Structures Superconductor – Topological Insulator: Theory and Experiment

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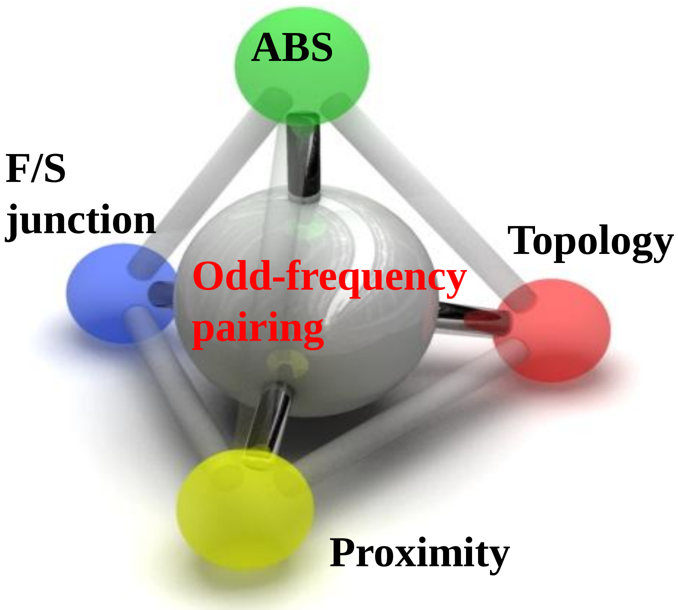

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SPINTECH

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Content

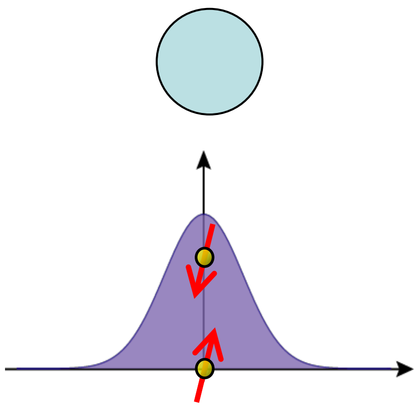
（1）Unconventional superconductivity

（2）Andreev bound states in unconventional junctions

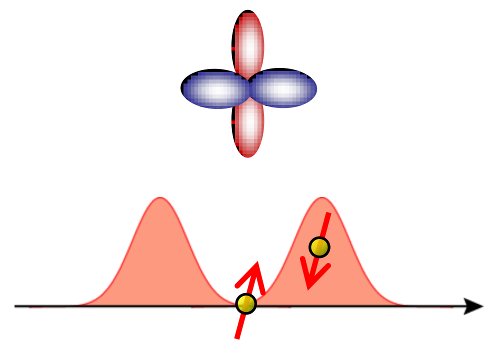
（3） Search of p-wave superconductivity in topological materials

Classification of Symmetry of Cooper pair

Spin-singlet Cooper pair ⟹ **Even Parity**

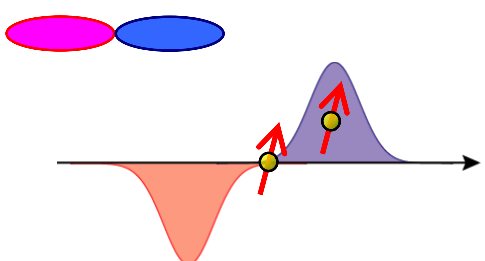


s-wave BCS



d-wave Cuprate

Spin-triplet Cooper pair ⟹ **Odd Parity**



p-wave ^{3}He Sr_2RuO_4

Topological superconductors

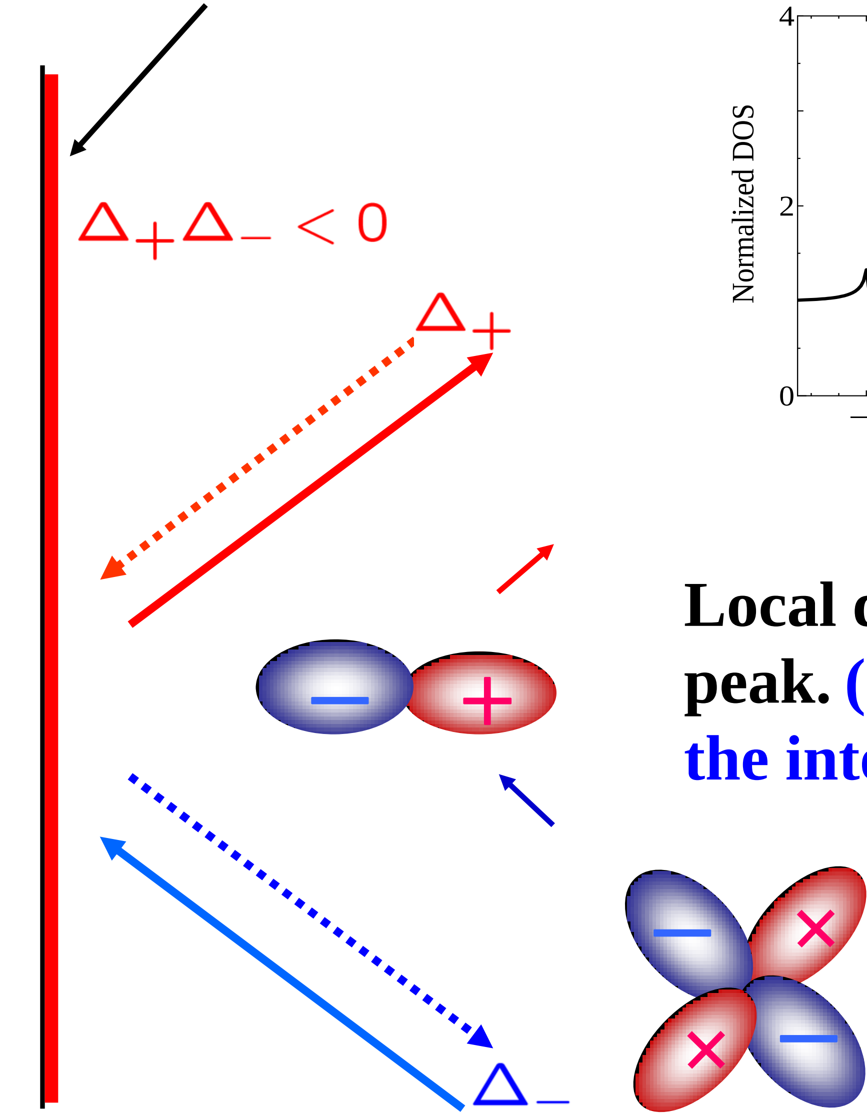
Corresponding edge state in the world of superconductivity (superfluid)

Andreev bound state generated at the surface of superconductors by the bulk-edge correspondence

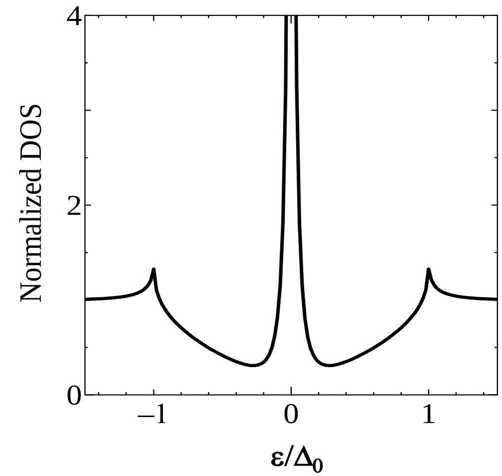
X. L. Qi, S.C. Zhang, PRL 102, 187001 (2009), Schnyder et. al, PRB 78 195125 (2008)

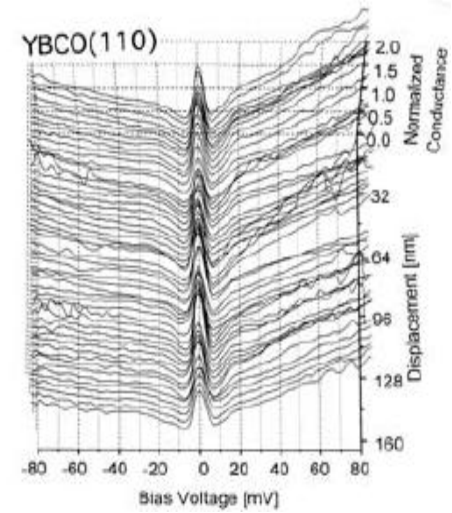
M. Sato and Fujimoto, PRB 79 094504 (2009), Y. Tanaka et. al, PRB 79 060505 (2009)

Classical example of Andreev bound state in unconventional superconductors (high Tc cuprate)



Interface (surface)





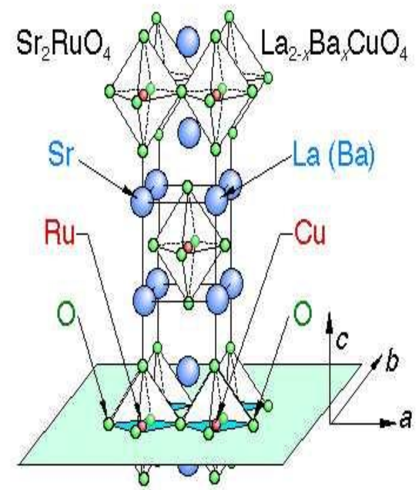
Local density of state has a zero energy peak. (Sign change of the pair potential at the interface)

Tanaka Kashiwaya PRL 74 3451 (1995); Hu(1994)
Kashiwaya, Tanaka, Rep. Prog. Phys. 63 1641 (2000)

