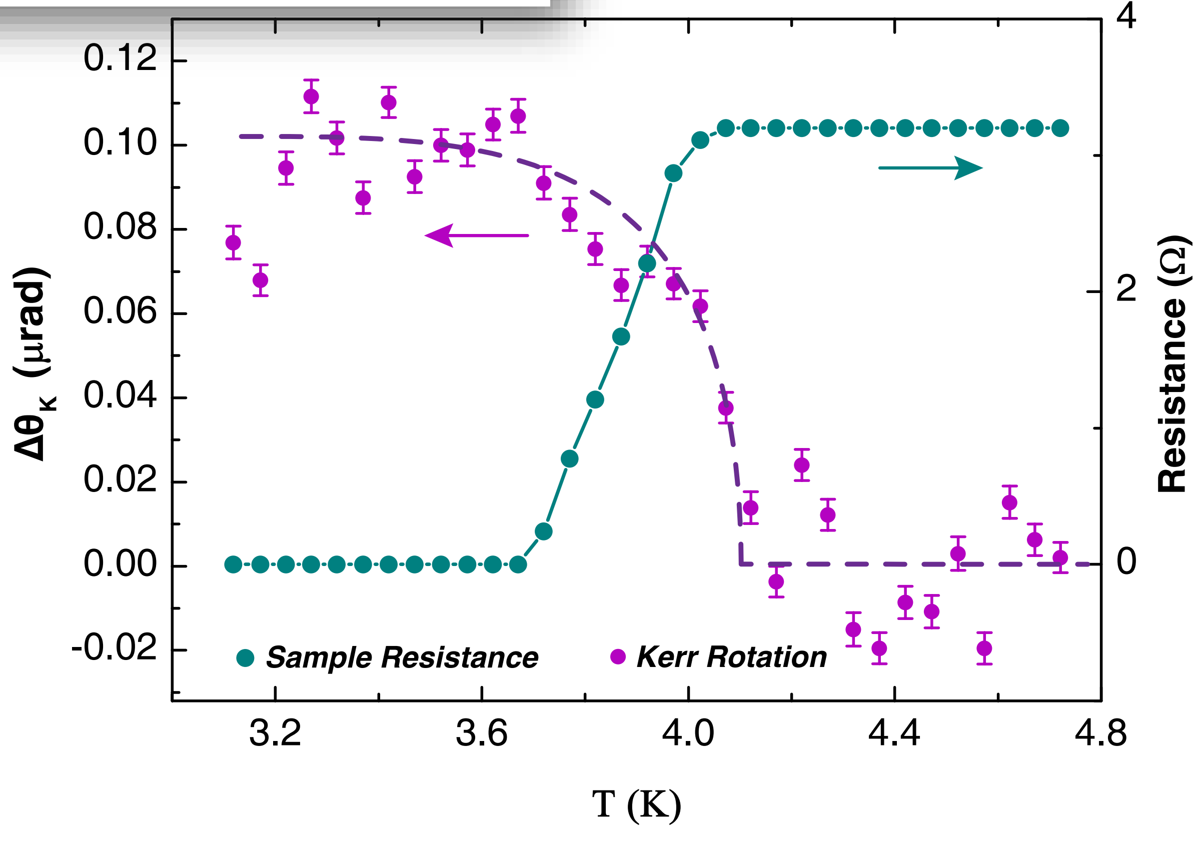
Due to its extremely strong spin-orbital coupling and the broken space-inversion symmetry at the surface or interface, the spin degeneracy of surface states of Bi thin film is lifted and the energy bands split in the momentum space, resulting a helical spin structure on the Fermi surface (Rashba Effect) resembling 3D topological insulators.

One could polarize this peculiar spin texture in the in-plane direction and introduce an effective pairing interaction through the out-plane magnetic fluctuation. The spin-orbital coupling Bi and magnetic fluctuation arising from Ni can cooperatively induce pairing channels with a finite total angular momentum. As such, the superconducting order parameter would break the TRS, and could be experimentally tested with Sagnac interferometer.

