空間反転対称性の破れた超伝導体におけるスピン流とトポロジカル絶縁体

Y.Tanaka, (Nagoya University)

T. Yokoyama N. Nagaosa (Univ. Tokyo)

A.V. Balatsky (Los Alamos)

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Contents of this talk

(1)Introduction (Background)

(2)Formulation (Andreev bound state)

(3)Interpretation from the view point of topology

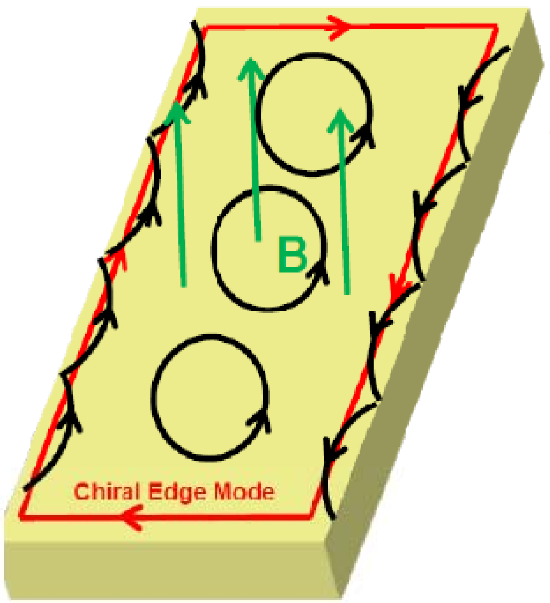
(4)Spin current

(5)Giant spin rotational angle in quantum spin Hall system

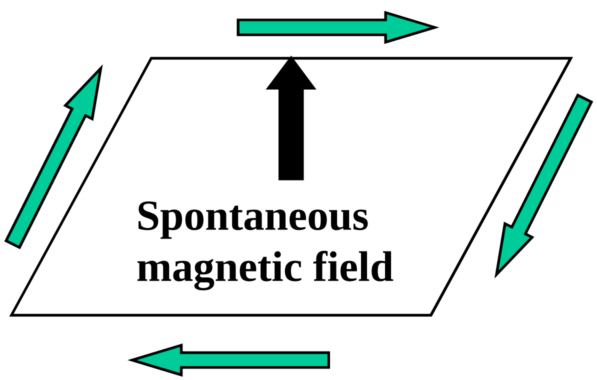
(6)Analogy to NCS superconductor

Topological analogy between chiral superconductor and QHS

Quantum Hall system



Chiral superconductor

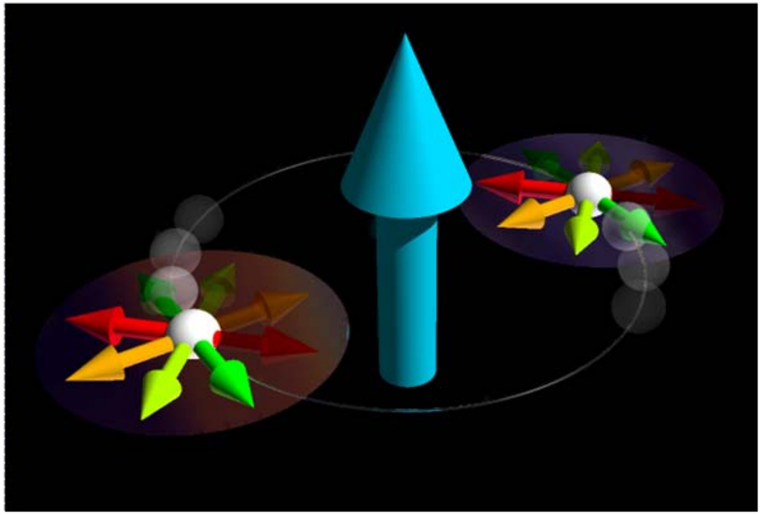


Spontaneous edge current

Analogy to Quantum Hall system (Goryo 1998, Furusaki 2001)

Chiral p-wave superconductors

Sr_2RuO_4 Maeno (1994)



Spin-triplet

Time-reversal symmetry broken

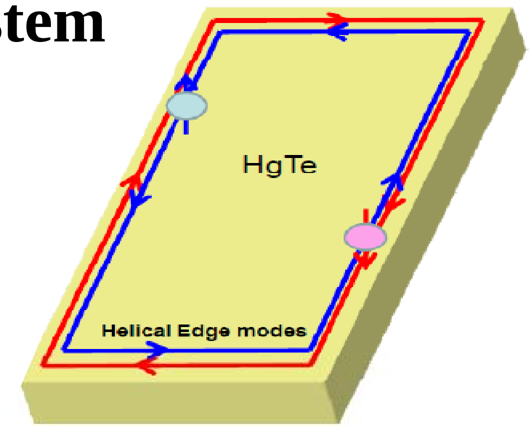
Edge state (Matsumoto Sigrist 1998)

Majorana fermion modes (Read Green 2000, Ivanov 2001)

Anomalous proximity effect (Tanaka, Golubov, Asano, 2007)

Superconducting system analogous to QSHS

Quantum spin Hall system

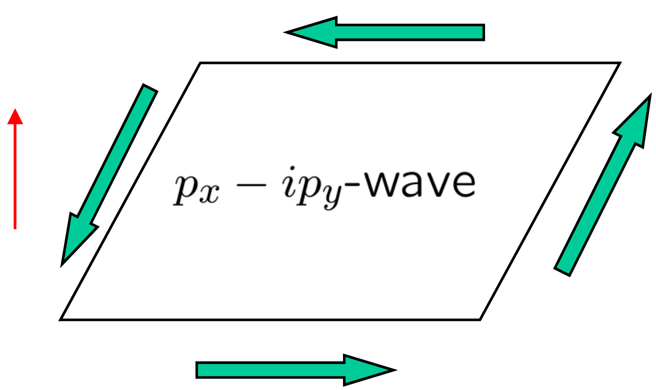


(Kane, Mele S.C. Zhang, Molenkamp, Murakami)

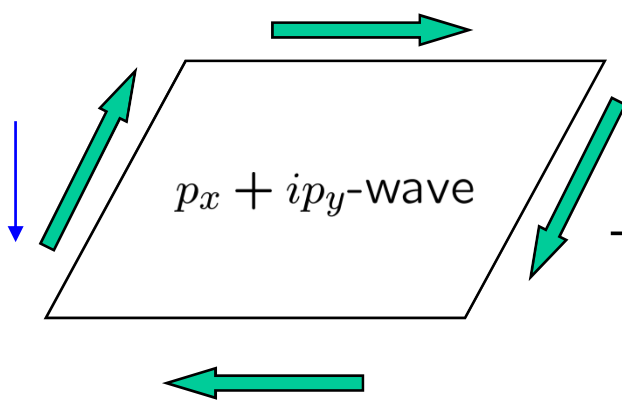
Charge current cancels; Only spin current flows at the edge

Helical superconductor **(Qi, S.C. Zhang, Sato, Fujimoto)**

for up-spin



for down-spin

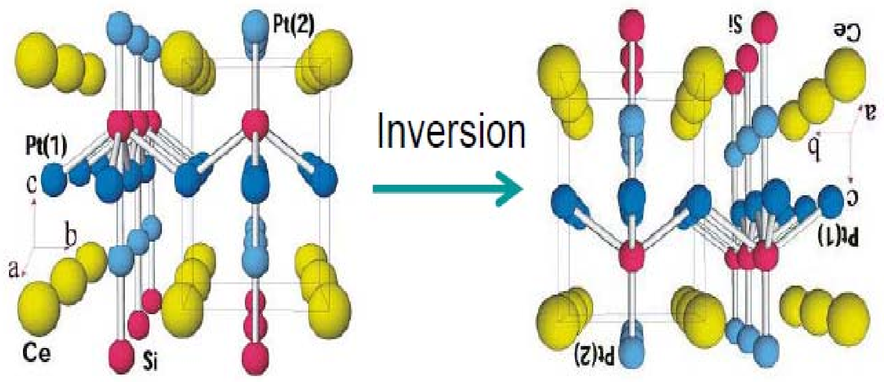


Thin film of Sr_2RuO_4

Tada,Fujimoto,Kawakami

Non-centrosymmetric superconductors

$CePt_3Si$, $CeRhSi_3$, $CeIrSi_3$, $Li_2Pd_xPt_{3-x}B$



Bauer PRL(2004)

