at Tsinghua University (Sept. 23, 2019)

"Energy Harvesting by Spin Current" - Power Spintronics -

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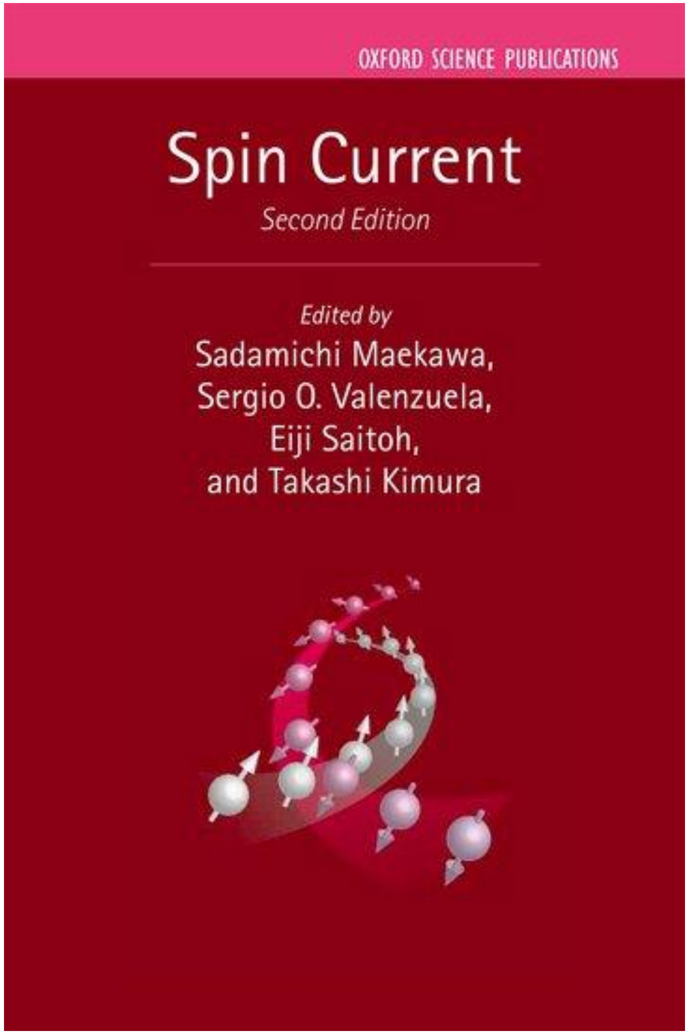
Reference:

*S. Maekawa et al. (eds.) "Spin Current" (Oxford University Press, 2012 and 2017),



Second Edition:
Published in September 2017

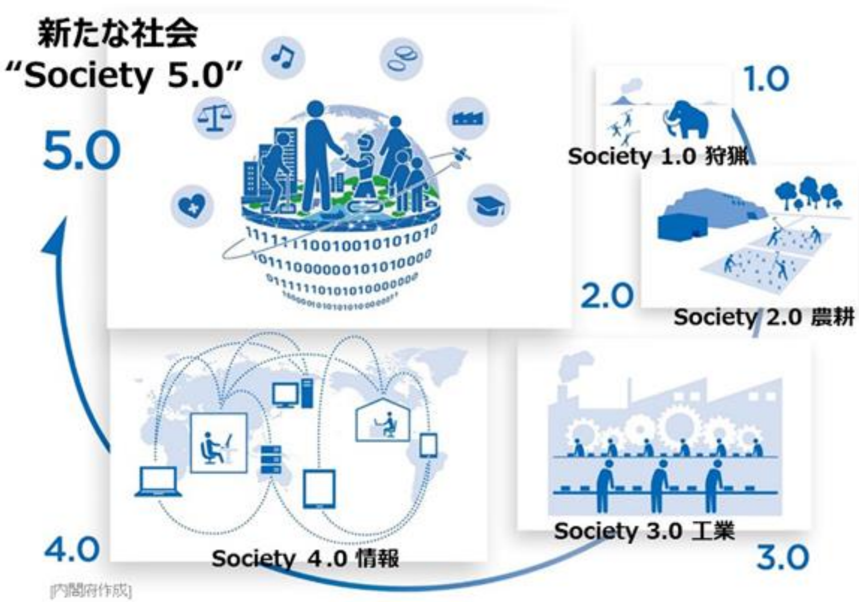
*** "<u>Spin Current</u>"(First Edition) : (Oxford University Press, 2012),**

Society (5.0):

(Proposal of the Japanese Government)

Hunting society (1.0) (狩猟社会)
Agricultural society (2.0)（農耕社会）
Industrial society (3.0)（工業社会）
Information society (4.0)（情報社会）
Future society (5.0)（AI, IoT,…)

Key issues:
energy, sensors, …



Content:

1. *Introduction to Spintronics,*
2. *Spin current,*
3. *Spin motive force,*
4. *Spin Seebeck effect,*
5. *Spin mechatronics.*

↓

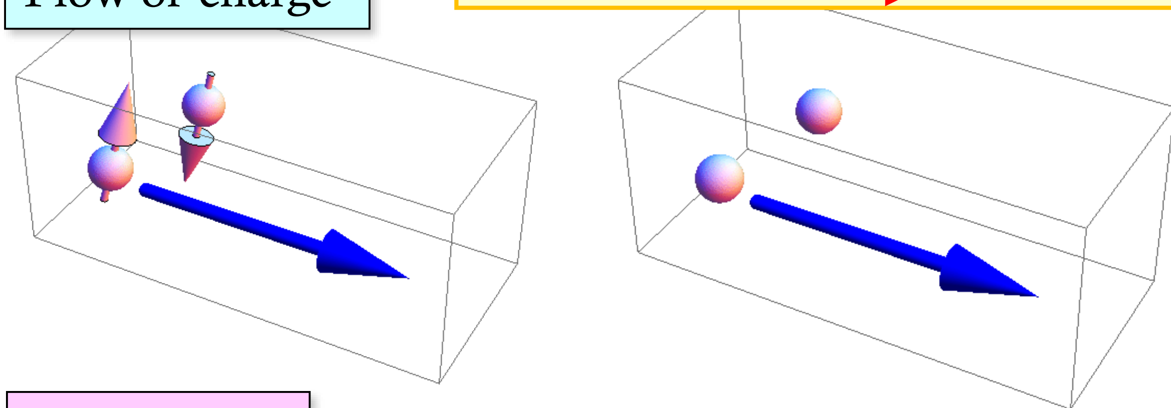
Energy harvesting by spin current
based on Angular momentum conservation

→ ***Power Spintronics***

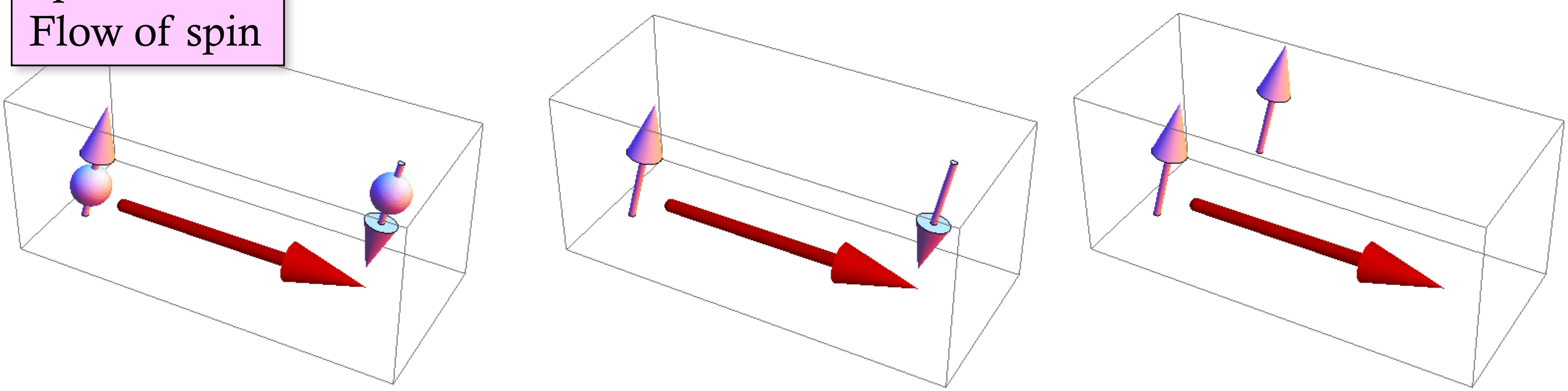
Spintronics

Spin current, charge current!

Electric current:
Flow of charge



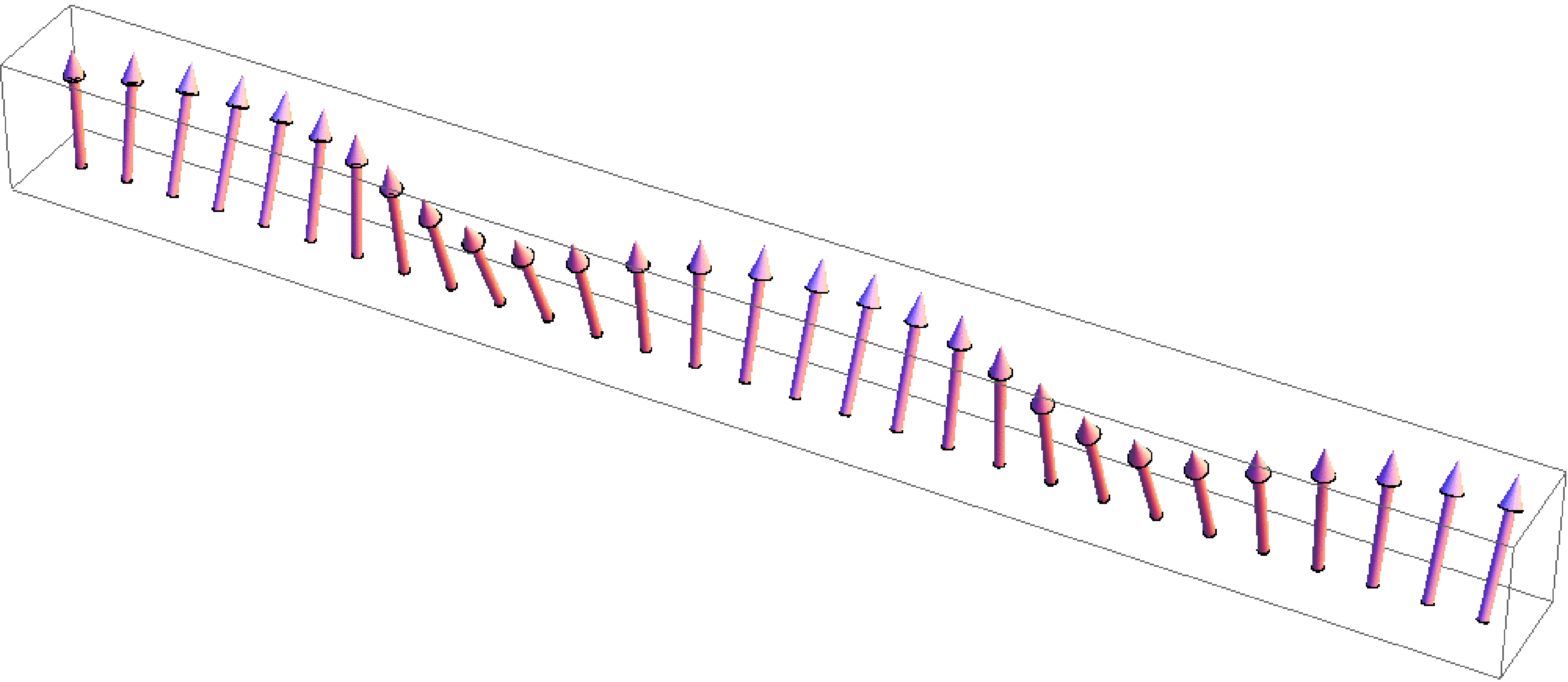
Spin current:
Flow of spin



Spin current is free from Joule heating!

