Superconductivity of nanoscopic systems

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Zjazd Fizyków Polskich (Gdańsk) **7 IX 2023**

OUTLINE

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- $\Longrightarrow$ **electron pairing in nanostructures**
- $\Longrightarrow$ **in-gap bound states**
- $\Longrightarrow$ **interplay with correlations**
- $\Longrightarrow$ **static & dynamical phase transitions**
- $\Longrightarrow$ **topological phases**
- $\Longrightarrow$ **Majorana quasiparticles**

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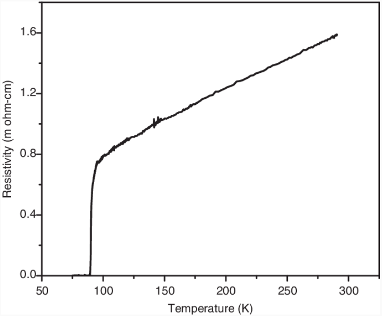
- $\Longrightarrow$ topological phases
- $\Longrightarrow$ Majorana quasiparticles

/ J. Spałek, D. Kaczorowski, I. Weymann /

Macroscopic superconductors

SUPERCONDUCTOR: PROPERTIES

perfect conductor



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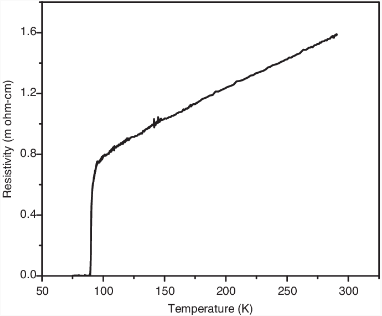

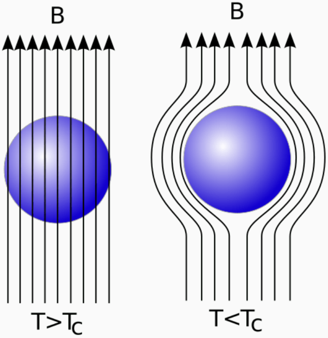

perfect diamagnet

ELECTRON PAIRING

BCS (non-Fermi liquid) ground state :

$$|\mathbf{BCS}\rangle = \prod_k \left(u_k + v_k \; \hat{c}^\dagger_{k\uparrow} \, \hat{c}^\dagger_{-k\downarrow} \right) \; |\mathbf{vacuum}\rangle$$

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$$\begin{aligned} \hat{\gamma}_{k\uparrow} &= u_k \hat{c}_{k\uparrow} + v_k \hat{c}^\dagger_{-k\downarrow} \\ \hat{\gamma}^\dagger_{-k\downarrow} &= -v_k \hat{c}_{k\uparrow} + u_k \hat{c}^\dagger_{-k\downarrow} \end{aligned}$$

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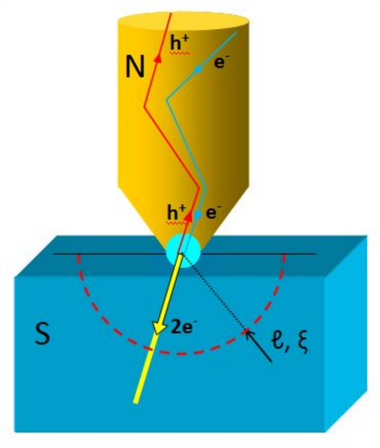
Charge is conserved modulo-2e due to Bose-Einstein condensation of Cooper pairs

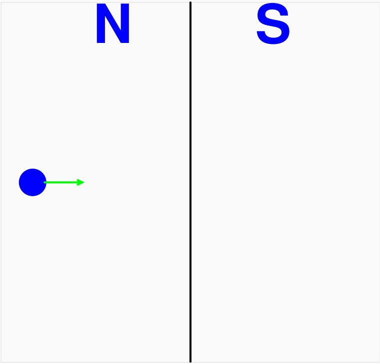
PARTICLE VS HOLE

In superconductors the particle and hole degrees of freedom are mixed with one another (as particularly evident near E_F)



PARTICLE VS HOLE

Let us consider the interface of metal N and superconductor S



where incident electron ...

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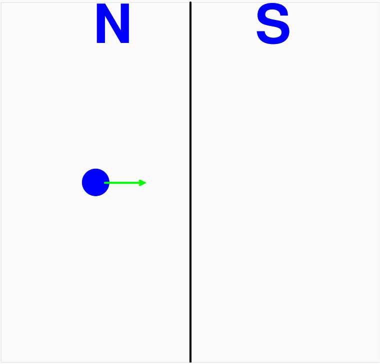

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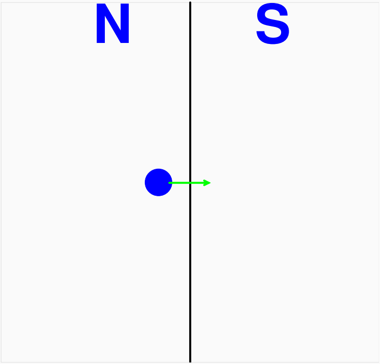

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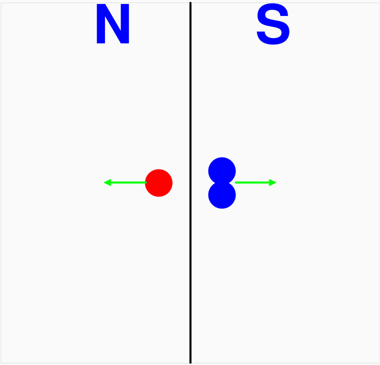

where incident electron is converted into: Cooper pair + hole.

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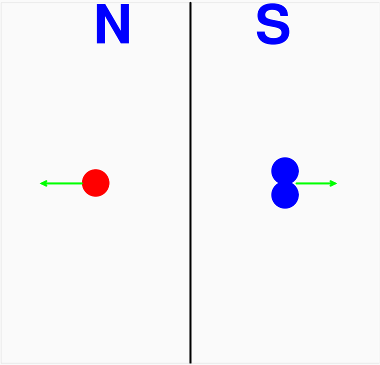

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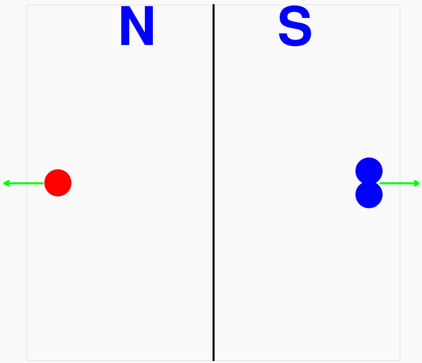

where incident electron is converted into: Cooper pair + hole.

Nanoscale superconductors

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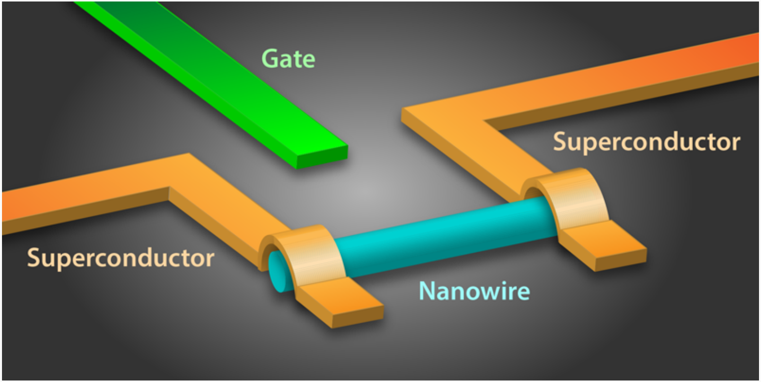
a few examples ...

1. JOSEPHSON-TYPE NANOSTRUCTURE

superconductor (S) - quantum dot (QD) - superconductor (S)



Cooper pairs can tunnel by imposing their phase-difference.

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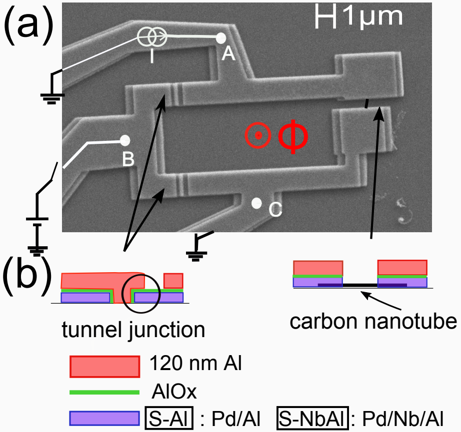

R. Delagrange et al, Phys. Rev. B **93**, 195437 (2016).

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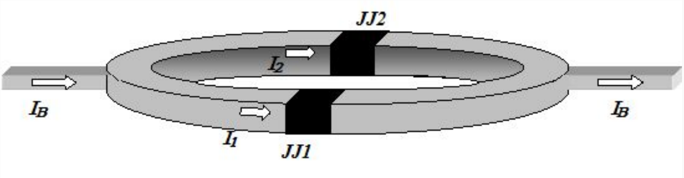
SQUID - superconducting quantum interferemoreter device



This device allows for extremely precise detection of magnetic fields

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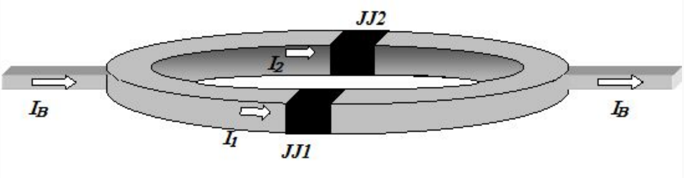

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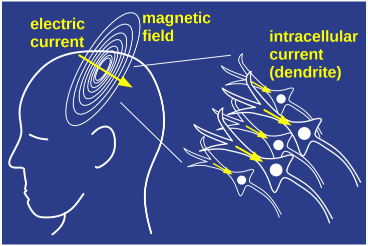
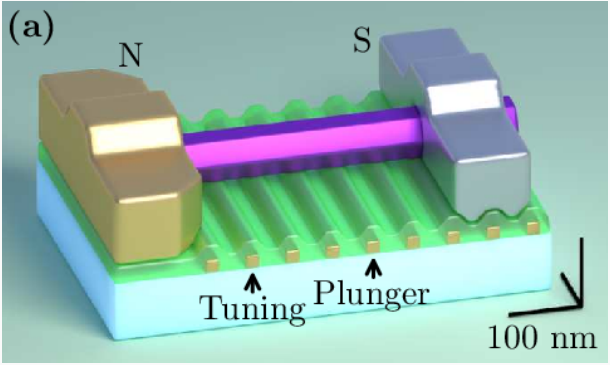


which is able to probe the neural currents in a human brain.