Spin-orbit coupling can induce two copies of chiral p-wave state

$p_x \pm ip_y$-wave state (like surface of B-phase in ^{3}He)

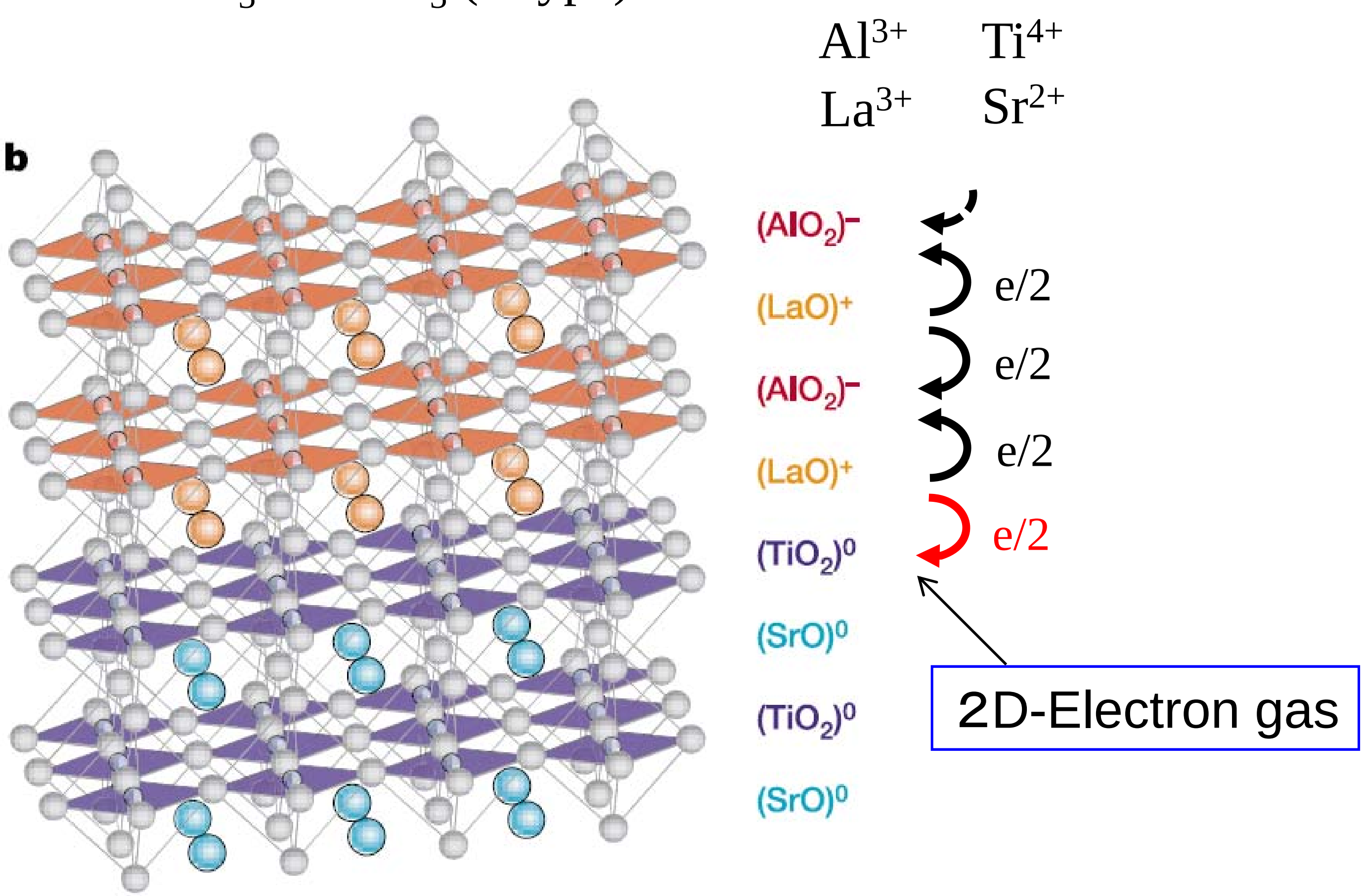
Mixture of spin-triplet p-wave and spin-singlet s-wave (Frigeri, Sigrist 2004)

Microscopic pairing mechanism (Yanase, Fujimoto, Yokoyama)

Interface superconductivity

Reyren Science (2007)

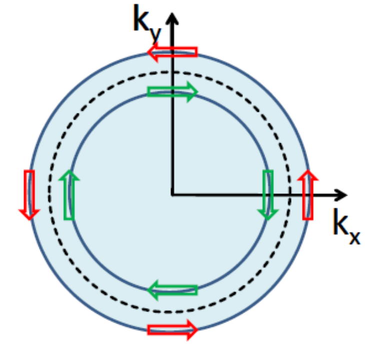
$SrTiO_3$/ $LaAlO_3$ (n-type)



Purpose of this work

- To solve Andreev bound state in 2D NCS superconductor.
- Spin current in N/NCS junctions
- Analogy to quantum spin Hall system

Hamiltonian of non-centrosymmetric (NCS) superconductor



Rashba spin-orbit coupling

$$\mathbf{V}(\mathbf{k}) = \lambda\left(k_y,\ -k_x, 0\right)$$

$$\check{H}_S = \begin{pmatrix} \hat{H}(\mathbf{k}) & \hat{\Delta}(\mathbf{k}) \\ -\hat{\Delta}^*(-\mathbf{k}) & -\hat{H}^*(-\mathbf{k}) \end{pmatrix}$$

$$\hat{H}(\boldsymbol{k}) = \xi_{\boldsymbol{k}} + \boldsymbol{V}(\boldsymbol{k}) \cdot \hat{\boldsymbol{\sigma}} \qquad \xi_{\boldsymbol{k}} = \hbar^2 \boldsymbol{k}^2/(2m) - \mu$$

$$\hat{\Delta}(\boldsymbol{k}) = [\boldsymbol{d}(\boldsymbol{k}) \cdot \hat{\boldsymbol{\sigma}}] i\hat{\sigma}_y + i\psi(\boldsymbol{k})\hat{\sigma}_y$$

$$\boldsymbol{d}(\boldsymbol{k}) = \Delta_p(\hat{\boldsymbol{x}}k_y - \hat{\boldsymbol{y}}k_x)/\mid \boldsymbol{k} \mid$$ **spin-triplet p-wave**

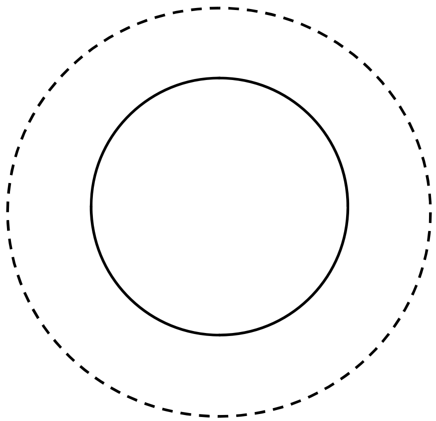
$$\Psi(\boldsymbol{k}) = \Delta_s$$ **spin-singlet s-wave**

In general, spin-triplet p-wave component and spin-singlet s-wave component can mix each other.

