Spin torque and Magnetic order induced by supercurrent

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in collaboration with
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Background: Superconducting Spintronics

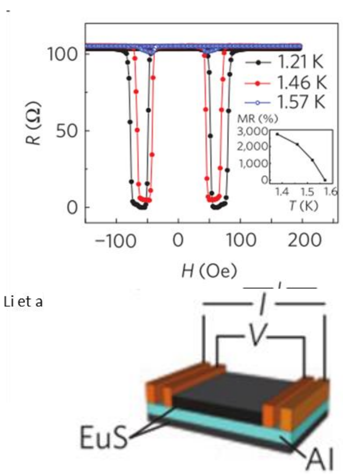
Superconducting correlation

- transport
- response to field

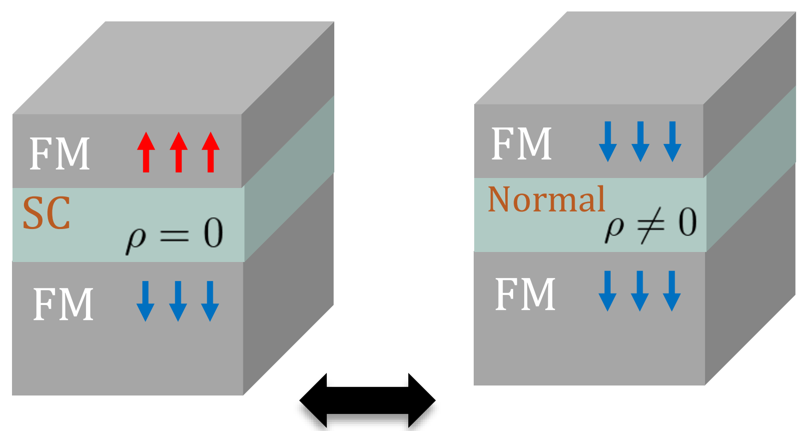
➡ **new spintronics devices?**

recent review) Linder&Robinson, Nat. Phys. (2015), Eschrig, Rep. Prog. Phys.(2015)

e.g.) **Spin valve** with Superconductivtiy (⇒ "Infinite" magnetoresistance)



Li *et al*. PRL (2013)



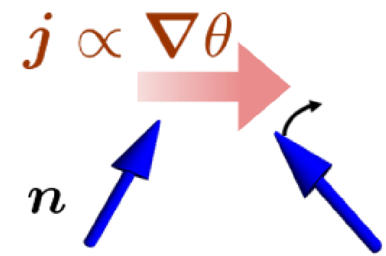
small magnetic field (~ 50 Oe)

e.g.) Spin hall effect of quasi-particle (Wakamura *et al*, Nat. mat (2015))

Spin injection in SC (H, Yang, et al, Nat. mat (2010))

Outline of this talk

1st part



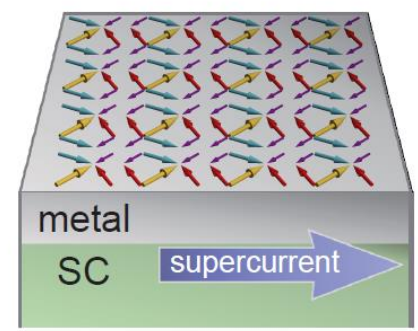
Spin-torque induced by spin-triplet supercurrent

R. Takashima, S. Fujimoto, T. Yokoyama, Phys. Rev. B **96**, 121203 (R) (2017)

2nd part

Noncollinear magnetic order

induced by supercurrent

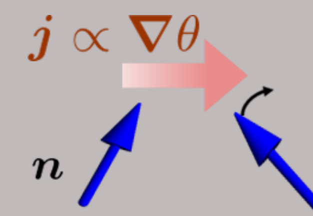


R. Takashima, Y. Kato, Y. Yanase, Y. Motome arXiv: 1710.11349

Outline

1st part

Spin-torque induced by spin-triplet supercurrent



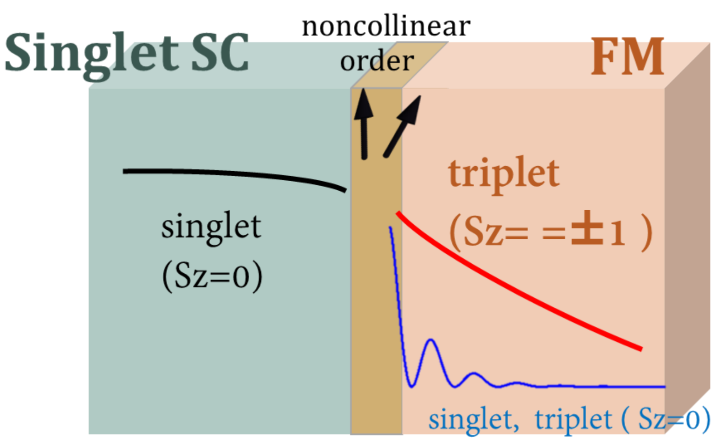
R. Takashima, S. Fujimoto, T. Yokoyama, Phys.Rev. B **96**, 121203 (R) (2017)

1. Motivation
2. Result : general form of spin torque
3. Application: Domain wall dynamics

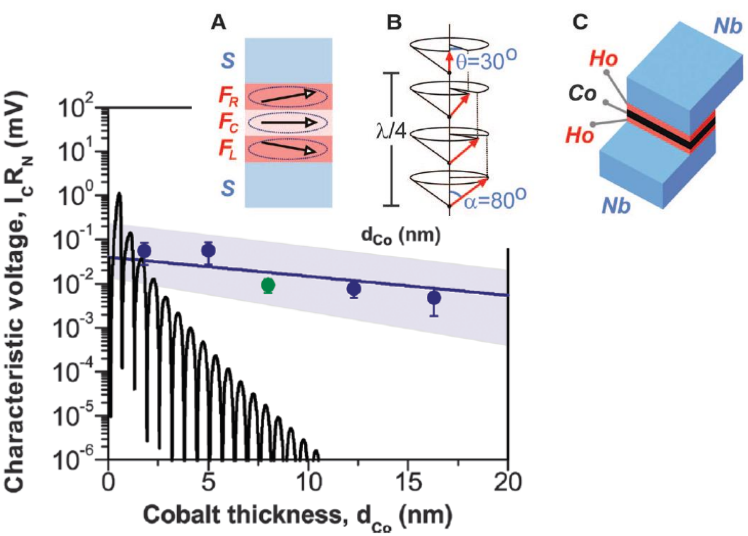
Triplet Cooper pairs

- **Spin-triplet** proximity effect inside ferromagnet(FM)

  - **triplet SC | FM** with Sr_2RuO_4 Anwar *et al.* Nat. commun. (2016)
  - **singlet SC | noncollinear magnet | FM** Robinson *et al*, Science (2010) Khaire et al, PRL (2010)



Singlet-Triplet Conversion



Robinson *et al*, Science (2010)

Interplay of **spin-triplet pairing** and **magnetic moment** ?