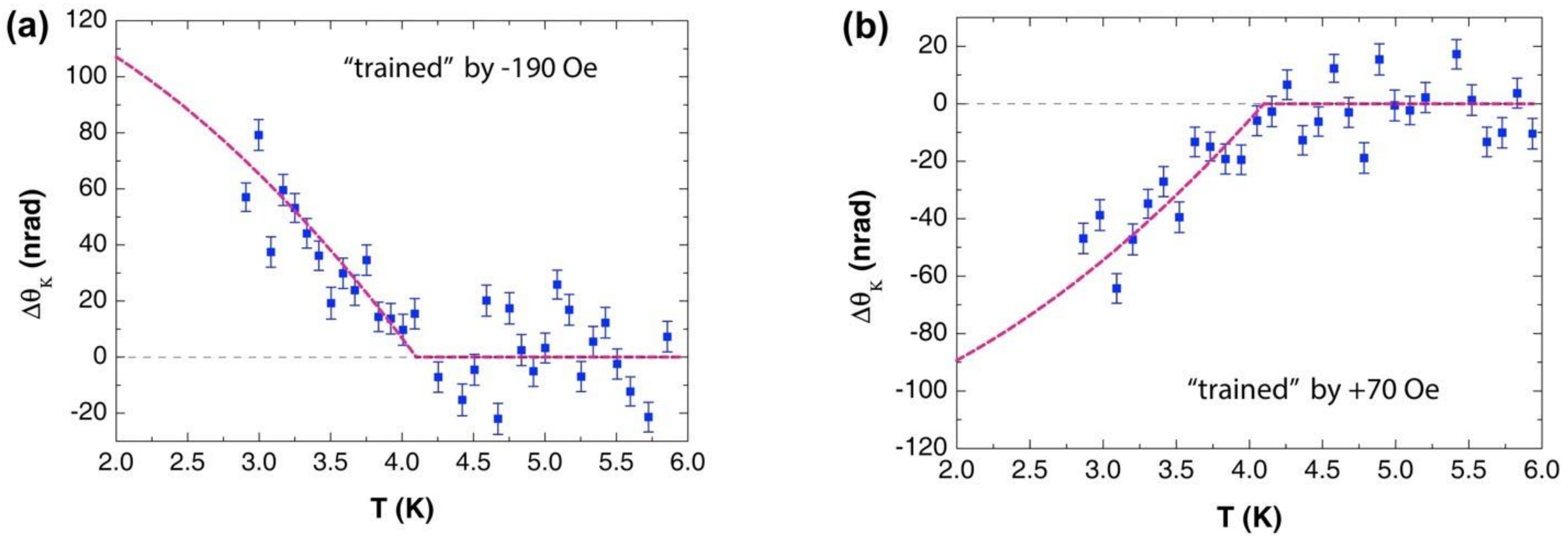
TRSB in Bi/Ni at B = 0







Chirality can be trained by a cooling field




SCIENCE ADVANCES | RESEARCH ARTICLE

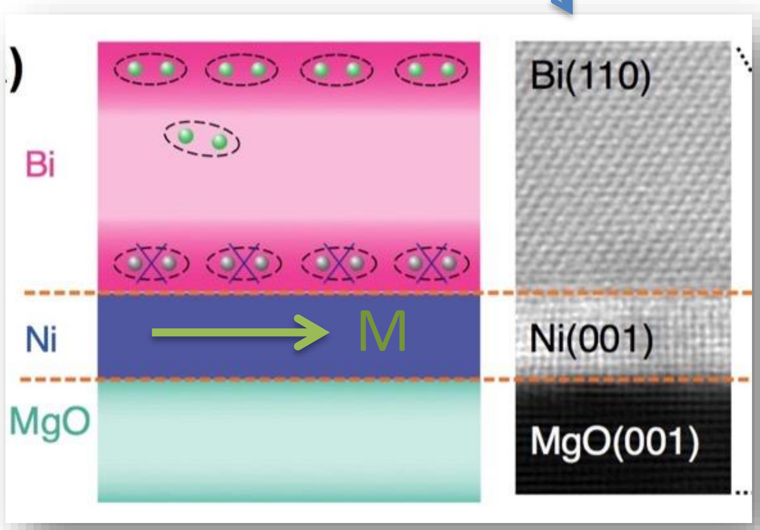
SUPERCONDUCTIVITY

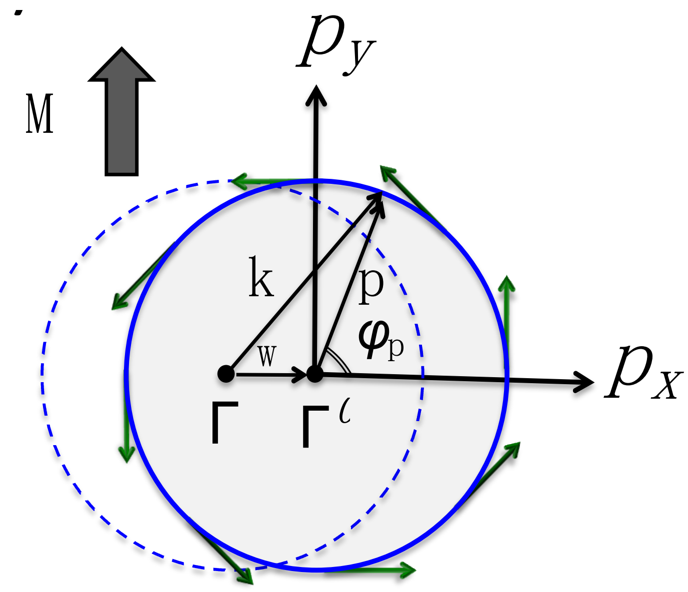
Time-reversal symmetry-breaking superconductivity in epitaxial bismuth/nickel bilayers