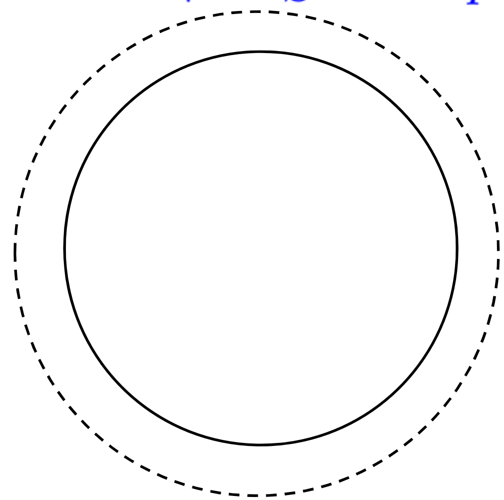
Fermi surface and energy gap

Energy gap

$\Delta_1 = \Delta_S + \Delta_p$



$\Delta_2 = |\,\Delta_S - \Delta_p\,|$



k_1 Fermi momentum

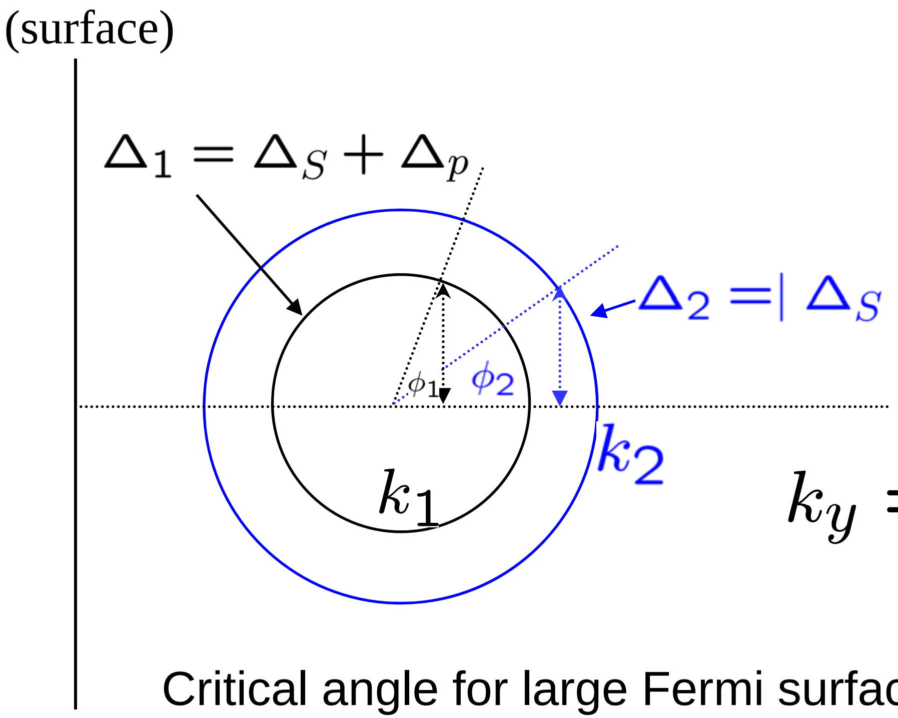
k_2 Fermi momentum

$$k_1 = -m\lambda/\hbar^2 + \sqrt{(m\lambda/\hbar^2)^2 + 2m\mu/\hbar^2}$$

$$k_2 = m\lambda/\hbar^2 + \sqrt{(m\lambda/\hbar^2)^2 + 2m\mu/\hbar^2}$$

Fermi surface splitting by Rashba interaction

Fermi surface and momentum conservation



$$k_y = k_1 \sin\phi_1 = k_2 \sin\phi_2$$

Critical angle for large Fermi surface $\phi_C = \sin^{-1}(k_1/k_2)$

For $|\phi_2| > \phi_C$, ϕ_1 can not become a real number

Condition of Andreev bound state

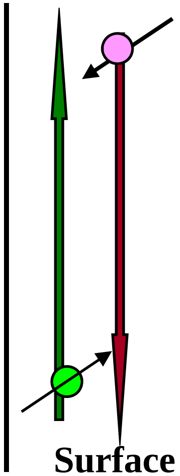
$$\Psi_S(x) = 0 \text{ at } x = 0$$

Andreev bound state (ABS)

ABS exists only for $\Delta_p > \Delta_s$

ABS locates at $E=0$ for $k_y=0$.

- The present ABS do not break the time reversal symmetry, since the edge current carried by each Kramers doublet flows in the opposite direction.
- They can be regarded as **helical edge modes.**



Low energy limit

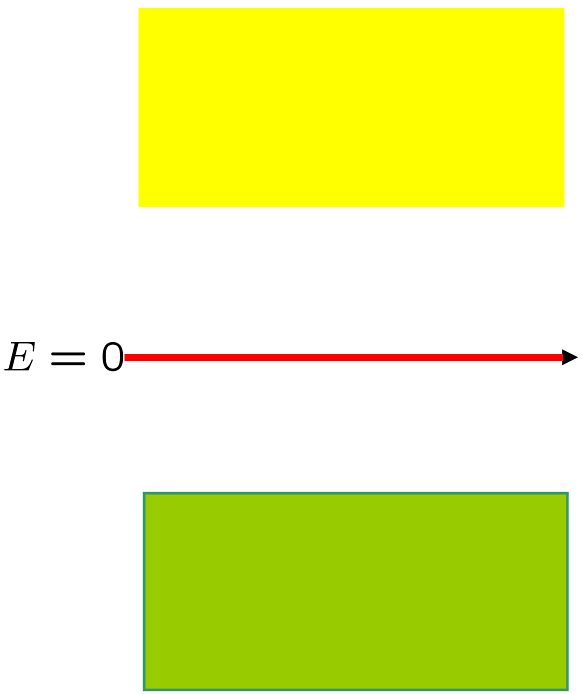
$$E = \pm \Delta_p \left(1 - \frac{\Delta_s^2}{\Delta_p^2}\right) \frac{k_1 + k_2}{k_1 k_2} k_y$$

$k_1(k_2)$ **small (large) Fermi momentum**

$\Delta_{p(s)}$ $p(s)$-wave pair potential

Feature of the Andreev bound states

d_{xy},p_x-wave



Hu(94)

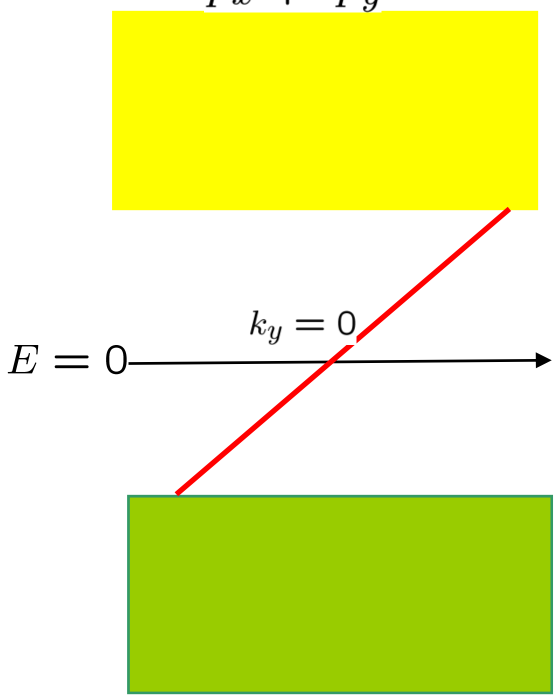
Tanaka Kashiwaya (95)

Buchholtz (81)