⇒Energy-saving devices; Solution to the heating problem in electronics.

Spin-wave (magnon) spin current



Interactions for spin current:

1. **Exchange interaction** between magnetic moment and conduction electrons (*sd* exchange interaction (J_{sd})),
2. **Spin-orbit interaction** in conduction electrons (SOI),
3. **Spin-rotation coupling** (SRC).

↓

Energy harvesting by spin current
Based on Angular momentum conservation

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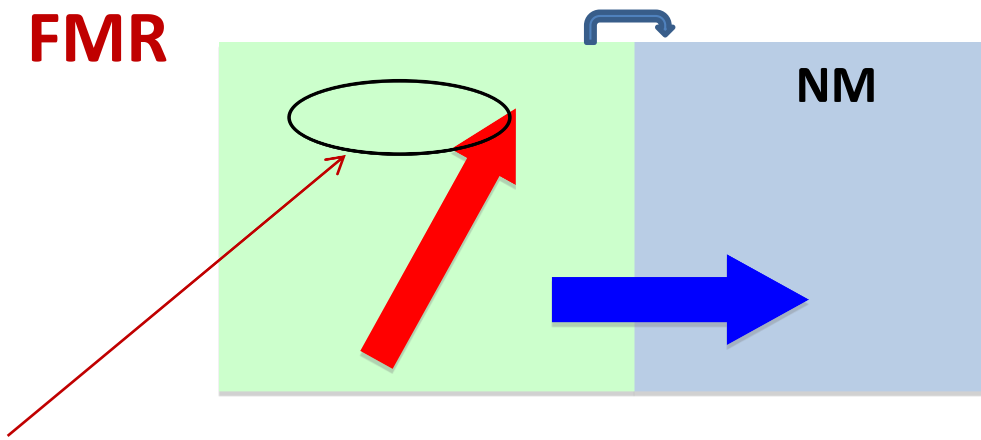
Energy harvesting by spin current
Based on Angular momentum conservation

Spin pumping

(spin current generation by FMR)

Exchange interaction(J_{sd})

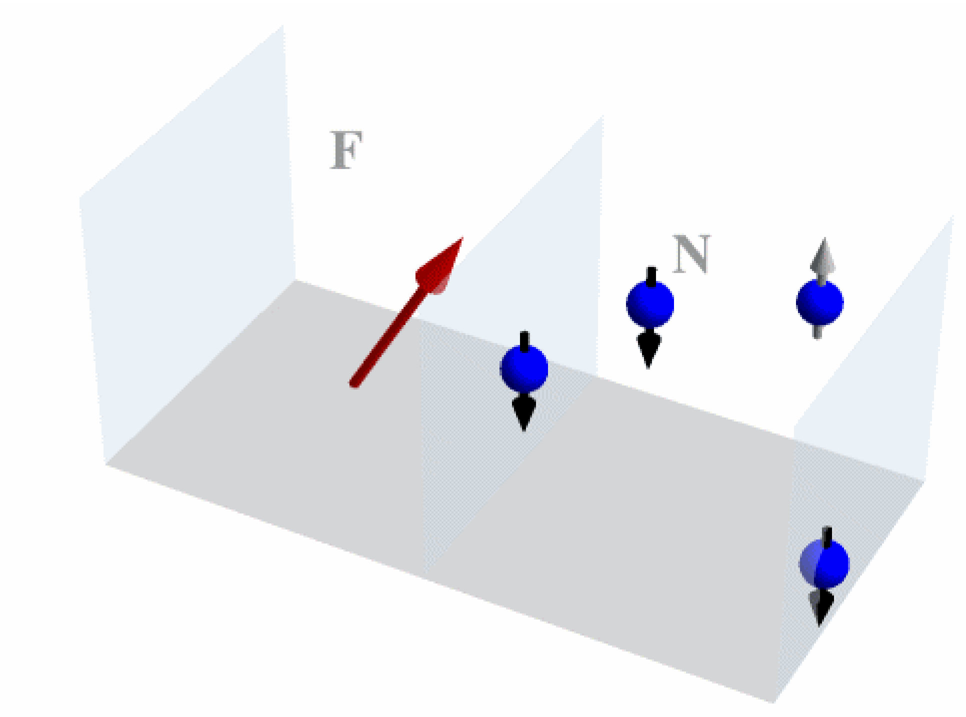
FMR



micro-waves

Spin current

Exchange interaction at the interface (Jsd)!!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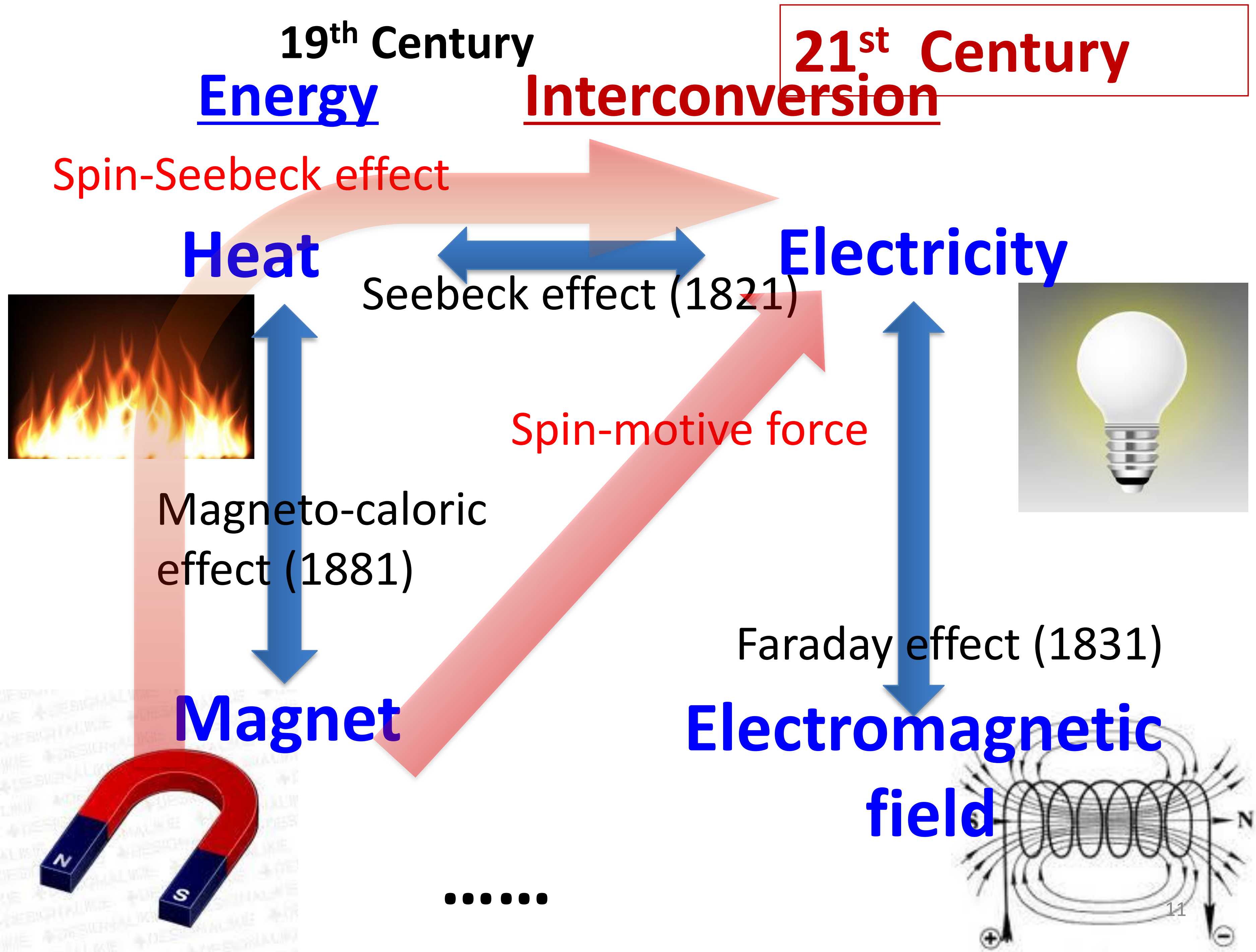

19th Century
21st Century
Energy Interconversion
Spin-Seebeck effect
Heat
Electricity
Seebeck effect (1821)
Spin-motive force
Magneto-caloric effect (1881)
Faraday effect (1831)
Magnet
Electromagnetic field
N
S
……

Content:

1. *Introduction to Spintronics,*
2. *Spin current,*
3. ***Spin motive force,***
4. *Spin Seebeck effect,*
5. *Spin mechatronics.*

↓

Energy conservation and harvesting by spin current

→ ***Power Spintronics***

Faraday's law of induction :

(after The Feynman Lectures on Physics (1964))

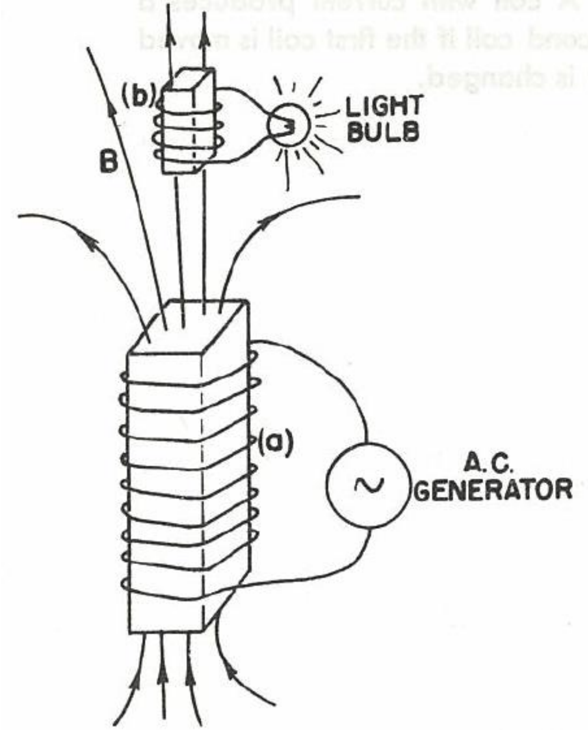
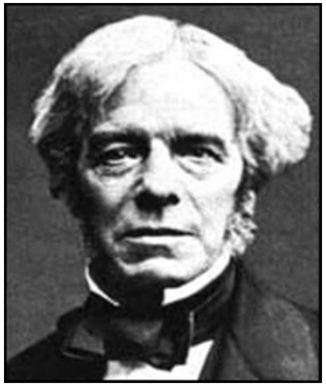


Fig. 16–5. Two coils, wrapped around bundles of iron sheets, allow a generator to light a bulb with no direct connection.

Modern electrical technology began with Faraday's law!!
(by Feynman)

from Faraday to Dirac, and more…



M. Faraday

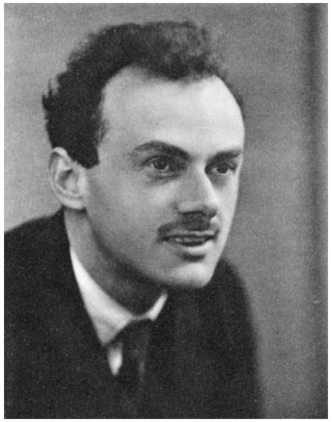
Faraday's law:

$$\mathcal{E} = -\frac{d\Phi}{dt}$$

(1831)

Maxwell Equation:

(1865)



P.A.M. Dirac

Dirac equation:

Q.M. + Special Relativity

→ Electron should have "spin."

(1928)

Spin current + Faraday's law!!