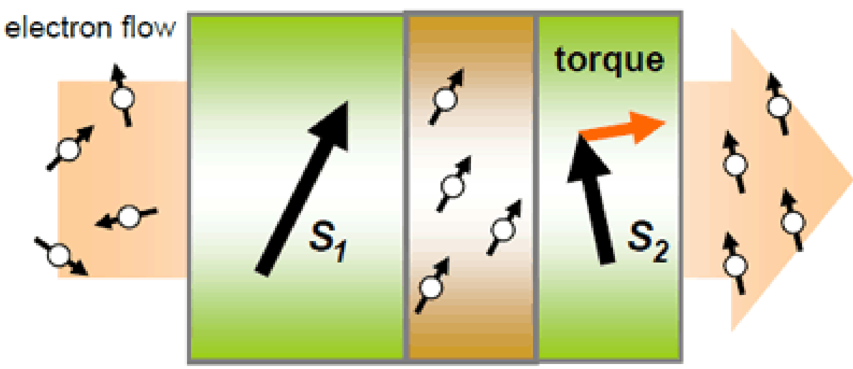
Current-induced torque in normal magnet

- Electric current in magnet exerts **spin-torque** on localized moment

(spin-transfer torque)

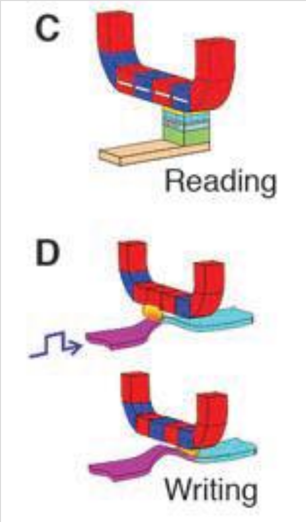
- **Manipulation of spin** $\Rightarrow$ Application in magnetic devices

Spin angular momentum is transferred

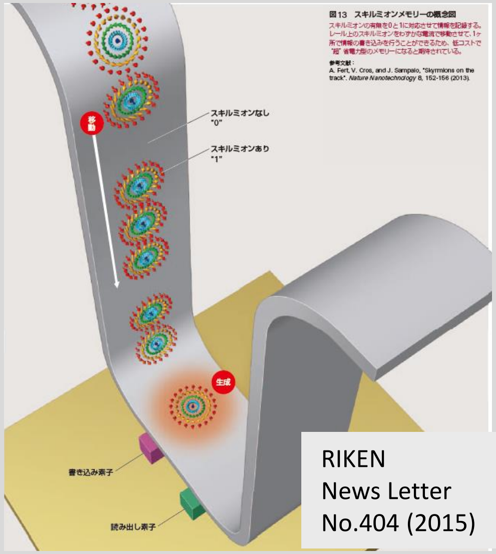


https://docs.quantumwise.com/

Racetrack memory using ***domain wall / Skyrmions***



Parkin et al Science (2008)

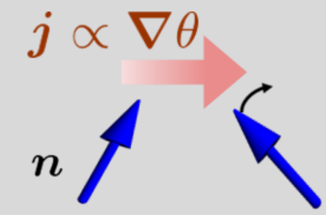


RIKEN
News Letter
No.404 (2015)

Motivation of our work

Question: How **triplet-correlation** changes **spin transfer torque?**

We study
spin-transfer torque induced by **triplet supercurrent**



c.f.) early works for spin-torque in magnetic Josephson junction:
Waintal& Brouwer PRB(2002), Y. Tserkovnyak &A. Brataas PRB (2002), etc

keypoint **:**

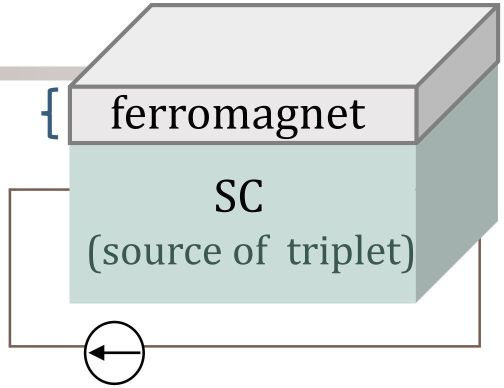
- Triplet order parameter (=***d*** vector) might give **new type of torque** ?

$$\chi_{\mu\nu} = \chi_1 \delta_{\mu\nu} - \chi_2 \langle \hat{d}_\mu(\boldsymbol{k}) \hat{d}_\nu(\boldsymbol{k}) \rangle_{FS}$$

(spin susceptibility characterizes spin-transfer process)

Model

model {



metallic magnet (**s-d model**)
with proximity induced **triplet pairing**

$$H = -t\sum_{\langle i,j\rangle} c^\dagger_{i\alpha}c_{j\alpha} - \mu\sum_i c^\dagger_{i\alpha}c_{i\alpha} - J_{\rm sd}S\sum_i \boldsymbol{n}(\boldsymbol{r}_i)\cdot\boldsymbol{\sigma}_{\alpha\beta}c^\dagger_{i\alpha}c_{i\beta}$$

$$+\frac{\Delta_0}{2}\sum_{\langle i,j\rangle} e^{i\boldsymbol{\kappa}\cdot(\boldsymbol{r}_i+\boldsymbol{r}_j)}c^\dagger_{i\alpha}\left[(\boldsymbol{d}_{ij}\cdot\boldsymbol{\sigma})i\sigma_y\right]c^\dagger_{j\beta} + H.c,$$

(square lattice)

$c_{i\alpha}$: conduction electron (site i, spin α)

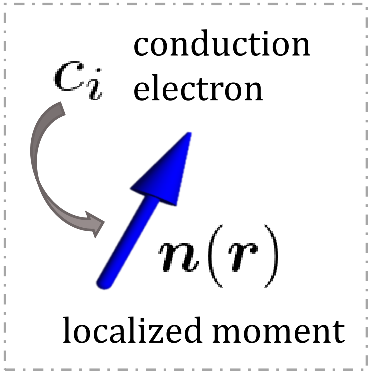
$\boldsymbol{n}_i$: localized moment (site i)

