Mesoscopic Spintronics

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Lecture 3
Today’s Topics

• 3.1 Spin transport in superconductors

• 3.2 Spin injection into a superconductor

• 3.3 Spin Hall effect in a superconductor

• 3.4 Superconducting spintronics with ferromagnetic Josephson junctions
Fundamentals of superconductors

What are superconductors?

Materials that show zero resistance below critical temperatures

Meissner effect

Magnetic vortices are expelled during the superconducting transition

Zero resistance and Meissner effect are the most important characteristics for superconductors.
Fundamentals of superconductors

How does superconductivity happen?

- **Normal state**
  - Electrons move independently.

- **Superconducting state**
  - Cooper pair

Electrons form pairs called “Cooper pair” below critical temperature $T_C$ through electron-phonon coupling (normal BCS type).
Fundamentals of superconductors

**Superconducting gap**

Electrons around the Fermi energy form cooper pairs and condensed into low energy state.

- Energy gap ($2\Delta$) around the Fermi energy ($E_F$)

**In conventional superconductors**

Spin singlet state $\Rightarrow$ No spin angular momentum (antiparallel)

Is it possible to flow spin currents through superconductors?
Fundamentals of superconductors

$T = 0$

All electrons form Cooper pairs

No contribution to spin currents (because they are spin-singlet).

$0 < T < T_C$

Some Cooper pairs are broken

Bogoliubov quasiparticles are single particle state, and have spin degree of freedom!
Fundamentals of superconductors

**Distinct properties of Bogoliubov quasiparticles**

Bogoliubov quasiparticles \(\Rightarrow\) Superposition of electron-like and hole-like excitations

Bogoliubov-Valatin transformation

\[
\begin{align*}
    a_{k\uparrow} &= u_k \gamma_{k\uparrow} + v_k^* \hat{S} \gamma_{-k\downarrow} \\
    a_{-k\downarrow} &= -v_k \hat{S}^\dagger \gamma_{k\uparrow} + u_k^* \gamma_{-k\downarrow}
\end{align*}
\]

where

\[
|u_k|^2 = \frac{1}{2} \left(1 + \frac{\xi_k}{E_k}\right), \quad |v_k|^2 = \frac{1}{2} \left(1 - \frac{\xi_k}{E_k}\right), \quad E_k = \left[\xi_k^2 + \Delta^2\right]^{1/2}
\]

\(a_{k\sigma}, \gamma_{k\sigma}, \hat{S}\) : annihilation operator of an electron, a quasiparticle and a condensate.

net charge of quasi particle: \(q_k = |u_k|^2 - |v_k|^2 = \frac{\xi_k}{E_k}\).

Depending on the wave vector, quasiparticles have fractional charges.

Spin Transport in Superconductors

Spin transport is mediated by

- Electrons (in normal metal)
- Bogoliubov quasiparticles (in superconductors)

**Distinctive Properties**

- e.g. Long Spin Relaxation Time $\tau_{sf}$
- Energy dispersion of quasiparticles:
  \[ E_k = \left( \xi_k^2 + \Delta^2 \right)^{1/2} \]
- Smaller group velocity of quasiparticles:
  \[ v_k = \hbar^{-1} \nabla_k E_k = (\xi_k/E_k) v_F \]
  ➞ Longer spin relaxation time

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Spin Hall Effect in Superconductors

$$\rho_{\text{SHE}} = a\rho_{xx} + b\rho_{xx}^2$$

Skew scattering  Side-jump & Intrinsic

In superconductors,

$$\rho_{xx}^{qp} = \frac{\rho_{xx}^0}{2f_0(\Delta)}$$

where

$$f_0(\Delta) = \frac{1}{\exp(\Delta/k_B T) + 1}$$

and $\rho_{xx}^0$ is the resistivity just above $T_c$.

$$\rho_{\text{SHE}} = a\frac{\rho_{xx}^0}{2f_0(\Delta)} + b\left(\frac{\rho_{xx}^0}{2f_0(\Delta)}\right)^2$$

and

$$\Delta R_{\text{SH}} \propto \rho_{\text{SHE}}.$$
Spin-Charge Separation

Anomally Long Spin Diffusion Length in Al

Strong in-plane magnetic field induces band split between upspin and downspin.