S. E. Barnes and S. Maekawa: PRL98, 246601 (2007)

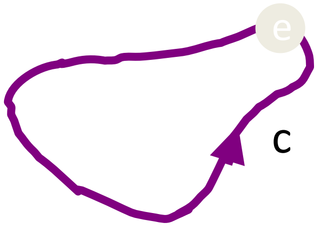
Case i:

Faraday's Law:

(1831)

- **induced electromotive force**

$$\mathcal{E} \equiv \frac{1}{-e}\oint_c \mathbf{f}_e \cdot d\mathbf{r} = -\oint_c \frac{\partial \mathbf{A}}{\partial t}\cdot d\mathbf{r} = -\frac{d\Phi}{dt}$$



- **force acting on electron**

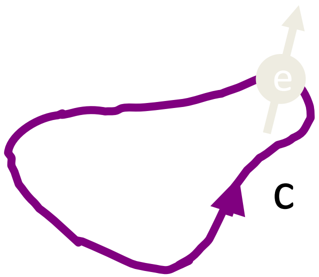
$$\mathbf{f}_e = (-e)\mathbf{E} = (-e)\left[-\nabla\varphi - \frac{\partial \mathbf{A}}{\partial t}\right]$$

Spin-Motive Force

Spin-motive force:

$$\mathcal{E}_s^{\pm} \equiv \frac{1}{-e} \oint_c \mathbf{f}_\mathbf{s}^{\pm} \cdot d\mathbf{r}$$

$\begin{cases} + & \text{: up spin} \\ - & \text{: down spin} \end{cases}$



• **force acting on "spin"**

(Barnes & Maekawa 2007)

for example, magnetic field

(Generalized Faraday's Law)

Electro-motive force:

$$\mathcal{E} \equiv \frac{1}{-e} \oint_c \mathbf{f}_e \cdot d\mathbf{r}$$

(Faraday 1831)

• **force acting on electric charge**

for example, electric field

Case ii:

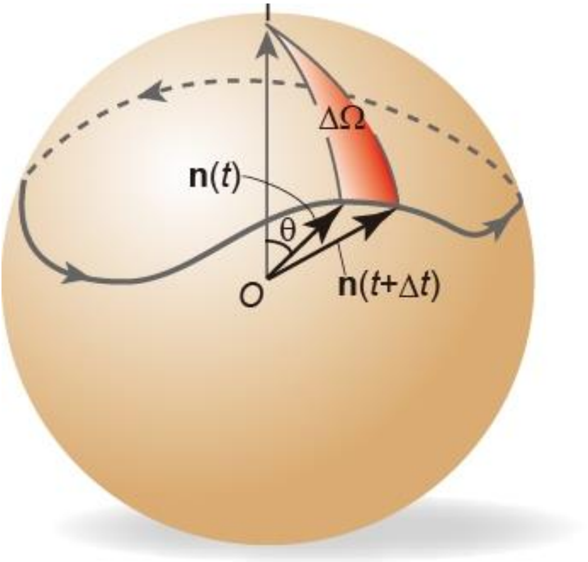
spin Berry phase

$$\mathcal{E} = -\frac{d\Phi}{dt}$$ (1831) (Faraday's Law)

$$\mathcal{E} = \frac{\hbar}{(-e)}\frac{d\gamma}{dt}$$ (2007) (Generalized Faraday's Law)

$$\gamma = \gamma_e + \gamma_s$$

$$\begin{cases} \gamma_e = \dfrac{(-e)}{\hbar}\Phi \\ \gamma_s = -\dfrac{\Omega}{2} \end{cases}$$



Force acting on electron charge: $\boldsymbol{f}_{\mathrm{e}} = -e(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$

Force acting on electron spin: $\boldsymbol{f}_{\mathrm{s}} = -e[\pm \boldsymbol{E}_{\mathbf{s}} + \boldsymbol{v} \times (\pm \boldsymbol{B}_{\mathbf{s}})]$

Spin electric field: $$E_{i\mathrm{s}} = \frac{\hbar}{2e} \boldsymbol{m} \cdot \left(\frac{\partial \boldsymbol{m}}{\partial t} \times \frac{\partial \boldsymbol{m}}{\partial x_i} \right)$$

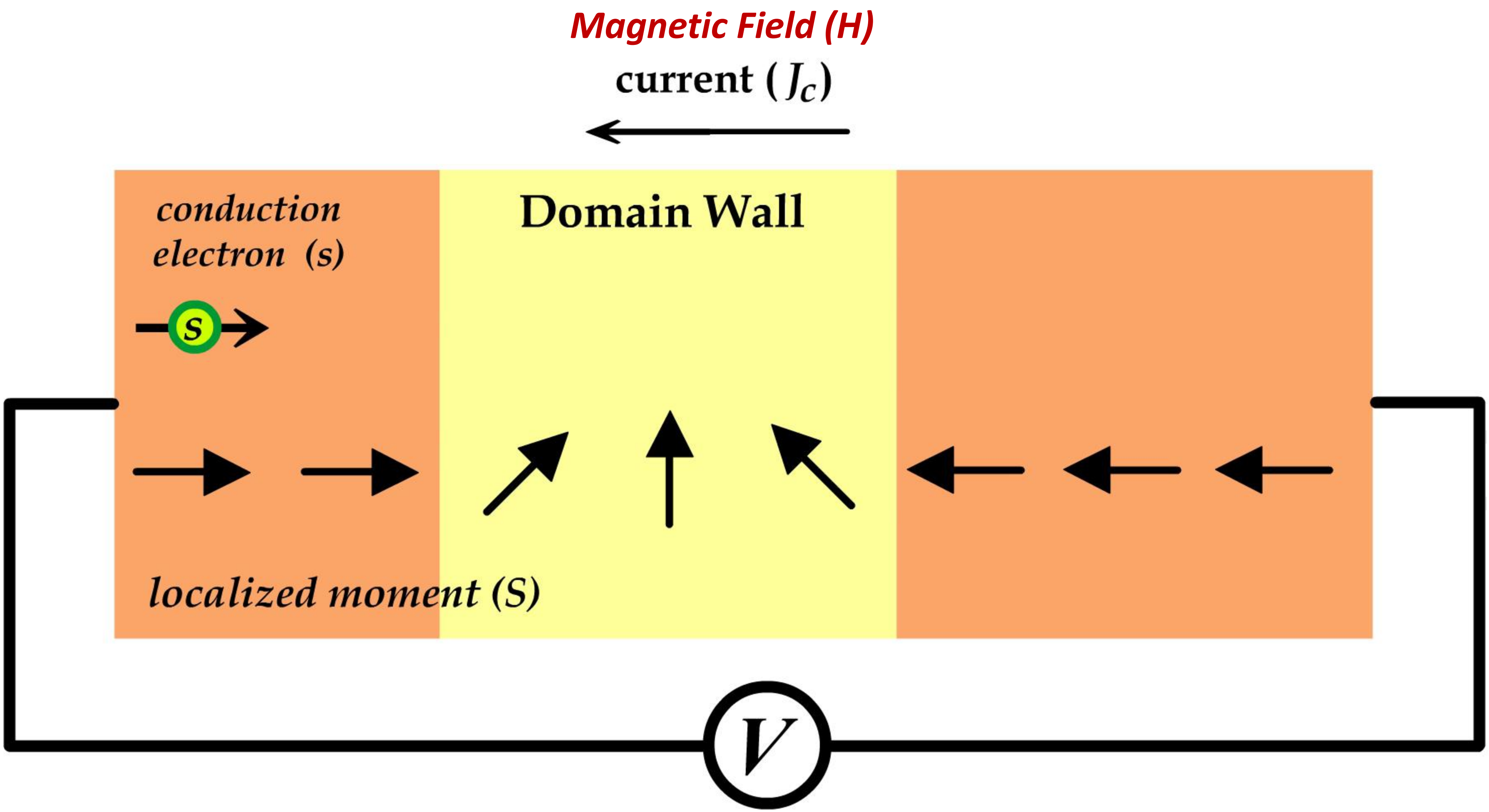
Spin magnetic field: $$B_{i\mathrm{s}} = -\epsilon_{ijk} \frac{\hbar}{4e} \boldsymbol{m} \cdot \left(\frac{\partial \boldsymbol{m}}{\partial x_j} \times \frac{\partial \boldsymbol{m}}{\partial x_k} \right)$$

Spin force:

$$\boldsymbol{f}_{\mathrm{nc}} = -\frac{P\hbar}{2} \boldsymbol{m} \cdot \left(\frac{\partial \boldsymbol{m}}{\partial t} \times \nabla \boldsymbol{m} \right)$$

Current-driven domain wall motion:

$$\theta = 2\cot^{-1} e^{-(z-z_0)/w}$$

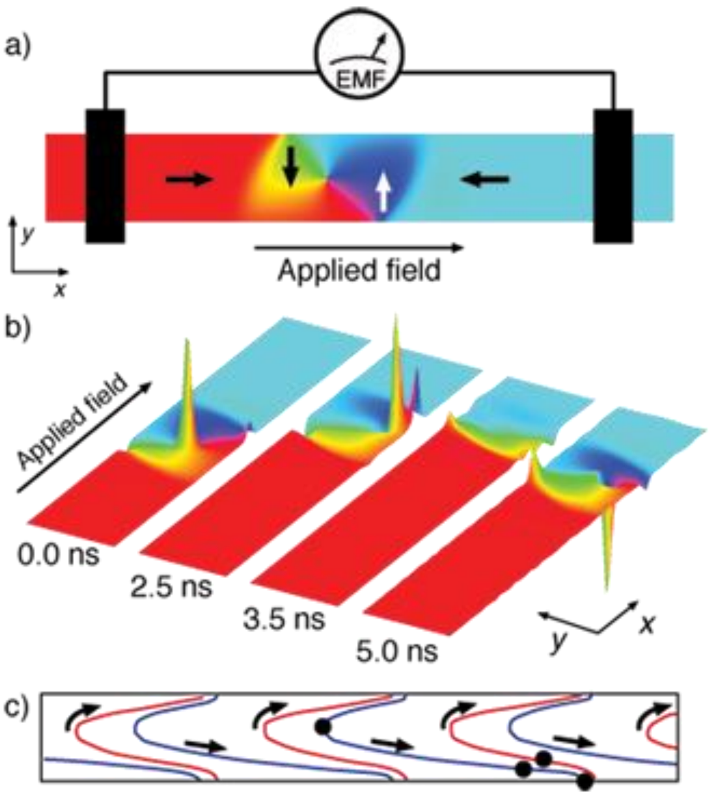


Domain wall motion by current: Spin transfer torque (STT),
Electric voltage by domain wall motion: Spin motive force (SMF).

STT and SMF are the front and back of a coin

SMF Case (1):

emf due to domain wall motion



$$\mathcal{E}_s = \frac{\hbar}{e}\frac{d\phi}{dt} = \frac{g\mu_B}{e}H$$

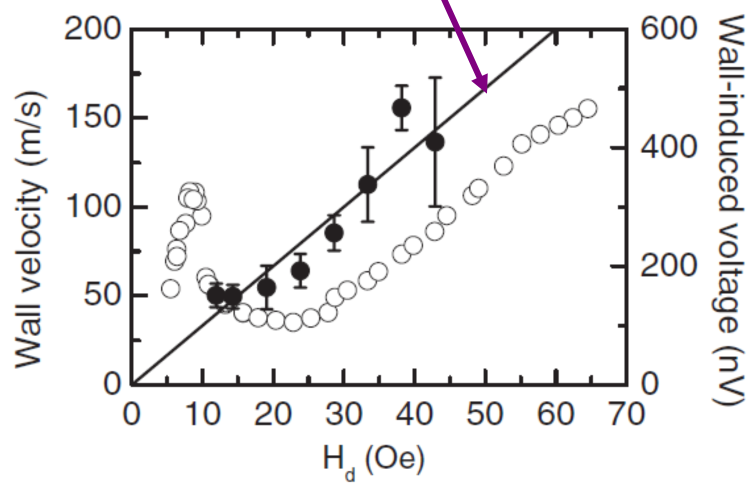


FIG. 4. Measured wall velocity (open symbols) and wall-induced voltage (solid symbols) versus drive-field. Solid line is fit with slope 10 nV/Oe.