2. ANDREEV-TYPE NANOSTRUCTURE

normal metal (N) - quantum dot (QD) - superconductor (S)



Charge tunneling via the electron-to-hole (Andreev) scattering.

2. ANDREEV-TYPE NANOSTRUCTURE

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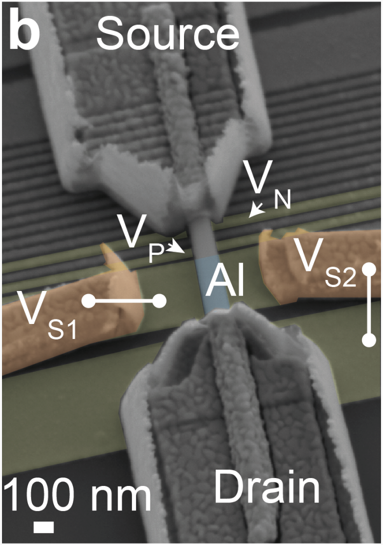
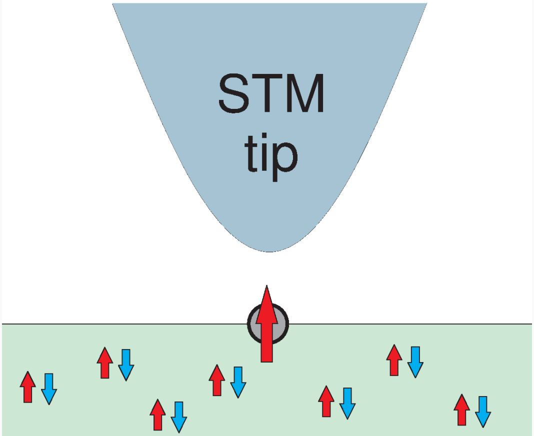


3. SCANNING SPECTROSCOPY

Quantum impurity on a surface of superconductor + STM tip



Scanning spectroscopy can locally probe the electronic states of impurities deposited on surface of bulk superconductors.

Cooper pairs in heterostructures

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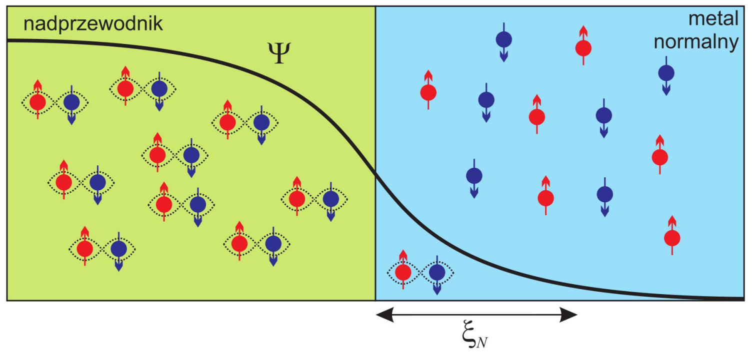
[superconducting proximity effect]

LEAKAGE OF COOPER PAIRS

Any normal material contacted with a bulk superconductor absorbs the Cooper pairs



Cooper pairs leak into non-superconducting region up to spatial length ξ_N.

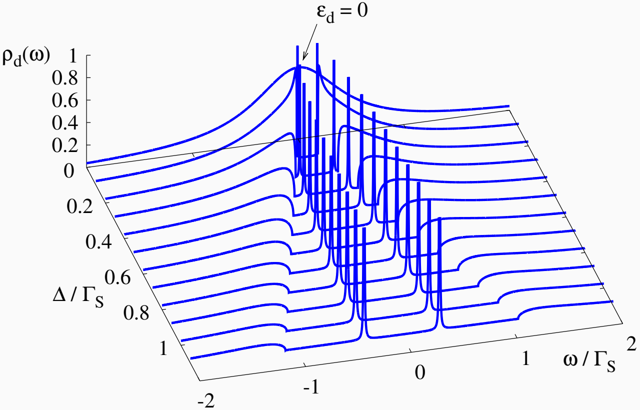
Electron pairing in nanostructures

Electron pairing in nanostructures

[atoms, molecules, nanowires, etc]

QUANTUM DOT + SUPERCONDUTOR

Typical spectrum of the uncorrelated quantum dot (QD) coupled to the s-wave supercondutor [exactly solvable case].



ε_d – energy level of QD, Δ – gap of superconductor, Γ_S – hybridization

SINGLE IMPURITY + BULK SUPERCONDUCTOR

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- **Proximity-induced pairing is manifested by:**

$\Longrightarrow$ **in-gap bound states**

SINGLE IMPURITY + BULK SUPERCONDUCTOR

- Proximity-induced pairing is manifested by:

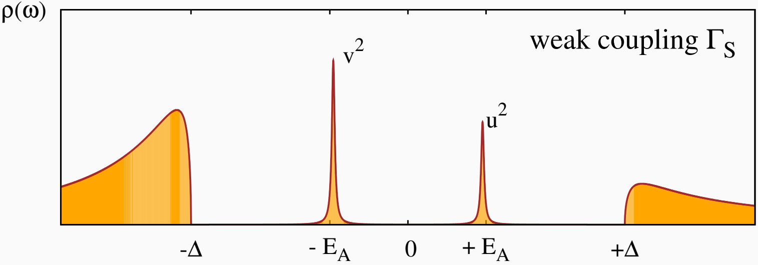
$\Longrightarrow$ **in-gap bound states**

- They originate from:

$\Longrightarrow$ **leakage of Cooper pairs on QD** **(Andreev)**

$\Longrightarrow$ **exchange int. of QD with SC** **(Yu-Shiba-Rusinov)**

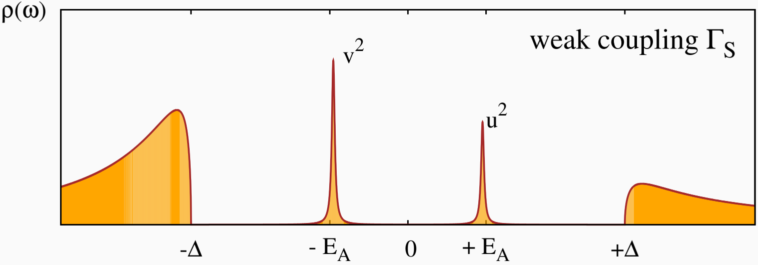
Spectrum of the quantum impurity coupled to superconductor



Bound states appear at $\pm E_A$ in the subgap region $E \in \langle -\Delta, \Delta \rangle$

IN-GAP STATES

Spectrum of the quantum impurity coupled to superconductor



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Let us focus on these in-gap bound states ...

Why are we interested in this issue ?

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selected headlines ...

Applied Physics Letters PERSPECTIVE scitation.org/journal/apl

A perspective on semiconductor-based superconducting qubits

Cite as: Appl. Phys. Lett. **117**, 240501 (2020); doi: 10.1063/5.0024124
Submitted: 4 August 2020 · Accepted: 9 November 2020 ·
Published Online: 14 December 2020

View Online Export Citation CrossMark

Ramón Aguado[a)]

AFFILIATIONS

Instituto de Ciencia de Materiales de Madrid (ICMM), Consejo Superior de Investigaciones Científicas (CSIC), Sor Juana Inés de la Cruz 3, 28049 Madrid, Spain

Quantum bits (qubits) can be constructed out of in-gap bound states, using either the Josephson junctions (transmons) or the semiconducting-superconducting hybrids (gatemons).

SUPERCONDUCTING QUBITS

REPORT

QUANTUM DEVICES

Coherent manipulation of an Andreev spin qubit

M. Hays[1*], V. Fatemi[1*], D. Bouman[2,3], J. Cerrillo[4,5], S. Diamond[1], K. Serniak[1†], T. Connolly[1], P. Krogstrup[6], J. Nygård[6], A. Levy Yeyati[5,7], A. Geresdi[2,3,8], M. H. Devoret[1*]

Two promising architectures for solid-state quantum information processing are based on electron spins electrostatically confined in semiconductor quantum dots and the collective electrodynamic modes of superconducting circuits. Superconducting electrodynamic qubits involve macroscopic numbers of electrons and offer the advantage of larger coupling, whereas semiconductor spin qubits involve individual electrons trapped in microscopic volumes but are more difficult to link. We combined beneficial aspects of both platforms in the Andreev spin qubit: the spin degree of freedom of an electronic quasiparticle trapped in the supercurrent-carrying Andreev levels of a Josephson semiconductor nanowire. We performed coherent spin manipulation by combining single-shot circuit–quantum-electrodynamics readout and spin-flipping Raman transitions and found a spin-flip time T_S = 17 microseconds and a spin coherence time T_{2E} = 52 nanoseconds. These results herald a regime of supercurrent-mediated coherent spin-photon coupling at the single-quantum level.