$\boldsymbol{d}_{ij}$: triplet order parameter (site i, j)

supercurrent flow is given by the spatial gradient of SC phase $e^{i\boldsymbol{\kappa}\cdot(\boldsymbol{r}_i+\boldsymbol{r}_j)}$

$$\boldsymbol{j} = -2ten_{\rm s}a^2\boldsymbol{\kappa} \quad (\kappa a \ll 1)$$

Calculation of spin torque



- local spin torque : $\tau_{\mathrm{STT}} = 2J_{\mathrm{sd}}\boldsymbol{n} \times \delta\boldsymbol{s}_i$

$\delta\boldsymbol{s}_i$ = local spin density of electrons under **supercurrent**

➡ we calculate **spin density** within **linear response**

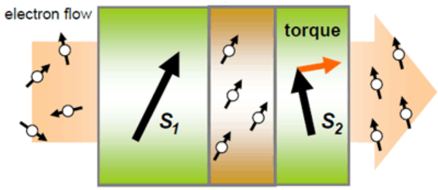
- We assume
  - Localized moment varies smoothly
  - Exchange splitting is large $J_{\mathrm{sd}}S \gg \Delta_0$

    ➡ we only take equal spin pairing ((anti)parallel to ***n***)

Result: supercurrent-induced torque

- Obtained torque $$\boldsymbol{\tau}_{\mathrm{STT}} = \sum_{\nu=x,y} \frac{-\tilde{P}_\nu a^3}{2eS} j_\nu \left(-\partial_\nu \boldsymbol{n} + \tilde{\beta}_\nu \boldsymbol{n} \times \partial_\nu \boldsymbol{n} \right).$$

j_ν : supercurrent density



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$$\frac{\partial \boldsymbol{n}}{\partial t} \sim \boldsymbol{\tau}_{\mathrm{STT}}$$

$\boldsymbol{\tau}_{\mathrm{STT}} \propto -\partial_\nu \boldsymbol{n}$: direct transfer of spin from neighboring sites (~"adiabatic torque")

$\boldsymbol{\tau}_{\mathrm{STT}} \propto \boldsymbol{n} \times \partial_\nu \boldsymbol{n}$: **deviation** from direct transfer (~"β term")

$\tilde{P}_\nu$ ~ spin polarization of electrons

$\tilde{\beta}_\nu$ -originate in **order parameter .** $\tilde{\beta}_\nu \propto |\Delta_0|^2$

- depend on the direction of ***n*** ***(spatial dependence)***

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explicit form:

$$\tilde{P}_\nu = \frac{J_{\mathrm{sd}} S}{n_e a^3} \left[\frac{1}{2} (\pi_\nu^{xx} + \pi_\nu^{yy}) + \frac{1}{|\partial_\nu \boldsymbol{n}|^2} \left(-\pi_\nu^{(1)} \left((\partial_\nu \theta)^2 - \sin^2\theta (\partial_\nu \phi)^2 \right) + 2\pi_\nu^{(2)} \sin\theta \partial_\nu \theta \partial_\nu \phi \right) \right],$$

$$\tilde{\beta}_\nu = -\frac{J_{\mathrm{sd}} S}{n_e a^3} \frac{1}{\tilde{P}_\nu} \frac{1}{|\partial_\nu \boldsymbol{n}|^2} \left(\pi_\nu^{(2)} \left((\partial_\nu \theta)^2 + \sin^2\theta (\partial_\nu \phi)^2 \right) + 2\pi_\nu^{(1)} \sin\theta \partial_\nu \theta \partial_\nu \phi \right),$$

$\pi_\nu^{xx}, \pi_\nu^{yy}, \pi_\nu^{(i)}$: spin-spin correlation

What causes β term?

c.f.) **Normal system**

Zhang& Li (2004) , Tatara et al. (2008), Tserkovnyak et al(2008)

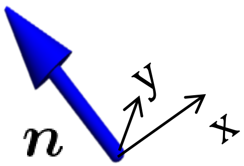
$$\boldsymbol{\tau}_{\rm nor} = \sum_{\nu=x,y} \frac{-Pa^3}{2eS} j_\nu^{\rm nor} \left(-\partial_\nu \boldsymbol{n} + \beta \boldsymbol{n} \times \partial_\nu \boldsymbol{n} \right).$$

- magnetic impurity scattering / mistracking $\rightarrow$ ***β* term**
- β is qualitatively important

With **triplet-SC correlation**

anisotropy in **spin susceptibility** → deviation from direct transfer

$$\tilde{\beta}_\mu \neq 0 \quad \Rightarrow \quad \begin{aligned} \pi^{xx} - \pi^{yy} &\neq 0 \\ \pi^{xy} &\neq 0 \end{aligned}$$

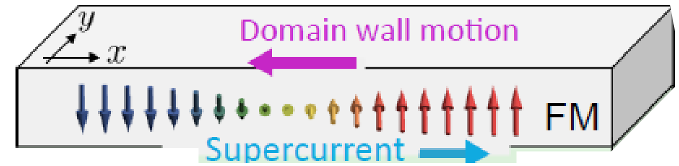


π^{ab}: spin-spin correlation

***β* term** can be controlled by **triplet order parameters (d-vector)**.

(⇔in normal metals, it depends on **extrinsic scattering**)

Domain wall dynamics



- Domain wall texture in ferromagnetic metal
- Assume the ***d***-vector

$$\boldsymbol{d}(\boldsymbol{k}) = (-\sin k_y, \sin k_x, \delta \sin k_x)$$

Possible origin:

spin-orbit coupling due to **structure inversion asymmetry** $\boldsymbol{g}_{\mathrm{so}}(\boldsymbol{k}) \cdot \boldsymbol{\sigma}$

➡ $\boldsymbol{d}(\boldsymbol{k}) \parallel \boldsymbol{g}_{so}(\boldsymbol{k})$ is favored