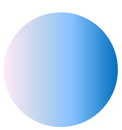
Buchholz, Zwicknagl(1981) Hara Nagai(1986)
Hu(1994), M. Sato(2011)

Chiral superconductor Sr_2RuO_4

Edge surface current



Similar structure to cuprate

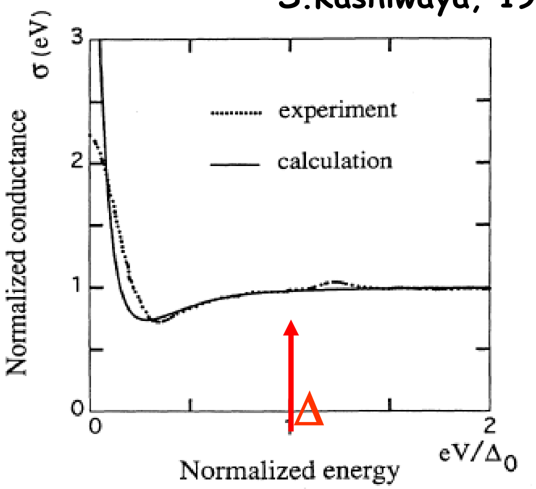


$$p_x + ip_y$$

Maeno (1994)

Tunneling spectrum in cuprate and Ruthenate

S.Kashiwaya, 1995



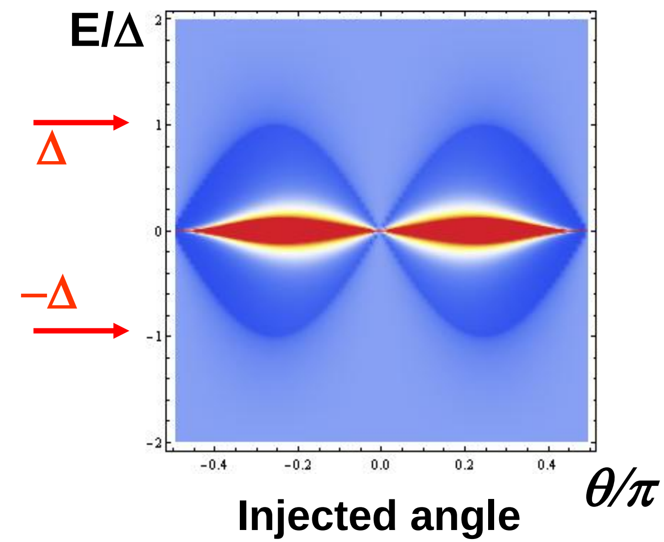
YBCO(110)

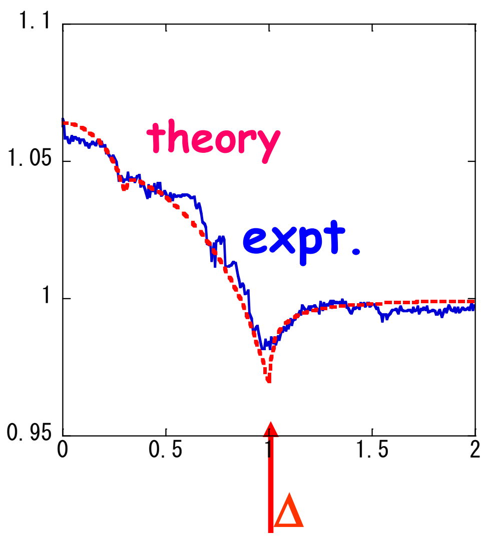
d_{x2-y2}-wave

Zero energy state

Dispersionless bound state

Angle resolved conductance



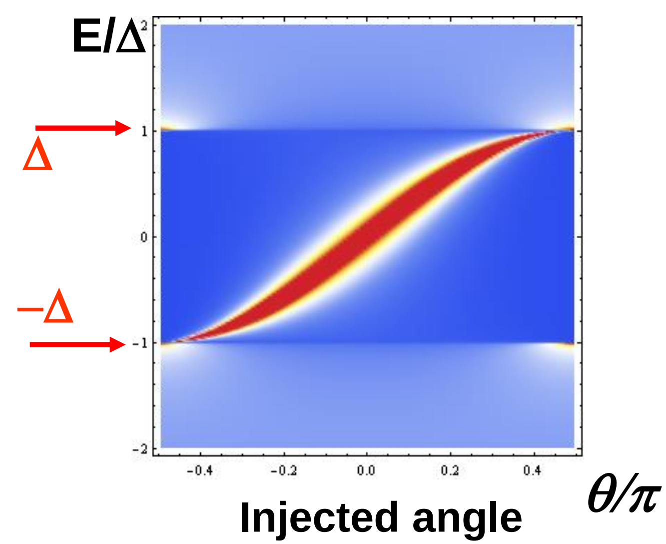


Sr_2RuO_4

chiral p-wave

Chiral edge state

Broad peak due to linear dispersion

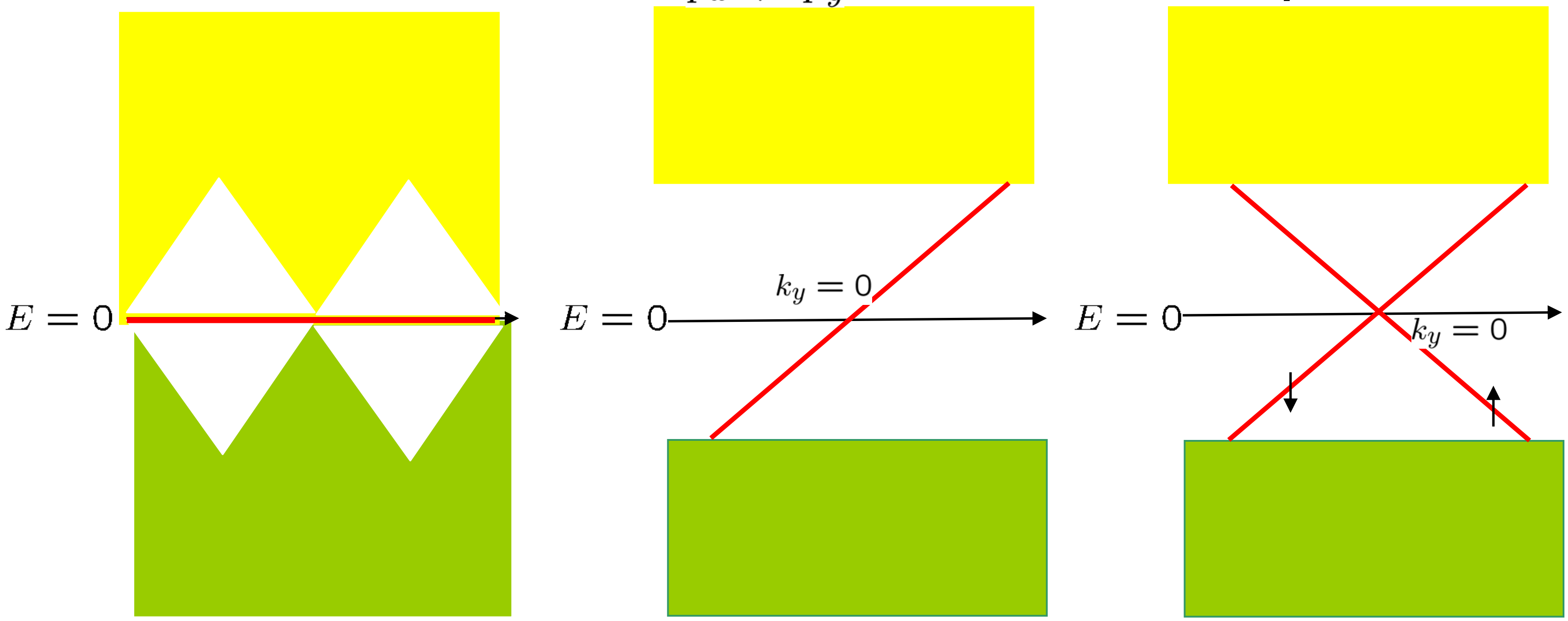


Phys. Rev. Lett. 107, 077003 (2011)

Feature of the Andreev bound states

Non-centrosymmetric superconductor (NCS)

d_{xy}-wave	Chiral p-wave $p_x + ip_y$ -wave	NCS (Helical) *p+s* -wave

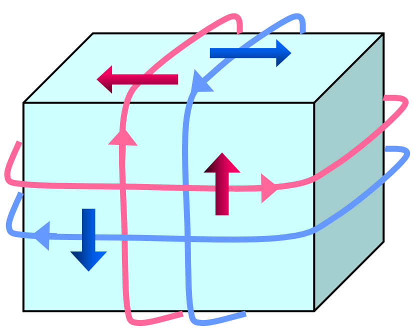


Hu(94) Tanaka Kashiwaya (95)	Tanaka Kashiwaya (97) Sigrist Honerkamp (98)	Iniotakis (07) Eschrig(08) Tanaka (09)
Flat	**Chiral**	**Helical**