Hays *et al.*, *Science* **373**, 430–433 (2021)   23 July 2021

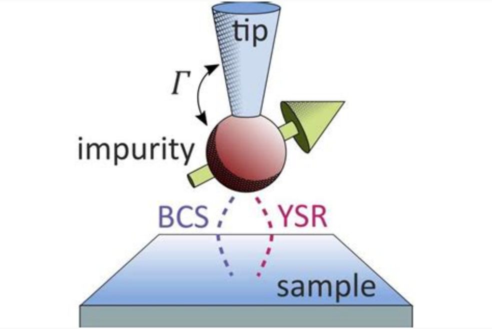
Recent evidence for experimental realization

Conventional bound states

Conventional bound states

[two scenarios]

Classical magnetic impurity on surface of bulk superconductor



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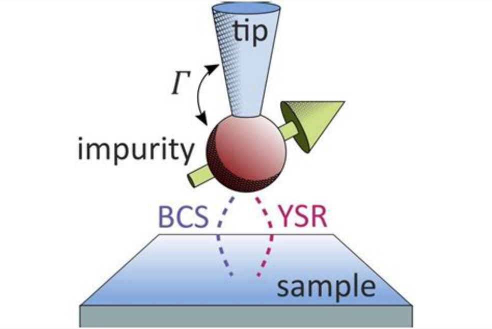
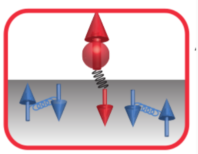
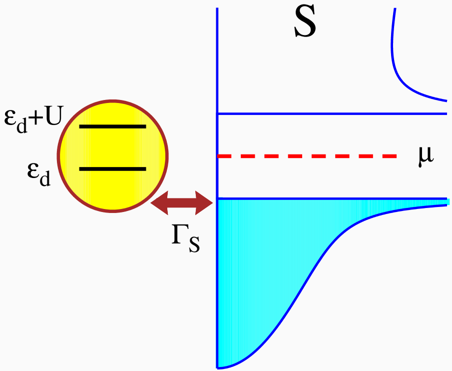


Impurity couples with unpaired electron of superconductor, forming a pair.



Yu - Shiba - Rusinov states

Correlated impurity coupled to the s-wave superconductor



ε_d – **energy level,** U – **Coulomb potential,** Γ_S – **hybridization**

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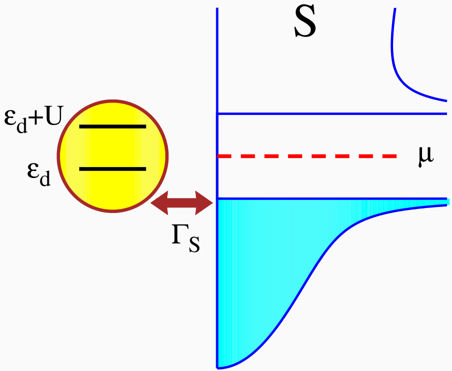

ε_d – energy level, U – Coulomb potential, Γ_S – hybridization

Coulomb repulsion competes with the Cooper pair leakage !

Pairing vs Coulomb repulsion

Pairing vs Coulomb repulsion

[omnipresent antagonism]

SINGLY OCCUPIED VS BCS-TYPE CONFIGURATIONS

Hamiltonian of the quantum dot proximitized to superconductor

$$\hat{H}_{QD} = \sum_{\sigma} \epsilon_d \, \hat{d}^{\dagger}_{\sigma} \, \hat{d}_{\sigma} \; + \; U_d \, \hat{n}_{d\uparrow} \hat{n}_{d\downarrow} - \left(\Gamma_S \, \hat{d}^{\dagger}_{\uparrow} \hat{d}^{\dagger}_{\downarrow} + \text{h.c.} \right)$$

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Eigen-states of this problem are represented by:

$|\uparrow\rangle$ **and** $|\downarrow\rangle$ $\Leftarrow$ **doublet states (spin $\frac{1}{2}$)**

$$\left. \begin{array}{l} u\,|0\rangle - v\,|\uparrow\downarrow\rangle \\ v\,|0\rangle + u\,|\uparrow\downarrow\rangle \end{array} \right\} \Leftarrow$$ **singlet states (spin 0)**

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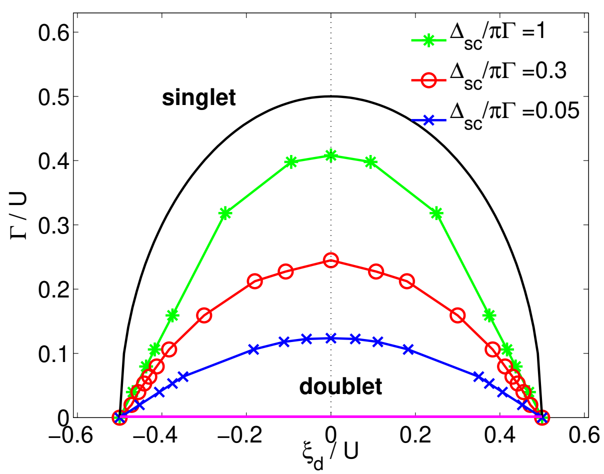
Upon varrying the ratio ε_d/U_d or Γ_S/U_d the doublet-singlet transition can be induced between these ground states.

QUANTUM PHASE TRANSITION

The singlet-doublet (quantum phase) transition): NRG results



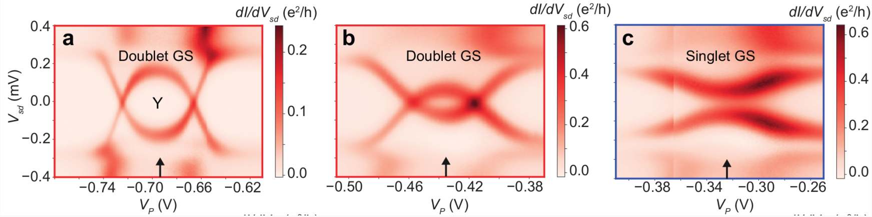
$$\xi_d \equiv \varepsilon_d - U/2$$

J. Bauer, A. Oguri & A.C. Hewson, J. Phys.: Condens. Matter 19, 486211 (2007).

SINGLET VS DOUBLET: EXPERIMENT

Differential conductance vs source-drain bias V_{sd} (vertical axis) and gate potential V_p (horizontal axis) measured for various Γ_S/U

$U \gg \Gamma_s$ $\quad$ $U \geq \Gamma_s$ $\quad$ $U < \Gamma_s$



J. Estrada Saldaña et al, Commun. Phys. 3, 125 (2020).

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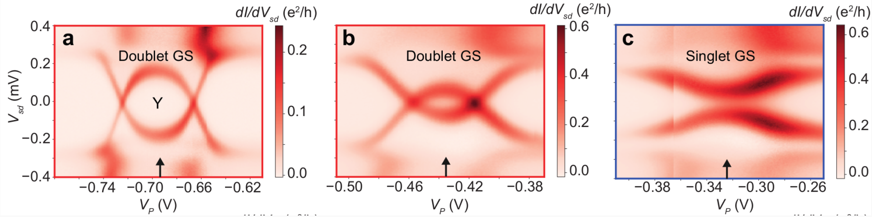


J. Estrada Saldaña et al, Commun. Phys. 3, 125 (2020).

Crossings of in-gap states correspond to the singlet-doublet QPT.

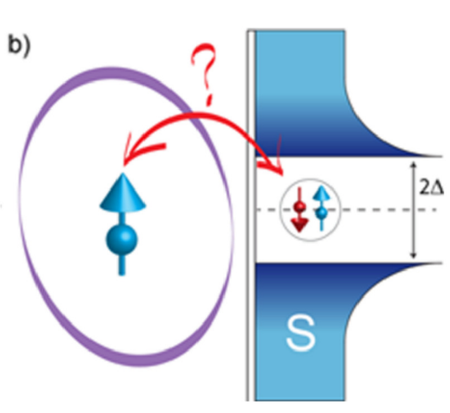
Localized vs itinerant electrons

Localized vs itinerant electrons

[Kondo effect]

RELEVANT QUESTION

Strongly correlated quantum dot coupled do superconductor



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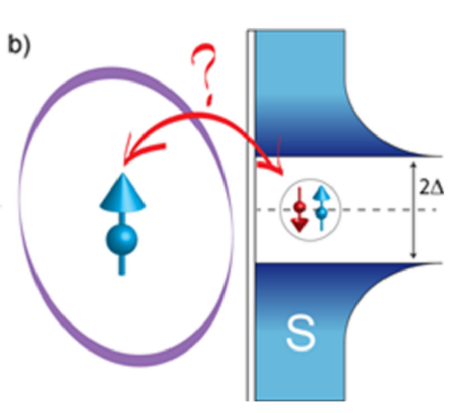
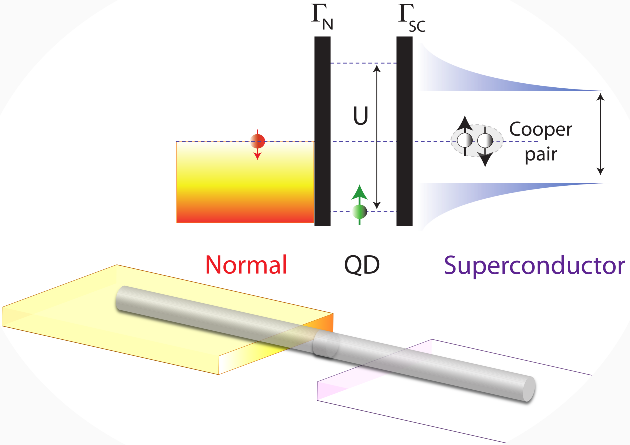


To screen or not to screen ?