- Apply a current ➡ Domain wall moves

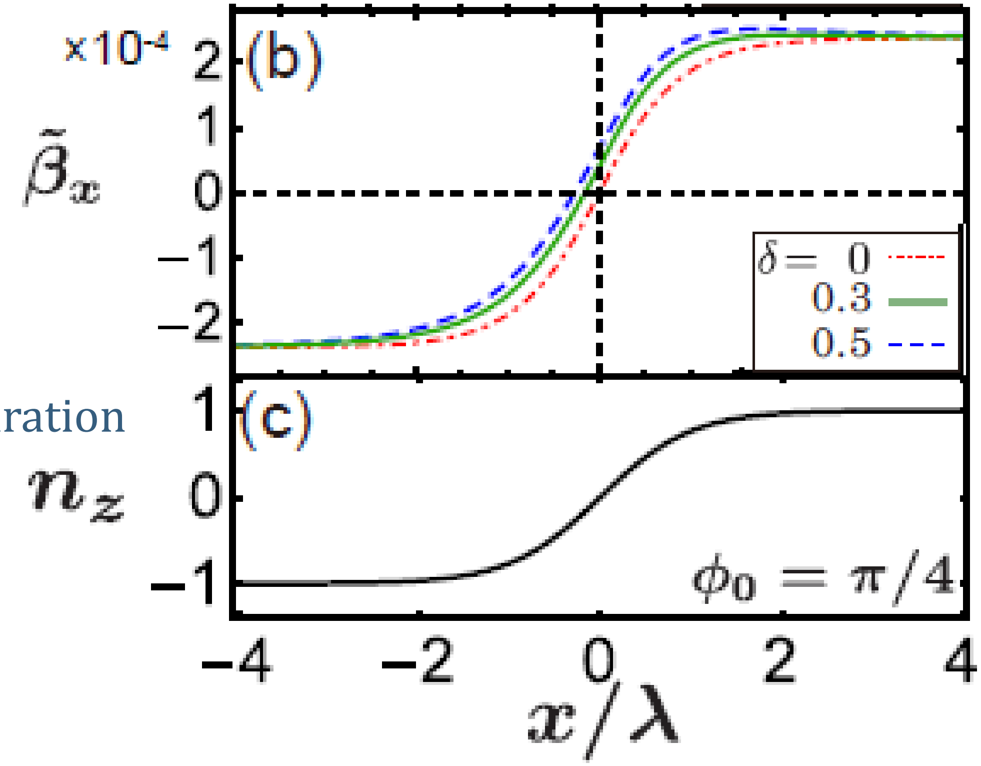
- EOM of collective coordinates (X: domain wall center)

$$\partial_t X = \frac{v_c}{(1+\alpha^2)} \left(\tau(\phi_0) j_x + \alpha F(\phi_0) j_x + \sin 2\phi_0 \right),$$

$$\partial_t \phi_0 = \frac{-1}{(1+\alpha^2) t_0} \left(\alpha \tau(\phi_0) j_x - F(\phi_0) j_x + \alpha \sin 2\phi_0 \right),$$

(detail) Spatial dependence of β

domain wall configuration

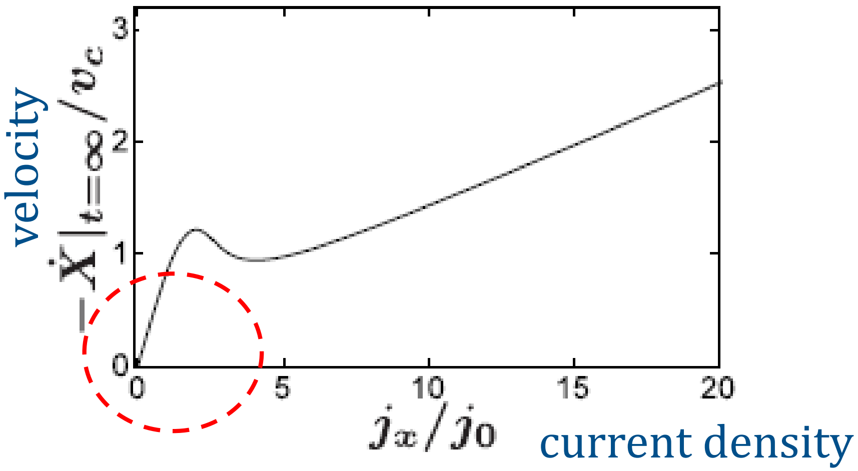


$\tilde{\beta}_\nu$ **has strong spatial dependence**

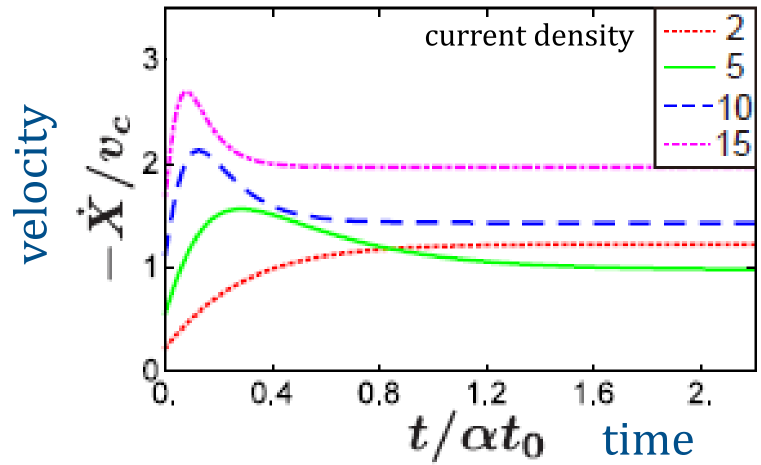
Domain wall dynamics

Under a constant supercurrent ,

Current dependence of domain wall velocity at t =∞



Time dependence of domain wall velocity



✓No threshold current density

*without extrinsic pinning

✓No oscillatory motion

⇔Normal metal, oscillation occurs

＊ This is due to β terms that arises from d-vector $\tilde{\beta}_\nu \propto |\Delta_0|^2$

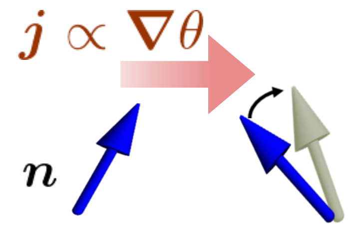
⇔ w/o β terms, threshold current exists

＊ β depends on ***n*** (space)

Summary of 1^{st} part

RT, Fujimoto, Yokoyama, PRB **96**, 121203 (R)

Spin-transfer torque by triplet supercurrent



✓ We obtain the spin-torque given by

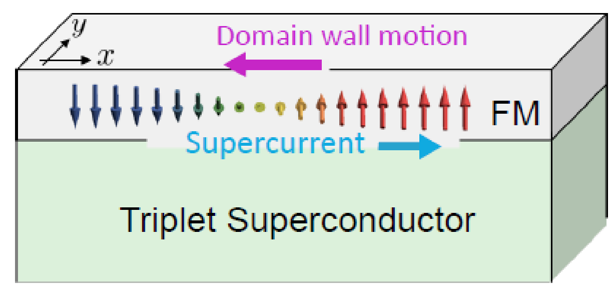
$$\tau_{\mathrm{STT}} = \sum_{\nu=x,y} \frac{-\tilde{P}_\nu a^3}{2eS} j_\nu \left(-\partial_\nu \boldsymbol{n} + \tilde{\beta}_\nu \boldsymbol{n} \times \partial_\nu \boldsymbol{n}\right).$$