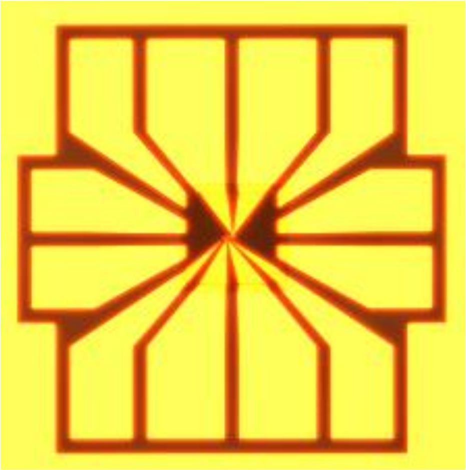
Electromotive force due to domain wall motion in a NiFe nanowire.

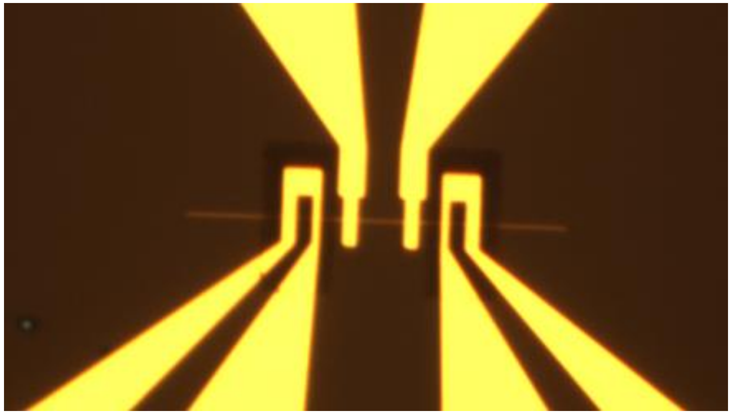
Yang et al., PRL **102,** 067201 (2009)

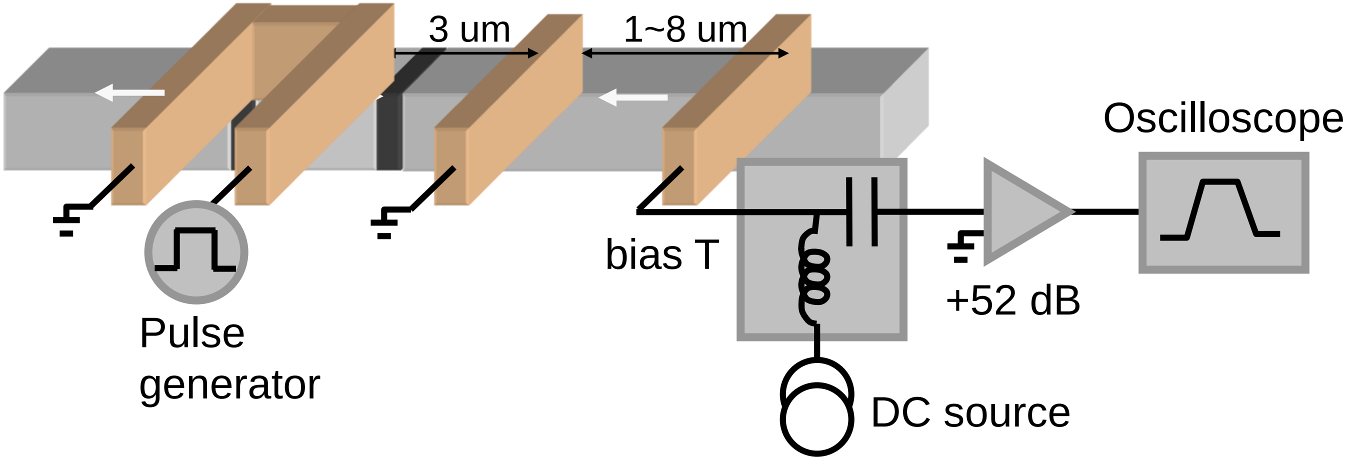
M. Hayashi et al:**PRL 108**, 147202 (2012)

(Real Time observation)

- Permalloy nanowires: e-beam lithography
- Dimension: 100-600 nm wide, 10-20 nm thick

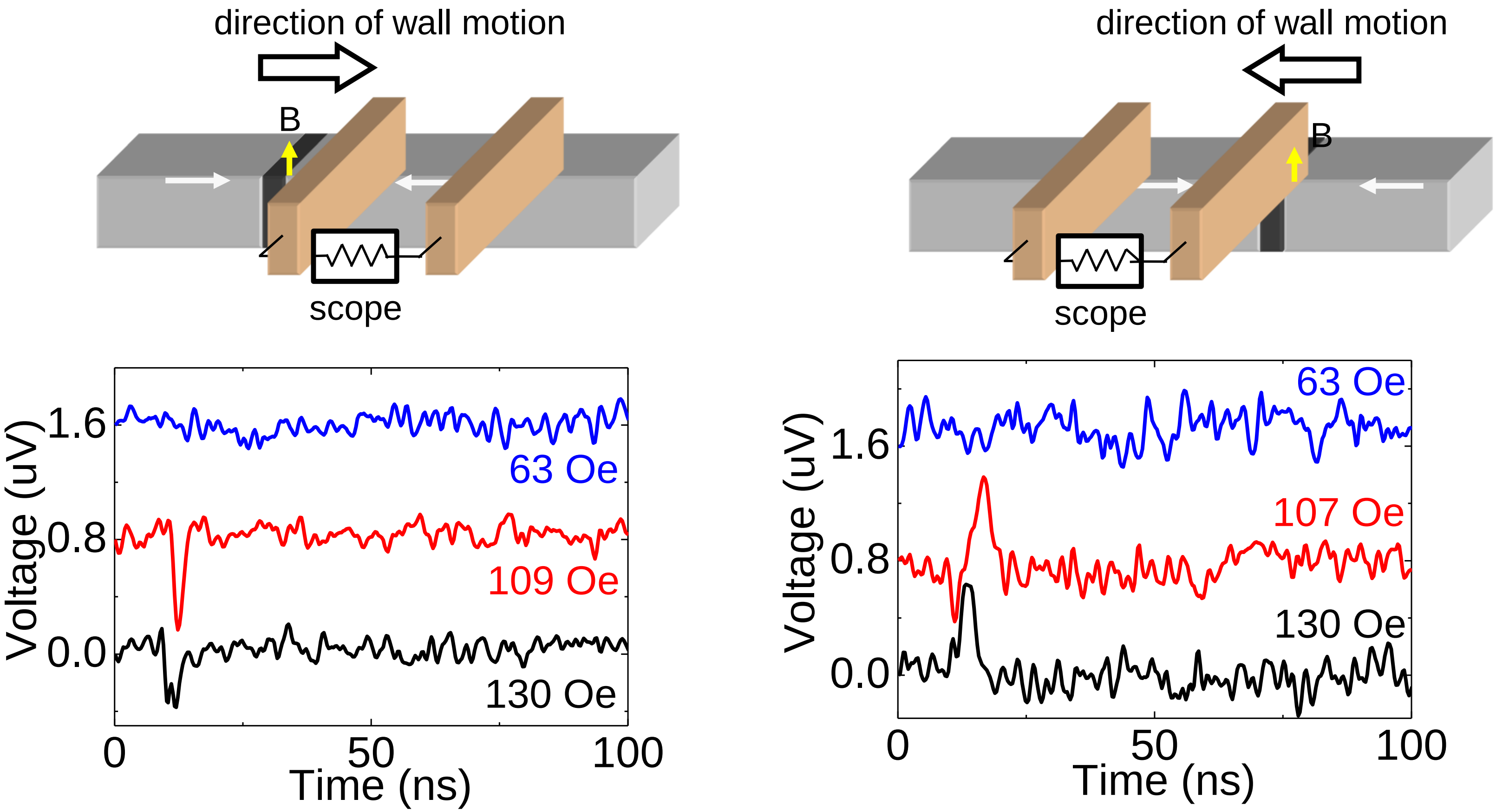






M. Hayashi et al:**PRL 108**, 147202 (2012)

Sign of the voltage: Left moving vs. right moving DW



- Sign of the voltage reverses when the motion direction is altered

Real Time observation ！

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21st Century

Energy Interconversion

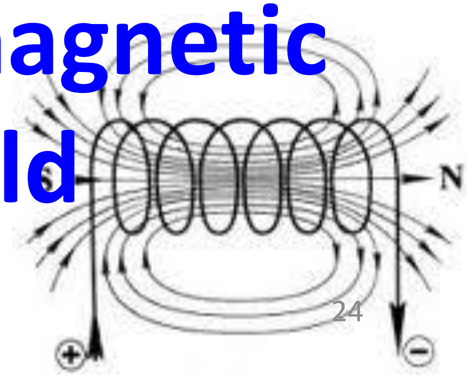
Heat ⟷ **Electricity**

Seebeck effect (1821)

Spin-Seebeck effect

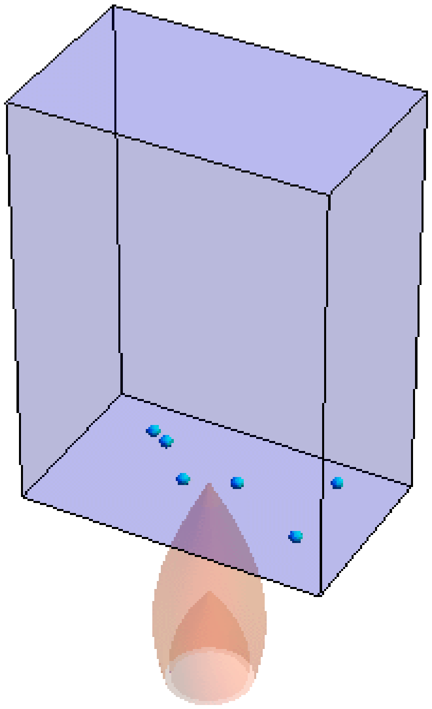
Magnet

Electromagnetic field



Seebeck effect, spin Seebeck effect

Boiling of water



Boiling of electrons
(Seebeck effect)

Boiling of spin current
(spin Seebeck effect)

Interactions for spin current:

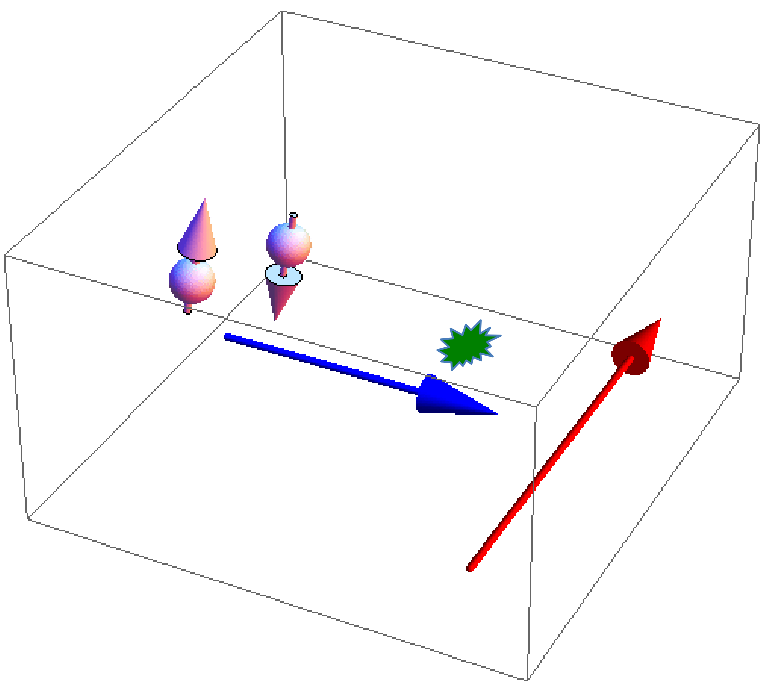
1. **Exchange interaction between magnetic moment and conduction electrons** (*sd* exchange interaction (J_{sd})),
2. **Spin-orbit interaction in conduction electrons (SOI),**
3. **Spin-rotation coupling (SRC).**

↓

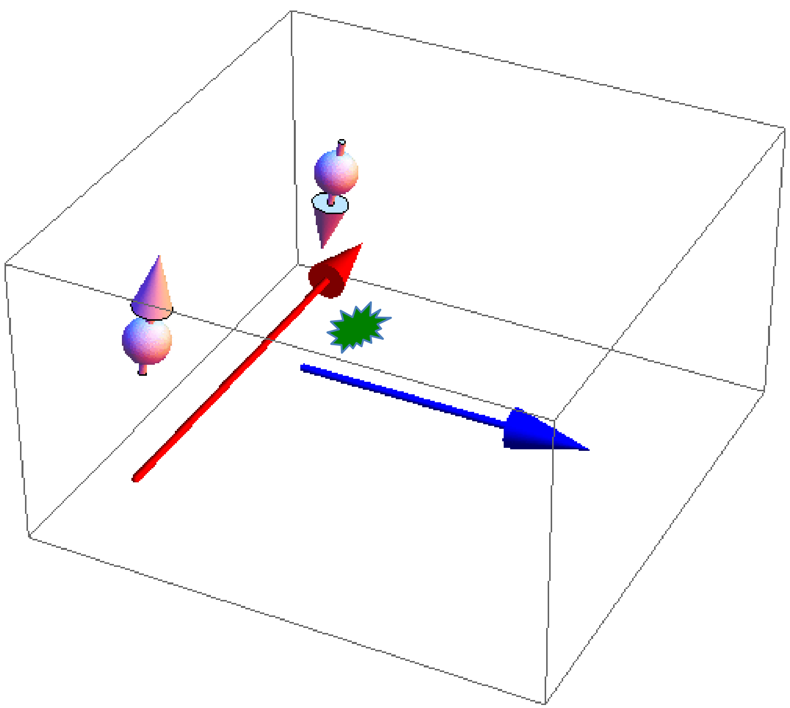
A variety of phenomena in spintronics.