Anomalously long spin diffusion length is achieved, which is much longer than the charge imbalance length

$$\lambda_s \sim 8 \mu m >> \lambda_{Q*}.$$
Experimental Studies

There are many theoretical proposals on spin transport in superconductors.

However

Few experimental studies have been reported. Even fundamental spin transport properties are still unclear.

e.g.

Spin relaxation time in superconductors


H. Yang et al., Nat. Mater. 9, 586 (2010).

Several previous works on $\tau_{sf}$ in superconductor

$\rightarrow$ Contradicting results

(Because of spurious effects)
Experimental Studies

Spin Hall effect in normal metals

Many kinds of materials are investigated.

Spin transport in superconductors

Only Aluminum (Al) has been used.

Spin Hall effect in superconductors has never been reported.

<table>
<thead>
<tr>
<th>Material</th>
<th>$w_{TM}$ (nm)</th>
<th>$t_{TM}$ (nm)</th>
<th>$L$ (nm)</th>
<th>$\eta$</th>
<th>$\lambda_{TM}$ (nm)</th>
<th>$\sigma_{TM}$ ($10^4 \Omega^{-1} \text{cm}^{-1}$)</th>
<th>$\sigma_{SHE}$ ($10^4 \Omega^{-1} \text{cm}^{-1}$)</th>
<th>$\sigma_{IH}$ (%)</th>
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<tbody>
<tr>
<td>Nb</td>
<td>370</td>
<td>11</td>
<td>700</td>
<td>0.35 ± 0.04</td>
<td>5.9 ± 0.3</td>
<td>11</td>
<td>$- (0.10 \pm 0.02)$</td>
<td>$- (0.87 \pm 0.20)$</td>
</tr>
<tr>
<td>Ta</td>
<td>250</td>
<td>20</td>
<td>1000</td>
<td>0.48 ± 0.04</td>
<td>2.7 ± 0.4</td>
<td>3</td>
<td>$- (0.011 \pm 0.003)$</td>
<td>$- (0.37 \pm 0.11)$</td>
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<tr>
<td>Mo</td>
<td>250</td>
<td>20</td>
<td>1000</td>
<td>0.24 ± 0.03</td>
<td>8.6 ± 1.3</td>
<td>28</td>
<td>$- (0.23 \pm 0.05)$</td>
<td>$- (0.80 \pm 0.18)$</td>
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<tr>
<td>Pd</td>
<td>250</td>
<td>20</td>
<td>1000</td>
<td>0.37 ± 0.04</td>
<td>13 ± 2</td>
<td>22</td>
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<td>1.2 ± 0.4</td>
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<tr>
<td>Pt</td>
<td>100</td>
<td>20</td>
<td>700</td>
<td>0.34 ± 0.03</td>
<td>11 ± 2</td>
<td>81</td>
<td>1.7 ± 0.4</td>
<td>2.1 ± 0.5</td>
</tr>
</tbody>
</table>


Motivation

Problems in previous studies

Despite the theoretical interests, experimental studies on spin transport are still lacking, and even fundamental spin transport properties (e.g. spin relaxation time) are not clear yet.

Also, only aluminum has been used as a superconductor in previous experimental studies.

Motivations and strategy

We first investigate spin relaxation time in a superconductor especially with large spin-orbit interaction, niobium, free from spurious effects.

Based on the knowledge we have acquired, we attempt to observe intriguing phenomena for spin transport in superconductors, especially the spin Hall effect.
Spin Absorption Technique

Spin Injection through Spin Absorption Technique


Spin Absorption Technique

Electrical Transport Measurement

\[ J_C \propto J_s \times S \]

Sample Fabrication

*Shadow Evaporation Technique*

(a) MMA PMMA

(b) Developing

(c) Deposition

(d) Deposition

(e) Lift-off
Sample Fabrication

Sample Structure

How does the Nb middle wire affect the nonlocal spin valve signal?