Superconducting junctions with topological materials

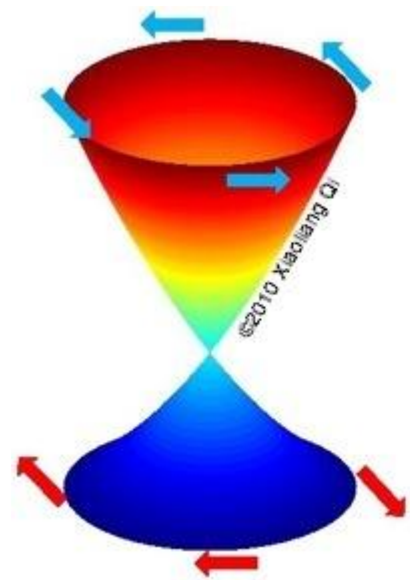
Topological insulator
3D systems

Spontaneous Spin current



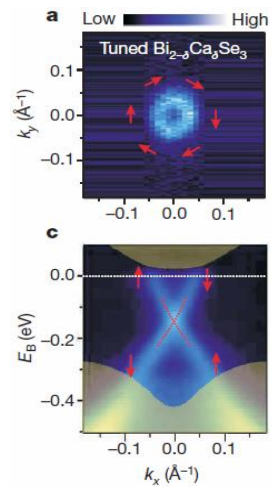
Fu Kane 2007

J. Moore 2007

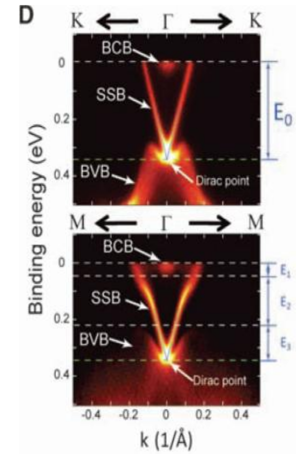


Surface Dirac Cone

Bi_2Se_3



Bi_2Te_3



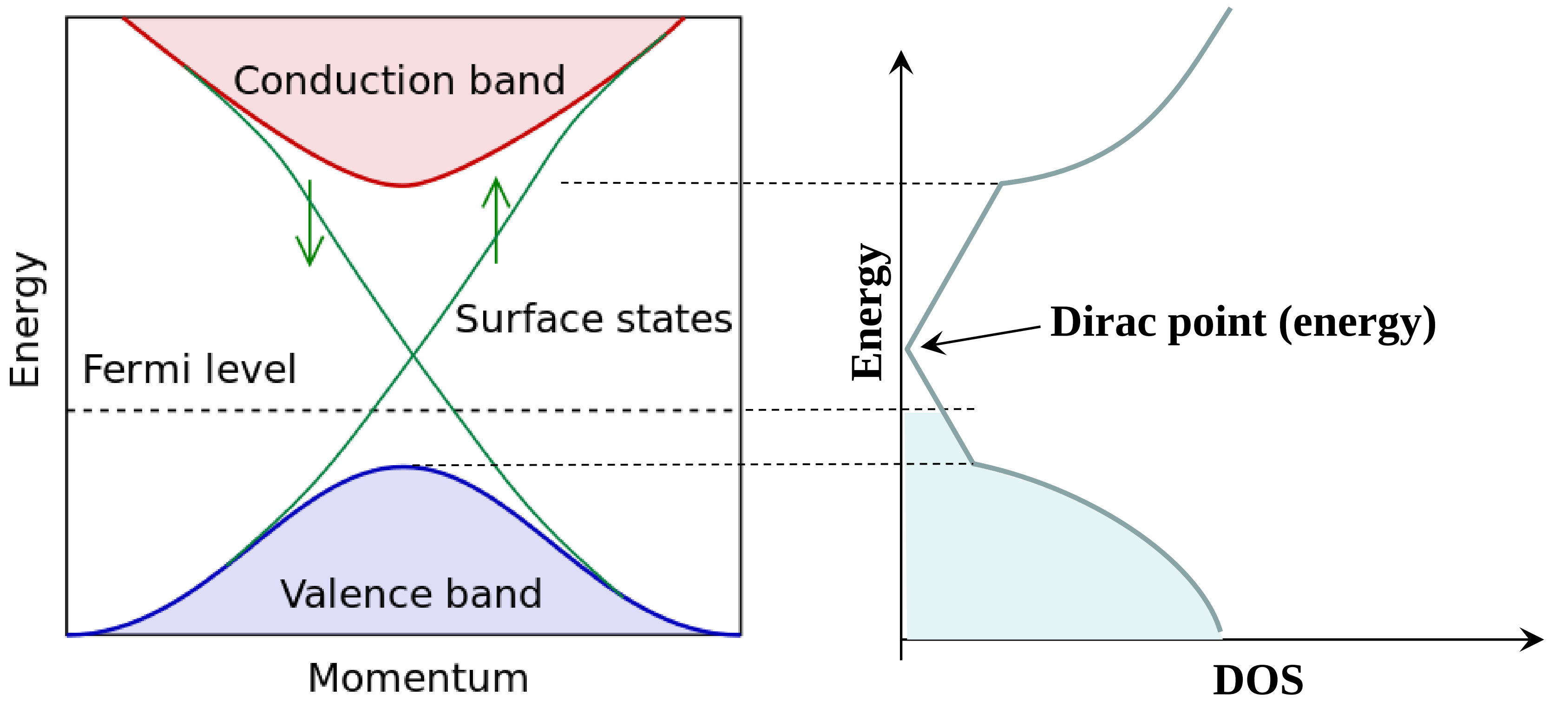
Hsieh et al., Nature (2009)

Quantum number Z_2 which specifies topological insulator

(Product of parities of wave function at time reversal invariant points in *k*-space)

Fu Kane 2007

3D Topological insulators: Ideal case



https://en.wikipedia.org/wiki/Topological_insulator

Motivation: high metallicity, forbidden backscattering, specific momentum-spin relations, possible induction of topological (p-wave) superconductivity, etc.

2D case: p-wave pairing symmetry

Pair wave function:

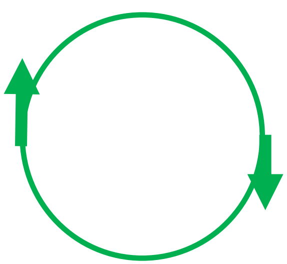
orbital x spin x frequency = asymmetric

Simplest superconductor (e.g. Nb or Al):

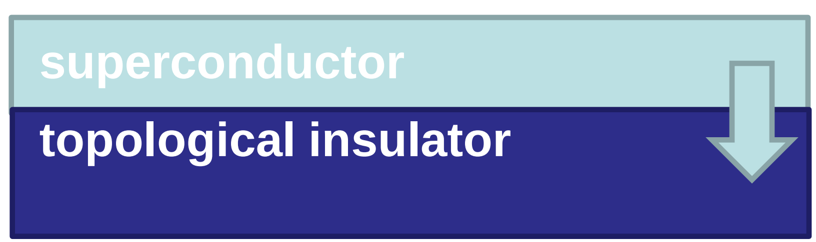
$|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$ **s-wave, singlet, even freq.**

Superconductivity in topological insulator:

$$|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \xrightarrow{yields} \frac{1}{2}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) + \frac{1}{2}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$$



50% s-wave, triplet, even freq. + 50% p-wave, triplet, even freq.



proximity effect

2D-case: p-wave pairing symmetry

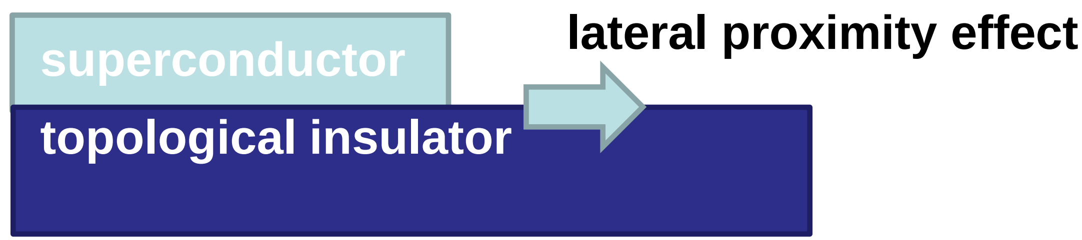
Superconductivity in topological insulator:

50% s-wave, singlet, even freq. + 50% p-wave, triplet, even freq.

breaking *time-reversal* symmetry

➔ Towards 100% p-wave, triplet, even freq.