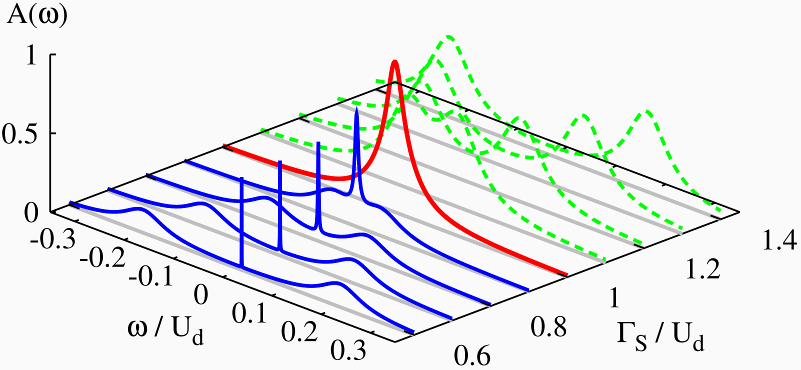
ANDREEV-TYPE HETEROSTRUCTURE

Let us consider the correlated quantum dot (QD) placed between the normal (N) and superconducting (S) electrodes



KONDO STATE VS PARITY CROSSING

Schriefffer-Wolff results obtained for half-filled QD ($\varepsilon_d = -U/2$)



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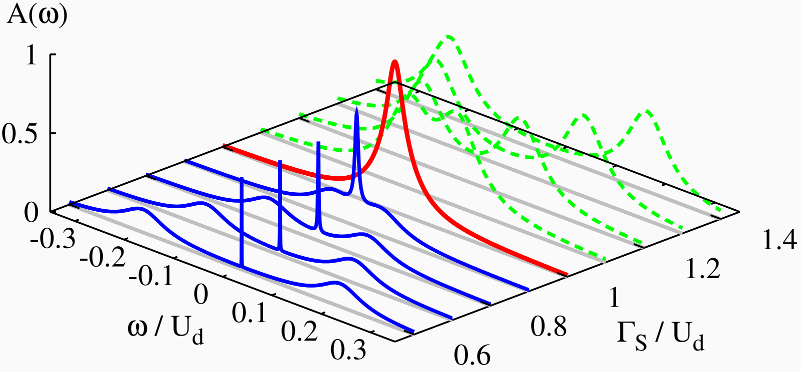
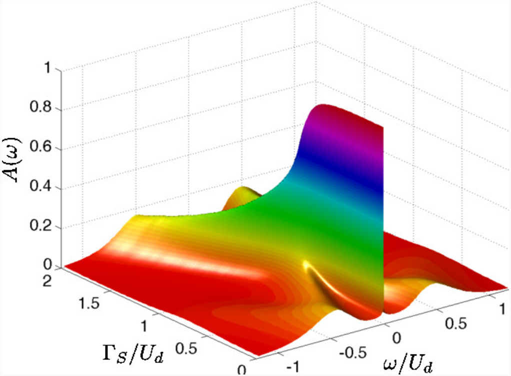


Kondo peak develops on the spinful (doublet) side and it is enhanced upon approaching the quantum phase transition.

T. Domański, I. Weymann, M. Barańska & G. Górski, Sci. Rep. 6, 23336 (2016).

KONDO STATE VS PARITY CROSSING

Results obtained by NRG (Budapest code) for the half-filled QD.



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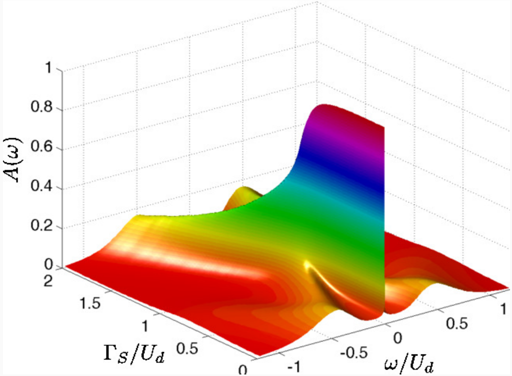


The zero-energy (Kondo) peak exist only in the doublet phase and it disappears upon traversing to the BCS-type phase.

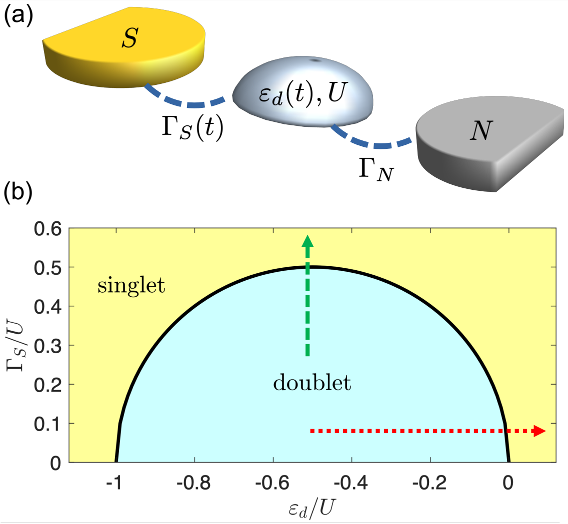
T. Domański, I. Weymann, M. Barańska & G. Górski, Sci. Rep. 6, 23336 (2016).

Dynamical singlet-doublet transition

Dynamical singlet-doublet transition

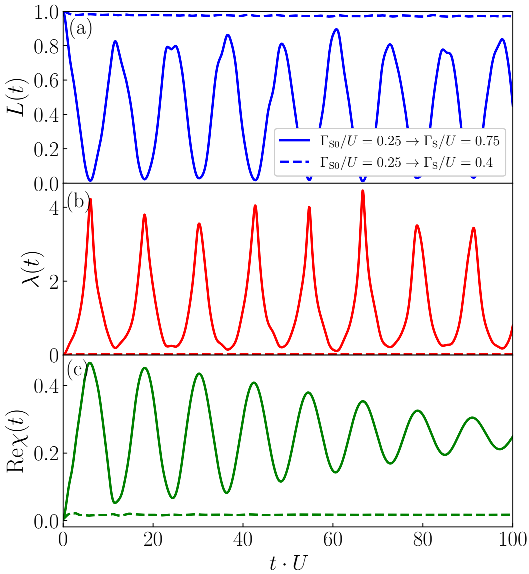
[transition in time-domain]

QUENCH ACROSS QPT BOUNDARY



K. Wrześniewski, I. Weymann, N. Sedlmayr & T. Domański, Phys. Rev. B 105, 094514 (2022).

t-NRG RESULTS



Loschmidt echo

$L(t) \equiv |\langle\Psi(t)|\Psi(0)\rangle|^2$

Return rate

$\lambda(t) = -(1/N) \log L(t)$

On-dot pairing

Re $\left\langle \hat{d}_\downarrow(t)\hat{d}_\uparrow\ (t)\right\rangle$

K. Wrześniewski, I. Weymann, N. Sedlmayr & T. Domański, Phys. Rev. B 105, 094514 (2022).

EMPIRICAL DETECTION

Dynamical singlet-doublet transition(s) can be detected:

- **by measuring the time-resolved Andreev current**

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Dynamical singlet-doublet transition(s) can be detected:

- **by measuring the time-resolved Andreev current**
- **by detecting the time-dependent magnetic moment**

Topological nano-superconductors

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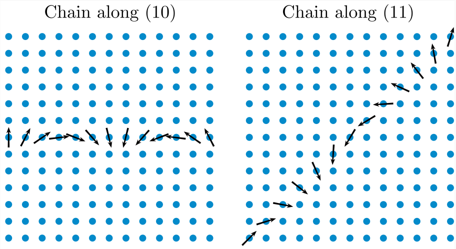
[1- and 2-dimensional platforms]

Magnetic chains and/or islands embedded in superconductors



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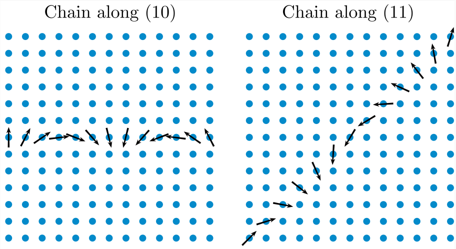
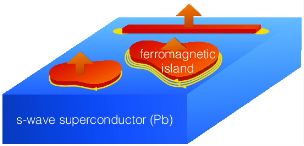
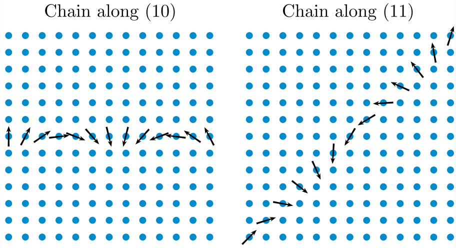


or magnetic islands

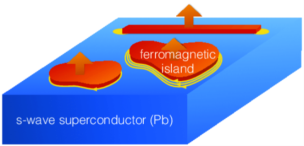


MAGNETIC OBJECTS IN SUPERCONDUCTORS

Magnetic chains and/or islands embedded in superconductors



or magnetic islands



arrange their in-gap bound states into Shiba-bands.

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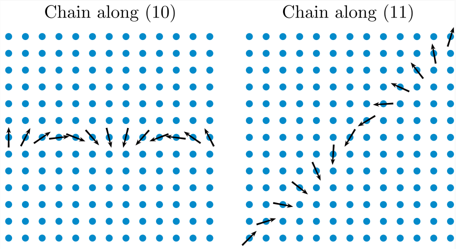
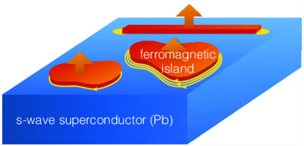


or magnetic islands

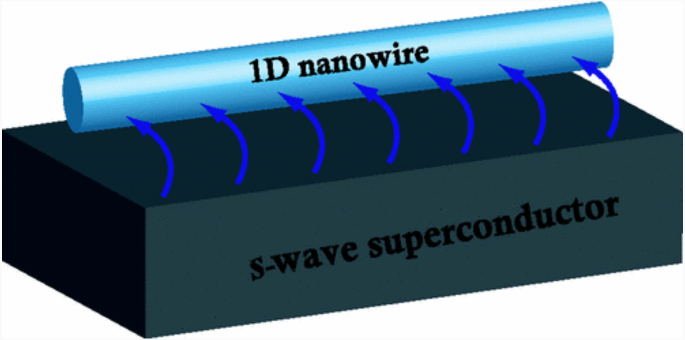


arrange their in-gap bound states into Shiba-bands.