$T_C^{Nb} = 5.5\, K$
Spin Injection into Nb

Usually, the NLSV signal $\Delta R$ is independent of the spin injection current $I$. 

![Diagram showing NLSV signal without and with Nb middle wire.](image)

- NLSV signal without Nb middle wire
- NLSV signal with Nb middle wire

Graphs showing the variation of $\Delta R$ with Magnetic Field [Oe] for $T = 10$ K with and without Nb, and with two different currents: $I = 20$ mA (with Nb) and $I = 100$ mA (with Nb).
Spin Injection into Nb

$T > T_c$

$T < T_c$

$\Delta R_s$

$\Delta R$

$T = 10$ K

$T = 370$ mK

Ferromagnet

Nonmagnet

$I$

$T_c$

$R_s$ [mΩ]

$H$ [Oe]

$I$ [μA]

$\Delta R_s$ [mΩ]
Spin Injection into Nb

Elucidation of Interface Resistance

Nb/Cu Interface

Temperature Dependence

\[ R_i : \text{Negative (from Current Inhomogeneity)} \]

\[ T > T_c \]

\[ T < T_c \]

Bias Dependence

\[ R_i : \text{Positive (Ohmic Contribution + Charge Imbalance)} \]

\[ T = 370 \text{ mK} \]

\( I < 150 \mu A \), the interface is still superconducting.
The relation between $T$ and $I$

\[ I = \sqrt{\frac{G}{Rt}} \quad (G \equiv \gamma V) \]

\[ \varepsilon = \gamma T^2 + AT^4 \]

\[ Q = RI^2t \]

\[ t = \frac{L_p^2}{D} \quad , \quad \sqrt{\frac{G}{Rt}} = 2.9 \times 10^{-5} \text{AK}^{-1} \]
Spin Absorption and Proximity Effect

Solving the Usadel Equation:

\[
\begin{aligned}
\frac{\hbar D}{2} \frac{\partial^2 \theta}{\partial x^2} + \left( iE - \frac{\hbar}{2\tau_{sf}} \cos \theta \right) \sin \theta + \Delta(x) \cos \theta &= 0,
\\
\Delta(x) &= N_S(0) \mathcal{V} \int_0^{\hbar \omega_D} \tanh \left( \frac{E}{2k_B T} \right) \text{Im}[\sin \theta] dE.
\end{aligned}
\]

Analysis

**Superconducting Proximity Effect**

Solving the Usadel Equation:

\[
\begin{align*}
\hat{h}D \frac{\partial^2 \theta}{\partial x^2} + \left( iE - \frac{\hat{h}}{2\tau_{sf}} \cos \theta \right) \sin \theta + \Delta(x) \cos \theta &= 0, \\
\Delta(x) &= N_S(0) \mathcal{V} \int_0^{\hbar \omega_p} \text{tanh} \left( \frac{E}{2k_B T} \right) \text{Im} [\sin \theta] dE.
\end{align*}
\]

\[n_S(E) = \text{Re} [\cos \theta] \text{: Normalized Density of States (DOS)}\]

\[
\frac{I_s^{\text{super}}}{I_s^{\text{normal}}} = \int_{-\infty}^{\infty} n_S(E) \left( -\frac{\partial f_0(E)}{\partial E} \right) dE
\]

\[
\frac{\Delta R_s^{\text{super}}}{\Delta R_s^{\text{normal}}} = \frac{Q_{\text{Nb}}^{\text{super}} I_s^{\text{super}}}{Q_{\text{Nb}}^{\text{normal}} I_s^{\text{normal}}}, \quad Q_{\text{Nb}}^{\text{super(normal)}} = \mathcal{R}_{\text{Nb}}^{\text{super(normal)}} / \mathcal{R}_{\text{Cu}}
\]
**Comparison with Theoretical Calculation**