Hara Nagai (86)

Chiral p-wave

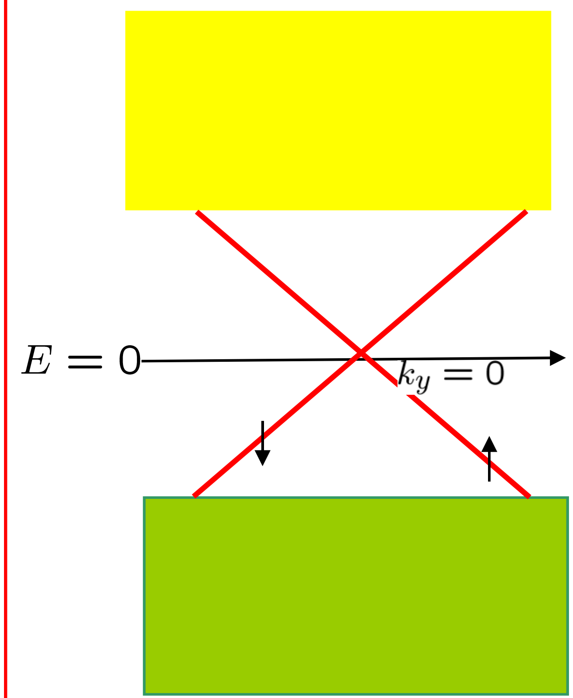
$p_x + ip_y$



Tanaka Kashiwaya (97)

Sigrist Honerkamp (98)

NCS (Helical)



Iniotakis (07)
Eschrig(08)

Non-centrosymmetric superconductor (NCS)

Topological properties of edge modes

$\Delta_p > \Delta_s$ **Presence of ABS as the Helical edge modes**

Topologically equivalent to pure p-wave case

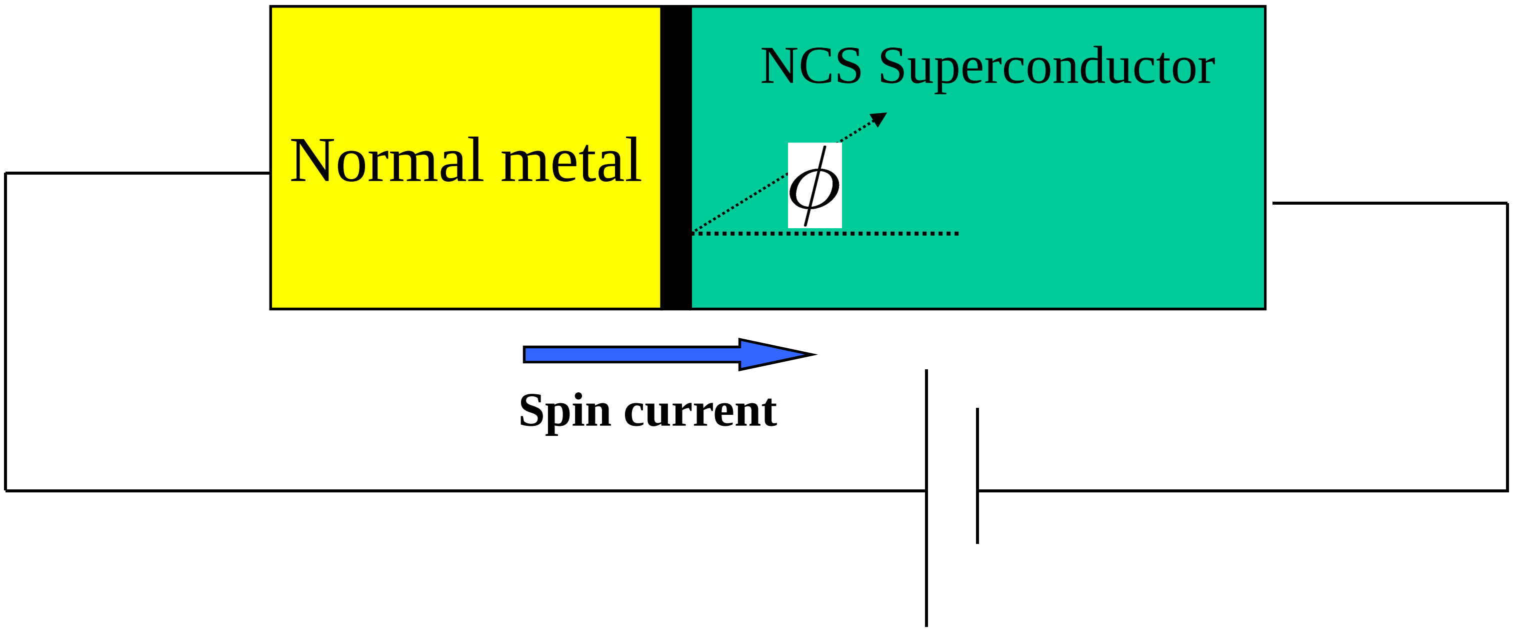
$\Delta_p = \Delta_s$ **Quantum phase transition where bulk gap closes**

$\Delta_s > \Delta_p$ **Absence of the Helical edge modes**

Topologically equivalent to pure s-wave case

Sato Fujimoto PRB(2009)