Spin Hall effect

Interconversion of electric current and spin current
(via spin-orbit interaction)



Electric current
→Spin current



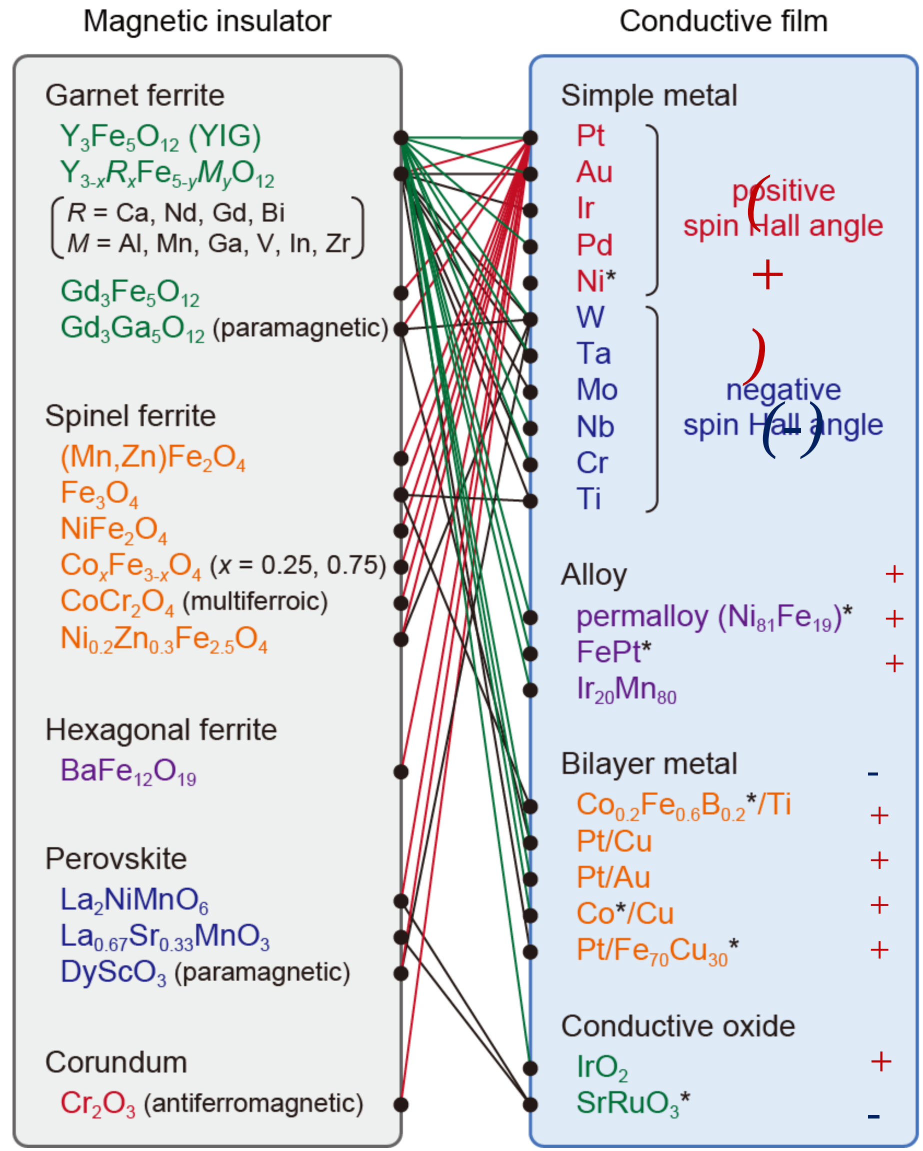
Spin current
→Electric current

Combination of magnetic insulators and conductive films used for measuring SSE

SSE is a universal phenomenon in magnetic materials

Model system:

Pt/$Y_3Fe_5O_{12}$ (YIG) junction



K. Uchida, H. Adahci, T. Kikkawa, A. Kirihara, M. Ishida, S. Yorozu, S. Maekawa, and E. Saitoh, "Thermoelectric generation based on spin Seebeck effects" (IEEE Proc. <u>106</u>,1946, (2016)).

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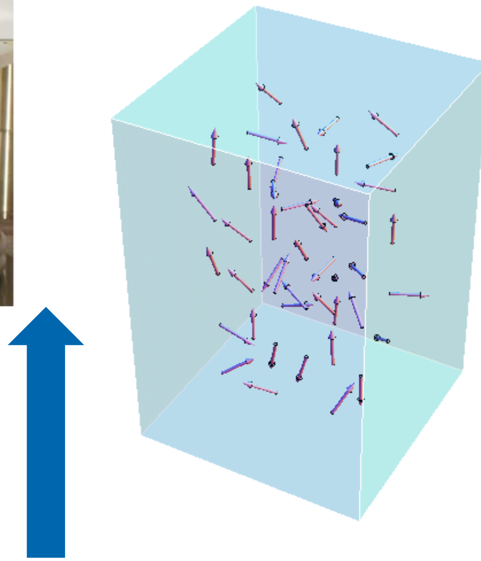
5.Spin mechatronics due to spin-rotaton coupling.

Fundamental phenomena (1915)

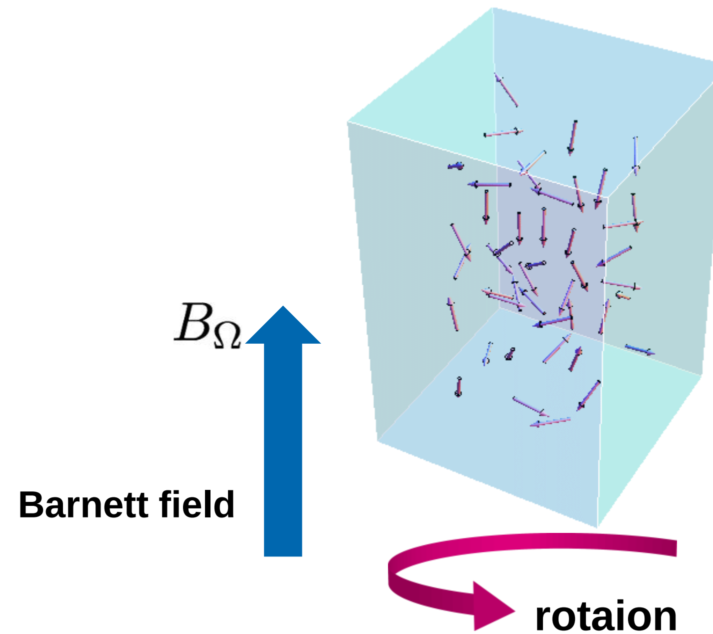
$$\mathcal{H} = -S \cdot \Omega$$

Einstein-de Haas effect



magnetism → rotation

Barnett effect



rotation → magnetism

Derivation of spin-rotation coupling

Dirac equation

$$\left[\gamma^{\mu}\left(p_{\mu}-\mathbf{i}\hbar\Gamma_{\mu}\right)-mc\right]\psi=0$$

γ^{μ} :gamma matrix m :mass
q :charge c :velocity of light

Spin connection

$$\Gamma_{\mu}=-\frac{1}{4}\bar{\gamma}_{\alpha}\bar{\gamma}_{\beta}e_{\nu}^{(\alpha)}g^{\nu\lambda}\left[\partial_{\mu}e_{\lambda}^{(\beta)}-\frac{1}{2}g^{\sigma\eta}\left(\partial_{\nu}g_{\eta\mu}+\partial_{\mu}g_{\eta\nu}-\partial_{\eta}g_{\mu\nu}\right)e_{\sigma}^{(\beta)}\right]$$

$e_{\mu}^{(\alpha)}$:vierbine $g^{\mu\nu}$:metric

low energy limit

$$\mathcal{H}=\frac{p^2}{2m}-(\boldsymbol{r}\times\boldsymbol{p})\cdot\boldsymbol{\Omega}-\frac{\hbar}{2}\boldsymbol{\sigma}\cdot\boldsymbol{\Omega}$$

Non-relativistic limit

$$\mathcal{H}_0=\frac{p^2}{2m}$$

$$U=\exp\left(\mathbf{i}\boldsymbol{J}\cdot\boldsymbol{\Omega}t/\hbar\right)$$

$\boldsymbol{J}=\boldsymbol{r}\times\boldsymbol{p}+\boldsymbol{S}$ total angular momentum

$$\mathcal{H}=U\mathcal{H}_0U^{\dagger}-\mathbf{i}\hbar U\frac{\partial U^{\dagger}}{\partial t}=\frac{p^2}{2m}-(\boldsymbol{r}\times\boldsymbol{p})\cdot\boldsymbol{\Omega}-\boldsymbol{S}\cdot\boldsymbol{\Omega}$$

Derivation of spin-rotation coupling

Non-relativistic limit

$$\mathcal{H}_0 = \frac{p^2}{2m} \quad \Leftarrow \quad U = \exp\left(\mathbf{i}\boldsymbol{J}\cdot\boldsymbol{\Omega}t/\hbar\right)$$

$\boldsymbol{J} = \boldsymbol{r}\times\boldsymbol{p} + \boldsymbol{S}$ total angular momentum

$$\mathcal{H} = U\mathcal{H}_0U^\dagger - \mathbf{i}\hbar U\frac{\partial U^\dagger}{\partial t} = \frac{p^2}{2m} - (\boldsymbol{r}\times\boldsymbol{p})\cdot\boldsymbol{\Omega} \boxed{-\boldsymbol{S}\cdot\boldsymbol{\Omega}}$$

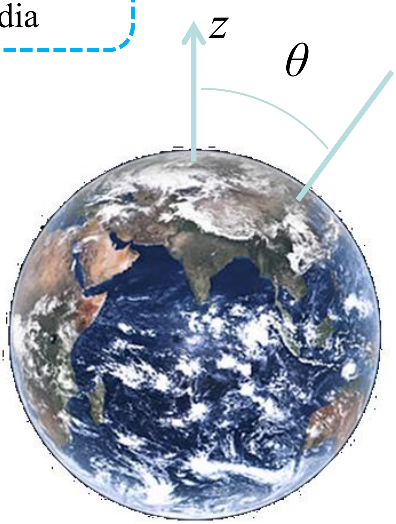
We need to observe the Barnett field in the rotating frame!!