**Long Spin Relaxation Time** $\tau_{sf}$

Smaller group velocity of quasiparticles:

$$v_k = \hbar^{-1} \nabla_k E_k = \left( \frac{\xi_k}{E_k} \right) v_F , \quad E_k = \left[ \xi_k^2 + \Delta^2 \right]^{1/2}$$

$\Rightarrow$ Longer spin relaxation time

Brief Summary

Spin transport is possible even in spin-singlet superconductors by exploiting Bogoliubov quasiparticles.

Distinctive properties of Bogoliubov quasiparticles make it possible to observe intriguing phenomena for spin transport unique for superconductors.

Spin injection into superconducting Nb is demonstrated by spin-absorption technique.

Through the fit for the decay of spin absorption of Nb with decreasing spin injection current, enhanced spin relaxation time for Bogoliubov quasiparticles is derived.
Spin Hall effect in Superconductors

Using NbN in place of Nb
(in collaboration with Prof. Akaike
in Prof. Fujimaki group, Nagoya University)

NbN: Type II superconductor, higher $T_c$
($T_c = 16$ K, in a textbook)
Spin and Change Imbalance

Inverse spin Hall effect in superconductor (S)s

\[ \text{Induce a shift of the chemical potential of quasiparticles} \ (\mu_n) \]  
\[ \text{(charge imbalance effect (CI))} \]

From the charge neutrality condition, the pair potential of condensates (\( \mu_p \)) also shifts to the opposite side.

Electrochemical pair potential of condensates:
\[ \Phi_p = \mu_p + e\phi \]

Condition for no electric field in Ss:
\[ \nabla \Phi_p = 0 \]

Because the CI decays in space, \( \nabla \mu_p \neq 0 \)

\[ \nabla \phi \neq 0 \]

Electrochemical potential for quasiparticles:
\[ \Phi_n = \mu_n + e\phi \]

From above, \( \nabla \Phi_n \neq 0 \)

Potential gradient induced by the ISHE
Spin Hall effect in a superconductor

$T_c = 10 \text{ K}$

$R[R]$

$T[K]$

$J_C \propto J_s \times S$

$T = 20 \text{ K}$

$I = 300 \mu\text{A}$

$R_{\text{Py}}[\Omega]$

$H[\text{Oe}]$
Spin Hall Effect in a Superconductor

$T > T_C$ \( \Delta R_{\text{ISHE}} \) is independent of \( I \).

$T < T_C$ \( \Delta R_{\text{ISHE}} \) is dramatically increasing with decreasing \( I \).
Experimental Results ($T < T_c$)

*Angular Dependence of ISHE*

\[
\begin{align*}
J_Q & \propto J_s \times s \\
\Delta R_{\text{ISHE}} & = \Delta R_{\text{ISHE}} (\theta = 90^\circ) \sin \theta
\end{align*}
\]

\[D_{\text{RISHE}} = D_{\text{RISHE}} (\theta = 90^\circ) \sin \theta\]

\[J_Q \propto J_s \times s\]

\[\Delta R_{\text{ISHE}} = \Delta R_{\text{ISHE}} (\theta = 90^\circ) \sin \theta\]
Spin Hall Effect in a Superconductor

Inverse spin Hall effect converts spin currents into:

- Electrical currents (in normal metals)
- Quasiparticles currents (in superconductors)

Quasiparticles currents eventually relax into Cooper pair formation.

Charge Imbalance:

- Normal metal
- Superconductor

Diagram:

(a) Hole-like and electron-like bands

(b) Pairs in condensate
How can we explain?