Spin current in Normal metal / NCS superconductor junctions

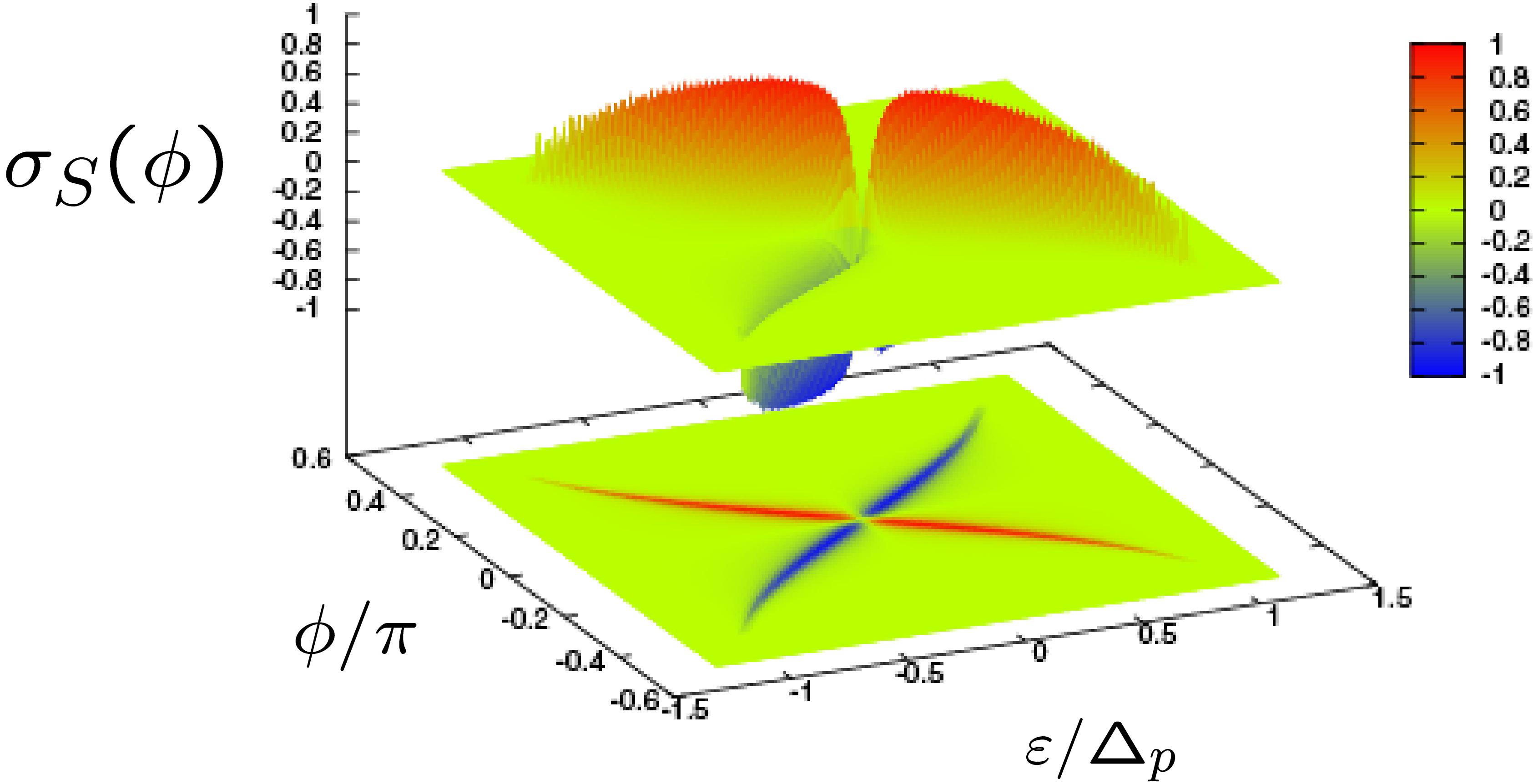


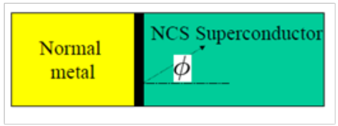
Spin current parallel to the surface

Vorontsov, Vekhter, Eschrig (2008)

Angle resolved spin conductance

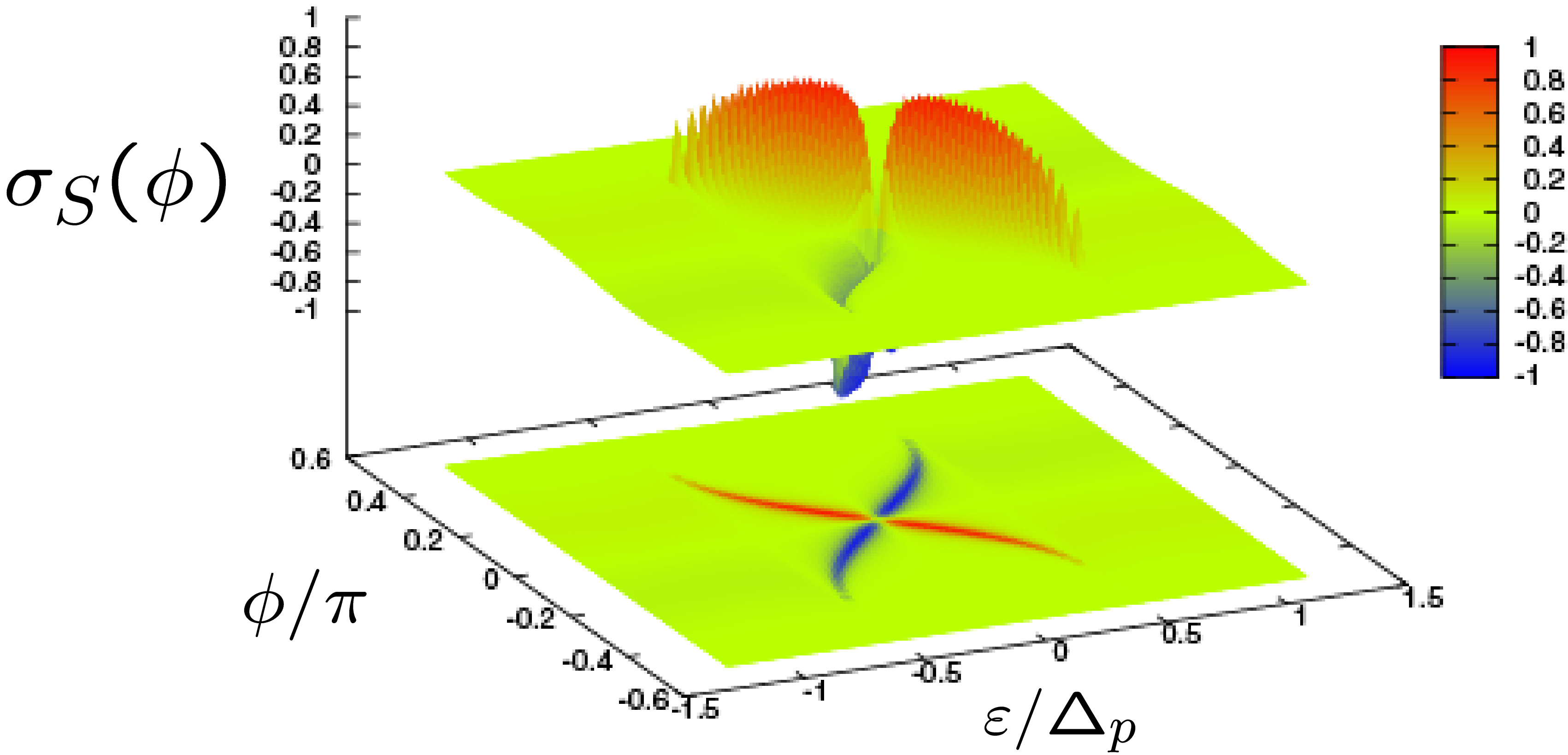
$$\lambda = 0.1E_F \quad \Delta_s = 0$$

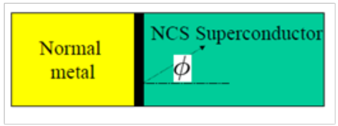




Angle resolved spin conductance

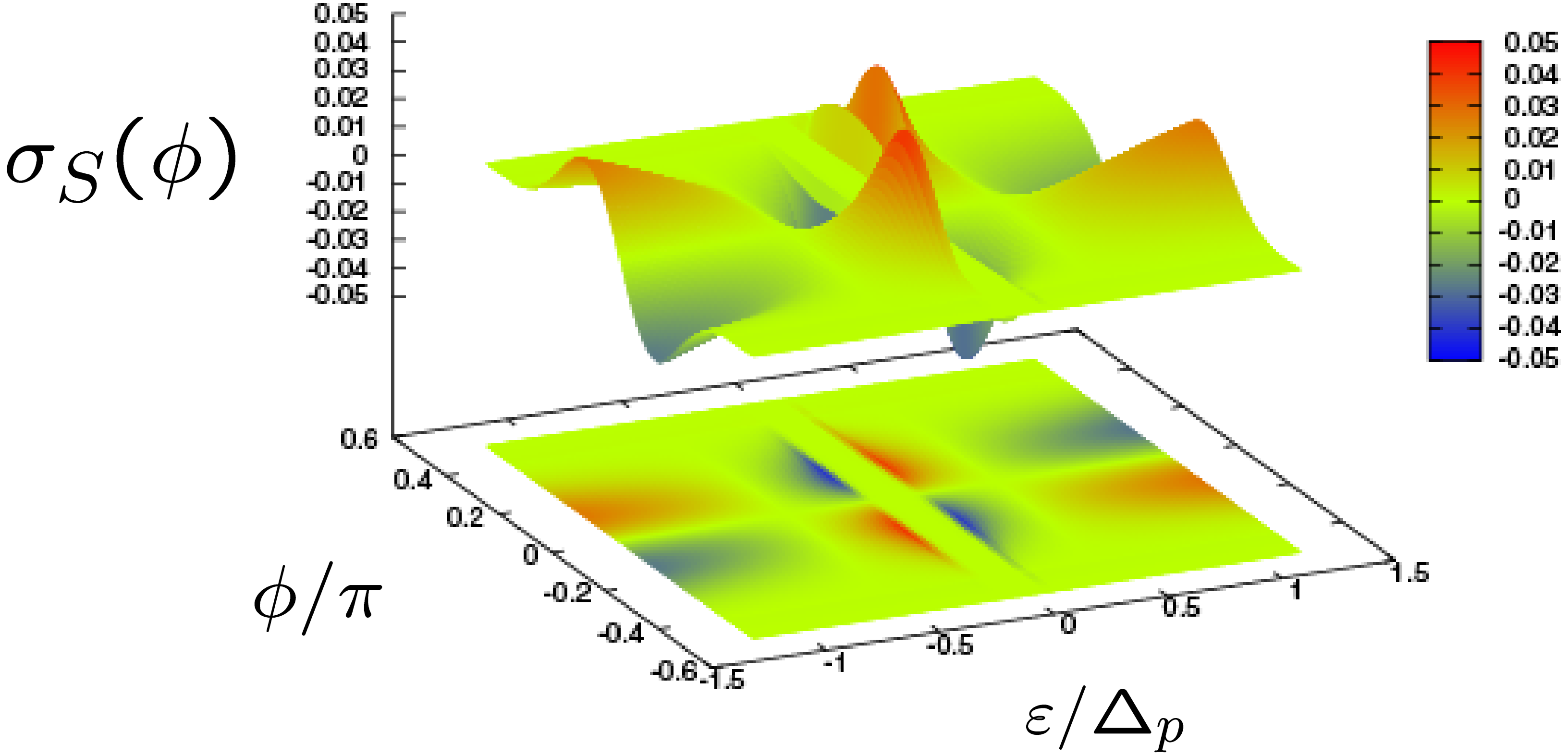
$$\lambda = 0.1 E_F \qquad \Delta_s = 0.5 \Delta_p$$