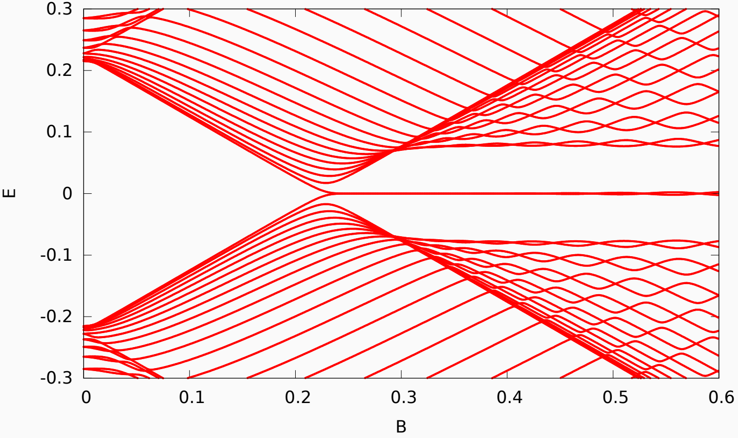
In particular, the proper magnetic textures in chains and islands can guarantee their topologically non-trivial character, hosting the exotic Majorana-type boundary modes !

1. Rashba nanowires

Leakage of Cooper pairs + spin-orbit coupling + Zeeman field induce effectively the *p-wave* electron pairs (Kitaev scenario).



Effective quasiparticle states of the Rashba nanowire



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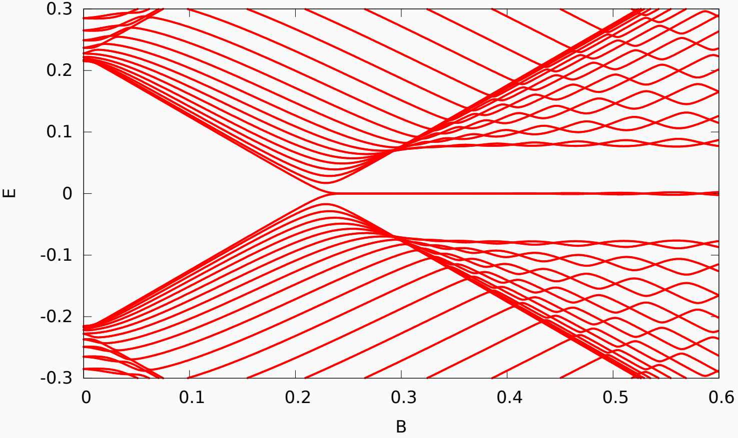
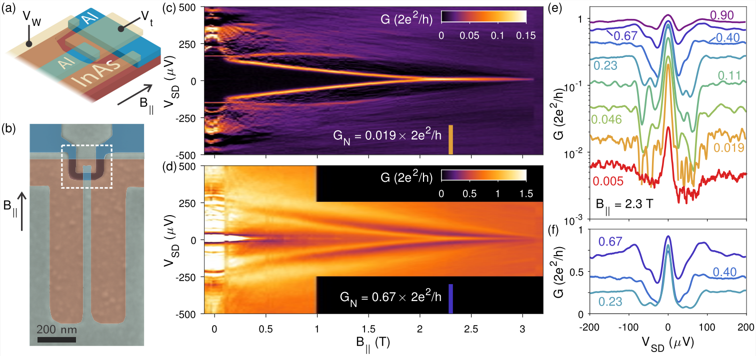


closing/reopening of a gap ⇔ band-invertion of topological insulators

M.M. Maśka, A. Gorczyca-Goraj, J. Tworzydło, T. Domański, PRB 95, 045429 (2017).

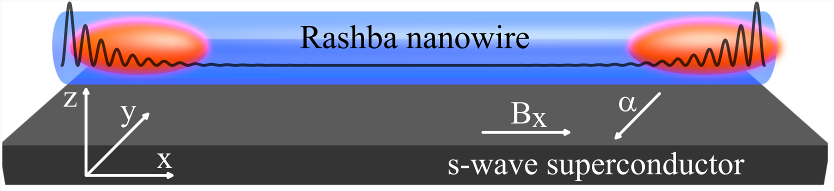
Litographically fabricated Al nanowire contacted to InAs



F. Nichele, ..., and Ch. Marcus, Phys. Rev. Lett. **119**, 136803 (2017).

/ Niels Bohr Institute, Copenhagen, Denmark /

Pairing of identical spin electrons is driven by the spin-orbit (Rashba) interaction in presence of magnetic field, using the semiconducting nanowires proximitized to conventional (*s-wave*) superconductor.



PROPERTIES OF MAJORANA QPS

- **particle = antiparticle** $\hat{\gamma}_{i,n}^\dagger = \hat{\gamma}_{i,n}$

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- spatially nonlocal

$\Rightarrow$ exist always in pairs at boundaries/defects

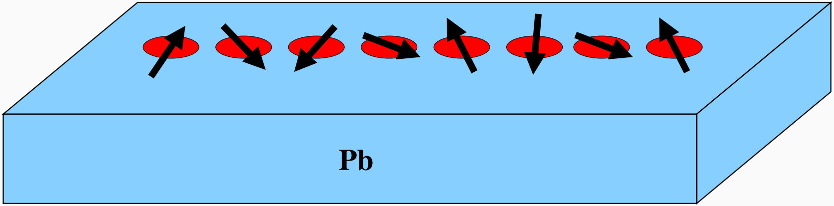
- topologically protected

$\Rightarrow$ immune to dephasing/decoherence

2. Selforganised magnetic chains

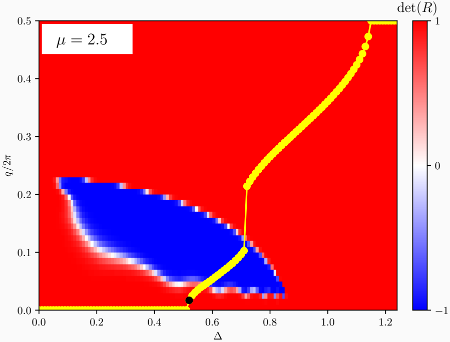
MAGNETIC CHAINS ON SUPERCONDUCTORS

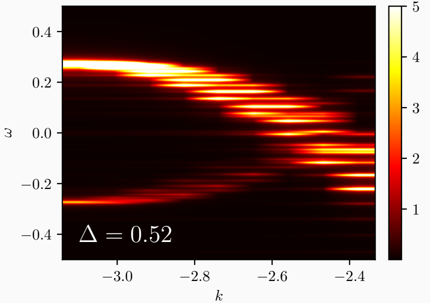
Magnetic atoms (like Fe) on a surface of s-wave superconductor (for example Pb) arrange themselves into such spiral order, where topological superconducting phase is selfsustained

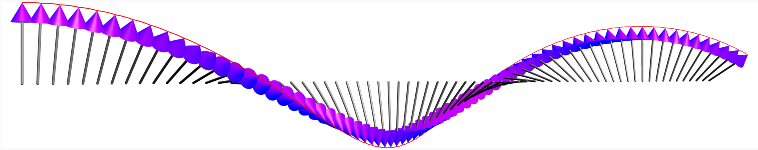


HELICAL SELFORGANISATION (TOPOFILIA)

A. Gorczyca-Goraj, T. Domański & M.M. Maśka, Phys. Rev. B <u>99</u>, 235430 (2019).







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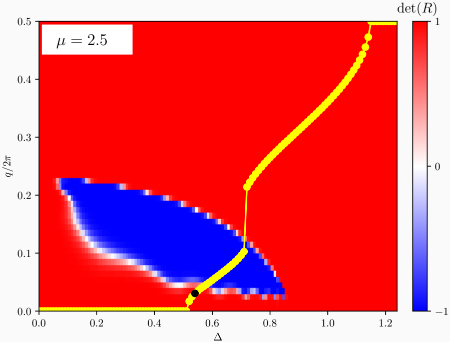

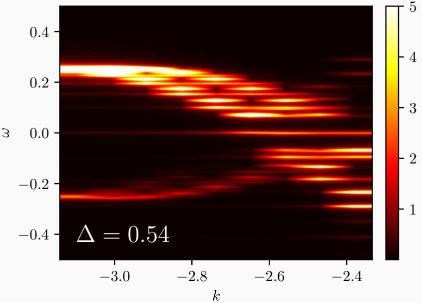

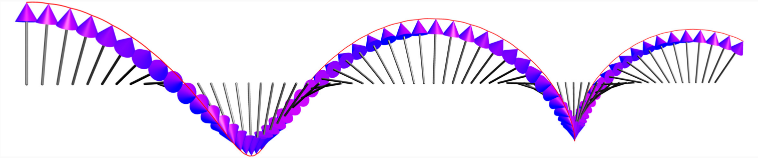

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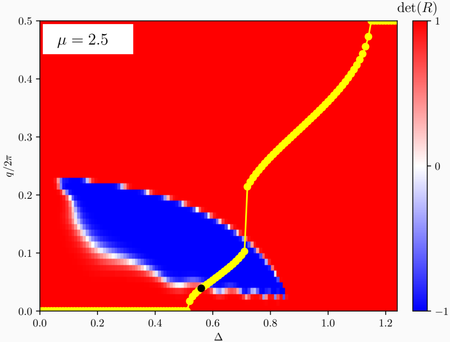