breaking *translational* symmetry

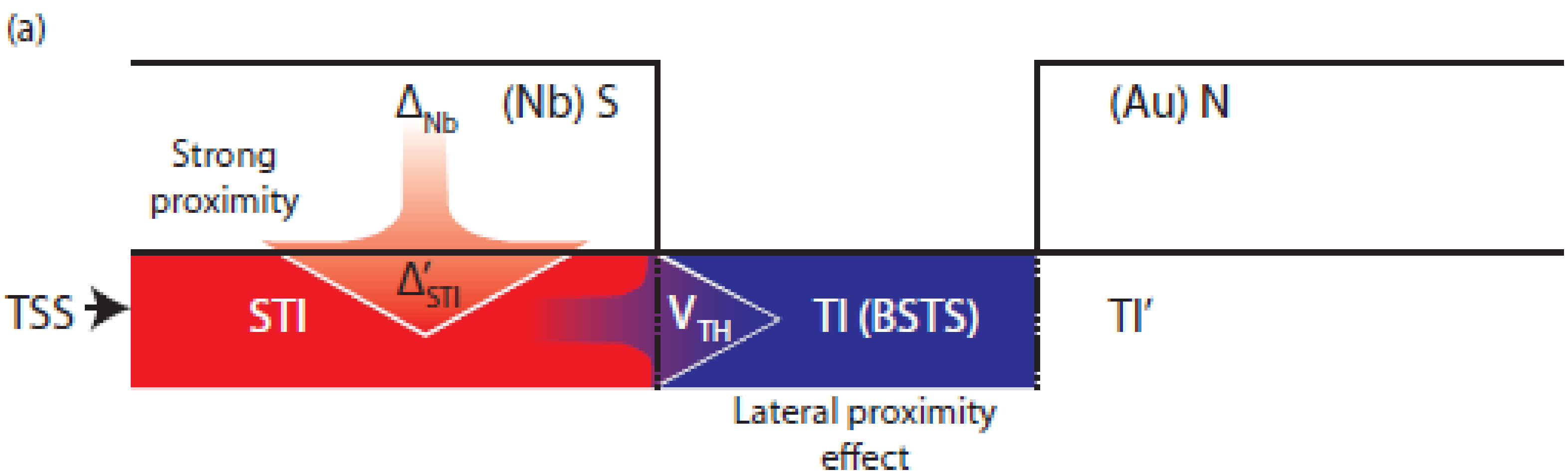


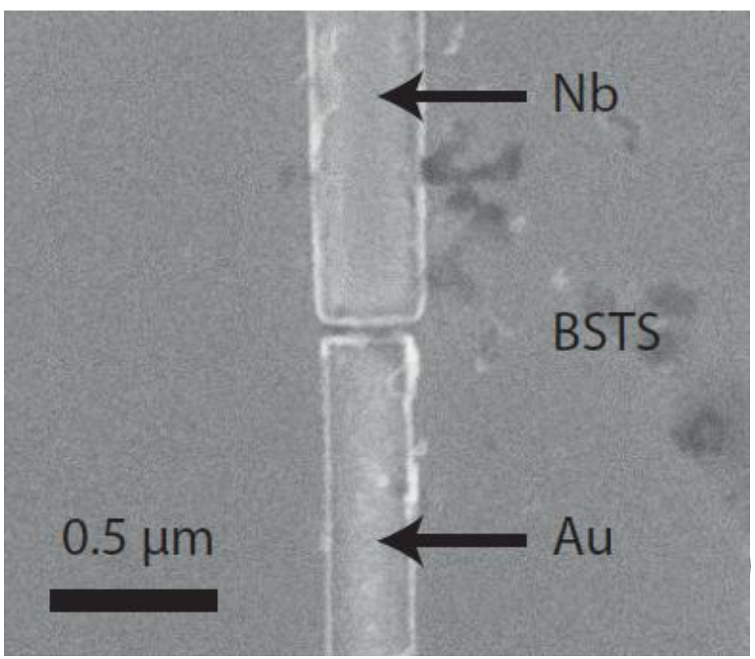
➔ 100% s-wave, triplet, odd freq.

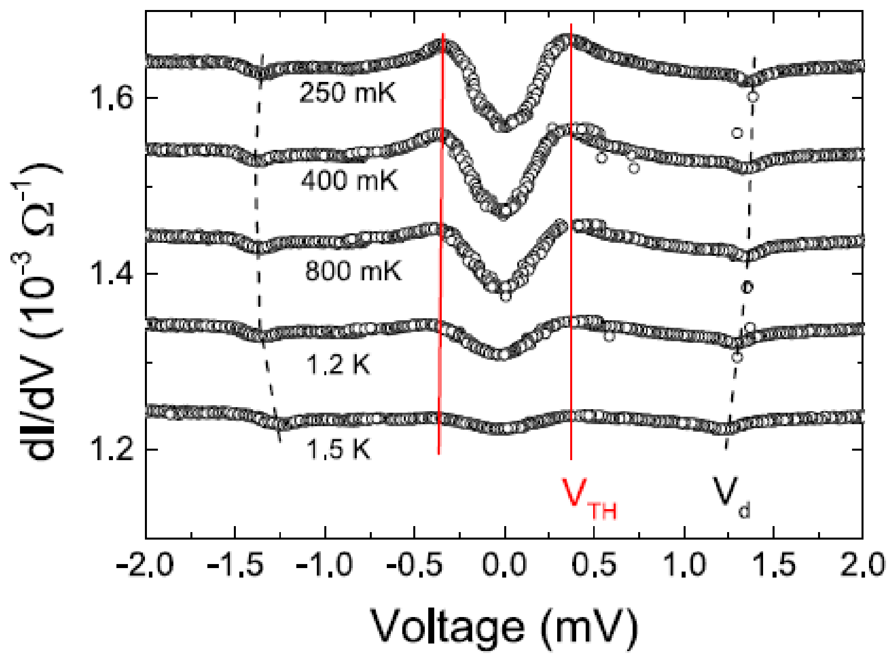
M. Snelder *et al.*, J. Phys.: Condens. Matter 27, 315701 (2015).

dI/dV proximity spectroscopy, experiment (University of Twente).

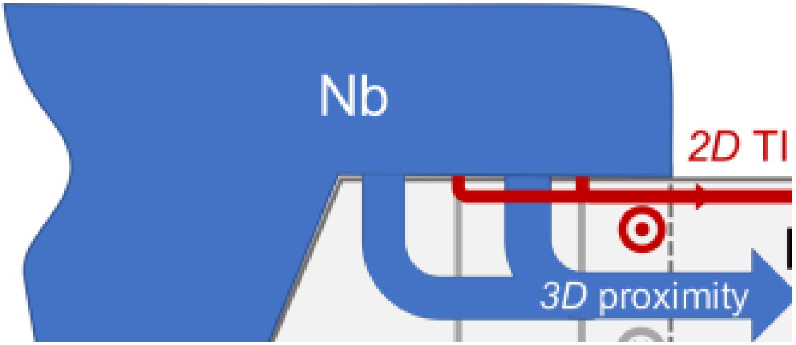
Diffusive regime: *no evidence of p-wave state*

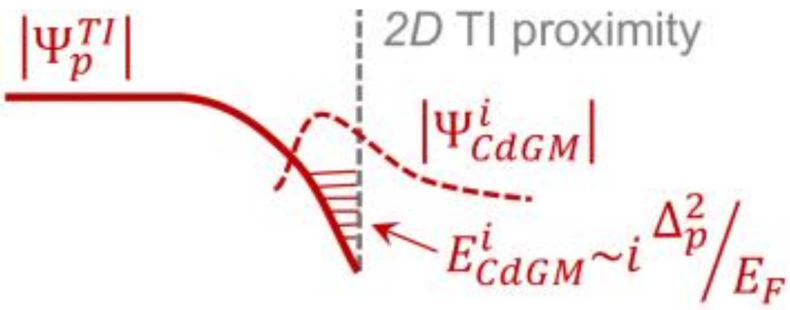






What can we expect in the ballistic regime ?





Normal reflections occur near the edge of the S – layer =>
suppression of the p-wave order parameter near the edge =>
fine structure of the energy levels
(similar to the Caroli - de Gennes – Matricon levels in a vortex core)

Michael Stone PRB 54, 13 222 (1996)

Geometric optics limit of Andreev reflection

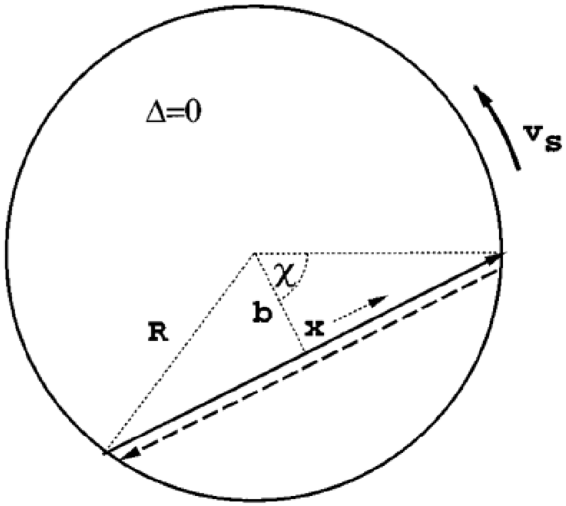
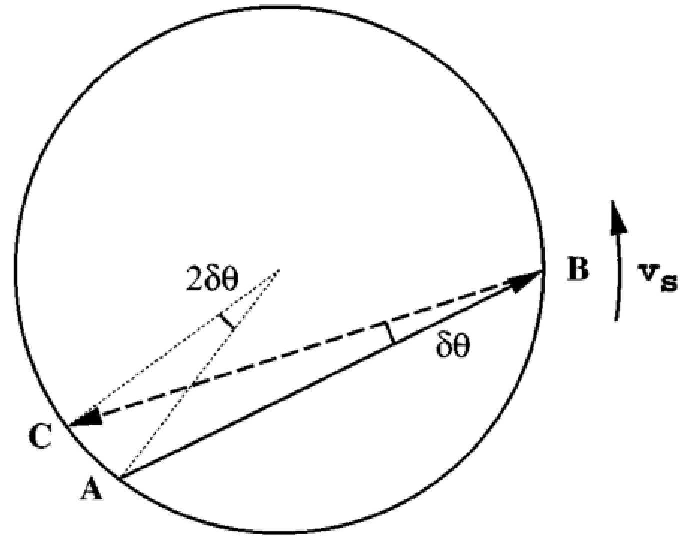


FIG. 1. A bound state with an electron (solid arrow) being Andreev reflected as a hole (dashed arrow).