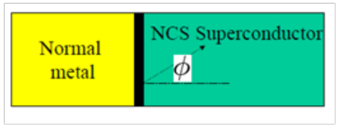




Angle resolved spin conductance

$$\lambda = 0.1 E_F \qquad \Delta_s = 1.1 \Delta_p$$





Features of angle resolved spin conductance

(1) Angle resolved spin conductance has a non zero value although the NCS superconductor does not break time reversal symmetry.

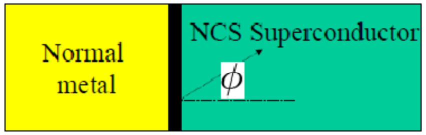
(2) Angle resolved spin conductance has a sharp peak for $\Delta_p > \Delta_s$ where Andreev bound state as helical edge mode exists.

Emergence of spin current

The presence of the helical edge modes in NCS superconductor is the origin of the large angle resolved spin current.

However, angular averaged spin current is absent due to the following relation.

$$\sigma_S(\phi) = -\sigma_S(-\phi)$$



Doppler effect

- Magnetic field which induces shielding current at the interface due to the Doppler shift offers an opportunity to observe the spin current in a much more accessible way.
- **Helical edge modes are influenced.**

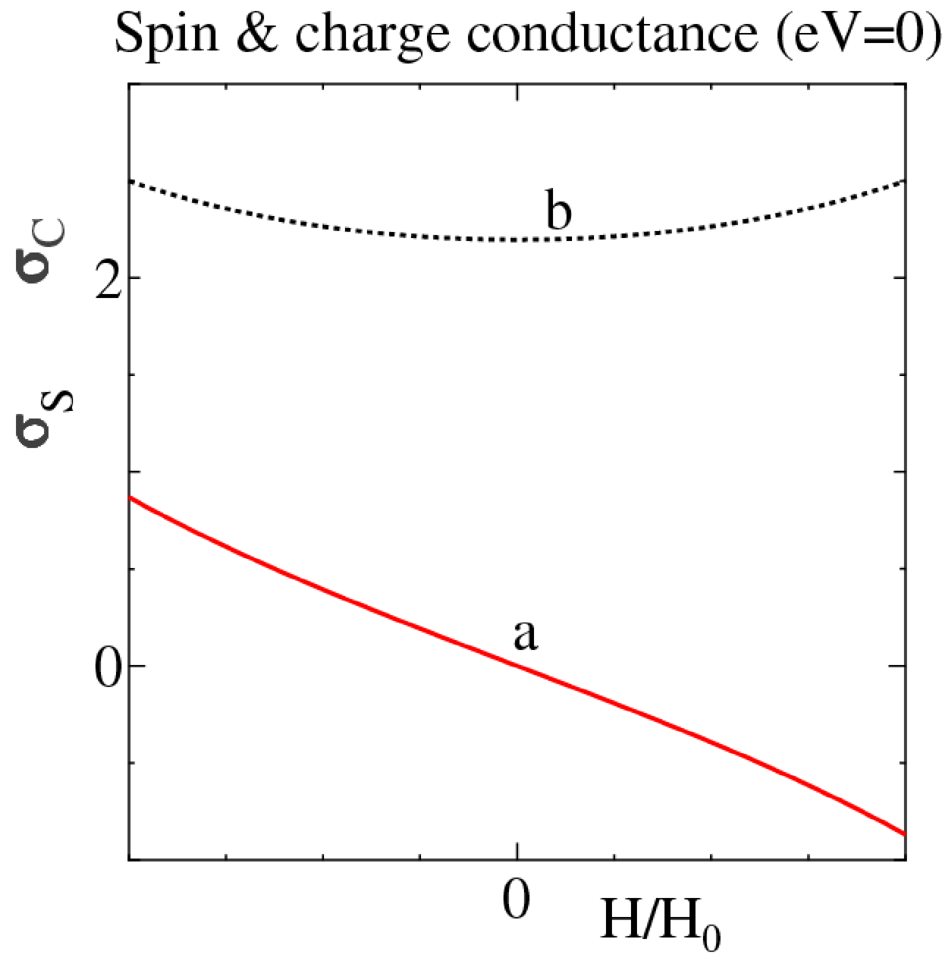
$$E = \Delta_p(1 + H/H_0)(k_y/k) \quad E = -\Delta_p(1 - H/H_0)(k_y/k)$$

➡ Angle averaged spin current remains.

Since the Zeeman energy is given by $\mu_B H$, the order of the energy of Doppler shift is $k_F\lambda_m$ times larger than that of Zeeman energy.

λ_m penetration depth

eV=0



Angle averaged spin conductance
σ_S

Angle averaged charge conductance
σ_C

$H_0 = h/(2e\pi^2\xi\lambda_m) \sim 0.2\text{Tesla}$

$$\sigma_S = \frac{\int_{-\pi/2}^{\pi/2} f_S(\phi)d\phi}{\int_{-\pi/2}^{\pi/2} f_{NC}(\phi)d\phi}$$

$$\sigma_C = \frac{\int_{-\pi/2}^{\pi/2} f_C(\phi)d\phi}{\int_{-\pi/2}^{\pi/2} f_{NC}(\phi)d\phi}$$

Summary (1)

(1)We have clarified that the **Andreev bound state** (ABS) in non-centrosymmetric (NCS) superconductors correspond to the helical edge modes in quantum spin Hall system.

(2)We have found the origin of large magnitude of the angle dependent spin polarized current in N/NCS superconductor junction is due to the helical edge modes.