Inverse spin Hall effect converts spin currents into

- Electrical currents (in normal metals)
- Quasiparticles currents (in superconductors)

Causes the shift of $\mu_{QP}$ ($\delta\mu_{QP}$); spatially dependent

\[ \delta\mu_{Q} \approx \frac{1}{2} \theta_{str} e \frac{\rho_{Q}}{w_{S}} J_{s} \left( \frac{x}{2w_{N}} \right) \]

\[ \delta\mu_{Q} = \frac{1}{2} \theta_{str} e \frac{\rho_{Q}}{w_{S}} J_{s} e^{-\left(\frac{x-w/2}{\lambda_{D}}\right)} \]

\[ \mu_{p} + e\phi = 0 \]

Courtesy of S. Takahashi
Experimental Results

*NbN Length Dependence of ISHE*

\[ V_{\text{ISHE}} = d_2 \]

\[ \lambda_Q = 5 \mu m \]

**Graphs:**
- **Graph 1:**
  - Title: \( T = 20 \text{ K}, I = 300 \mu \text{A} \)
  - Data points for different magnetic fields for distances \( d_1 \) and \( d_2 \).
- **Graph 2:**
  - Title: \( T = 3 \text{ K}, I = 1 \mu \text{A} \)
  - Data points for different magnetic fields for distances \( d_1 \) and \( d_2 \).
Analysis

\[ \rho_{\text{SHE}} = a \rho_{xx} + b \rho_{xx}^2 \]

- **Term linear in \( \rho_{xx} \): Skew scattering contribution**

- **Term quadratic in \( \rho_{xx} \): Intrinsic contribution, side-jump effect**

\[ \rho_{\text{SHE}} = \frac{w_M}{x} \left( \frac{I}{I_s} \right) \Delta R_{\text{ISHE}} \]

\[ \Delta R_{\text{ISHE}} = \left( \frac{I_s}{I} \right) \frac{x}{w_M} (a \rho_{xx} + b \rho_{xx}^2) \]

\[ \frac{\Delta R_{\text{ISHE}}^{\text{super}}}{\Delta R_{\text{ISHE}}^{\text{normal}}} = \left( \frac{I_{s}^{\text{super}}}{I_{s}^{\text{normal}}} \right) \frac{x_{\text{super}}}{x_{\text{normal}}} \frac{a \rho_{xx}^{\text{QP}} + b (\rho_{xx}^{\text{QP}})^2}{a \rho_{xx}^{0} + b (\rho_{xx}^{0})^2}, \quad \rho_{xx}^{\text{QP}} = \frac{\rho_{xx}^{0}}{2 f_0(\Delta)} \]

\( f_0(E) \): Fermi distribution function

- \( w_M \): Width of a middle wire
- \( x \): Shunting factor
- \( I \): Spin injection current
- \( I_s \): Injected spin current
Analysis

\[ \alpha_{\text{SHE}} \equiv \rho_{\text{SHE}} / \rho_{xx} = a + b \rho_{xx}, \quad \rho_{xx} \propto T \]

From figures above, we can determine \( a \) and \( b \), and found \( a \ll b \), then

\[ \frac{\Delta R_{\text{ISHE}}^{\text{super}}}{\Delta R_{\text{ISHE}}^{\text{normal}}} = \left( \frac{I_{s}^{\text{super}}}{I_{s}^{\text{normal}}} \right) \frac{x_{\text{super}}}{x_{\text{normal}}} \frac{1}{(2f_{0}(\Delta))^{2}} \]
Analysis

\[ \frac{\Delta R_{\text{ISHE}}^{\text{super}}}{\Delta R_{\text{ISHE}}^{\text{normal}}} = \left( \frac{I_s^{\text{super}}}{I_s^{\text{normal}}} \right) \frac{x_{\text{super}}}{x_{\text{normal}}} \frac{1}{(2f_0(\Delta))^2} \]

\[ \frac{I_s^{\text{super}}}{I_s^{\text{normal}}} = \int_{-\infty}^{\infty} \frac{|E|}{\sqrt{E^2 - \Delta^2}} \left( -\frac{\partial f_0}{\partial E} \right) dE \]

\[ \Delta = \frac{x}{\xi} \Delta_0 \]

\[ \xi \sim \lambda_{sf} \sim 4 \text{ nm} \]

\[ \chi/(2f_0(\Delta))^2 \]

Contribution from \( \rho^2 \) term
How can we relate spin injection currents to an effective temperature?