Caroli - de Gennes – Matricon levels in a vortex core

$$\epsilon_n(l) = \frac{v_f}{4R\ \sin\chi}\,[2\chi + 2\pi(n+\tfrac{1}{2})]$$

$$\epsilon_{-1}(l) = -\omega_0 l, \quad \omega_0 = \frac{1}{2mR^2}.$$

$$R \approx v_f/\Delta$$

=> $\varepsilon \sim \Delta^2/\varepsilon_F$

Physical mechanism:

loss of retroreflection property of the Andreev reflection process

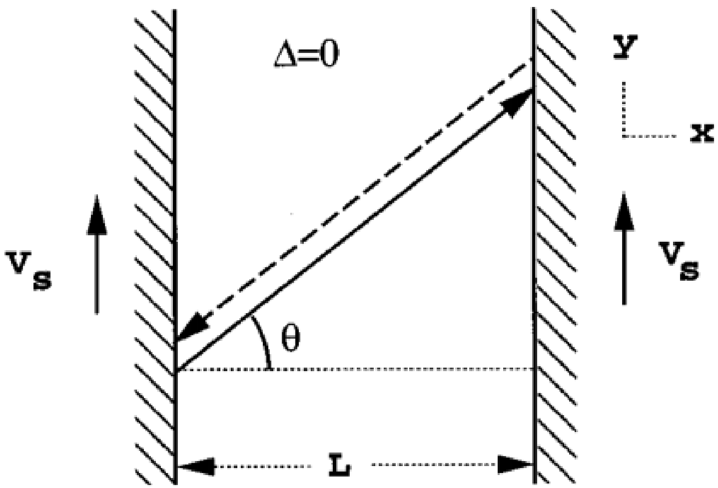
(beyond the quasiclassical approximation)

$$\delta\theta \sim v_s/v_f$$

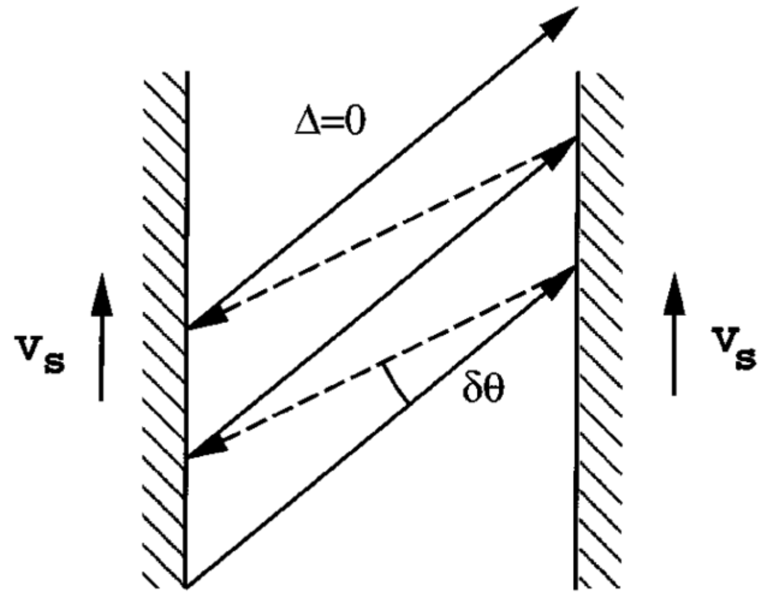
SN interfaces in the presence of superflow

M PRB .54, 13 222 (1996)

loss of retroreflection property of the Andreev process
(beyond the quasiclassical approximation)

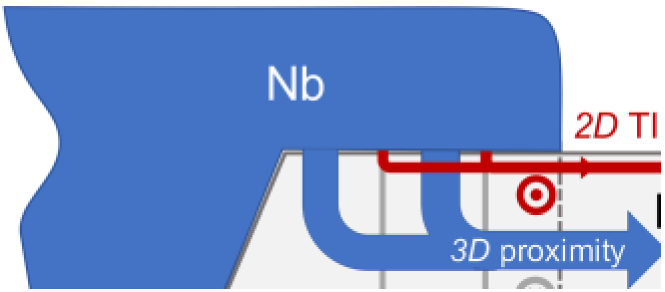


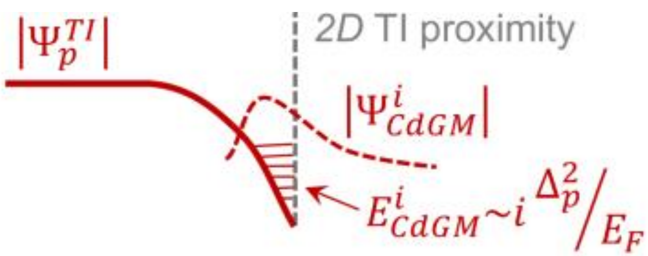
=>

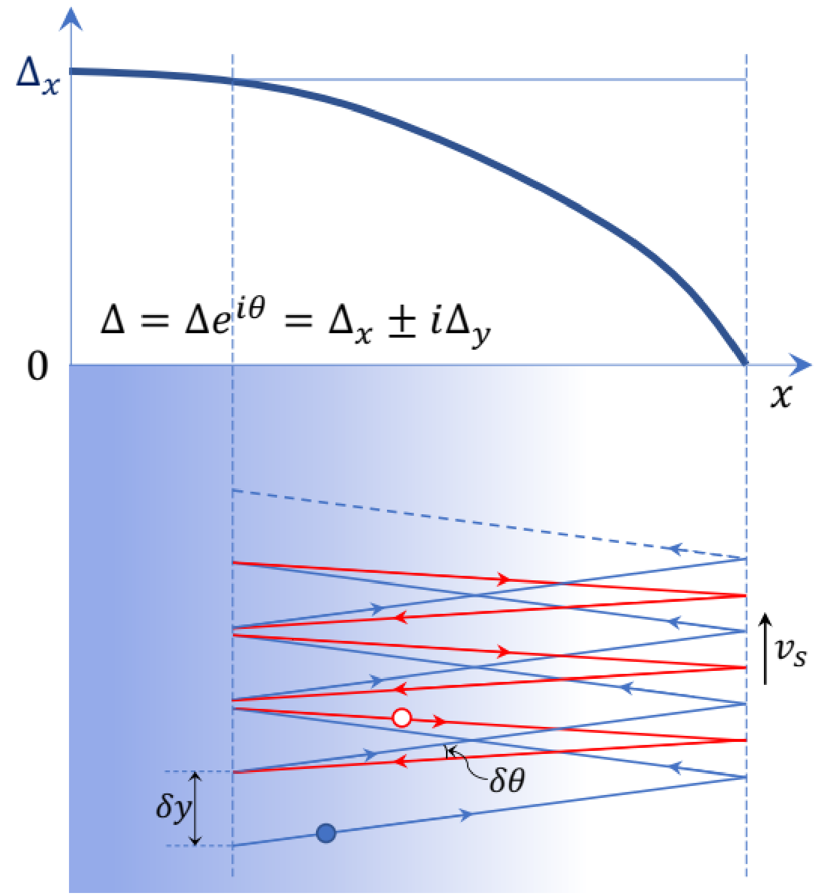


$$\delta\theta \sim v_s / v_f$$

Application of the *geometric optics regime of Andreev reflection* to the topological junction







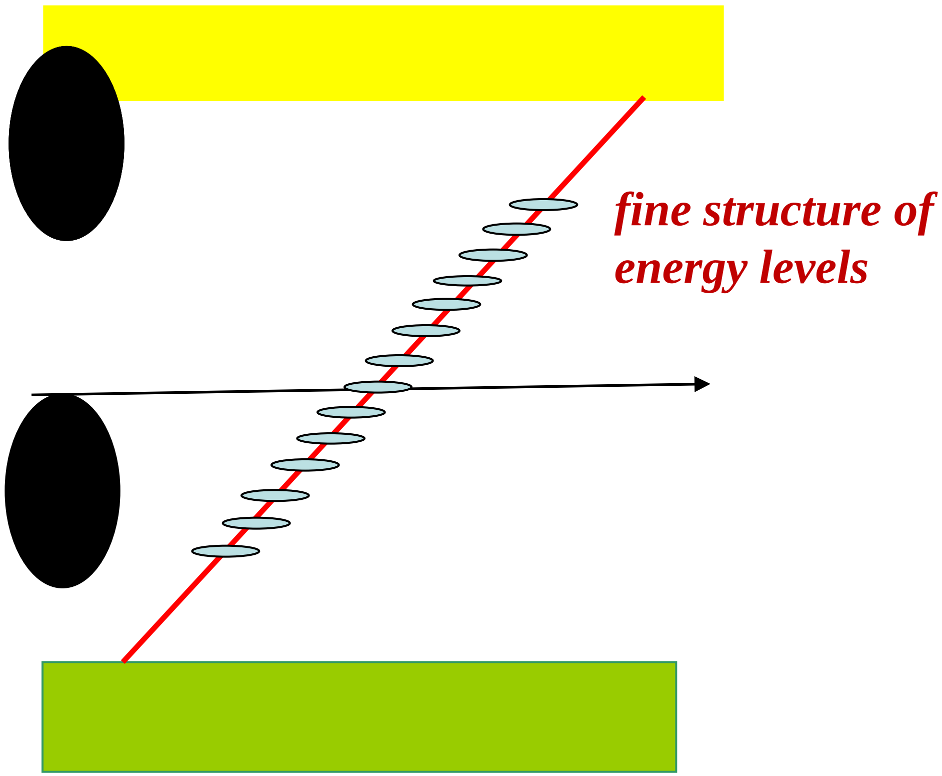
$$\epsilon_n(l) = \frac{v_f}{4R\ \sin\chi}\left[2\chi + 2\pi\left(n + \tfrac{1}{2}\right)\right]$$