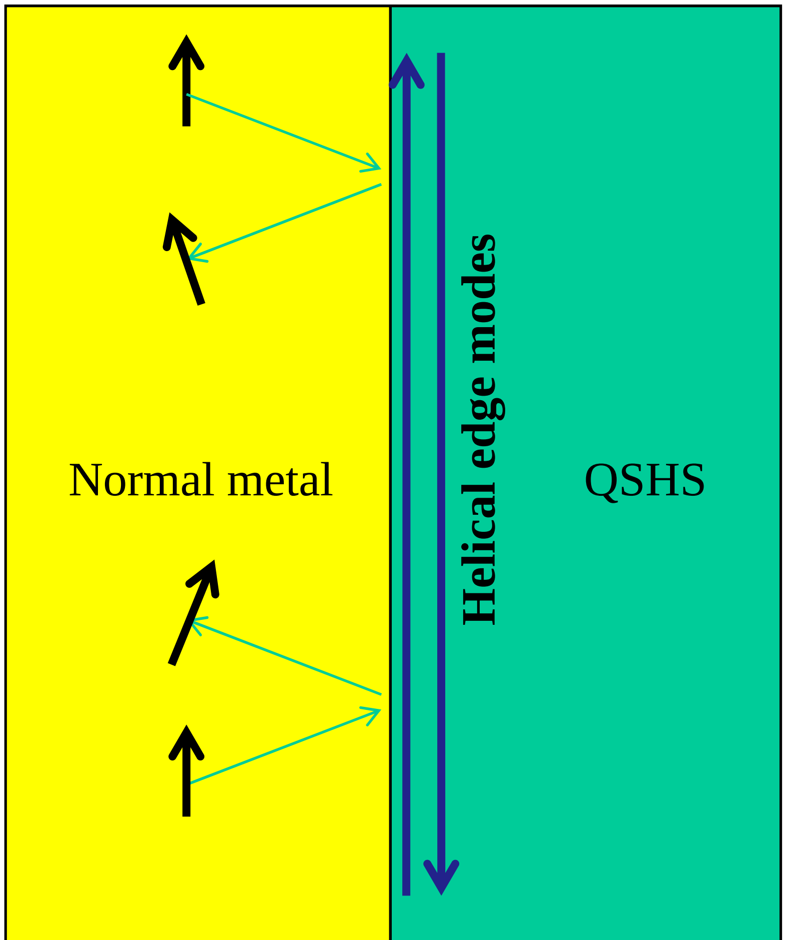
(3)When the weak magnetic field is applied, even the angle-integrated current is spin polarized.

Giant spin rotation in the normal metal/ quantum spin Hall junction

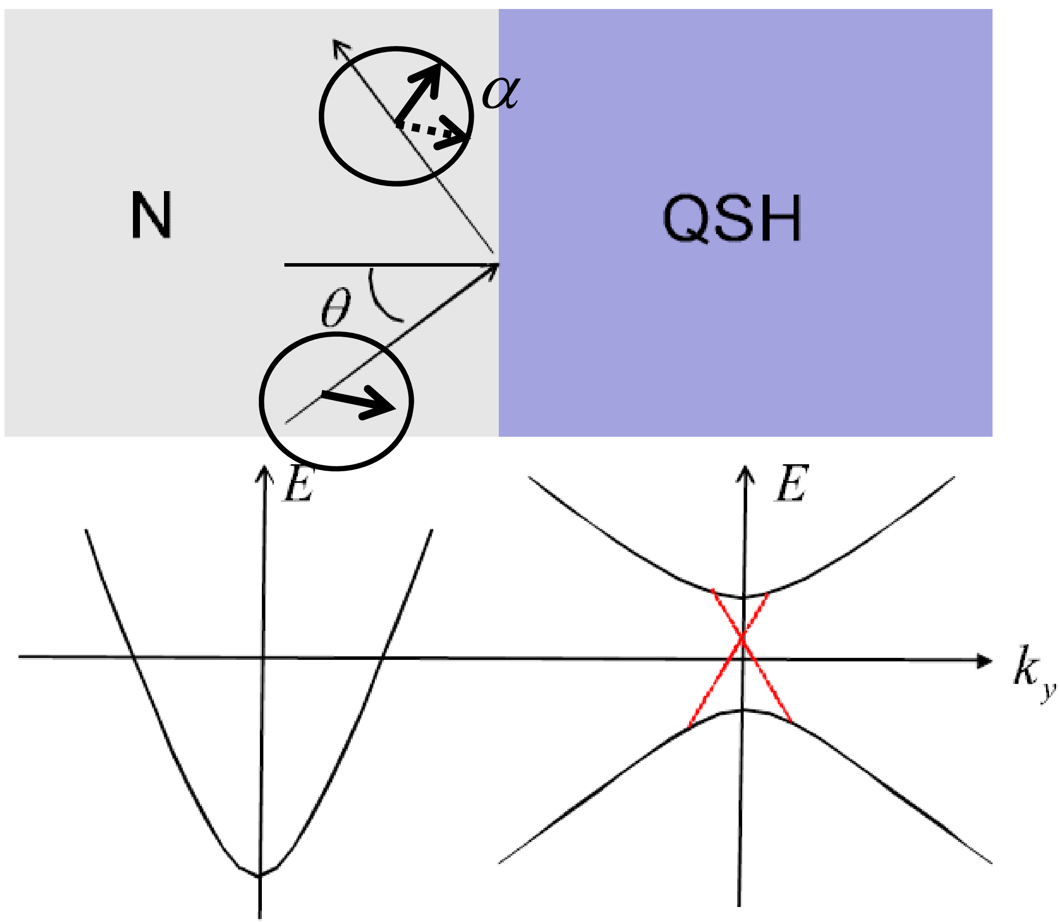
Phys. Rev. Lett. Vol. 102, 2009 (arXiv:0901.0438)

Takehito Yokoyama, Yukio Tanaka, Naoto Nagaosa

Spin transport properties at the junction with QSHS



Reflection at the N/QSH boundary



$$\mathcal{H} = \begin{pmatrix} h(k) & 0 \\ 0 & h^*(-k) \end{pmatrix},$$
$$h(k) = \epsilon(k)\mathrm{I}_{2\times 2} + d_a(k)\sigma^a,$$
$$\epsilon(k) = C - D(k_x^2 + k_y^2),$$
$$d_a(k) = (Ak_x, -Ak_y, M(k)),$$
$$M(k) = M - B(k_x^2 + k_y^2)$$

$M > 0$ Usua l insulator

$M < 0$ QSH

M. Koenig et al.

$$Z = U/(Dk_F)$$

α : Spin rotation angle within xy-plane $\alpha(\theta) = -\alpha(-\theta)$

Spin rotation angle

$(a)\quad C = -0.1eV$

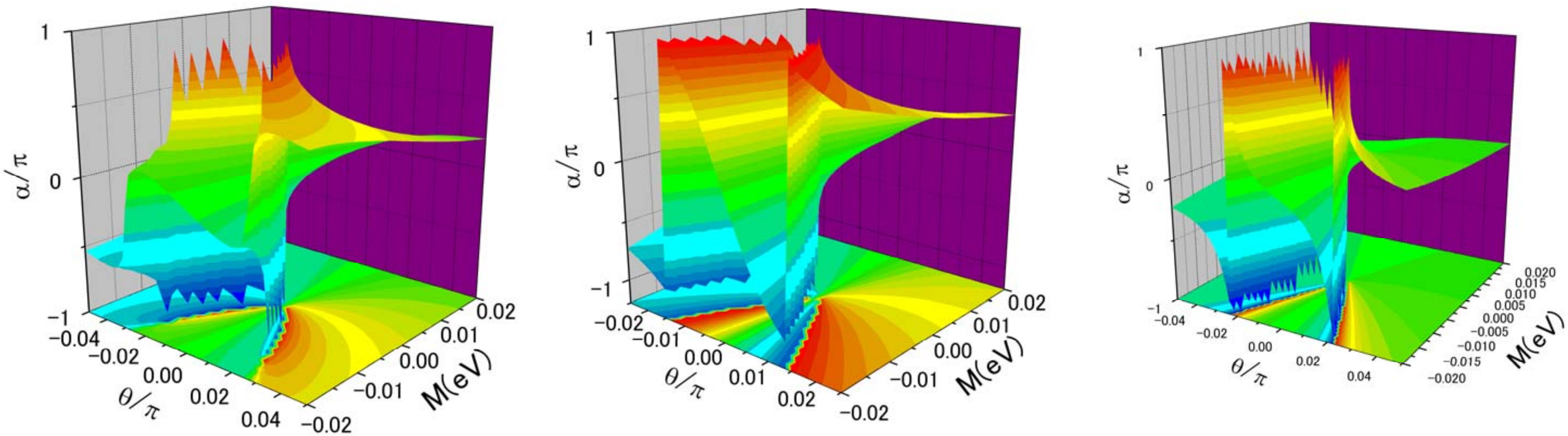
Z=0 (No barrier)