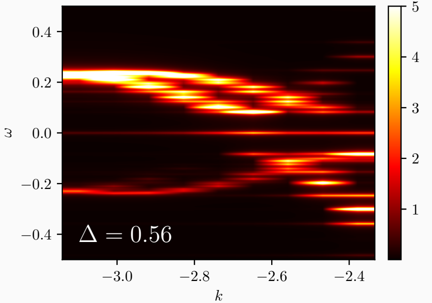

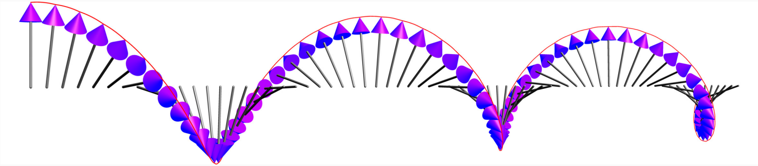

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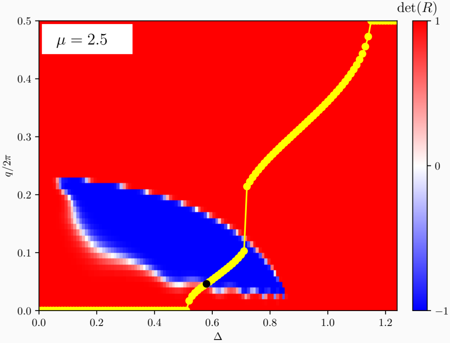

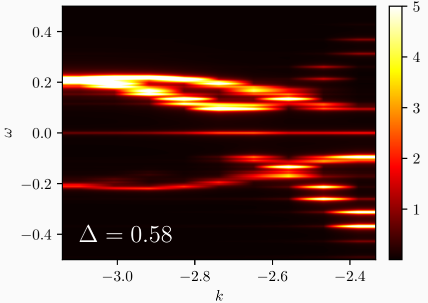

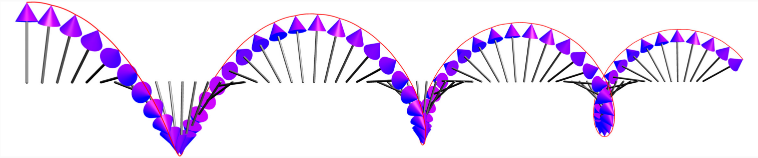

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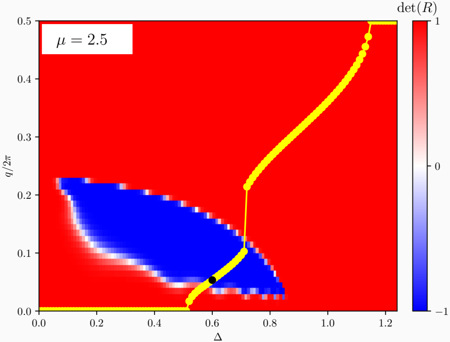

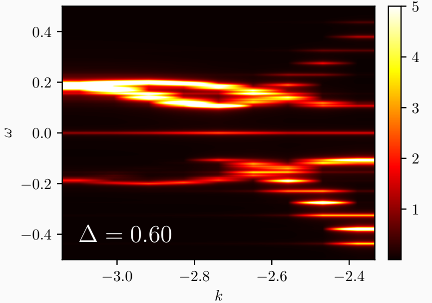

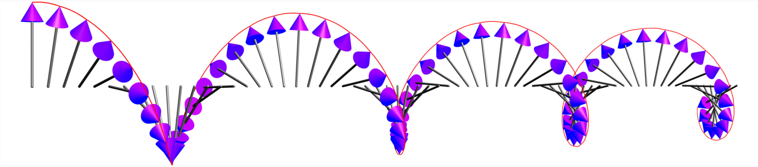

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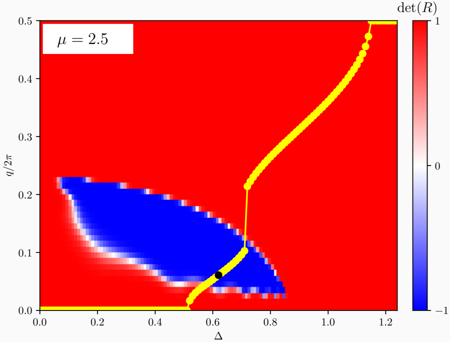

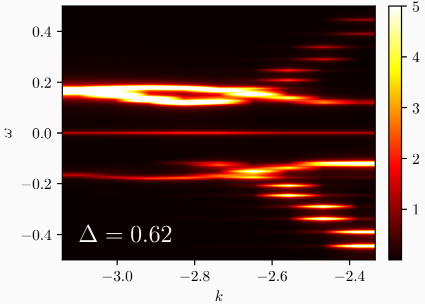

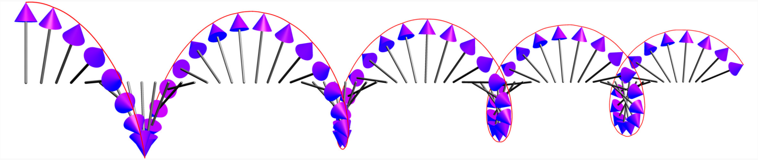

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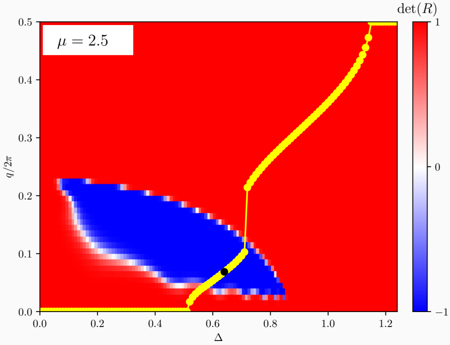

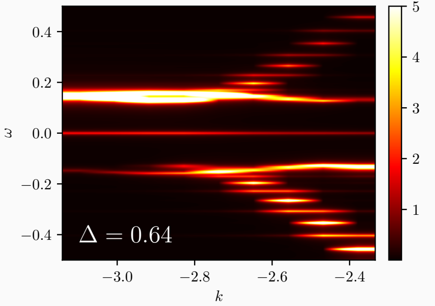

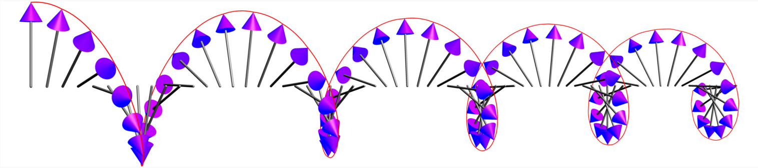

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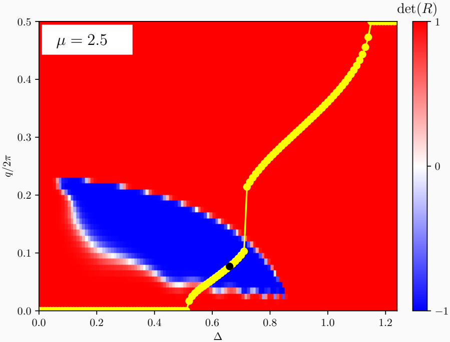

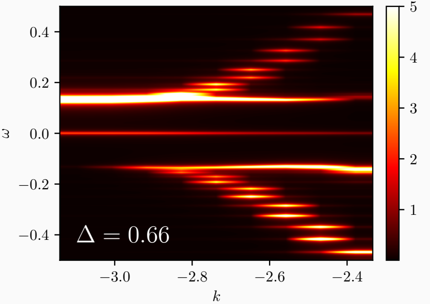

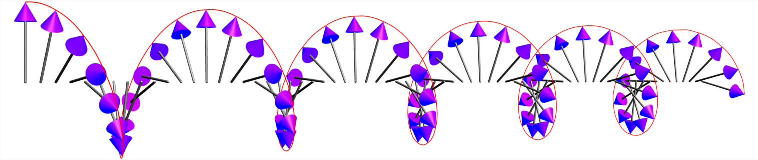

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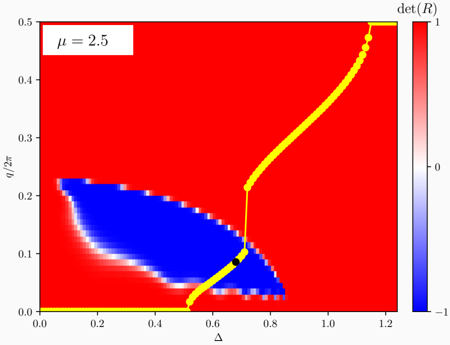

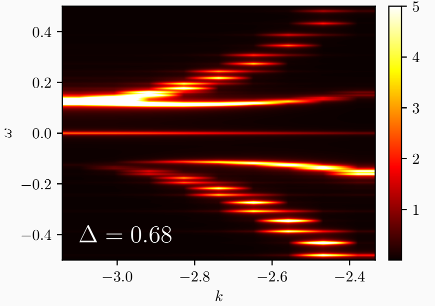

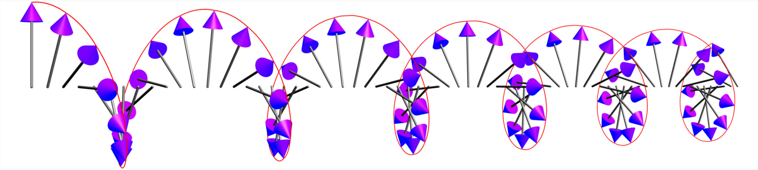

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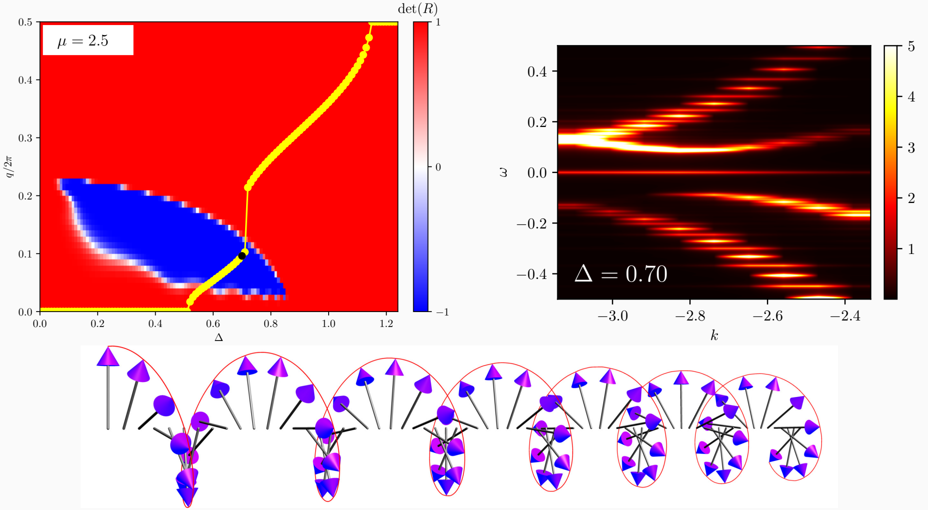