✓ a new type of $\tilde{\beta}$ term : **Interplay** of ***d***-vector and magnetic moment ***n***

triplet correlation changes spin susceptibility of electrons (~spin transfer process)

✓domain wall dynamics

- threshold current density is lowered
- No oscillatory motion



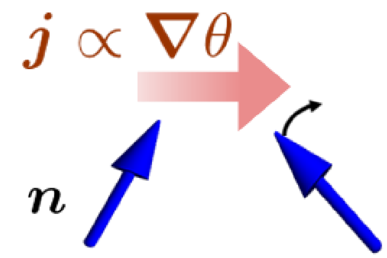
∗ Our calculation is limited to the linear response

→some relaxation might occur after a long time

Outline of this talk

1^{st} part

Spin-torque induced by spin-triplet supercurrent



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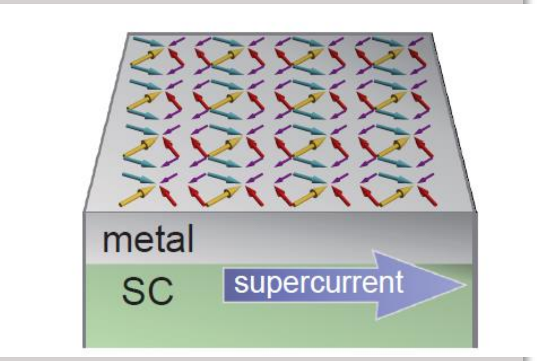
2^{nd} part

Noncollinear magnetic order

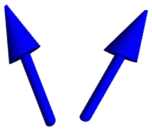
induced by supercurrent



R. Takashima, Y. Kato, Y. Yanase, Y. Motome arXiv: 1710.11349

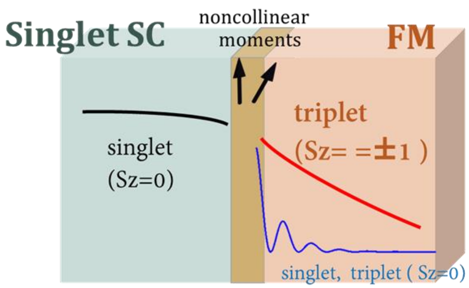
Noncollinear magnetism and SC proximity effect

Noncollinear magnetic order : Spins are not in parallel/antiparallel

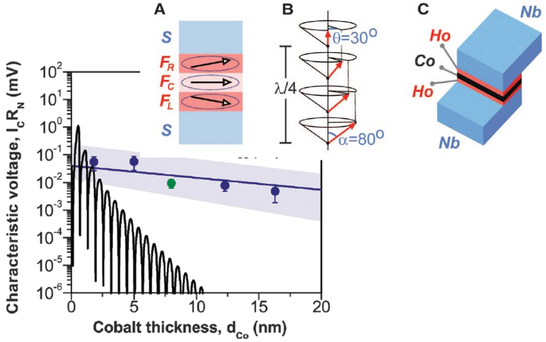


Noncollinear magnetic order is important in physics of **SC proximity effects**

- Singlet-triplet pairing conversion — Keizer et al, Nat. Lett. (2006); Robinson *et al*, Science (2010)
- Topological superconductor **w/o spin-orbit coupling** — Klinovaja et al. (2013)

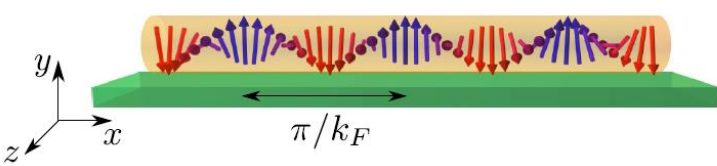


Singlet-Triplet Conversion



Robinson *et al*, Science (2010)

helical order+ s-wave pair
→1d p-wave topo. SC



Klinovaja et al. (2013)

Motivation of our work

Question: Can we **switch/control** noncollinear magnetic order in the presence of SC proximity effect?

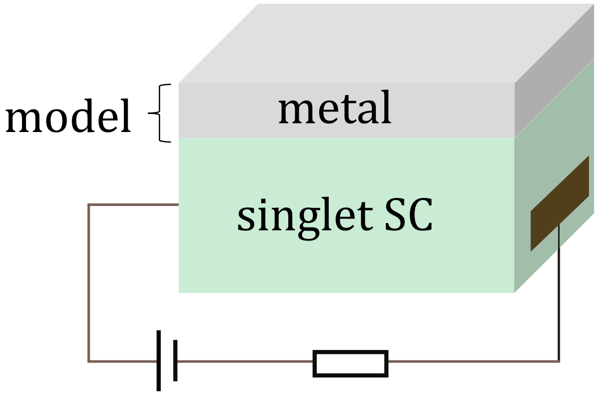
➡ can be used

- to switch /optimize **the singlet-triplet conversion**
- to externally **control topological SC** and Majorana zero modes etc

In our work:

We propose a new way to induce **noncollinear magnetic order** by a **supercurrent**

Model



2d Correlated metal

attached to **s-wave SC** with a supercurrent

repulsive Hubbard interaction

$$H = \sum_{\boldsymbol{k}\sigma} \xi_{\boldsymbol{k}} c^\dagger_{\boldsymbol{k}\sigma} c_{\boldsymbol{k}\sigma} - \frac{2U}{3} \sum_i \boldsymbol{m}_i \cdot (c^\dagger_{i\sigma} \boldsymbol{\sigma}_{\sigma\sigma'} c_{i\sigma'}) + \sum_i (\Delta e^{2i\boldsymbol{\kappa}\cdot\boldsymbol{r}_i} c^\dagger_{i\uparrow} c^\dagger_{i\downarrow} + \mathrm{h.c.}) + \frac{2U}{3} \sum_i |\boldsymbol{m}_i|^2$$

- mean field of spin density

$$\boldsymbol{m}_i = \frac{1}{2} \langle c^\dagger_{i\sigma} \boldsymbol{\sigma}_{\sigma\sigma'} c_{i\sigma'} \rangle$$