Foucault Pendulum

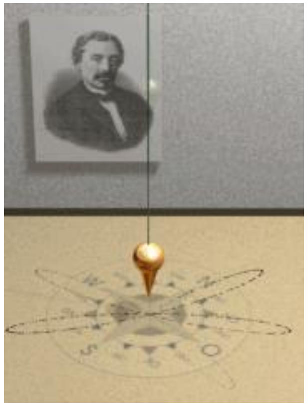
Period (day) = 1day/sin φ (φ: latitude)
cf. wikipedia

Rotation freq.(Earth) Ω = 1 round/day,
$\varphi = 90° - \theta$, $\sin(\pi/2-\theta)=\cos\theta$

Rotation freq. = $\Omega\cos\theta$



$$\mathcal{H} = -L\cdot\Omega$$



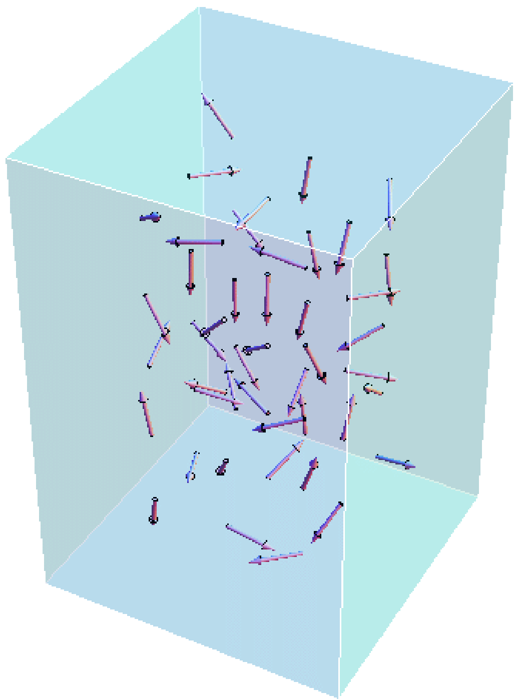
Foucault pendulum in the Southern Hemisphere
（Reverse in the Northern Hemisphere）

Rotation couples to angular momentum:

$$\mathcal{H} = -\boldsymbol{L}\cdot\boldsymbol{\Omega}$$

Ω : angular velocity of rotation

L : angular momentum



Magnetic field couples to magnetic moment:

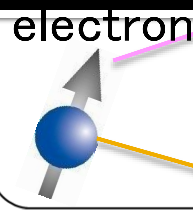
$$\mathcal{H} = -\boldsymbol{S}\cdot\boldsymbol{\Omega} \equiv -\mu\cdot\boldsymbol{B}_\Omega$$

μ: magnetic moment

$$\boldsymbol{\mu} = \gamma\boldsymbol{S},\ \boldsymbol{B}_\Omega = \frac{\boldsymbol{\Omega}}{\gamma}$$

γ: gyromagnetic ratio

Electron: Spin and Charge

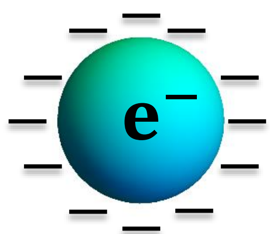


σ spin

e^- charge

Electron charge

～「ball of charge」

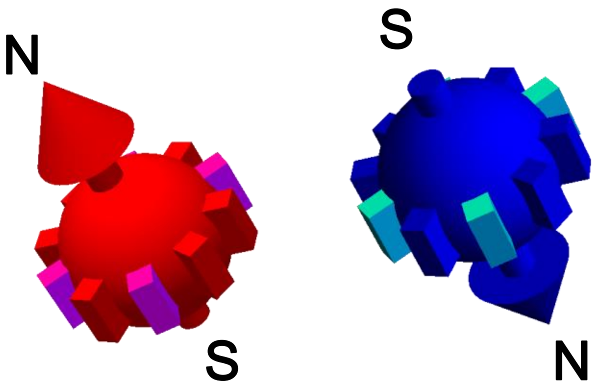


Negative charge

⇒ electricity

Spin: angular momentum

～「rotor」

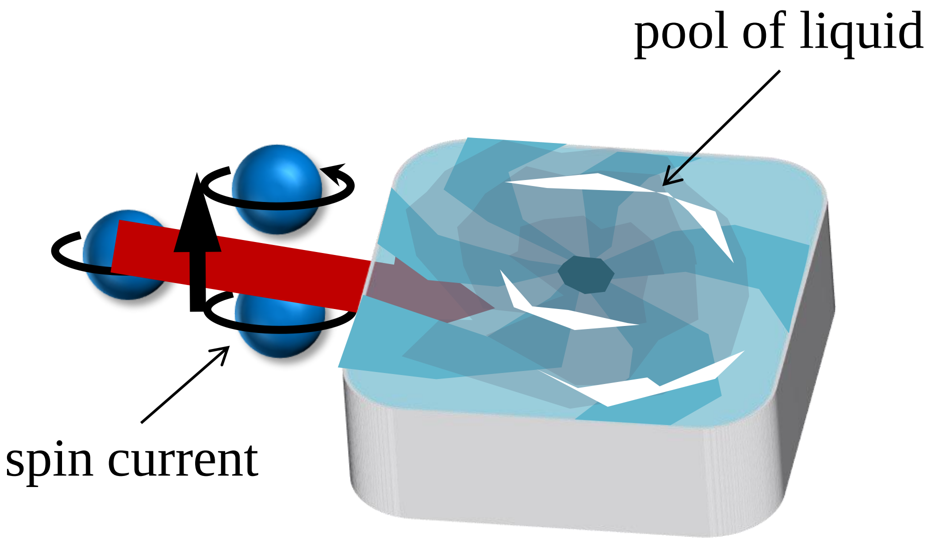


Right rotation   Left rotation

⇒magnetism, rotational motion

Electron ＝ microscopic rotor

spin current injection into liquid

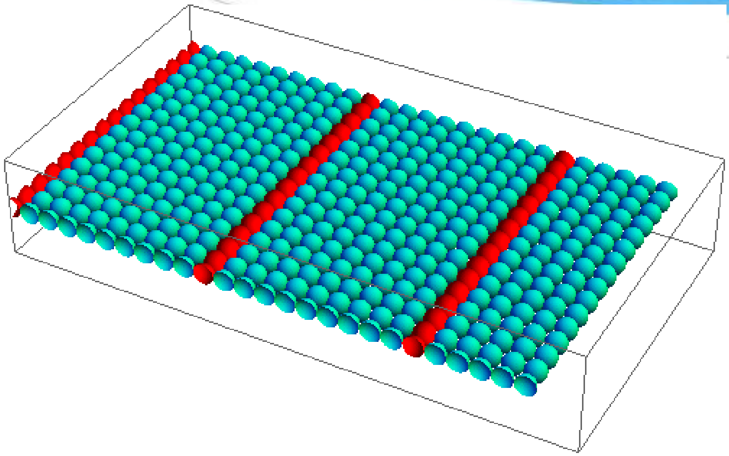


electron spin is a kind of rotation

→ Spins create a whirl!!

spin current generation from fluid motion

Rotation motion can be created by a flow of liquid metals such as Hg



empirical velocity distribution in a pipe

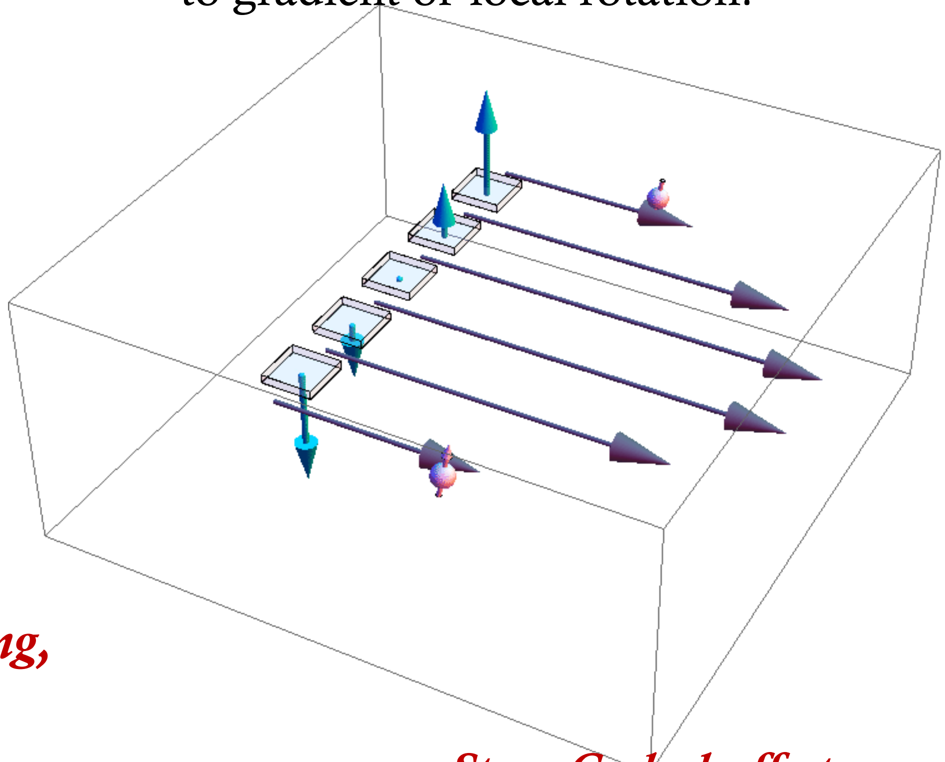
there are local rotational motions (vorticity)

***H* = S ・Ω: spin-rotation coupling,**

***v(r)* : velocity of liquid metal,**

$\Omega = \nabla \times v$ (vorticity)

Spin current is induced parallel to gradient of local rotation.

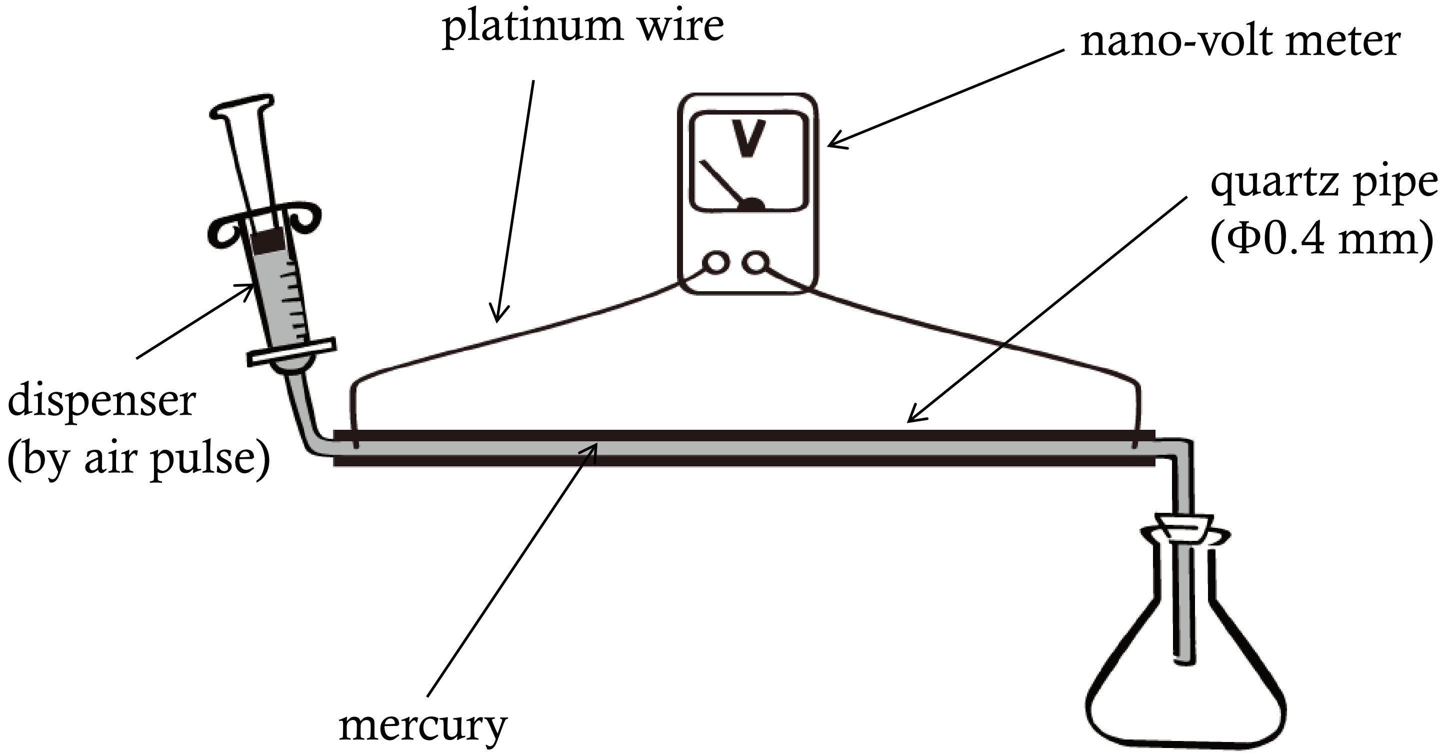


Stern-Gerlach effects:

$F_s = \nabla \cdot B$

$= \nabla \cdot \Omega$

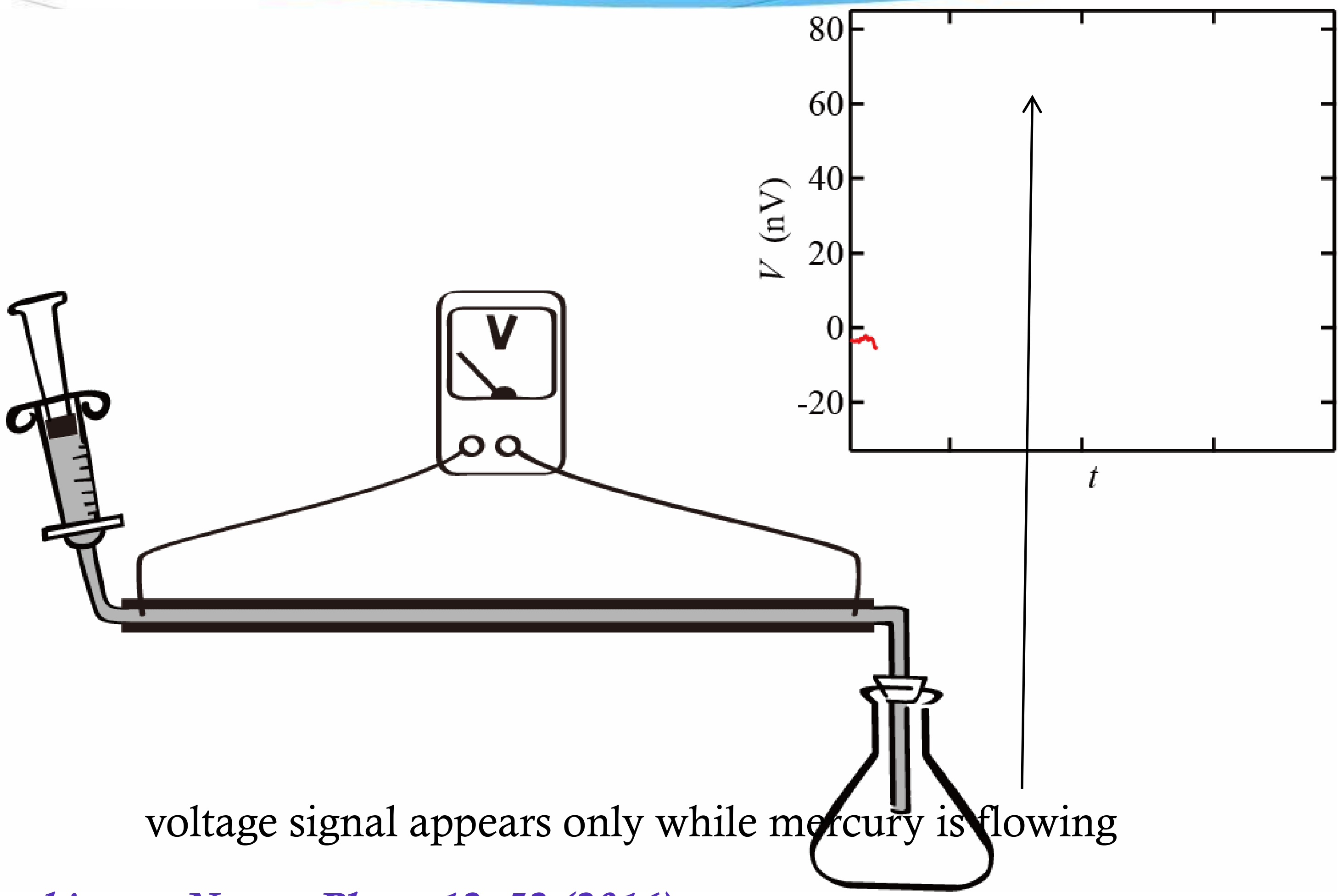
Experimental setup



R.Takahashi et a., Nature Phys., 12, 52 (2016).

overview

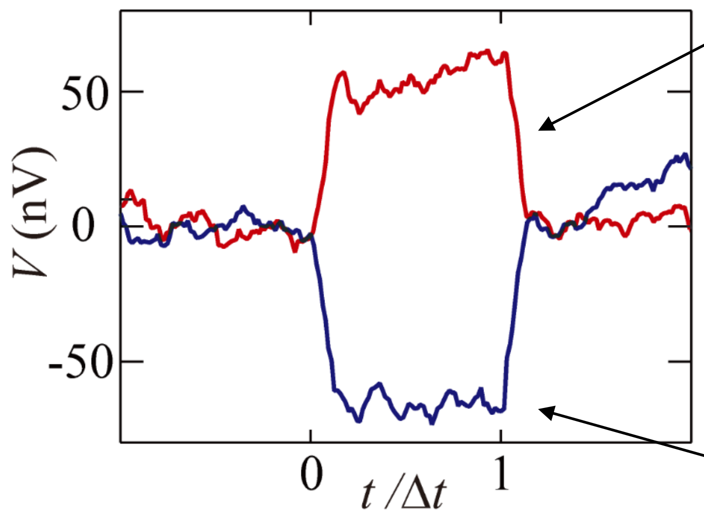
measurement result

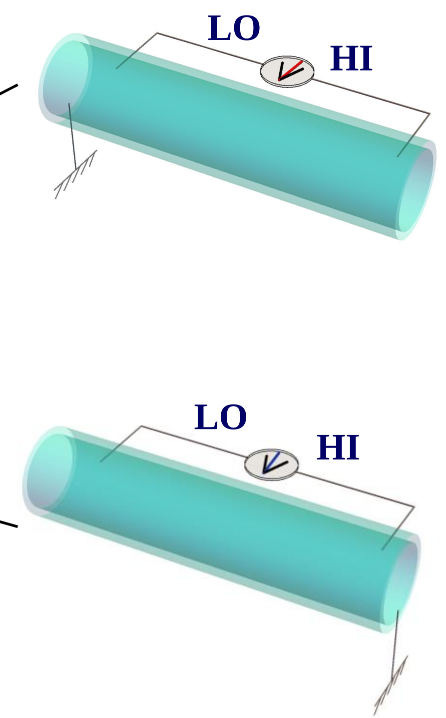


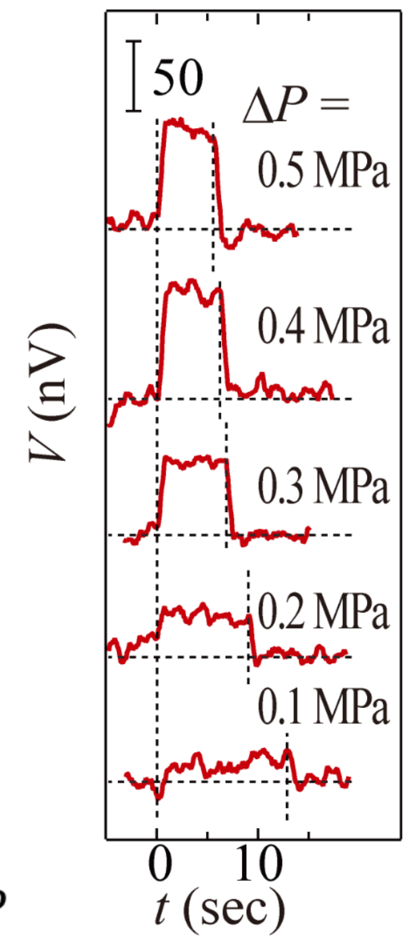
voltage signal appears only while mercury is flowing

R.Takahashi et a., Nature Phys., 12, 52 (2016).

Result 1 -SHD Signal Measurement







Δt 5.9 sec, 2.7 m/s

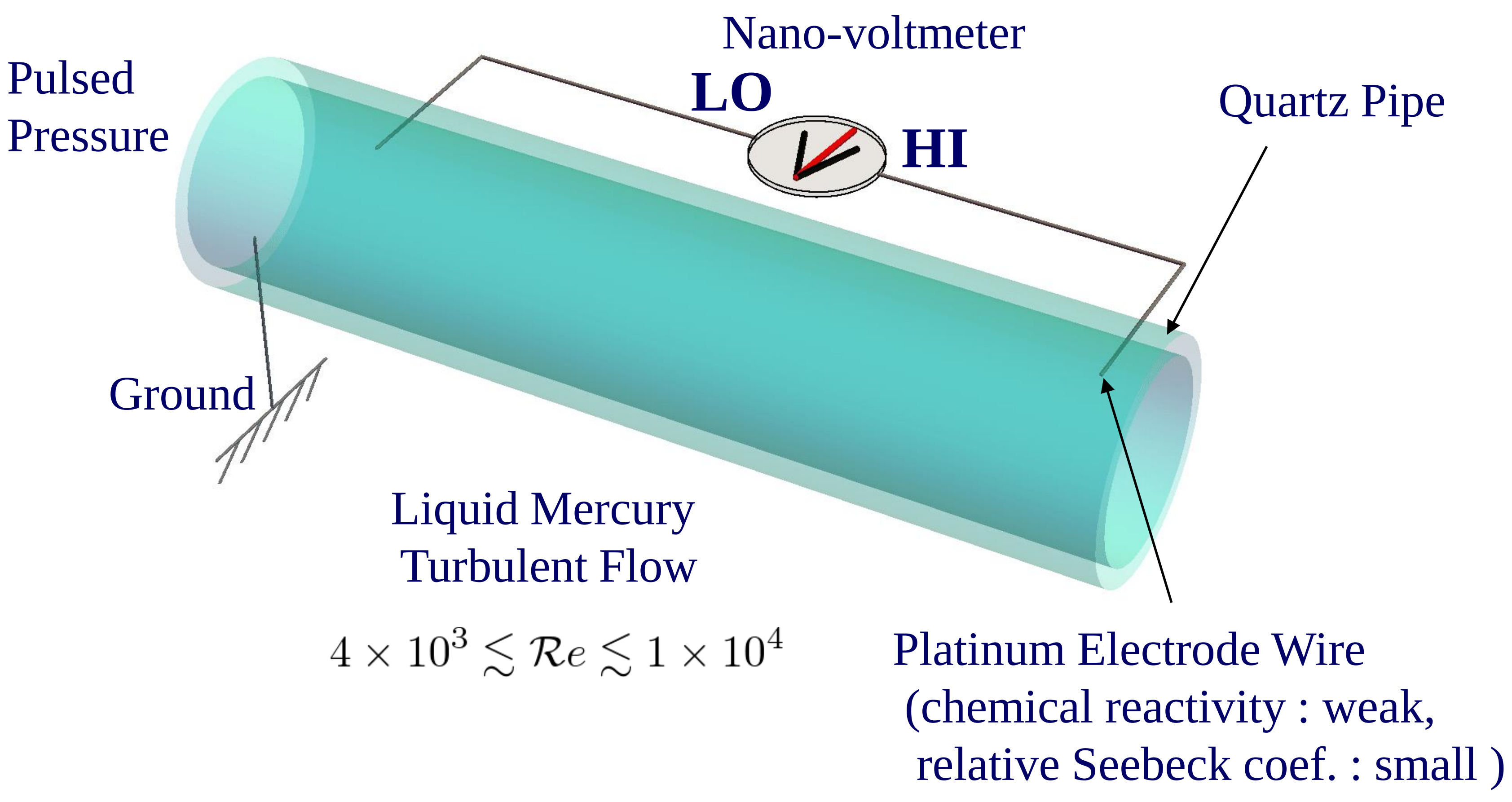
Internal Diameter ϕ 0.4 mm

Length L 80 mm

- Signal is reversed by reversing the flow direction
- Signal increases with increasing pulsed pressure ΔP

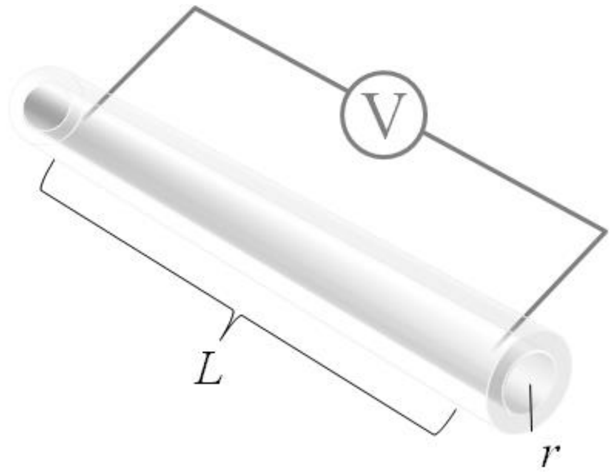
Spin current ⇄ Mechanical motion!!

