Spin-orbit interaction as a source of magneto-electric and triplet proximity effects in superconducting heterostructures

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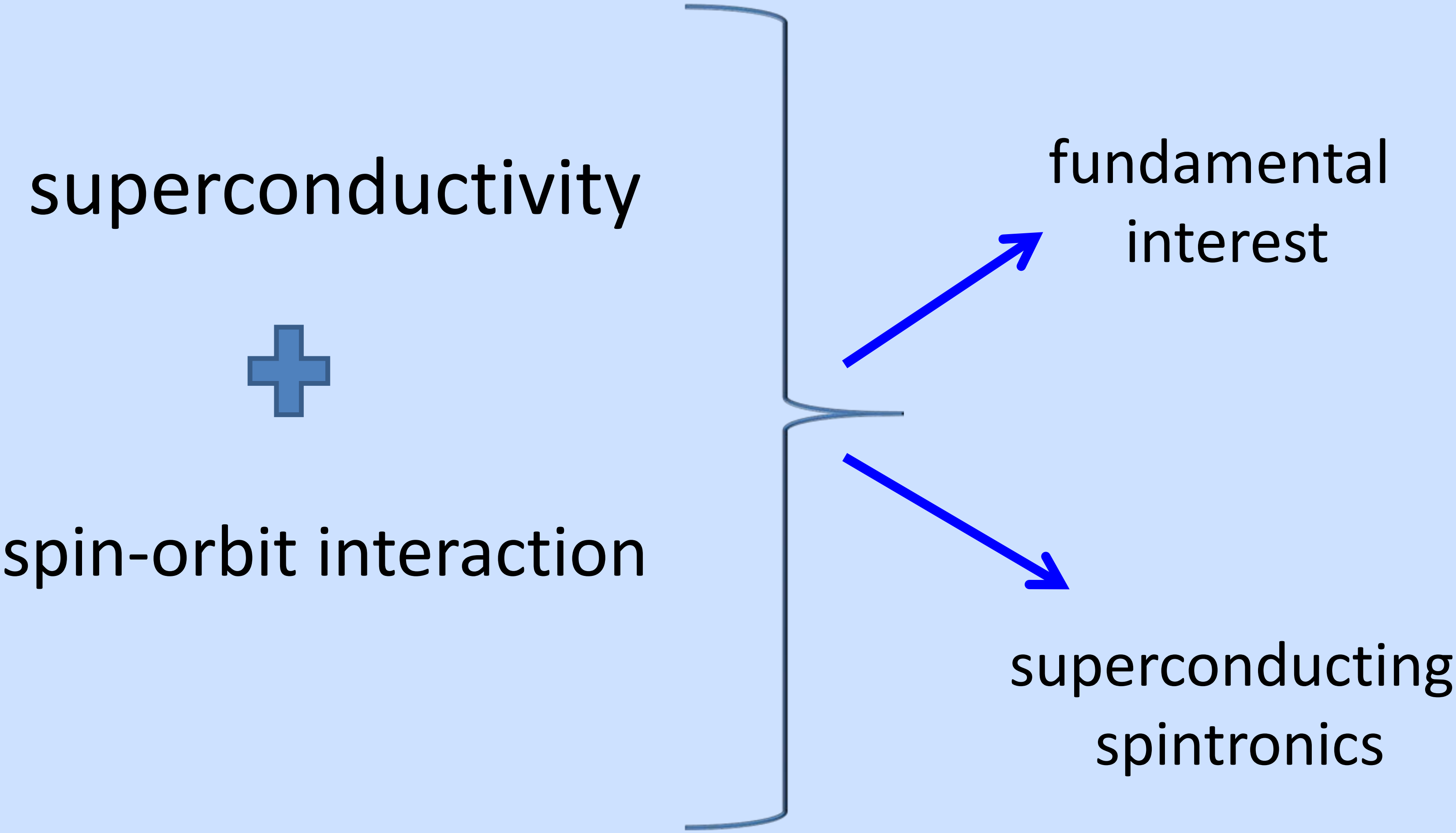
Lecture for the international school "Superconducting hybrid nanostructures: physics and application", September, 25, MIPT, Dolgoprudny, Russia

Motivation



superconductivity

+

spin-orbit interaction

fundamental interest

superconducting spintronics

Superconducting spintronics

dissipative:

✓full spin polarization of quasiparticles in superconductors

✓possible to create pseudo-chargeless spin-1/2 excitations in superconductors with extremely long spin lifetimes.

dissipationless:

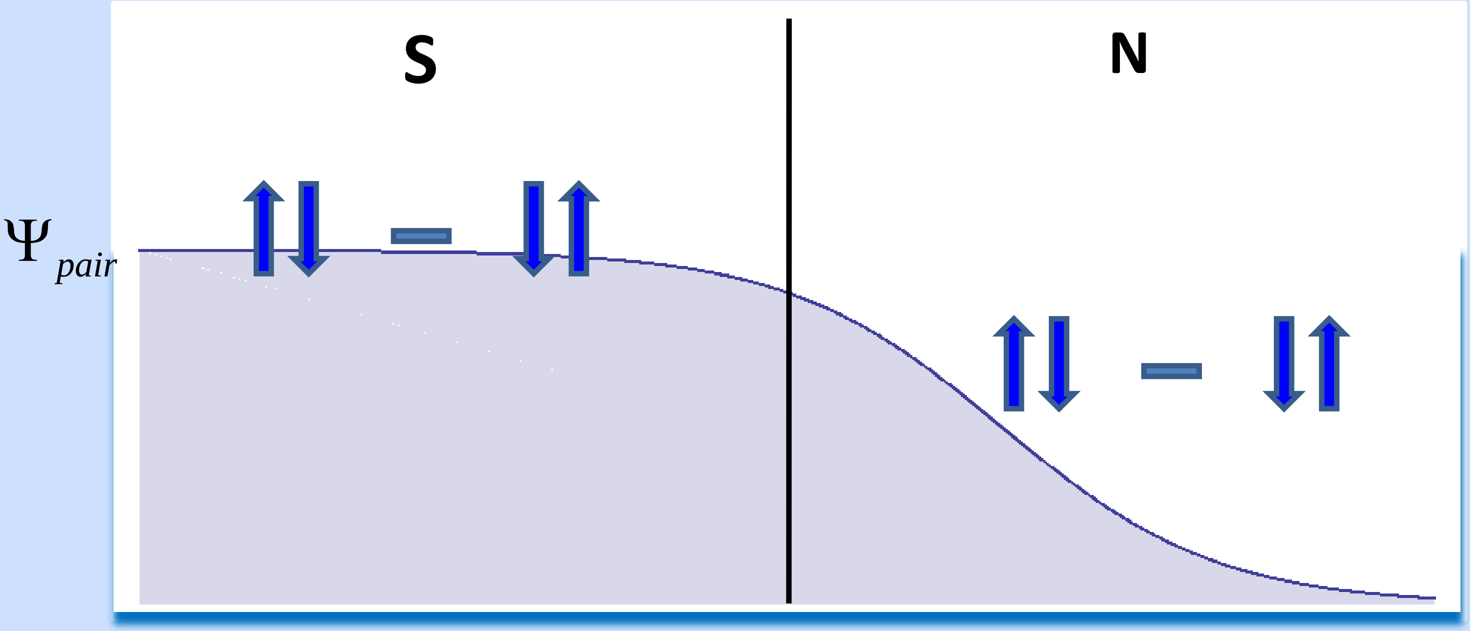
spin-triplet Cooper pairs

To learn more: J. Linder, J. Robinson, Nature Physics, (2015);
M. Eschrig, Reports on Progress in Physics (2015)

Outline

- ☐ Motivation
- ☐ Triplet proximity effect at superconductor/ferromagnet interfaces
- ☐ Triplet proximity effect at superconductor/spin-orbit material interfaces
- ☐ Magnetoelectric effects in normal heterostructures
- ☐ Magnetoelectric effects in superconducting heterostructures:
    - ✓ Direct magnetoelectric effect in homogeneous superconductors
    - ✓ ----//---- in superconducting heterostructures
    - ✓ Inverse magnetoelectric effect in homogeneous superconductors
    - ✓ ----//---- in superconducting heterostructures

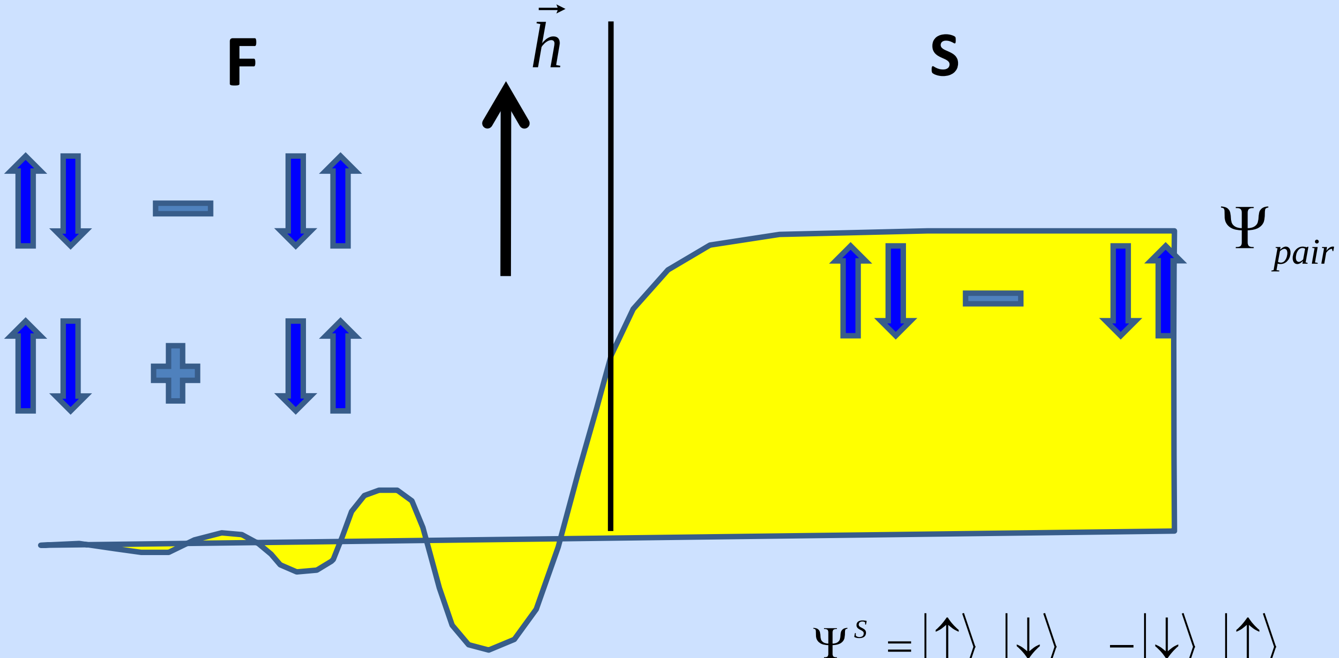
Proximity effect at a superconductor/normal metal interface



$$\Psi_{pair} \propto e^{-x/\xi_N}$$

$$\xi_N = \sqrt{\frac{D}{2\pi T}}$$

Proximity effect at a superconductor/ferromagnet interface

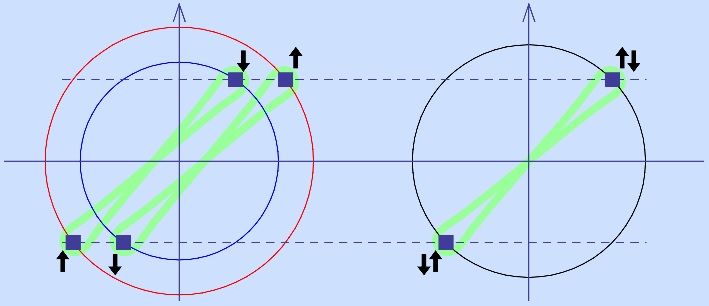


$$\Psi^S = |\uparrow\rangle_p |\downarrow\rangle_{-p} - |\downarrow\rangle_p |\uparrow\rangle_{-p}$$

$$\Downarrow$$

$$\Psi^F = |\uparrow\rangle_p |\downarrow\rangle_{-p} e^{\frac{2ihx}{v_x}} - |\downarrow\rangle_p |\uparrow\rangle_{-p} e^{-\frac{2ihx}{v_x}} =$$

$$(|\uparrow\rangle_p |\downarrow\rangle_{-p} - |\downarrow\rangle_p |\uparrow\rangle_{-p}) \cos\frac{2hx}{v_x} + (|\uparrow\rangle_p |\downarrow\rangle_{-p} + |\downarrow\rangle_p |\uparrow\rangle_{-p}) i \sin\frac{2hx}{v_x}$$