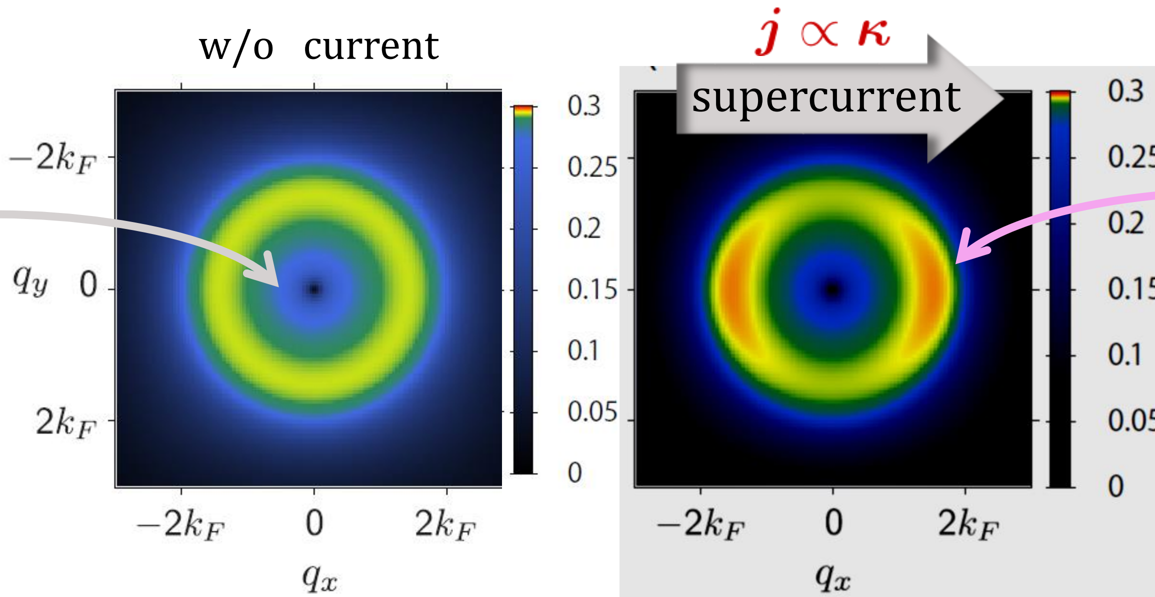
- singlet supercurrent $\boldsymbol{j} \propto \boldsymbol{\kappa}$

(spatial gradient of SC phase)

Magnetic instability

- bare spin susceptibility $\chi(\boldsymbol{q})$ in the continuum model : $\xi_{\boldsymbol{k}} = \dfrac{k^2}{2m} - \epsilon_F$

suppression
by singlet gap
$q \sim 0$
Anderson&Suhl (1959)



increase

$\kappa/k_F = 0.022$
$\Delta/\epsilon_F = 0.05$

$$\chi(\boldsymbol{q}) - \chi_{\boldsymbol{\kappa}=\mathbf{0}}(q) = \frac{a^2|\boldsymbol{\kappa}|^2}{\epsilon_F} f\left(\frac{q}{k_F}, \frac{|\Delta|}{\epsilon_F}\right) + \frac{a^2(\boldsymbol{\kappa}\cdot\hat{\boldsymbol{q}})^2}{\epsilon_F} g\left(\frac{q}{k_F}, \frac{|\Delta|}{\epsilon_F}\right) + O\left((\kappa/k_F)^4\right)$$

much smaller than g

>0 and peak at $q/k_F \sim 2$

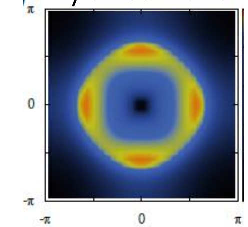
$$g(x,y) = \frac{x^2}{\pi^2}\int_0^\infty \int_0^{2\pi} \tilde{k}d\tilde{k}d\theta \frac{\sqrt{(\tilde{\xi}_1^2+y^2)(\tilde{\xi}_2^2+y^2)} - \tilde{\xi}_1\tilde{\xi}_2 - y^2}{\sqrt{(\tilde{\xi}_1^2+y^2)(\tilde{\xi}_2^2+y^2)}\left(\sqrt{(\tilde{\xi}_1^2+y^2)} + \sqrt{(\tilde{\xi}_2^2+y^2)}\right)^3},$$

Supercurrent leads to **magnetic instability**

Magnetic order in lattice system

- square lattice model : $\xi_{\boldsymbol{k}} = -2t(\cos(k_x a) + \cos(k_y a)) - \mu$

w/o current



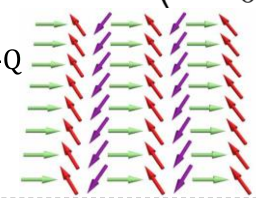
Instability : $\boldsymbol{m}_{\boldsymbol{q}=(\pm Q,0)}$, $\boldsymbol{m}_{\boldsymbol{q}=(0,\pm Q)}$ $(Q \sim 2\pi/3a)$ $\mu/t = -2.96$

- Variational ansatz

(M_0, Q: variational parameter)

$$\boldsymbol{m}_i^{\text{single}} = M_0 \begin{pmatrix} \cos(Qx_i) \\ \sin(Qx_i) \\ 0 \end{pmatrix}$$

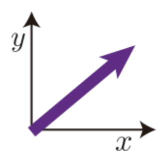
single-Q



$$\boldsymbol{m}_i^{\text{double}} = M_0 \begin{pmatrix} \cos(Qx_i) \\ \cos(Qy_i) \\ 0 \end{pmatrix},$$