In the p-wave case: $2\chi = \pi + 2\,\delta\theta$, R ~ ξ

$\delta\theta \sim v_s/v_f$ => $\varepsilon \sim \Delta^2/\varepsilon_F$

The result: splitting of the liner spectral branch into discrete energy levels

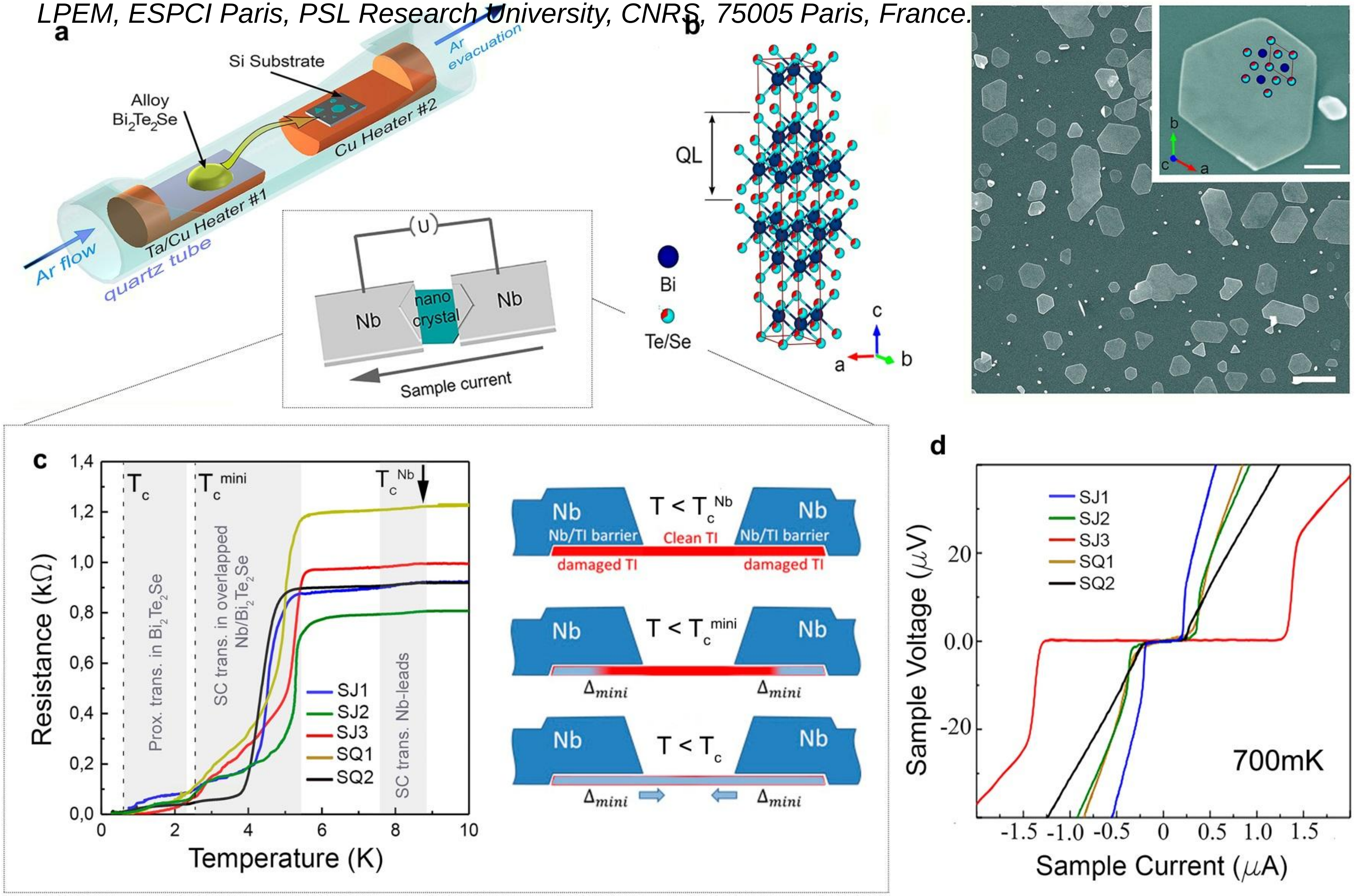
Chiral p-wave
$p_x + ip_y$

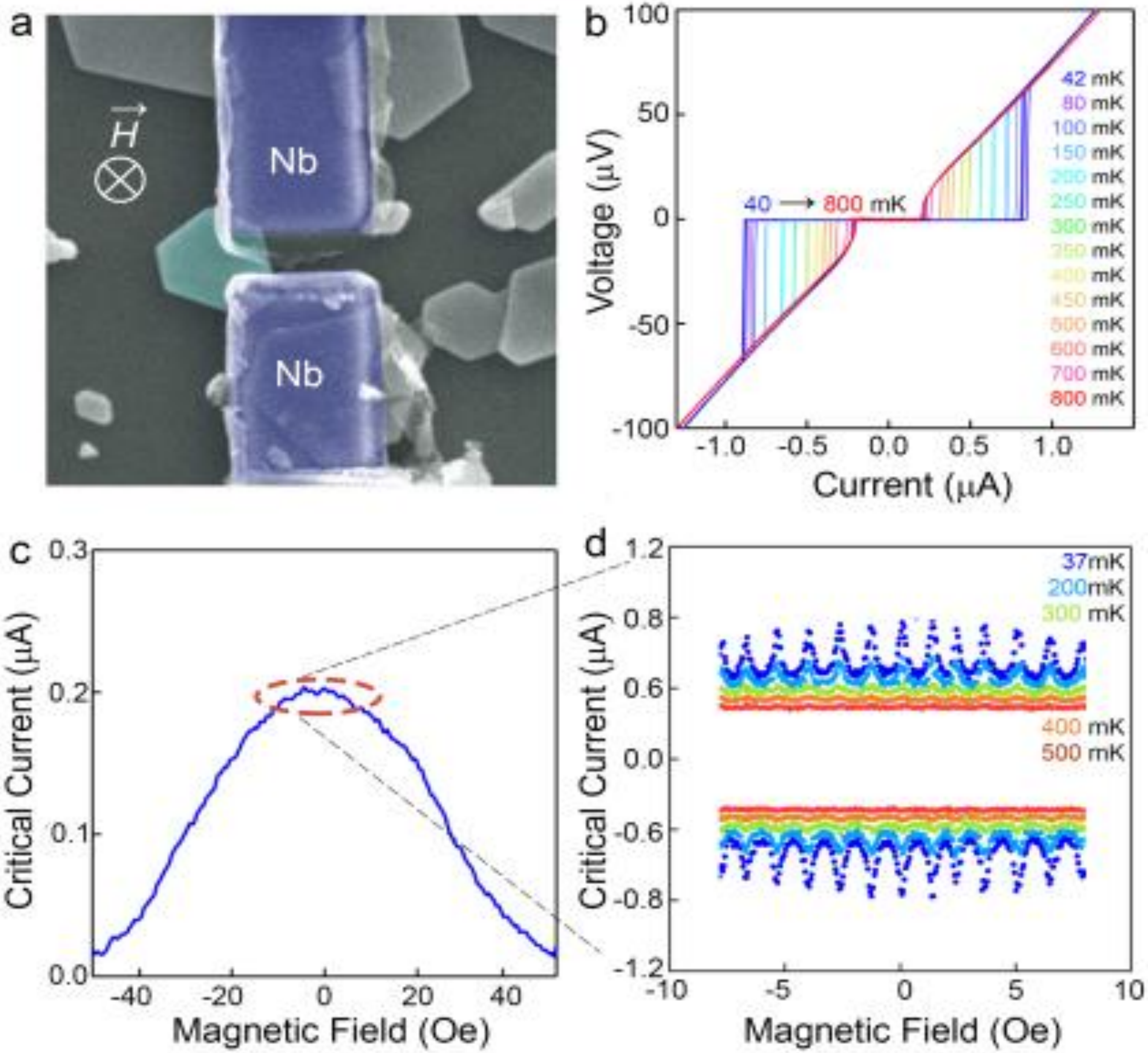


Fine structure should lead to small-scale periodicity of junction properties, e.g. to short-periodic oscillations in a magnetic field

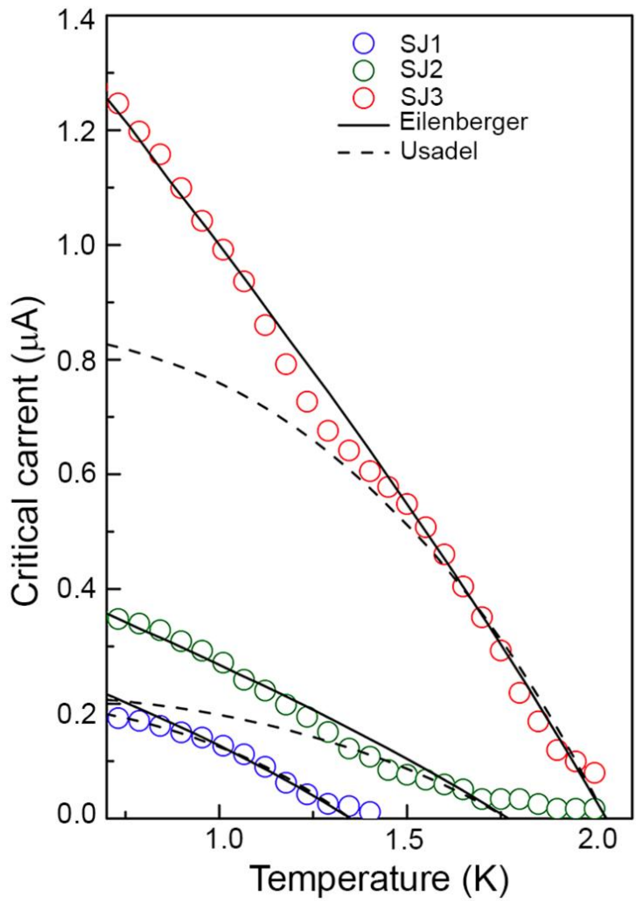
Recent experiment: Nb - Bi2Te2.3Se0.7 – Nb Josephson junctions