To learn more: A. Buzdin, Rev. Mod. Phys. (2015)

Possible types of triplet correlations

$$\Psi_{pair} = g(p)\chi_{12}$$

Pauli principle ⇒ $g(p)\chi_{12} = -g(-p)\chi_{21}$

⇓

$for \quad g(k) = g(-k) \quad \text{the pairing is singlet :} \quad \chi_{12} = \left|\uparrow\downarrow\right\rangle - \left|\downarrow\uparrow\right\rangle$

$$for \quad g(k) = -g(-k) \quad \text{the pairing is triplet :} \quad \chi_{12} = \begin{cases} \left|\uparrow\uparrow\right\rangle, \quad \mathrm{S_z} = 1 \\ \left|\uparrow\downarrow\right\rangle + \left|\downarrow\uparrow\right\rangle, \quad \mathrm{S_z} = 0 \\ \left|\downarrow\downarrow\right\rangle, \quad \mathrm{S_z} = -1 \end{cases}$$

But in a **diffusive heterostructure the pair is s-wave:** $g(k) = g(-k)$

Does it mean that triplet pairing is not possible? **No**

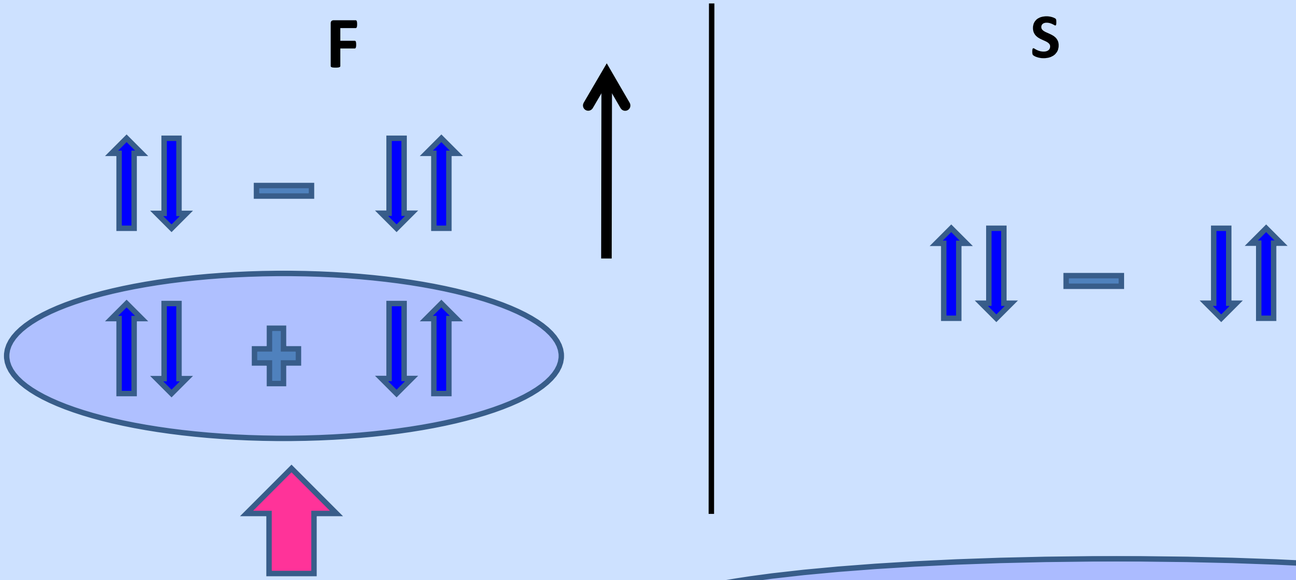
$$\Psi_{pair} = \Psi_{pair}(t_1, t_2)$$

$and \quad if\ g(k) = g(\text{-}k) \quad \& \quad \chi_{12} = \chi_{21} \Rightarrow \Psi_{\mathrm{pair}}(t_1, t_2) = -\Psi_{\mathrm{pair}}(t_2, t_1)$

$\Psi_{pair}(t,t) = 0 \Rightarrow$ in the frequency representation $\Psi_{pair}(\omega_n) = -\Psi_{pair}(-\omega_n)$