double-Q

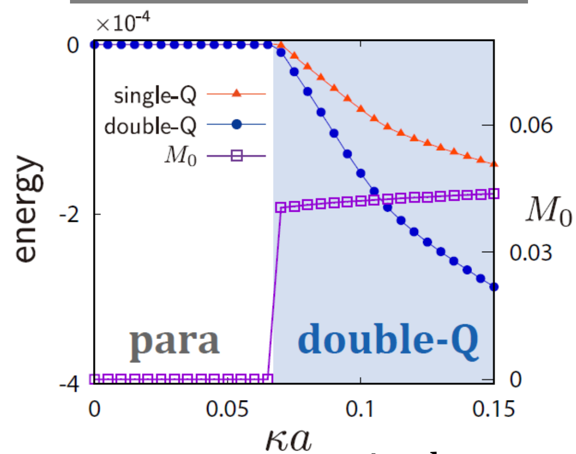
$\boldsymbol{j} \propto \kappa(1,1)$



T=0K

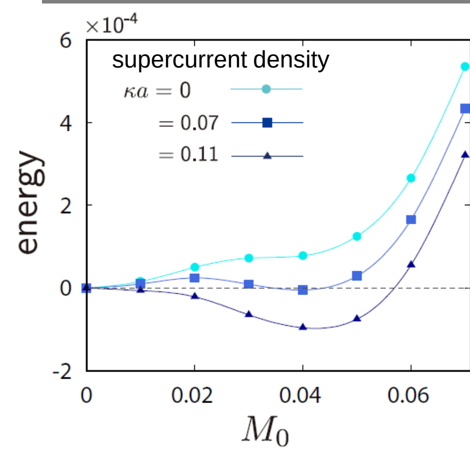
fixed U

double-Q order is stabilized



current magnitude

1st order transition behavior

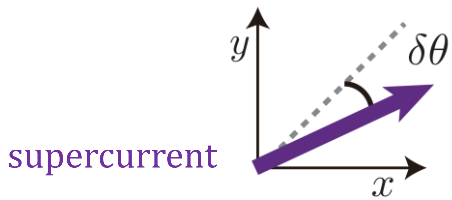


for double-Q

Supercurrent induces **first-order transition** to **double-Q state**

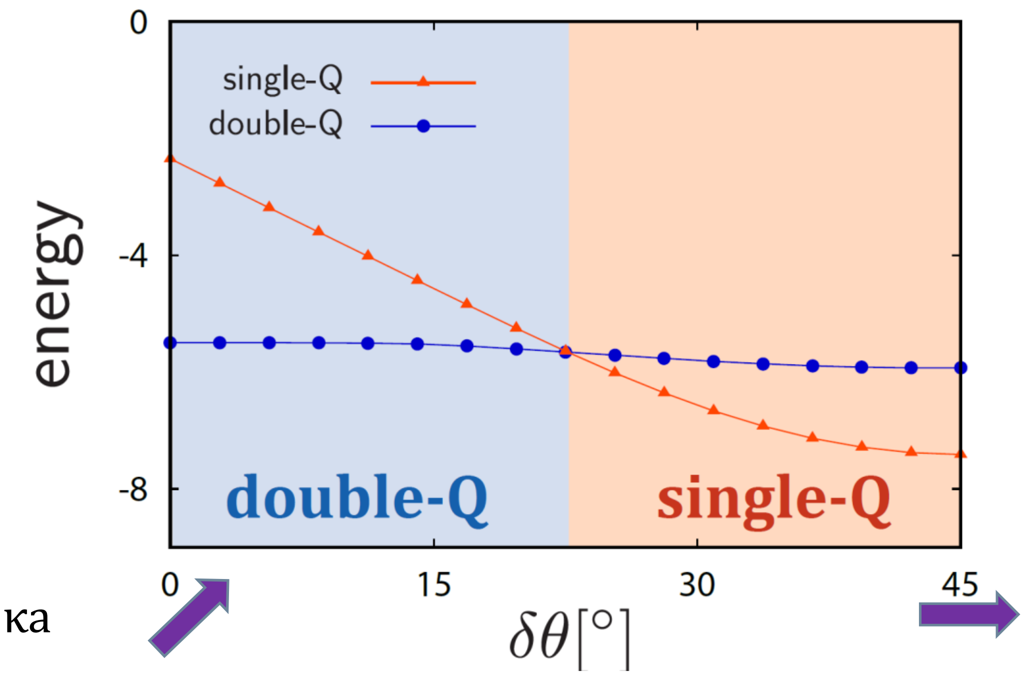
Switch to single-Q magnetic order

We can **switch** magnetic state by the **direction of supercurrent**

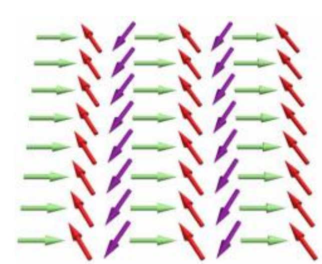


$$\boldsymbol{j} \propto \kappa(\cos(45^\circ - \delta\theta), \sin(45^\circ - \delta\theta), 0)$$

fixed U, κa

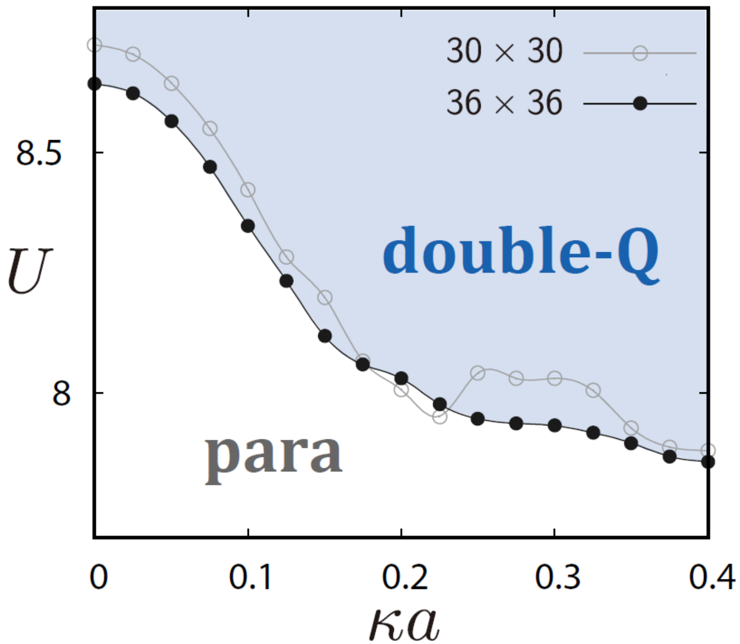


current angle



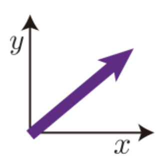
Phase diagram (T=0K)