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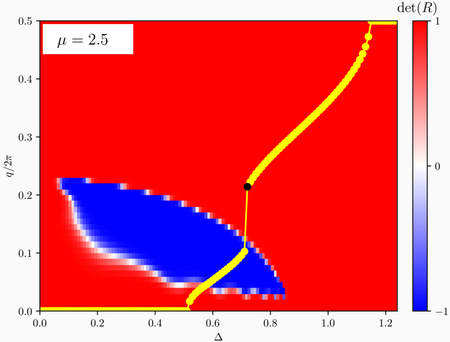
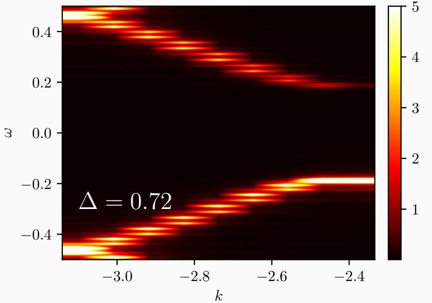
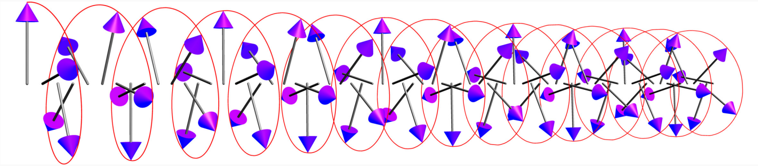
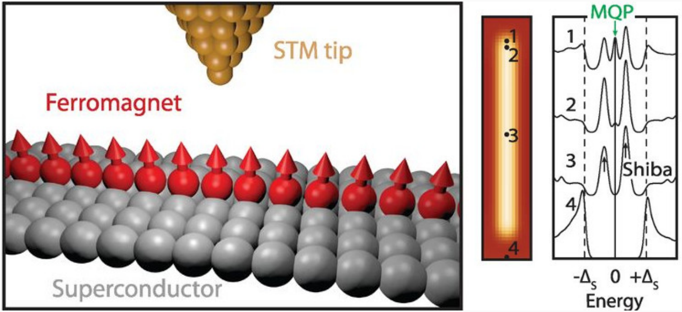






EXAMPLE OF EMPIRICAL REALIZATION

STM measurements for the nanochain of Fe atoms self-organized on a surface of superconducting Pb.



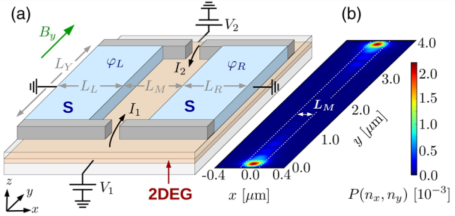
S. Nadj-Perge, ..., and A. Yazdani, Science **346**, 602 (2014).

/ Princeton University, USA /

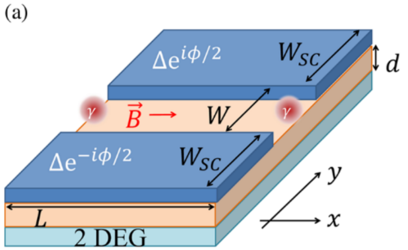
Majorana modes in Josephson junctions

PLANAR JOSEPHSON JUNCTIONS

Idea: Narrow metallic region with the strong spin-orbit interaction and in presence of magnetic field embedded between external superconductors.



Michael Hell et al., PRL 118, 107701 (2017)



F. Pientka et al., Phys. Rev. X 7,021032 (2017)

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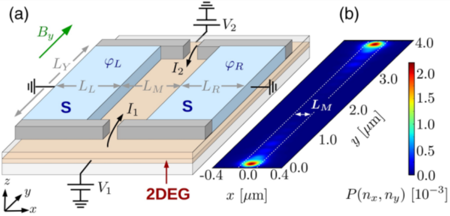
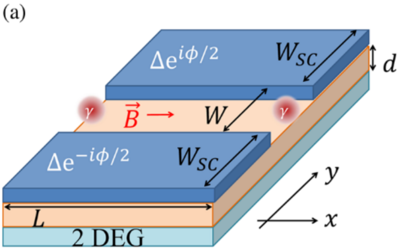


Michael Hell et al., PRL 118, 107701 (2017)



F. Pientka et al., Phys. Rev. X 7,021032 (2017)

Benefit:

Phase-tunable topological superconductivity induced in the metallic stripe.

PLANAR JOSEPHSON JUNCTIONS

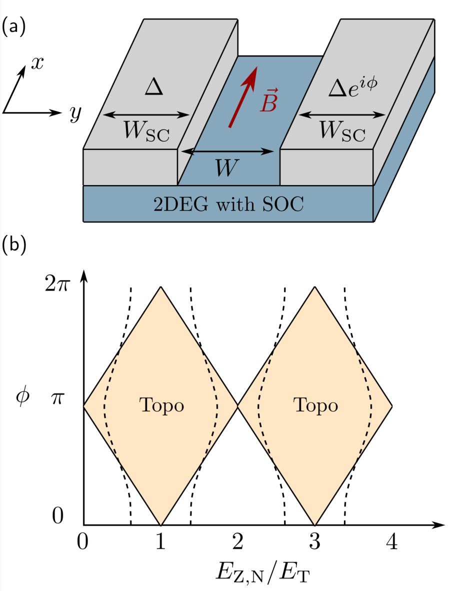
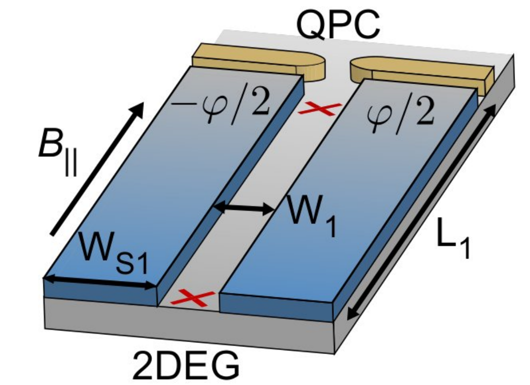


Diagram of topological superconducting state vs
– phase difference ϕ,
– magnetic field E_z.

PLANAR JOSEPHSON JUNCTIONS: EXPERIMENT

Two-dimensional electron gas of InAs epitaxially covered by a thin Al layer



Width:

W_1 = 80 nm

Length:

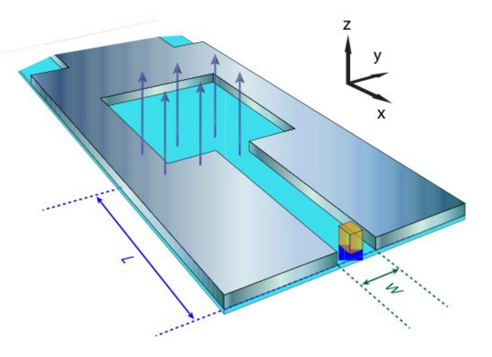
L_1 = 1.6 μm

A. Fornieri, ..., Ch. Marcus and F. Nichele, Nature 569, 89 (2019).

Niels Bohr Institute (Copenhagen, Denmark)

PLANAR JOSEPHSON JUNCTIONS: EXPERIMENT

Two-dimensional HgTe quantum well coupled to 15 nm thick Al film



Width:

W = 600 nm

Length:

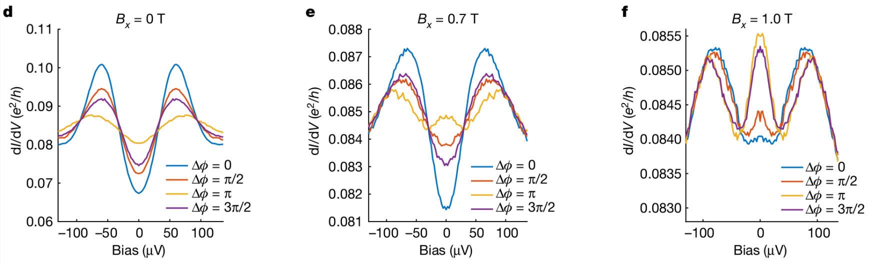
L = 1.0 μm

H. Ren, ..., L.W. Molenkamp, B.I. Halperin & A. Yacoby, Nature 569, 93 (2019).

Würzburg Univ. (Germany) + Harvard Univ. (USA)