Odd-frequency
spin triplet
s-wave pairing

Proximity effect at a superconductor/ferromagnet interface



Odd-frequency
spin triplet
s-wave pairing

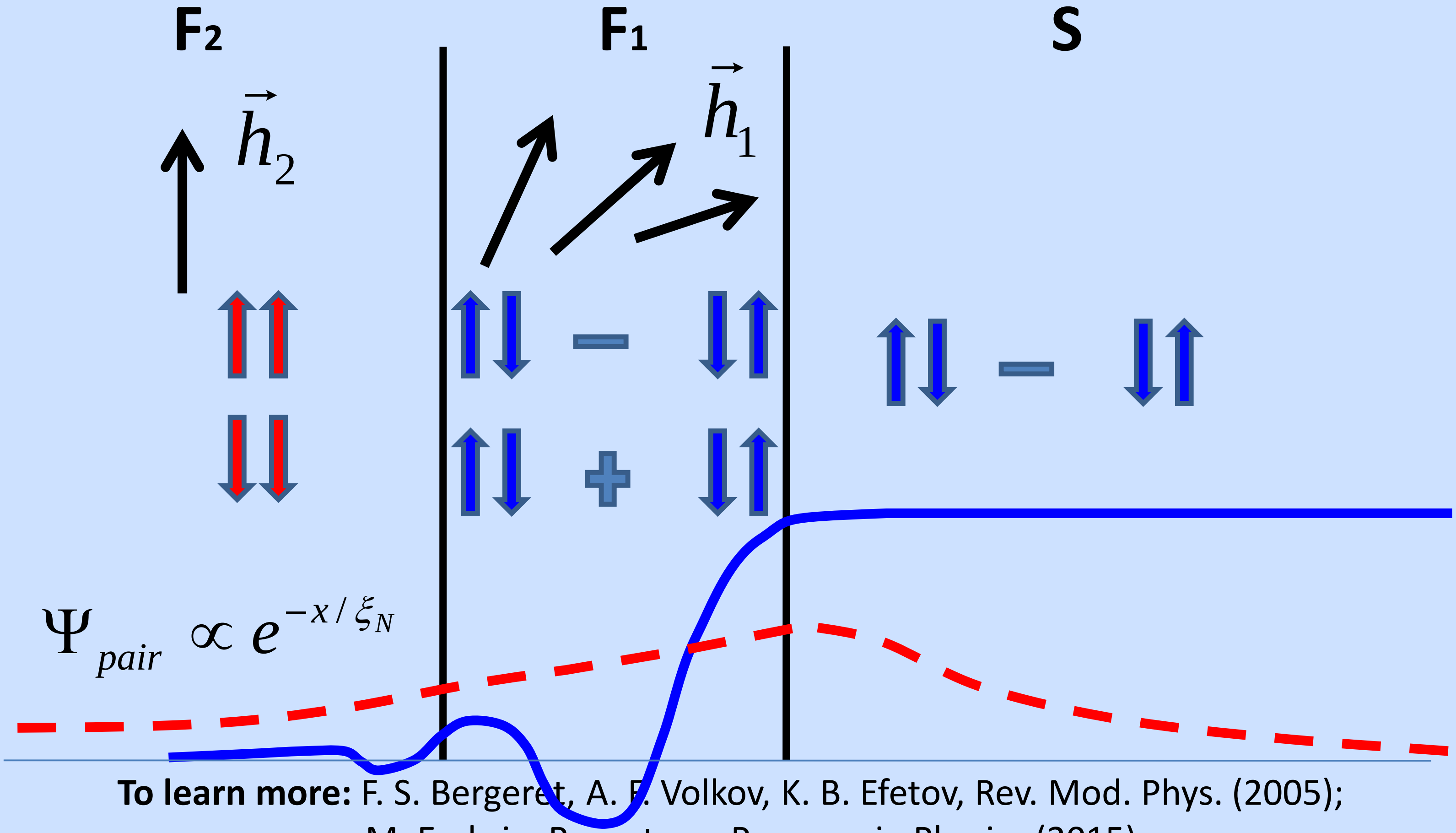
But there are two problems with this triplets:

- ✓<**S**> is zero
- ✓the correlations are short-range: $\Psi_{pair} \propto e^{-x/\xi_m}$

$$\xi_m = \sqrt{\frac{D}{h}} << \xi_N = \sqrt{\frac{D}{2\pi T}}$$

A way to fix the both problems simultaneously:

magnetic inhomogeneity



$$\Psi_{pair} \propto e^{-x/\xi_N}$$

To learn more: F. S. Bergeret, A. F. Volkov, K. B. Efetov, Rev. Mod. Phys. (2005);
M. Eschrig, Reports on Progress in Physics (2015)

What else can be a source of triplet proximity pairs?

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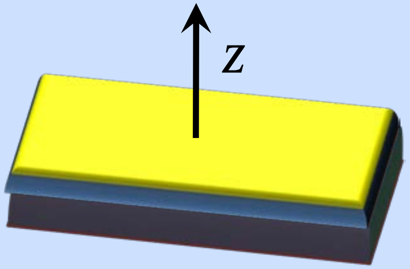
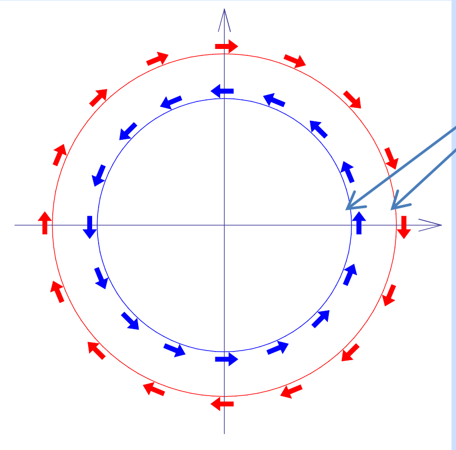
Spin-orbit coupling



$$\hat{H} = \frac{p^2}{2m} - \frac{1}{2m} A_j^\alpha \sigma^\alpha p_j - \varepsilon_F$$

Rashba spin-orbit coupling: $A_x^y = -A_y^x = \alpha$

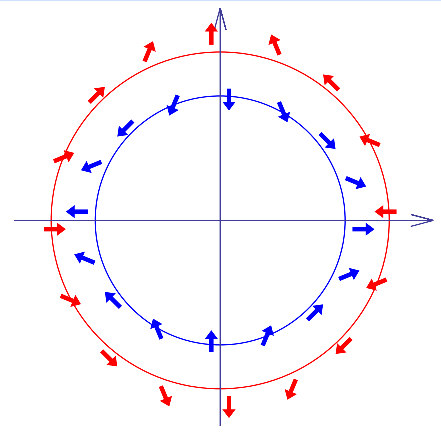
from the asymmetry of the confinement in the z-direction



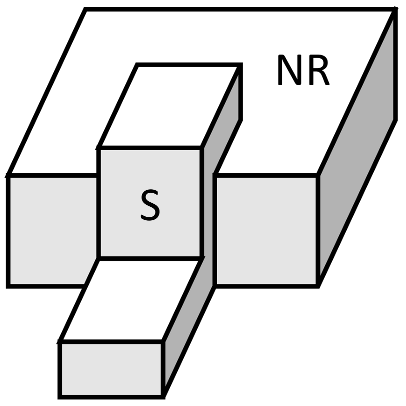
$\propto \alpha p_F$

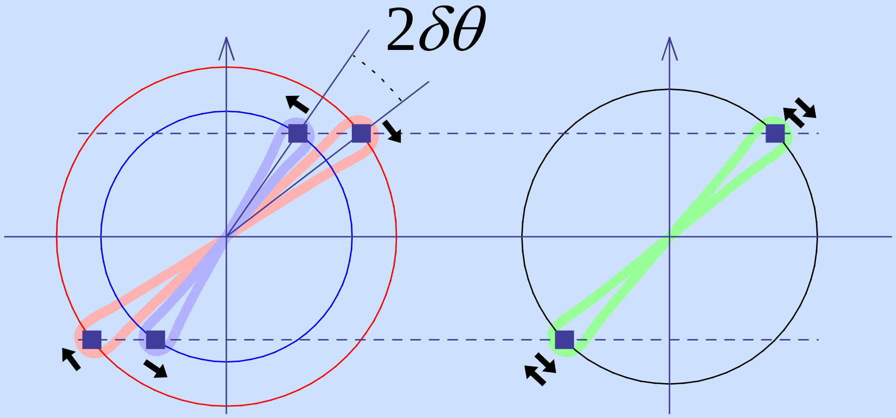
Dresselhaus spin-orbit coupling: $A_x^x = -A_y^y = \beta$

from the broken inversion symmetry of the material, a bulk property



Triplet pairing at superconductor/Rashba metal interface





$$\delta\theta = \frac{p_y}{p_x}\frac{\alpha p_F}{4\varepsilon_F}$$

$$\left|\uparrow(\downarrow)\right\rangle_p \to \left(1 \pm i\frac{\delta\theta}{2}\right)\left|\uparrow(\downarrow)\right\rangle_p \pm i\frac{\delta\theta}{2}\left|\downarrow(\uparrow)\right\rangle_p$$