Experimental setup for Spin hydrodynamic generation

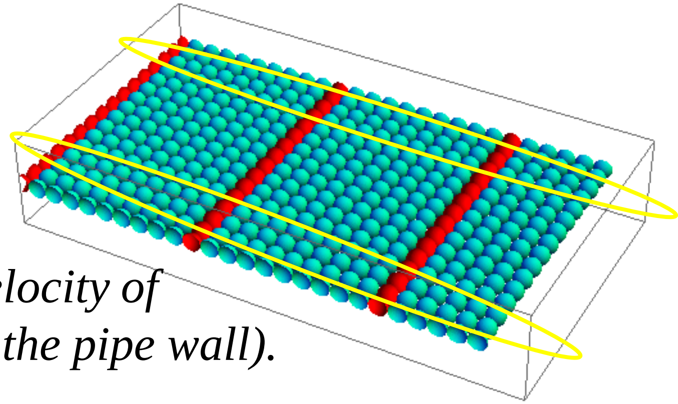


Electric voltage due to spin current

- ✓ *Fluid dynamics*
- ✓ *Spin dynamics*
- ✓ *Spin Hall effect*



$$V_{\rm ISHE} \sim \left(\frac{4e}{\kappa\hbar}\frac{\theta_{\rm SHE}\lambda_{\rm sf}^2\zeta}{R_\delta \nu\sigma}\right)\left(\frac{L}{r}v_*^2 - R_\delta \nu \frac{L}{r^2}v_*\right)$$



κ: Karman constant
ν: dynamic viscosity
θ_{SHE}: spin hall angle
σ: conductivity
λ_{sf}: spin diffusion length
R_δ: sublayer Reynolds number
ς: modification of ν

v is the so-called friction-velocity of turbulent flow (velocity near the pipe wall).*

spin current is mainly generated in the vicinity of the pipe wall.

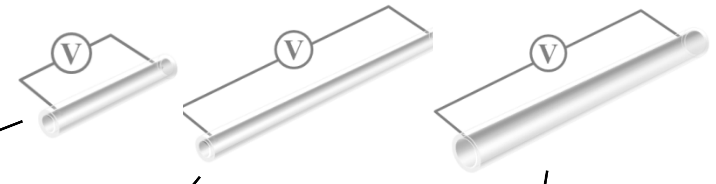
pipe size dependence measurement

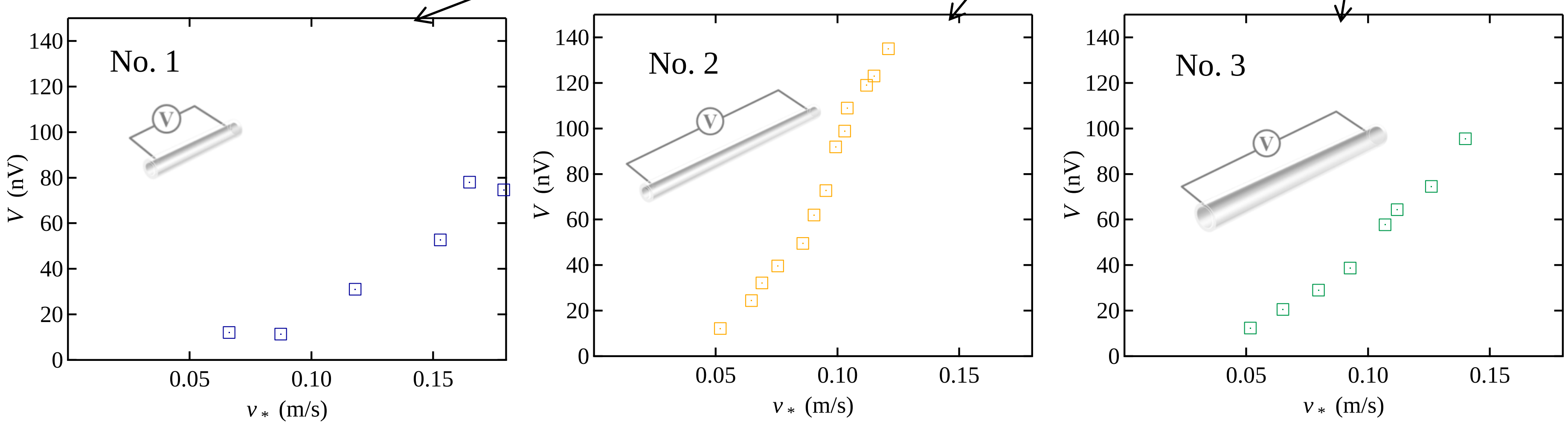
$$V \propto \frac{L}{r} v_* \left(v_* - \frac{R_\delta \nu}{r} \right)$$

$$V r^3 / L \propto v_* r (v_* r - R_\delta \nu)$$

scale independent relation

No.	1	2	3
r	0.2 mm	0.2 mm	0.5 mm
L	82 mm	400 mm	400 mm





pipe size dependence measurement

$$V \propto \frac{L}{r} v_* \left(v_* - \frac{R_\delta \nu}{r} \right)$$

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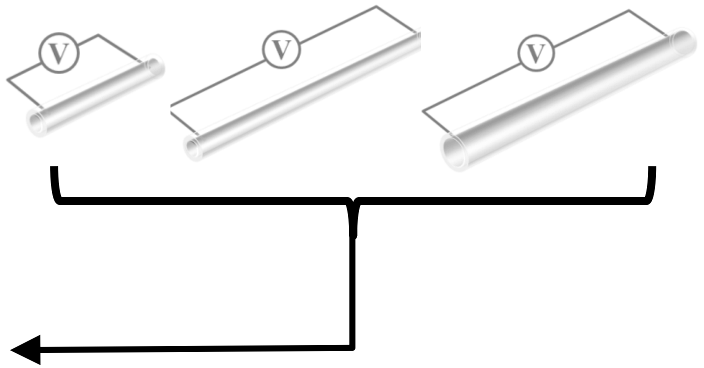
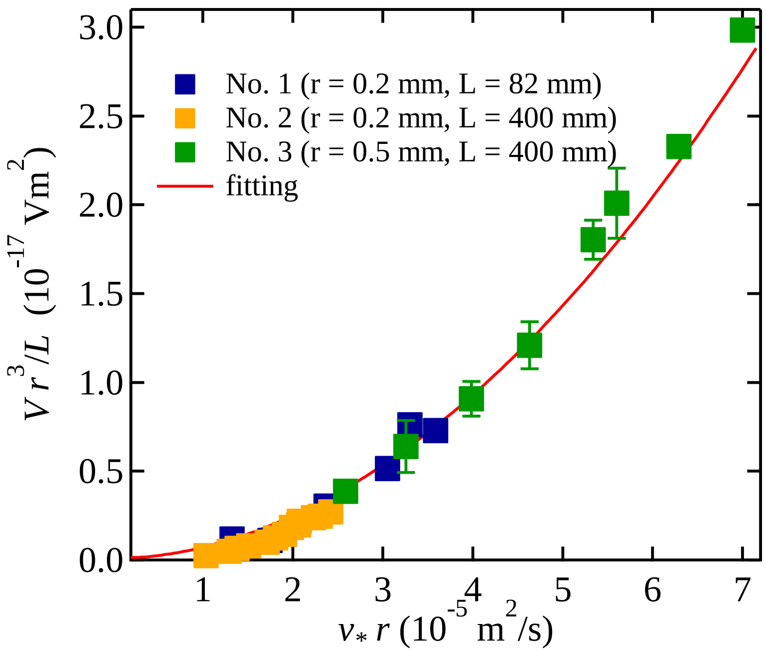
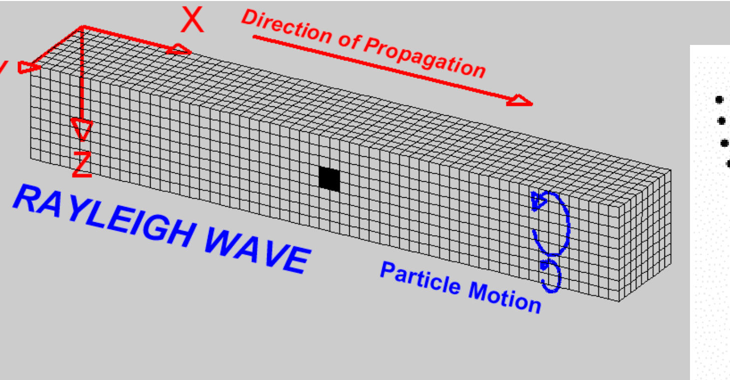




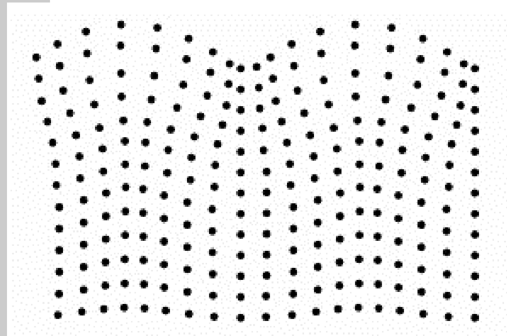
All results can be fitted by the same parameter set

$$V \propto \nu^2$$

Angular momentum in phonons ～surface phonons～

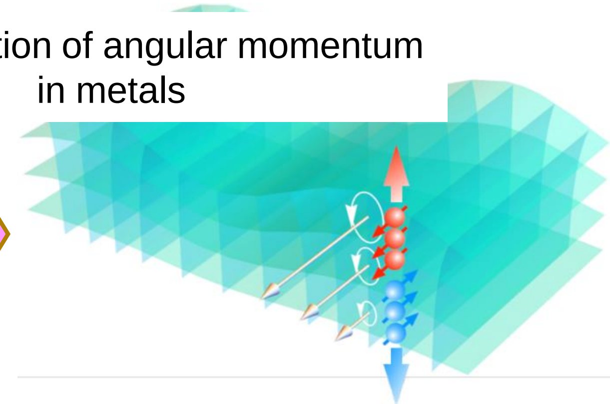


Rayleigh wave



Lattice motion

Injection of angular momentum
in metals



Spin current

acteristics:

- Elliptical motion of lattice
- Lattice rotation（～GHz）near surface (~μm)
- Long distance（~mm）
- Rayleigh wave in metal thin films

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Mechanical generation of spin current by spin-rotation coupling

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Whirlpool