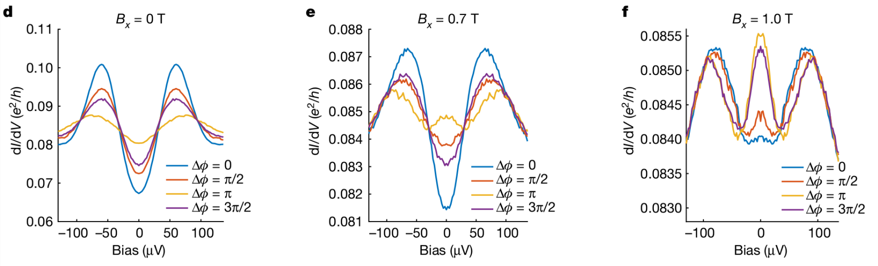
PLANAR JOSEPHSON JUNCTION: EXPERIMENT

H. Ren, ..., L.W. Molenkamp, B.I. Halperin & A. Yacoby, Nature 569, 93 (2019).

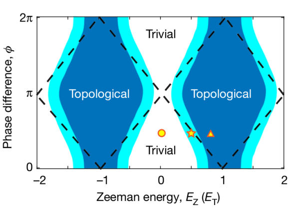


PLANAR JOSEPHSON JUNCTION: EXPERIMENT

H. Ren, ..., L.W. Molenkamp, B.I. Halperin & A. Yacoby, Nature 569, 93 (2019).



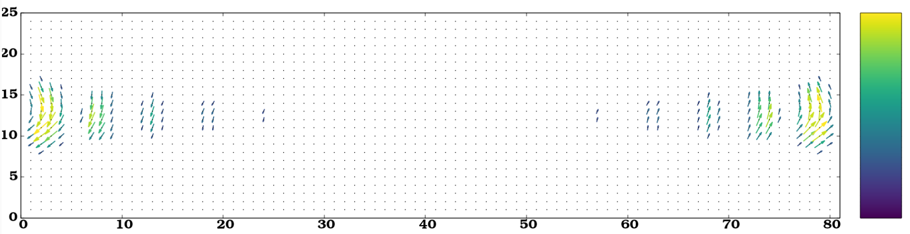
Experimental data obtained for three different magnetic fields indicated by the symbols in phase diagram ⇒.



Topography of Majorana modes

TOPOGRAPHY OF MAJORANA MODES

Spatial profile of the zero-energy quasiparticles of a homogeneous metallic strip embedded into the Josephson junction for the phase difference $\phi = \pi$ (which is optimal for topological state).



"Majorana polarization" $u_{\uparrow,n}v_{\uparrow,n} - u_{\downarrow,n}v_{\downarrow,n}$ obtained for eigenvalue $E_n = 0$.

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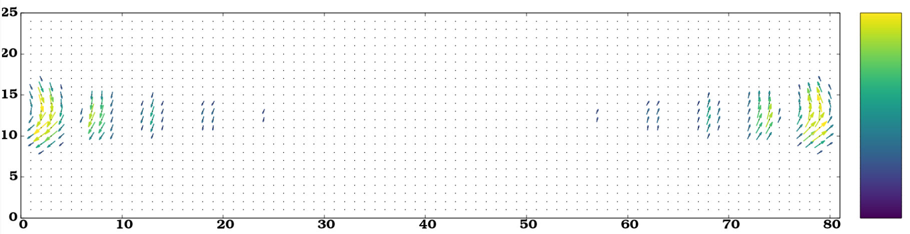
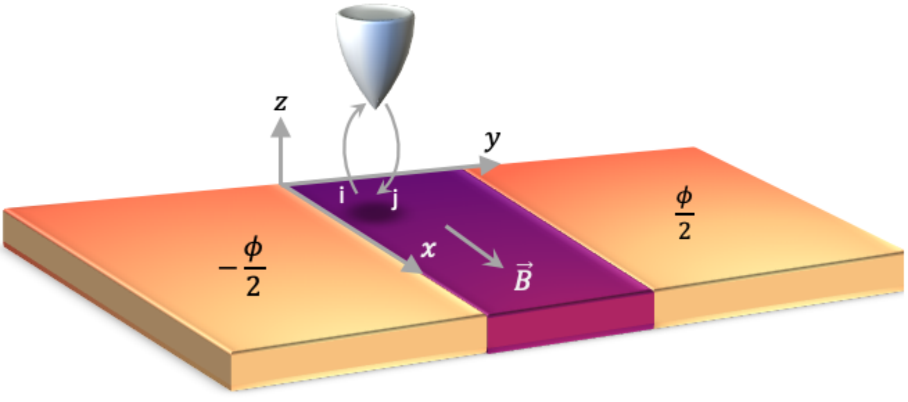


"Majorana polarization" $u_{\uparrow,n}v_{\uparrow,n} - u_{\downarrow,n}v_{\downarrow,n}$ obtained for eigenvalue $E_n = 0$. Magnitude of this quantity is measurable by the conductance of SESAR spectroscopy. For details see:

Sz. Głodzik, N. Sedlmayr & T. Domański, PRB 102, 085411 (2020).

TOPOGRAPHY OF MAJORANA MODES

Selective Equal Spin Andreev Reflection (SESAR) spectroscopy:



Sz. Głodzik, N. Sedlmayr & T. Domański, PRB 102, 085411 (2020).

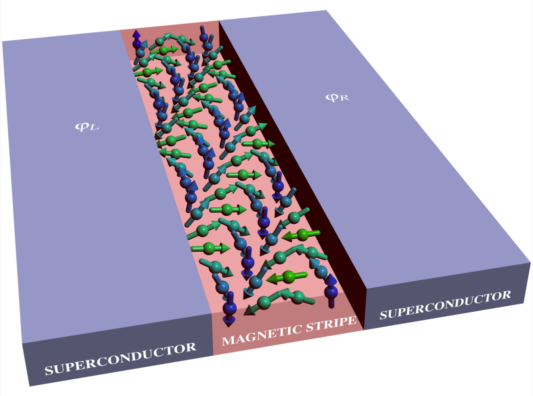
Topological Josephson junctions

Topological Josephson junctions

with self-organized magnetic stripe

JJ WITH SELFORGANIZED MAGNETIC STRIPE

Narrow metallic stripe with the classical magnetic moments placed between two s-wave superconductors, differing in phase $\phi_L \neq \phi_R$.



M.M. Maśka, M. Dziurawiec, M. Strzałka & T.D. **– work in progress**

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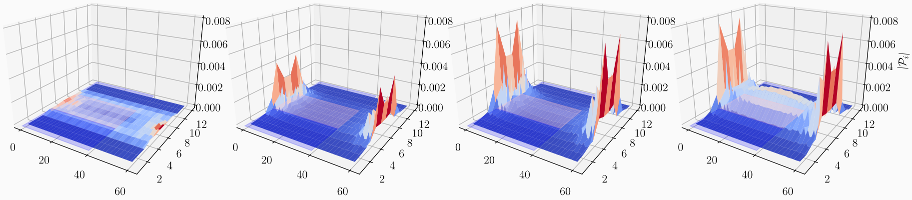
JJ WITH SELFORGANIZED MAGNETIC STRIPE

Spatial profiles of the (zero-energy) Majorana quasiparticles for selected values of the phase difference $\phi_R - \phi_L$.



$\phi_R - \phi_L = 0.6\pi$ $\phi_R - \phi_L = 0.4\pi$ $\phi_R - \phi_L = 0.2\pi$ $\phi_R - \phi_L = 0.0$

M.M. Maśka, M. Dziurawiec, M. Strzałka & T.D. – work in progress

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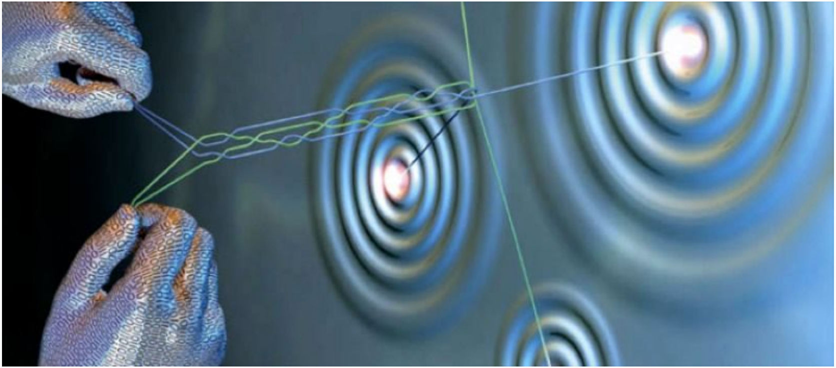
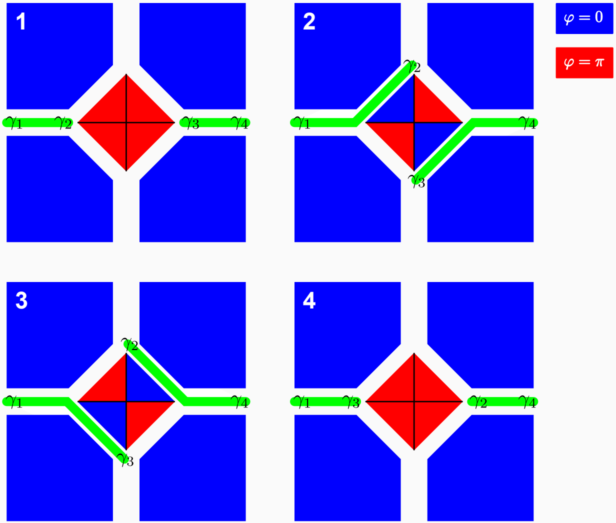
CHALLENGING ISSUE

Can one braid the Majorana modes ?



BRAIDING PROTOCOL

Braiding of the Majorana pairs in Josephson platform



TAKE-HOME MESSAGE

Magnetism and superconductivity in nanoscopic systems:

$\Longrightarrow$ **can cooperate between themselves**

$\Longrightarrow$ **inducing novel (topological) states of matter**

$\Longrightarrow$ **hosting in-gap (Andreev/Yu-Shiba-Rusinov/Majorana) states**

$\Longrightarrow$ **useful for quantum bits / quantum computing**

http://kft.umcs.lublin.pl/doman/lectures

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