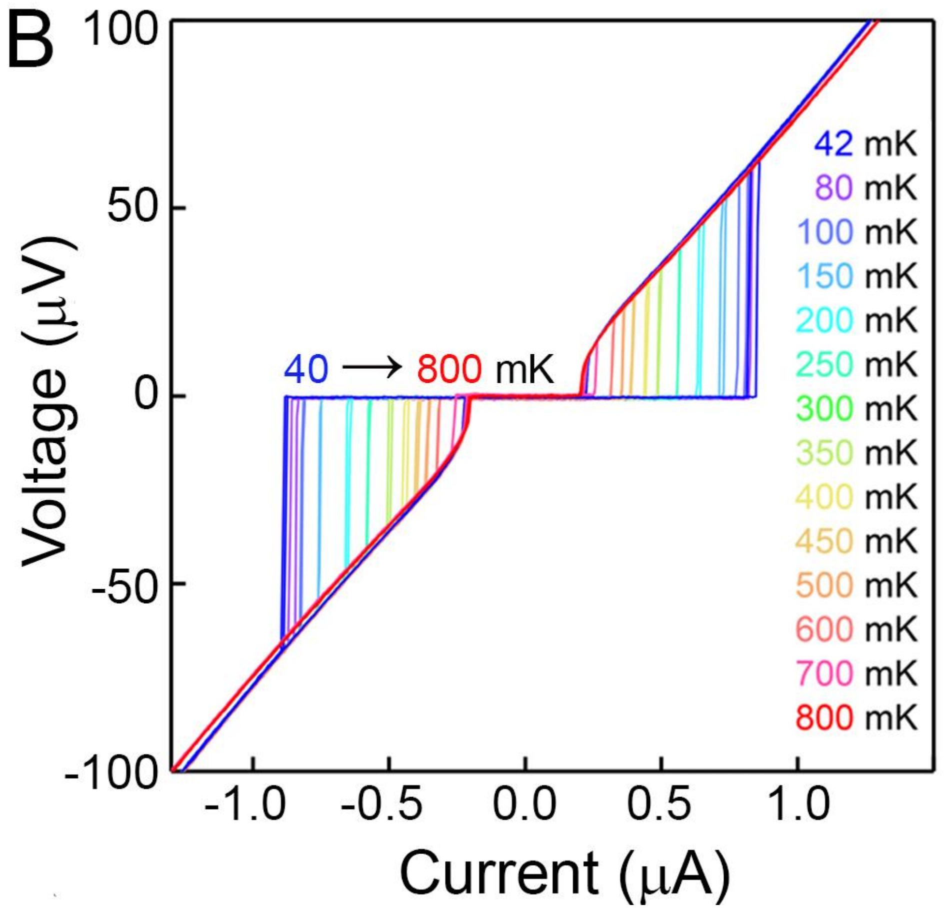
V.S. Stolyarov, Communication Materials (2020)
Moscow Institute of Physics and Technology, Russia
LPEM, ESPCI Paris, PSL Research University, CNRS, 75005 Paris, France.




a
H
Nb
Nb
b
Voltage (μV)
Current (μA)
40 → 800 mK
42 mK
80 mK
100 mK
150 mK
200 mK
250 mK
300 mK
350 mK
400 mK
450 mK
500 mK
600 mK
700 mK
800 mK
c
Critical Current (μA)
Magnetic Field (Oe)
d
Critical Current (μA)
Magnetic Field (Oe)
37mK
200mK
300 mK
400 mK
500 mK

Josephson phenomena in Nb-$Bi_2Te_{2.3}Se_{0.7}$-Nb S-TI-S junctions

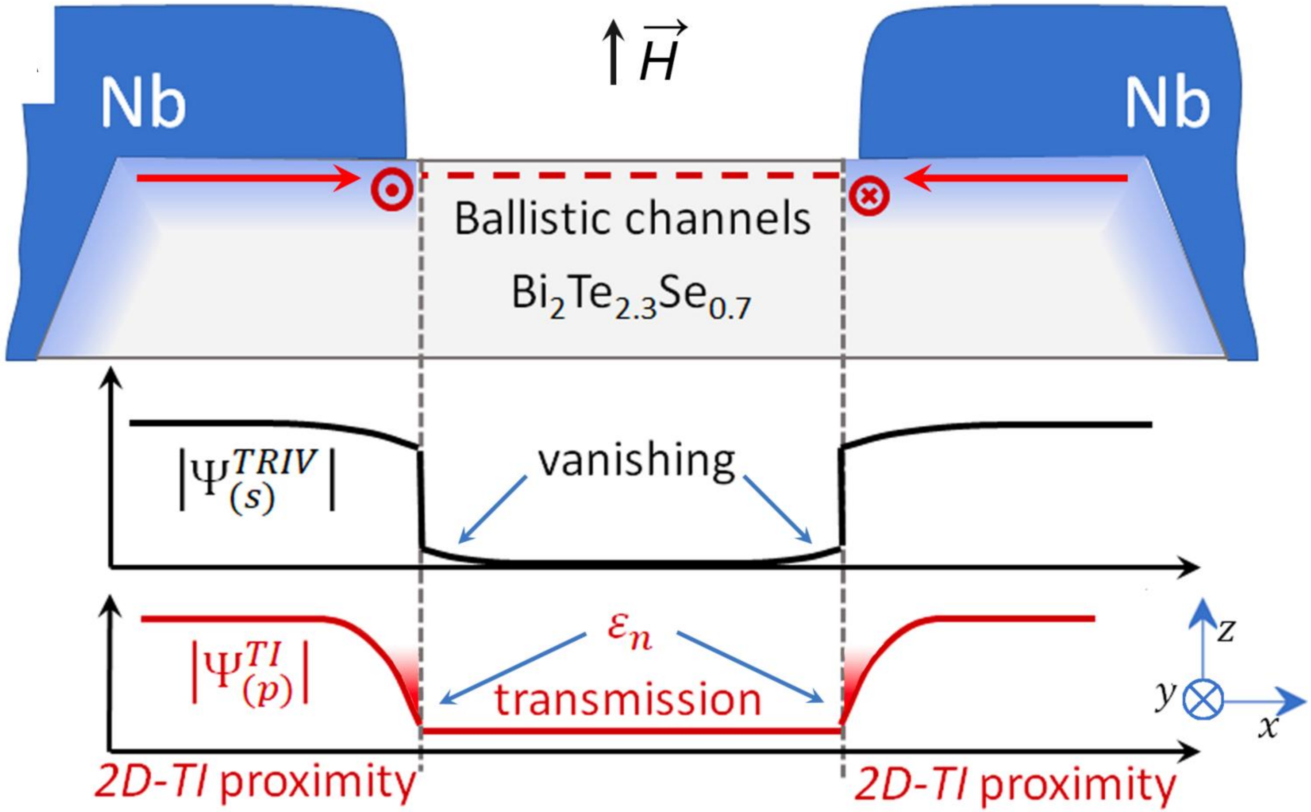




V. S. Stolyarov, etr al. Communications Materials 1, 38 (2020)

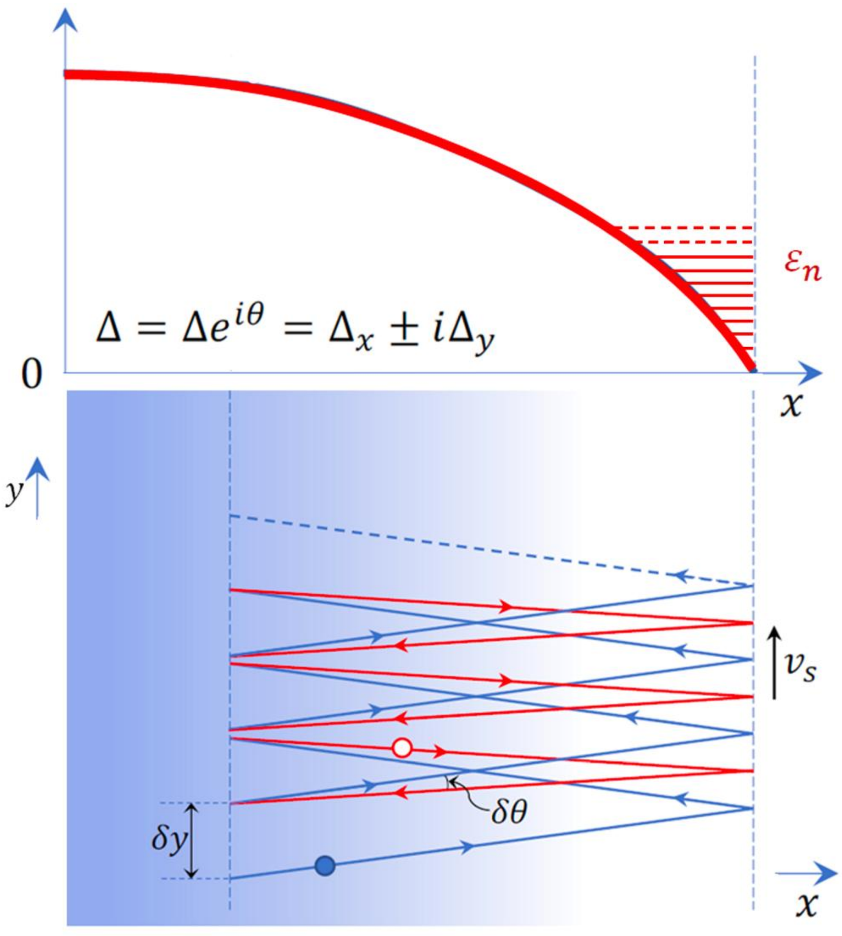
Transmittance by ~ 10 ballistic surface channels; no bulk