For NbN, \( T = 3 \, \text{K} \)

\[
Q = RI^2 t, \quad t = \frac{L_p^2 \gamma}{D}
\]

\[
\Delta \varepsilon = \gamma(T^2 - T_0^2) + A(T^4 - T_0^4)
\]

\[
RI^2 t = \gamma V(T^2 - T_0^2) + AV(T^4 - T_0^4)
\]

\( T_0 = 3 \, \text{K} \) (environmental temperature)
Analysis

\[ RI^2t = \gamma V (T^2 - T_0^2) + AV (T^4 - T_0^4) \]

\[ I^2 = a (T^2 - T_0^2) + b (T^4 - T_0^4) \]

\[ \Delta R_{ISHE} \] saturates at small \( I \).

If we assume

\[ T = T_0 + c I^{1/2} \]

\( c \): constant

\( \Delta R_{ISHE} \) saturates at small \( I \).

Experimental data can be reproduced.

Only effective temperature increase plays a role for gigantic spin Hall effect?
Brief Summary

- Inverse spin Hall effect in superconducting NbN is demonstrated.

- Both at 20 K (above $T_C$) and 4.2 K (below $T_C$), clear inverse spin Hall signals are observed.

- Below $T_C$, the gigantic enhancement of the inverse spin Hall signals is seen as the spin injection currents decrease.

- Angular dependence of the observed signals show that they are ISHE origin.

- The enhancement cannot be explained only by decreasing effective temperature of Bogoliubov quasiparticles, and further studies are essential.
Symmetry of Cooper pairs

Based on the Pauli principle, “spin-triplet” Cooper pairs are also possible.

<table>
<thead>
<tr>
<th>Spin</th>
<th>Frequency</th>
<th>Momentum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singlet (odd)</td>
<td>Even</td>
<td>Even</td>
</tr>
<tr>
<td>Odd</td>
<td>Odd</td>
<td>Odd</td>
</tr>
<tr>
<td>Even</td>
<td>Odd</td>
<td>Odd</td>
</tr>
<tr>
<td>Odd</td>
<td>Even</td>
<td>Even</td>
</tr>
</tbody>
</table>


Can contribute to spin transport!
Symmetry of Cooper pairs

Triplet-pairing

- observed in bulk materials (e.g. Sr$_2$RuO$_4$, UPt$_3$ etc.)
- However, they do not have s-wave gap symmetry
- weak to disorder (Anderson’s theorem)

How can we easily obtain spin-triplet Cooper pairs?

Supercurrents in a half metal!?

Half metal = Ferromagnet, with only one spin channel at the Fermi energy

However, supercurrents are observed.

Fundamentals on Josephson junctions

What happens when two superconductors are connected through metal or insulator?

Two superconductors can crosstalk by tunneling or penetration of Cooper pairs through the inserted layer

\[ I_{12} = I_c \sin \theta \quad \theta = \phi_L - \phi_R \]

What happens if you make Josephson junctions with superconductors and a ferromagnet?
Josephson junctions

Spin-singlet Cooper pairs

- Two spins are antiparallel

Ferromagnets

- favor parallel spin alignments

Spin-singlet Cooper pairs are immediately broken in normal ferromagnets.

How can we generate spin-triplet Cooper pairs with spin-singlet Cooper pairs and ferromagnets?