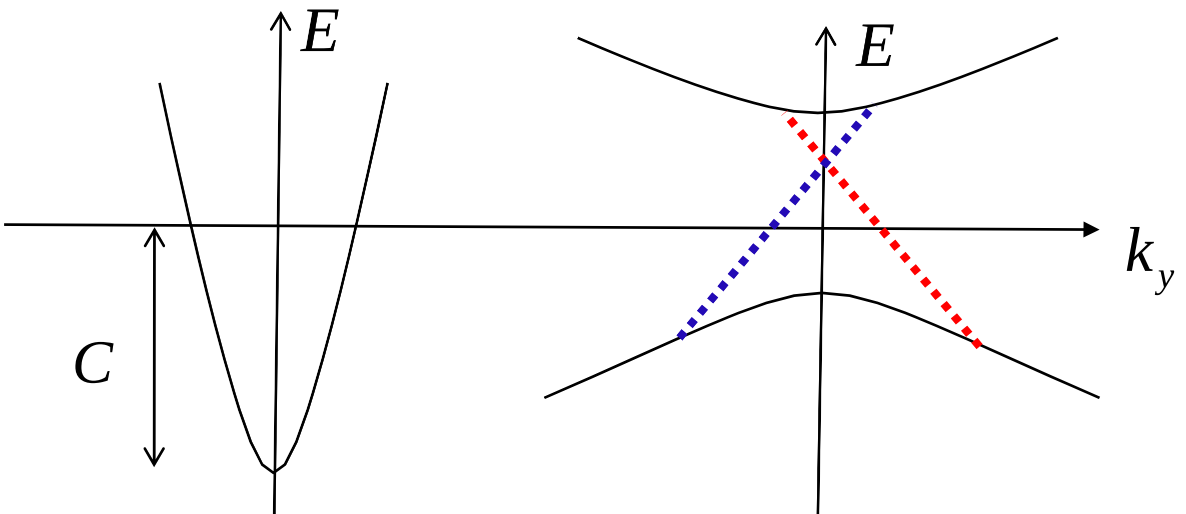
$(b)\quad C = -1eV$

Z=0 (No barrier)

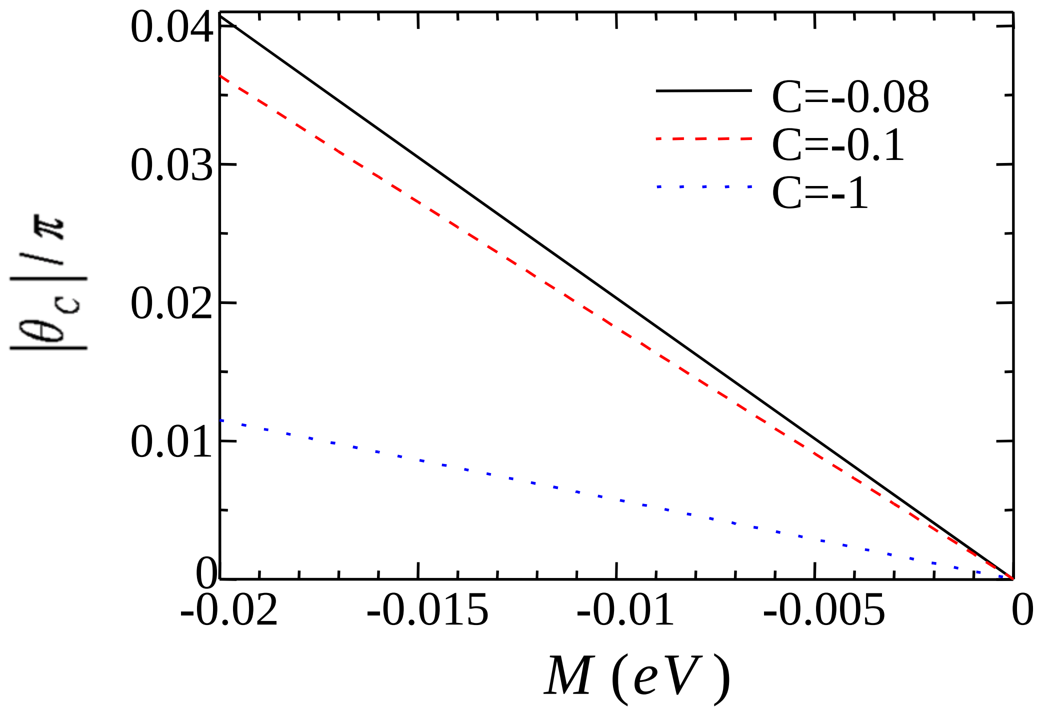
$(c)\quad C = -1eV$

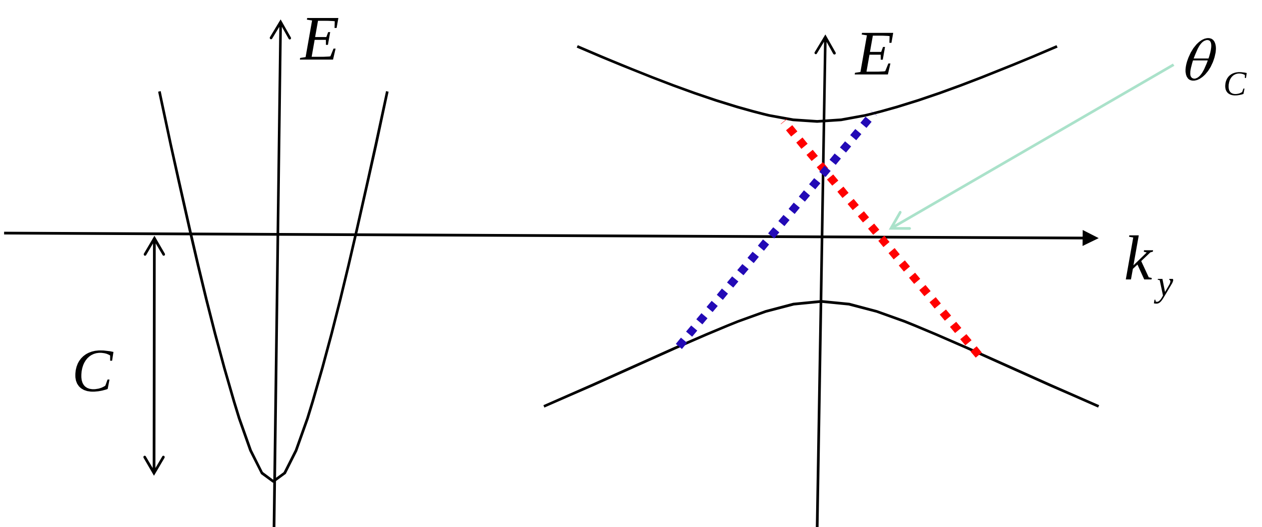
Z=3 (with barrier)





Relevance to the helical edge modes





Summary（2）

- Topological spin current induces giant spin rotational angle both in quantum spin Hall insulator.