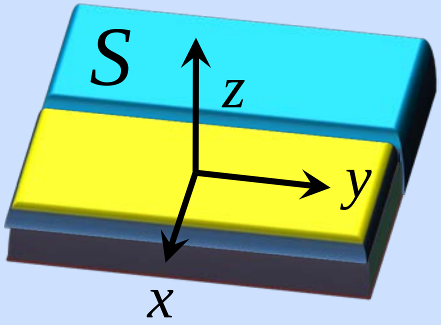
$$\left|\downarrow(\uparrow)\right\rangle_{-p} \to \left(1 \pm i\frac{\delta\theta}{2}\right)\left|\downarrow(\uparrow)\right\rangle_{-p} \pm i\frac{\delta\theta}{2}\left|\uparrow(\downarrow)\right\rangle_{-p}$$

$$\Psi^S = \left|\uparrow\right\rangle_p\left|\downarrow\right\rangle_{-p} - \left|\downarrow\right\rangle_p\left|\uparrow\right\rangle_{-p} \longrightarrow \Psi^S + i\delta\theta\left(\left|\uparrow\right\rangle_p\left|\downarrow\right\rangle_{-p} + \left|\downarrow\right\rangle_p\left|\uparrow\right\rangle_{-p} + \left|\uparrow\right\rangle_p\left|\uparrow\right\rangle_{-p} + \left|\downarrow\right\rangle_p\left|\downarrow\right\rangle_{-p}\right)$$

Triplet pairing at superconductor/Rashba metal interface: result of the strict calculation

$$\boldsymbol{\Psi} = \begin{pmatrix} \Psi_x \\ \Psi_y \\ \Psi_z \end{pmatrix}:$$

$$\Psi_{pair} = \left(\Psi_S + \boldsymbol{\Psi}\boldsymbol{\sigma}\right) i\sigma_y$$



at $\frac{\alpha p_F}{\varepsilon_F} << 1$

$\Psi_x \propto \left|\uparrow\uparrow\right\rangle - \left|\downarrow\downarrow\right\rangle \propto \frac{\alpha p_F}{\varepsilon_F} \frac{p_y}{p_F}$ - is zero after averaging over trajectories

$$\Psi_y \propto \left|\uparrow\uparrow\right\rangle + \left|\downarrow\downarrow\right\rangle \propto \frac{\alpha p_F}{\varepsilon_F} \frac{p_y^2}{p_F^2}$$

$$\Psi_z \propto \left|\uparrow\downarrow\right\rangle + \left|\downarrow\uparrow\right\rangle = 0$$

disorder-stable
odd-frequency
triplet component

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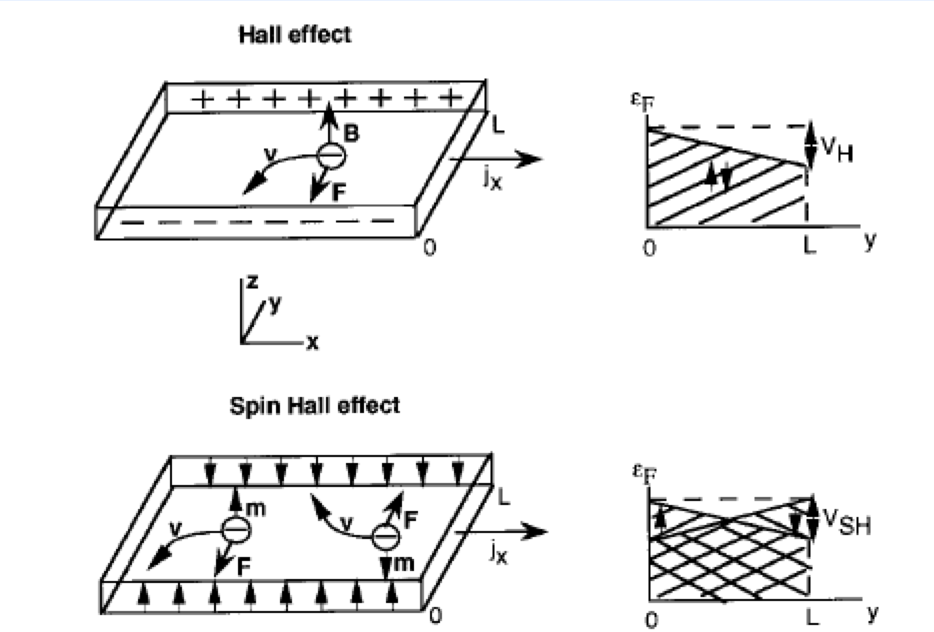
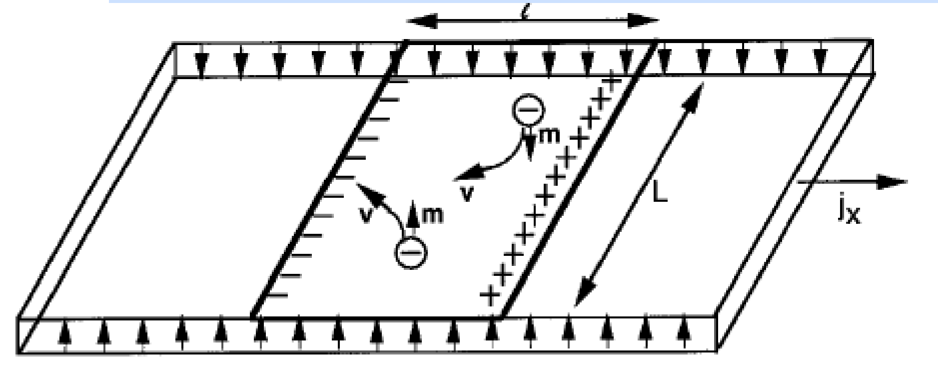
Magnetoelectric effects in normal metal