Critical U decreases as current increases

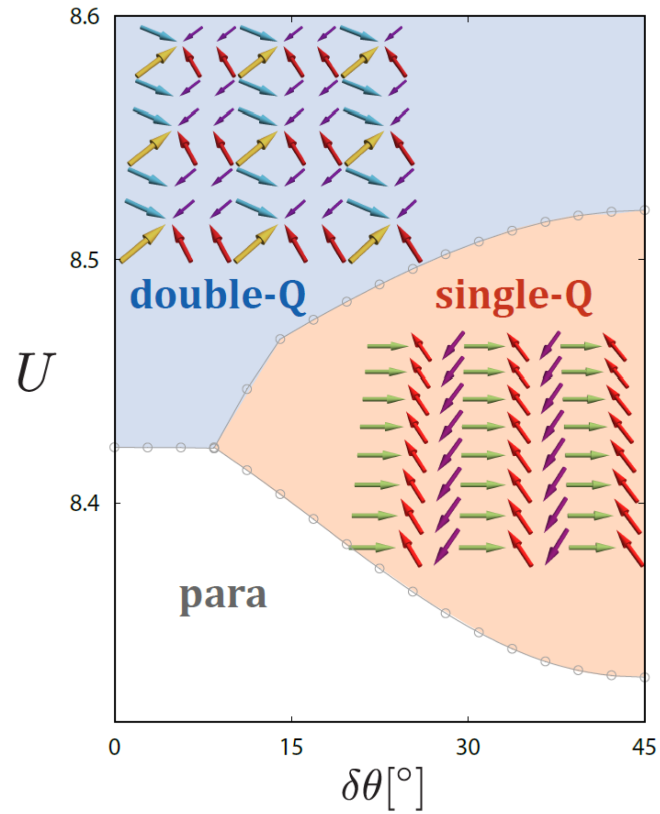


magnitude of current

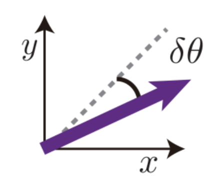
$\boldsymbol{j} \propto \kappa(1,1)$



"switch" of magnetic states



current angle



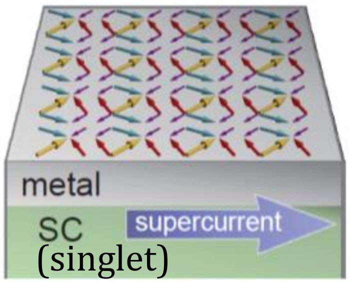
Summary of 2^{nd} part

We propose a new way to control **noncollinear order** by supercurrent

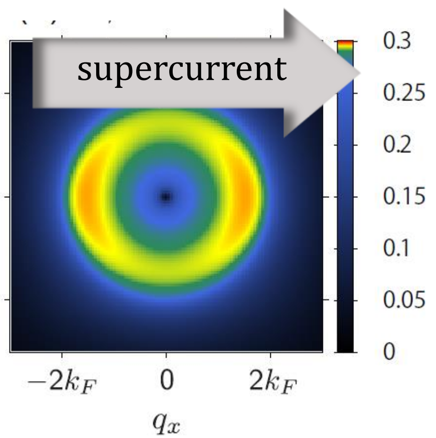
✓Supercurrent induces

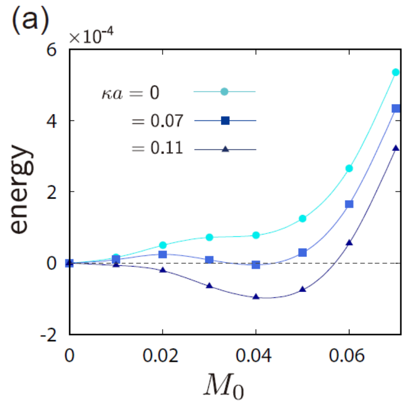
1st order phase transition to double-Q state

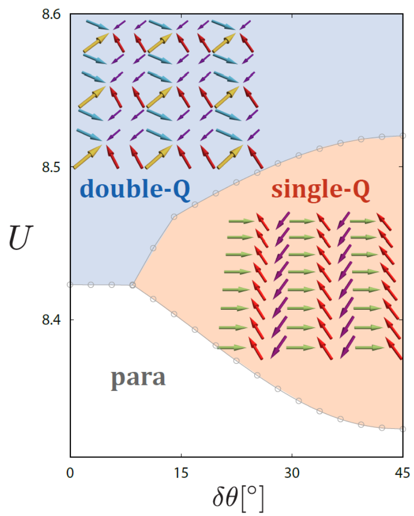
✓Switch magnetic states by **current direction**



$\boldsymbol{j} \propto \boldsymbol{\kappa}$







Remark

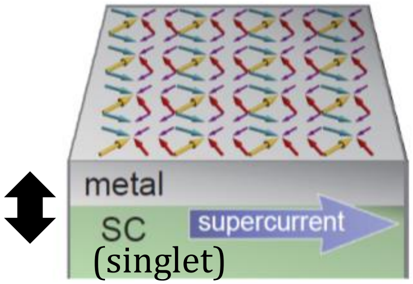
1) First-order transition→ metastable state of magnetic order w/o supercurrent

2) Different lattices/pairing ➡ a wide range of magnetic states, e.g. skyrmion

3)Rashba Spin-orbit coupling

Rashba spin orbit coupling

- Rashba SOC at the interface



$$H_{so} = \alpha \sum_{\boldsymbol{k}} \boldsymbol{g}(\boldsymbol{k}) \cdot (c^{\dagger}_{\boldsymbol{k}\sigma_1} \boldsymbol{\sigma} c_{\boldsymbol{k}\sigma_2}),$$

- Energy functional

$\boldsymbol{j} \propto \boldsymbol{\kappa}$

$$E[\{\boldsymbol{m}\}] = \frac{2UN}{3} \sum_{\boldsymbol{q}} \left(1 - \frac{2U}{3}\chi^{\mu\nu}(\boldsymbol{q})\right) m^{\mu}_{-\boldsymbol{q}} m^{\nu}_{\boldsymbol{q}} + F \sum_{i} (\hat{\boldsymbol{z}} \times \boldsymbol{\kappa}) \cdot \boldsymbol{m}_{\boldsymbol{i}},$$

① spin-spiral plane is locked

②Inverse-Edelstein effect

➡ **in-plane magnetic field**

Realized magnetic states would be modulated

cf) w/o SOC

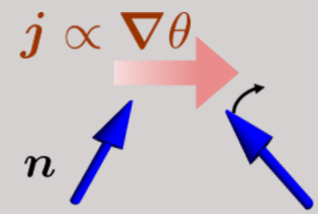
$$E[\{\boldsymbol{m}\}] = \frac{2UN}{3} \sum_{\boldsymbol{q}} \left(1 - \frac{2U}{3}\chi(\boldsymbol{q})\right) |\boldsymbol{m}_{\boldsymbol{q}}|^2,$$

Conclusion

1st part

Background experiments on triplet-proximity effect in magnet

Model **metallic magnet + triplet pairing potential**



Spin-triplet supercurrent give a new type of **spin-transfer-torque**

RT, Fujimoto, Yokoyama,PRB **96**, 121203 (R)

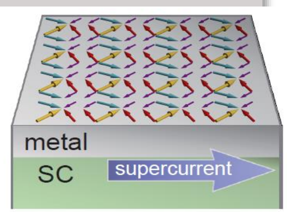
2nd part

Background Rich physics arise from interplay of noncollinear order and SC

Model **2d correlated metal + singlet pairing potential**

Supercurrent induce double-Q/single-Q magnetic order

R. Takashima, Y. Kato, Y. Yanase, Y. Motome arXiv: 1710.11349



Possible Setup