Xinxin Gong,[1,2] Mehdi Kargarian,[3] Alex Stern,[1] Di Yue,[2] Hexin Zhou,[2] Xiaofeng Jin,[2] Victor M. Galitski,[3] Victor M. Yakovenko,[3] Jing Xia[1]*

Do we have an understanding?

Bi(110) surface is metallic.





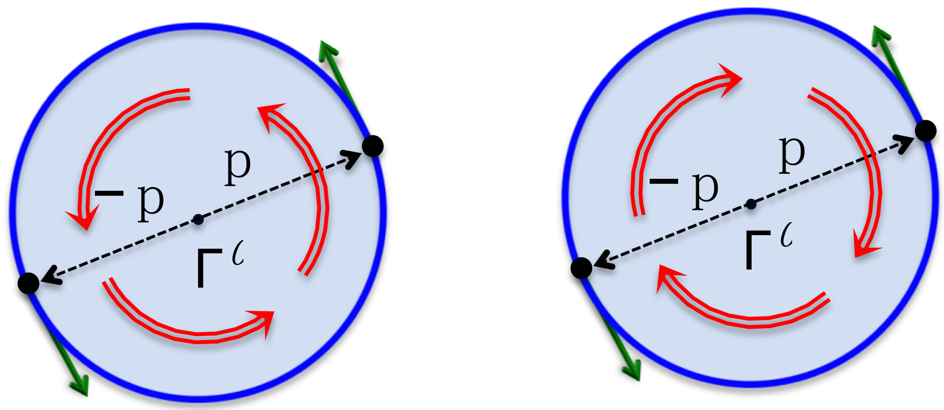
The original Fermi circle at *Γ* is shifted by the vector **w** to the solid-blue circle centered at *Γ′* due to the in-plane magnetization **M** from Ni.

The green arrows show spin polarization locked to the momentum direction due to strong Rashba-type spin-orbit coupling.

Theory by Victor M. Yakovenko, Mehdi Kargarian, Victor M. Galitski

d+ id superconductor

$H_{training}$ ⊙ $H_{training}$ ⊗



$J_z = 2$ $J_z = -2$

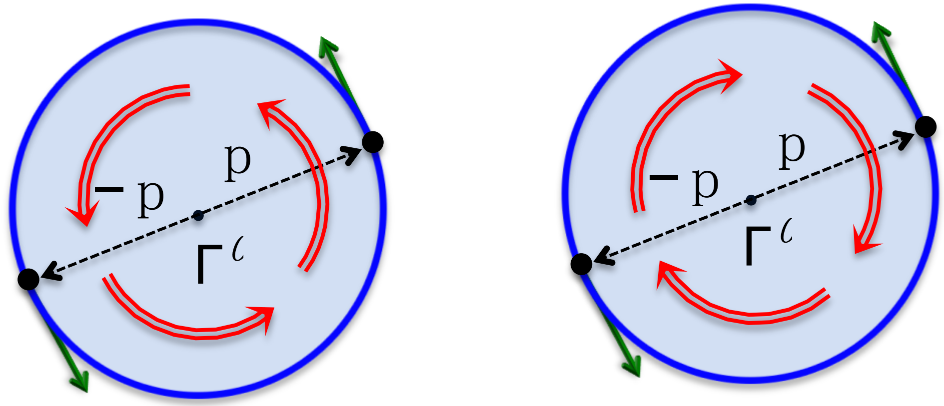
$d + id$ $d - id$

NOTE: p+ip is not allowed because Bi surface is non-degenerate due to large spin-orbit interaction.

Superconducting pairing of the electrons with opposite spins and opposite momenta **p** and **-p**. The time-reversal-breaking condensate has the total angular momentum *Jz=±2*, corresponding to *d±id* pairing, as indicated by the double red curved arrows. A weak training magnetic field can select one of the two degenerate states.

d+ id state

$H_{training}$ ⊙ $H_{training}$ ⊗



$J_z = 2$ $J_z = -2$

$d + id$ $d - id$

Superconductivity spontaneously breaks time-reversal symmetry and is topologically non-trivial with $J = \pm 2$, so there are two Majorana chiral edge states moving in the same direction.