direct spin Hall effect

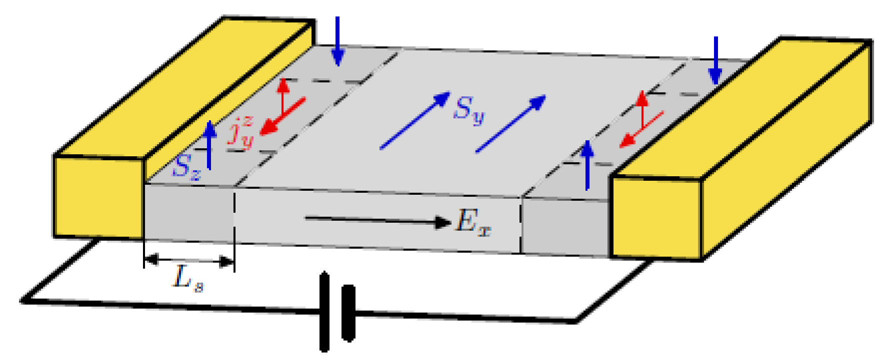


“Spin Hall effect”, J.E. Hirsh,
PRL **83**, 1834 (1999)

inverse spin Hall effect



Magnetoelectric effects in normal metal



E. G. Mishchenko, A.V. Shytov, and B. I. Halperin,
PRL **93**, 226602 (2004)

Inverse Edelstein effect
(spin-galvanic effect)

$$j_k = \sigma_k^a \left[g\mu_B \dot{B}^a \right]$$

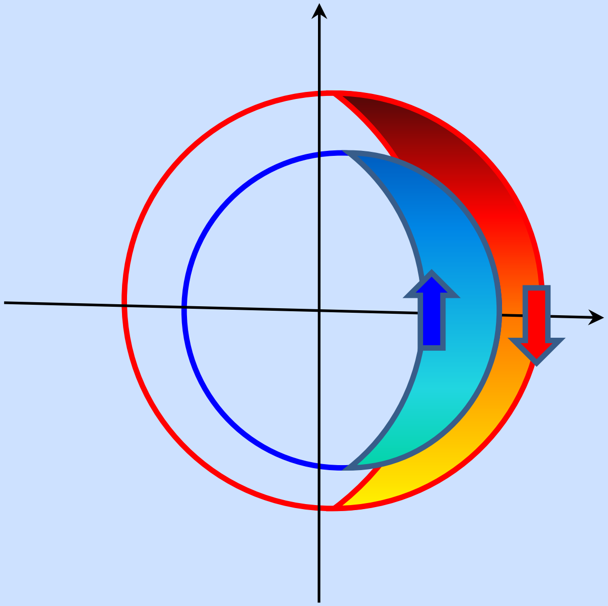
K. Shen, G. Vignale, and R. Raimondi,
PRL **112**, 096601 (2014)

dissipative effects

Edelstein effect
or
direct magnetoelectric effect

$$S^a = \sigma_k^a E_k$$

V. Edelstein, Solid state Comm.,
73, 233 (1990)



1. What magnetoelectric effects are known in superconducting systems?

2. What new physics do they bring?

Magnetoelectric effects in superconductors

Generation of triplet pairing :

$$f_s \xrightarrow{SO\ coupling} f_t$$

$$\left|\uparrow\downarrow - \downarrow\uparrow\right\rangle \rightarrow \left|\uparrow\uparrow\right\rangle, \left|\downarrow\downarrow\right\rangle$$

$$2e \rightarrow 2e, \mathbf{S}$$

Superconducting Edelstein effect

Superconducting inverse Edelstein effect

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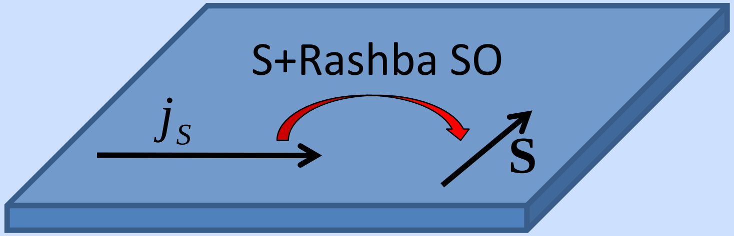
- ✓ ----//---- in superconducting heterostructures

Direct magneto-electric effect (Edelstein effect)



$$\mathbf{S} = d\left(\mathbf{c}\times\frac{j_s}{ev_F}\right)$$

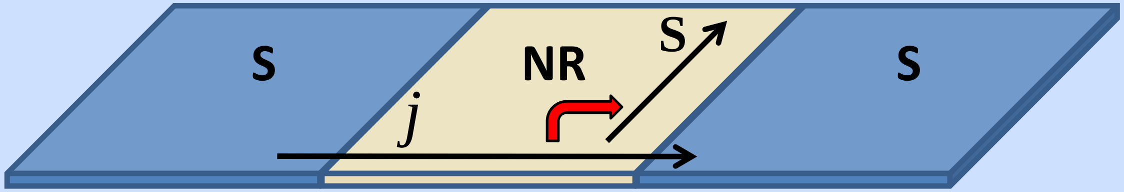
for $1 << \frac{p_F\alpha}{\pi T} << \varepsilon_F$:

$$d \propto \frac{\alpha p_F}{\varepsilon_F}$$

polarization per one electron $\approx 10^{-4}$

V.M. Edelstein, PRL **75**, 2004 (1995); V.M. Edelstein PRB **72**, 172501 (2005)

Magneto-electric effect (Edelstein effect) in Josephson junctions



Josephson current → spin polarization

$$\mathbf{S} = d\left(\mathbf{c} \times \frac{j_s}{e v_F}\right)$$

Ballistic regime:

$$d \propto \frac{\alpha p_F}{\varepsilon_F} \frac{L}{\xi}$$

I.V. Bobkova, A.M. Bobkov, in preparation

Diffusive regime:

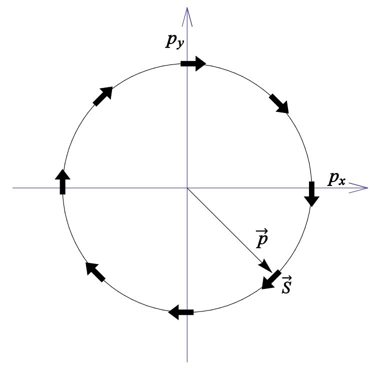
$$d = \frac{\alpha p_F}{4\varepsilon_F}$$

A.G. Mal'shukov and C.S. Chu,
PRB **78**, 104503 (2008)

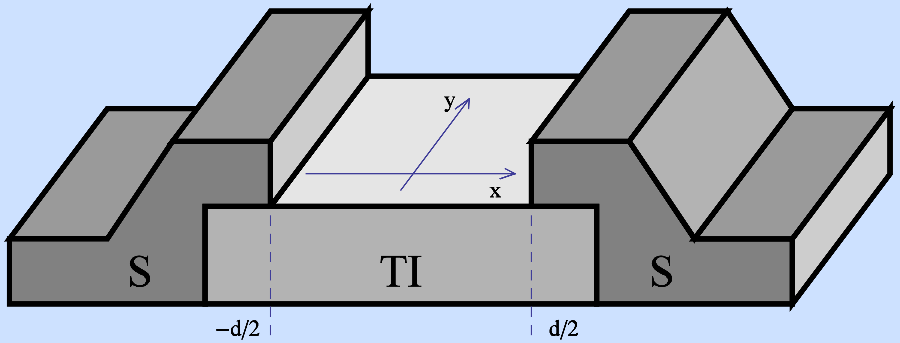
ac Josephson regime: $j_s \propto \sin 2eVt \quad \Rightarrow \quad S \propto \sin 2eVt$

Direct magnetoelectric effect in S/3D TI/S junctions

S/3D TI/S:



full spin-momentum locking

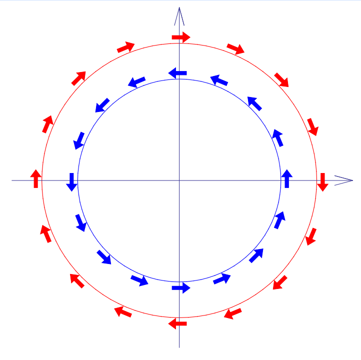


$$S_y = \frac{j_s}{4ev_F}$$

I. V. Bobkova, A. M. Bobkov, A. A. Zyuzin, M. Alidoust, arXiv: 1608.01311, accepted to PRB

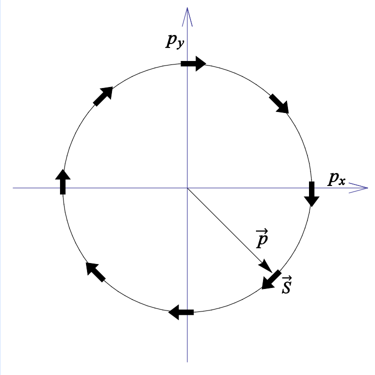
Direct magnetoelectric effect: Rashba metal vs 3D TI

S/Rashba metal/S:



two helical bands

S/3D TI/S:



full spin-momentum locking

$$\mathbf{S} = d\left(\mathbf{c} \times \frac{j_s}{ev_F}\right)$$

$$d \propto \frac{\alpha p_F}{\varepsilon_F}$$

$$d \propto 1$$

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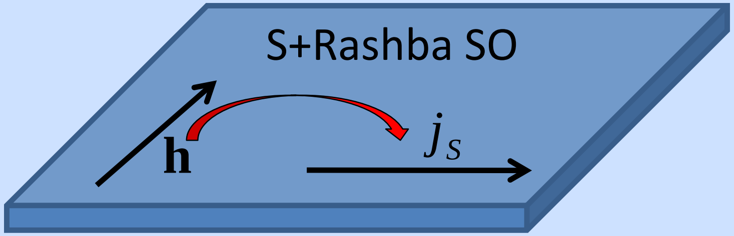
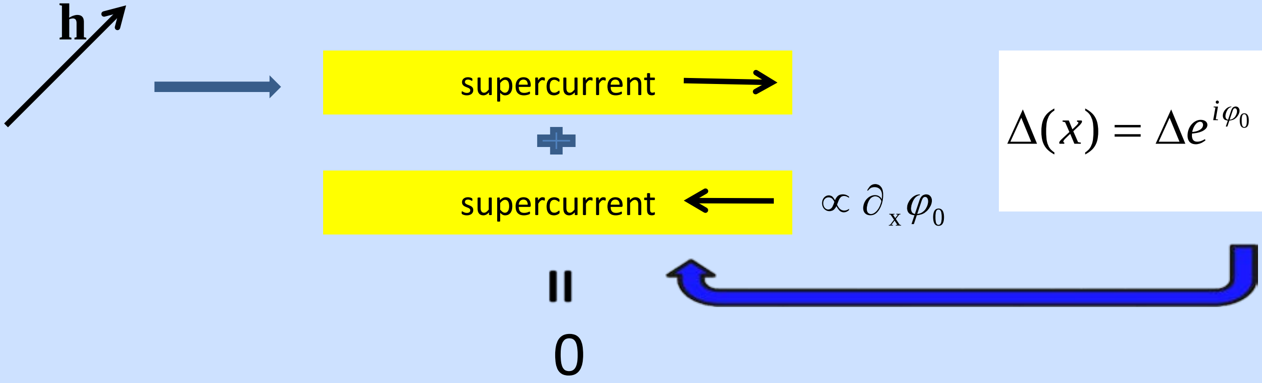
Inverse magneto-electric effect (spin-galvanic effect)



It’s not a true ground state!