Spin-triplet supercurrents

In ferromagnets, wave vectors are spin-dependent

\[ |\psi\rangle = |0,0\rangle_z = \frac{1}{\sqrt{2}} \left( |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) \]

\[ |\psi\rangle = \frac{1}{\sqrt{2}} \left( |\uparrow\downarrow\rangle e^{iQx} - |\downarrow\uparrow\rangle e^{-iQx} \right) \]

\[ = \frac{1}{\sqrt{2}} \left[ (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) \cos(Qx) + i (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle) \sin(Qx) \right] \]

\[ = |0,0\rangle \cos(Qx) + |1,0\rangle_z \sin(Qx) \]

Phase factor from orbital part

At the S/F interface, spin-triplet (S=0) component is generated.
Spin-triplet supercurrents

**Spin-triplet states**

\[
|\uparrow\rangle_1|\uparrow\rangle_2 \quad |\downarrow\rangle_1|\downarrow\rangle_2 \quad \frac{1}{\sqrt{2}}\left(|\uparrow\rangle_1|\downarrow\rangle_2 + |\downarrow\rangle_1|\uparrow\rangle_2\right)
\]

Spin-singlet state \(\rightarrow\) Rotationally invariant

Three spin-triplet states transform into each other when the quantization direction changes.

Assume a S/F’/F” structure. When the magnetization of the F’ and F” are parallel (z-direction), the quantization axis of spin-triplet pairs are z-direction. S=0 spin-triplet Cooper pairs rapidly decay inside F” (Fig. A).

Spin-triplet supercurrents

When the magnetization of F’ points to y, the quantization axis of Cooper pairs is y direction. Assume that the magnetization of F” points to z direction (Fig. B).

\[ S = 0 \text{ spin-triplet state to } y\text{-axis can be written as a sum of } S=|1| \text{ spin-triplet states to } z\text{-axis!} \]

→ S=1 spin-triplet pairs can survive inside F”!

Two noncolinear magnetization can generate long-range spin-triplet pairs!

Spin-triplet supercurrents

S/F’/F/F”/S structure

\[ I_c \propto \sin \phi_L \sin \phi_R \]

Candidates for F’ and F”: magnetic domain walls, spiral magnets, helical magnets etc.


Spin-triplet supercurrents

*Experimental results*

Spin mixer (conical magnet, domain wall, inhomogeneous magnetization etc.) helps long-range spin triplet supercurrents in ferromagnets.

Holmium (Ho): Conical magnet

Nb/Ho/Co/Ho/Nb junction

Nb/Rh/Co/Rh/Nb junction
(Rh is normal metal, for comparison)

Spin-triplet supercurrents

Decay of supercurrents (fitted as a voltage $I_CR_N$) for the Nb/Ho/Co/Ho/Nb junction (blue or green dots) shows much longer length than that for the Nb/Rh/Co/Rh/Nb junction (experimental: black dots, theoretical: black curve)

→ Signature of spin-triplet supercurrents

Fraunhofer-like patterns are clearly observed (Fig. B). (shift of the origin to $H$ is due to demagnetizing field of Co)

→ Supercurrents coexist with magnetization of Co

Spin-triplet supercurrents

**Spin-triplet supercurrents in lateral geometry**

Focused-Ion-Beam (FIB) deposited W/
Single crystal Co nanowire/ FIB W Josephson junction

Even when the distance between two W superconducting contacts ($L$) is 600 nm, clear supercurrents are observed at around 4 K.

→ Signature of spin-triplet supercurrents

Anisotropic magnetoresistance (AMR) signals are observed for Co nanowire above $T_c$, implying that Co is ferromagnetic.

J. Wang et al., Nat. Phys. 6, 389 (2010).
Brief Summary

Spin-triplet Cooper pairs can transfer spin angular momentum, thus are applicable to spintronics.

Ferromagnetic Josephson junctions with noncolinear spacer ferromagnet between superconductor and normal ferromagnet can generate long-range spin-triplet supercurrents (s-wave) through the ferromagnets.

Both for lateral and longitudinal devices, the above spin-triplet Cooper pairs have been experimentally demonstrated.

These spin-triplet supercurrents might be applied to exert spin-transfer torque, with lower energy consumption.