Josephson phenomena in Nb-$Bi_2Te_{2.3}Se_{0.7}$-Nb S-TI-S junctions



Hypothesis: two-component superconducting correlations; ballistic topological channels carry only $p-$ component

Josephson phenomena in Nb-$Bi_2Te_{2.3}Se_{0.7}$-Nb S-TI-S junctions



Andreev bound states with dispersion:

$$\varepsilon = \Delta \sin(k_y y)$$

$$\delta\theta \sim v_s/v_F \sim \Delta/\varepsilon_F$$

mid-gap state at $k_y = 0$

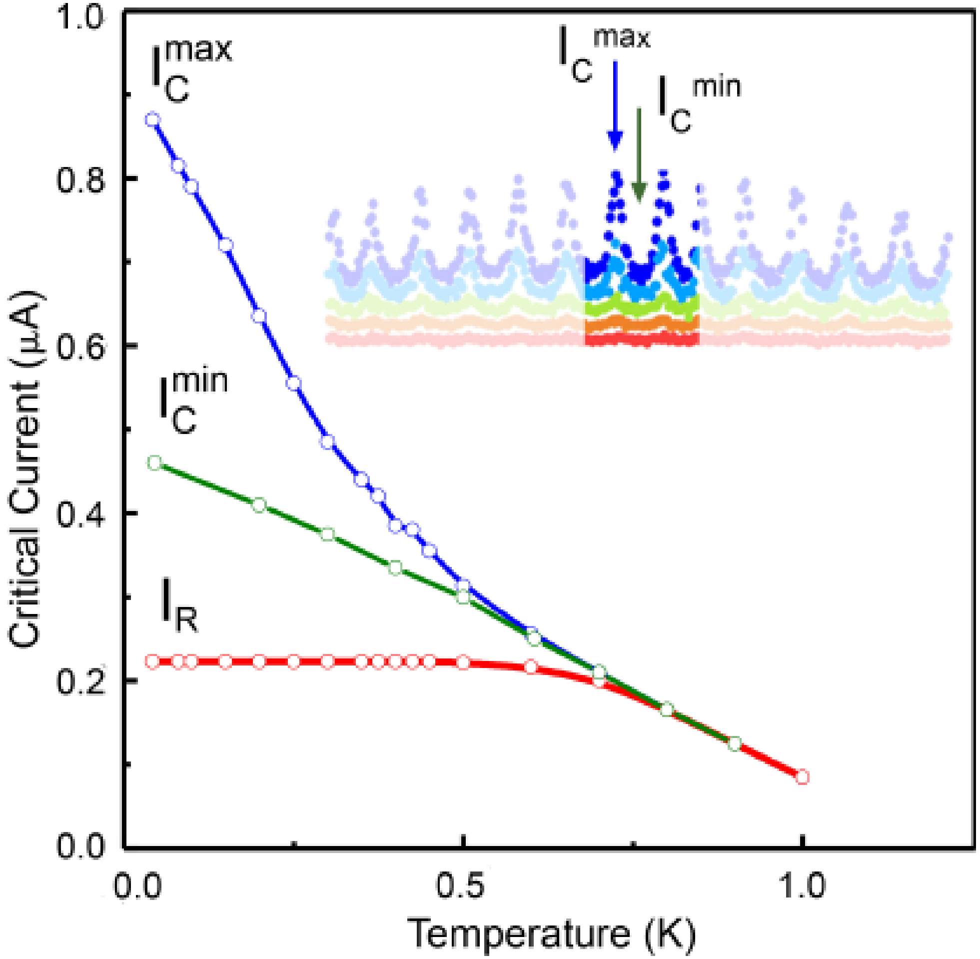
$$\varepsilon_n \sim \Delta(v_s/v_F)n \sim (\Delta^2/\varepsilon_F)n$$

i.e. similar to Caroli-Matricon-deGennes states in the vortex core!
In the case of $Bi_2Te_{2.3}Se_{0.7}$ **(**$\Delta \approx 0.3meV, \varepsilon_F \approx 0.1eV$**),**

$$\frac{\Delta^2}{\varepsilon_F} \sim 1\ \mu\mathrm{eV}$$

Sort of Fabry-Perot interferometer with phase-shifting mirrors.
Magnetic field creates an extra phase shift.

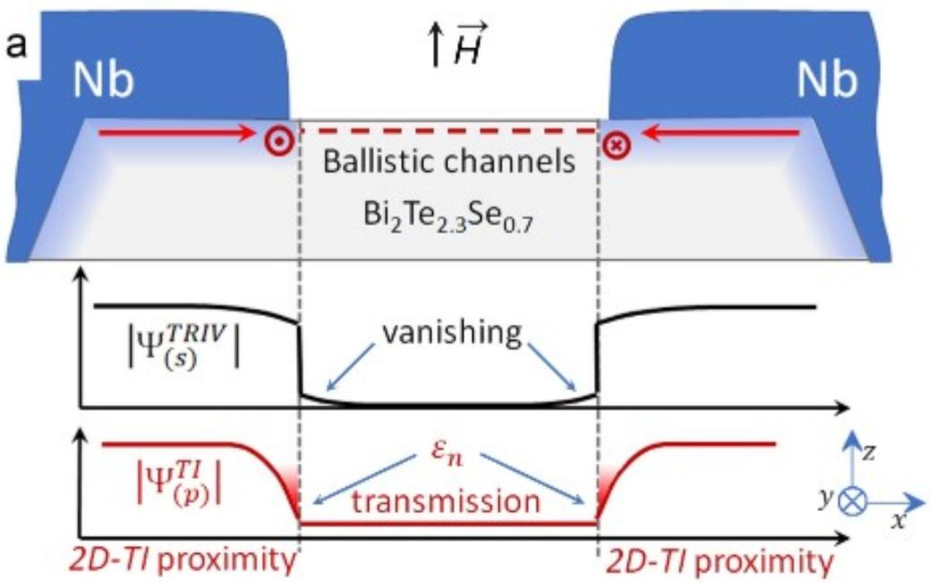
Josephson phenomena in Nb-$Bi_2Te_{2.3}Se_{0.7}$-Nb S-TI-S junctions



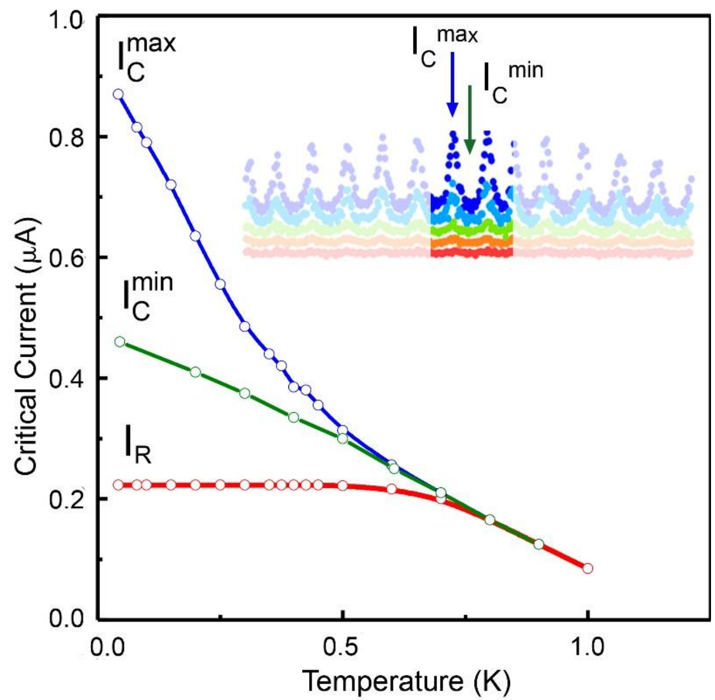
Observed strong temperature dependence is expected : $\sim\Delta^2/T$

Tanaka, Y. & Kashiwaya, S. Phys. Rev. B, 56, 892912 (1997)
Ilichev, E. et al.Phys. Rev. Lett. 86, 5369 (2001).

The expected spatial variation of s-wave and p-wave correlations inside the nanocrystal



The evolution of the maximum and minimum critical currents. Inset: T = 37 mK



The observed oscillations reflect the resonant contribution from the Andreev levels to Ic

The data provide the evidence of the p-wave topological nature of the proximity-induced superconductivity at the TI surface

Summary

(1) Midgap Andreev bound states – key property of **unconventional superconductivity**

(2) Signatures of p-wave superconductivity in diffusive systems:
anomalous proximity effect in DN/spin-triplet p-wave junction due to generation of the odd-frequency pairing state

(3) Signatures of p-wave superconductivity in ballistic systems:
observed **fine structure of low-energyAndreev bound states at the surface of** *Bi2Te2.3Se0.7*