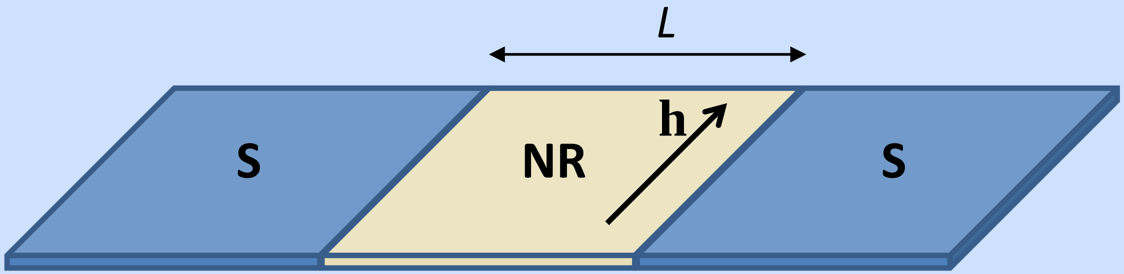


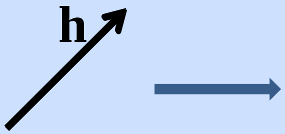
$\propto \partial_x \varphi_0$

$$\Delta(x) = \Delta e^{i\varphi_0} = \Delta \exp\left(i \frac{h \alpha p_F}{\varepsilon_F v_F} x \right)$$

Samokhin, PRB (2004); Kaur, Agterberg, and Sigrist, PRL (2005); Dimitrova and Feigelman PRB (2007)

Spin-galvanic effect and anomalous phase-shift in Josephson junctions



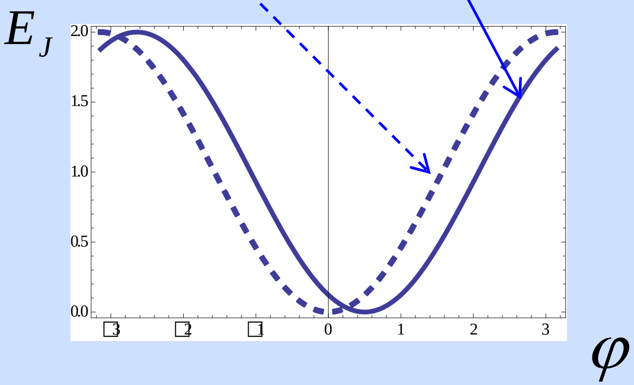


φ_0 - junction

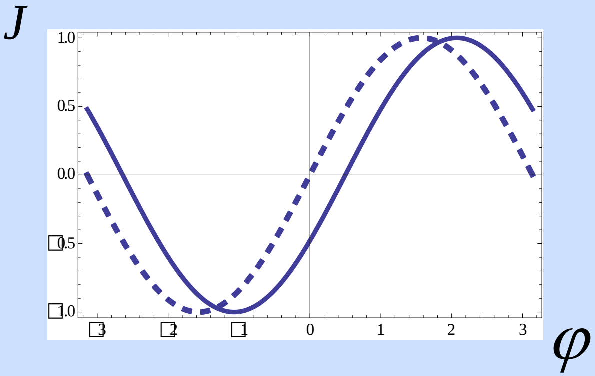
What is a □0 – junction?

□0 -junction

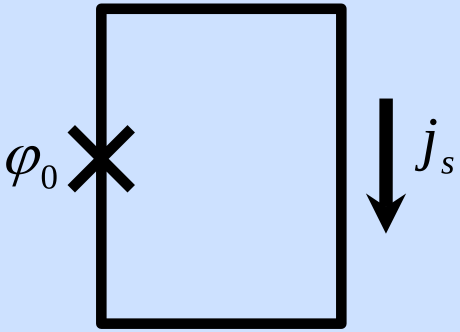
0-junction



$$E_J = J_c\left(1-\cos(\varphi-\varphi_0)\right)$$



$$J = J_c\sin(\varphi-\varphi_0)$$



the phase does not discharge

$\square_0$ – junction in Josephson systems with spin-orbit materials and 3D TI

spin-orbit interlayers

$$\varphi_0 \propto \frac{\alpha p_F hL}{\varepsilon_F v_F}$$

Buzdin PRL **101**, 107005 (2008)

topological insulator interlayers

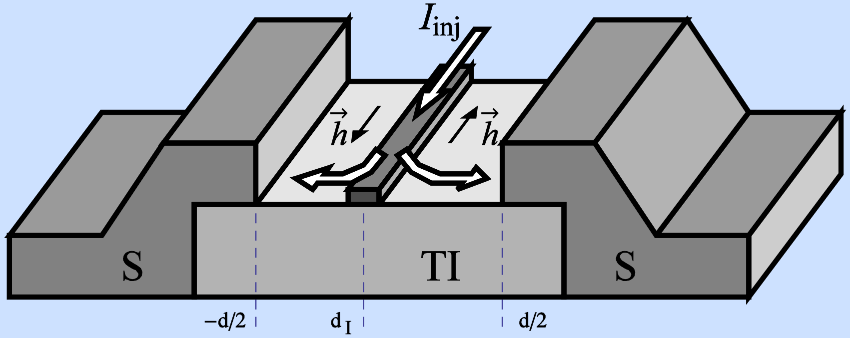
$$\varphi_0 \propto \frac{hL}{v_F}$$

Y. Tanaka, T. Yokoyama, and N. Nagaosa, PRL (2009);

F. Dolcini, M. Houzet, and J. Meyer, PRB (2015).

A. Zyuzin, M. Alidoust, D. Loss, PRB (2016)

For 3D TI interlayers there is also a possibility to have □$_0$ – junction without any ferromagnetic elements and applied magnetic field



$$\varphi_0 \propto \frac{\lambda N_F V d}{v_F}$$

- electrically controllable □$_0$ - junction

I. V. Bobkova, A. M. Bobkov, A. A. Zyuzin, M. Alidoust, arXiv: 1608.01311, accepted to PRB

Thank you for your attention!

If you are interested in calculation techniques
please ask me after the lecture

Homogeneous spin-orbit coupled superconductors and S/Rashba metal interfaces:
Gor’kov Green’s functions technique – very complicated approach:
R.Reeg and D.Maslov, PRB **92**, 134512 (2015);
V. Edelstein, PRB **67**, 020505 (2003);
V.M. Edelstein, PRL **75**, 2004 (1995); V.M. Edelstein PRB **72**, 172501 (2005)

S/spin-orbit material/S: appropriate quasiclassical techniques:
weak spin-orbit interaction: I. Bobkova, A. Bobkov, in preparation;
strong spin-orbit interaction: D. F. Agterberg and R. P. Kaur, PRB **75**, 064511 (2007);
M. Houzet, J. S. Meyer, PRB **92**, 014509 (2015) – boundary conditions are not derived

S/3D TI/S structures: appropriate quasiclassical technique:
A.Zyuzin, M. Alidoust, D. Loss, PRB (2016);
I. V. Bobkova, A. M. Bobkov, A. A. Zyuzin, M. Alidoust, arXiv: 1608.01311, PRB,
to be published