KITS Workshop (May 4-6, 2018)

"Spin Mechatronics"
- Mechanical effects on Spintronics -

***Message**: mechanical rotation provides*
A new degree of freedom in quantum matter!!

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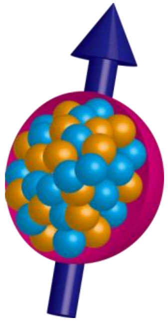
1. Riken Center for Emergent Matter Science, Wako, Japan,
2. Kavli Institute for Theoretical Sciences,, Beijing, China.

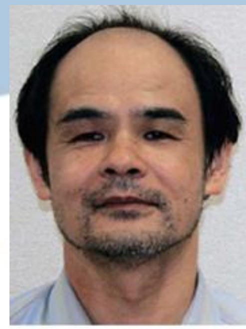


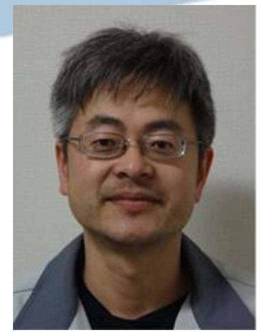
In collaboration with
M.Matsuo and Y.Ohnuma (KITS, Beijing),
Talk by M.Matsuo on May 6.

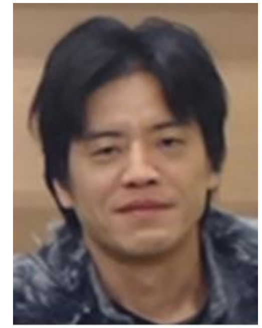
Collaborators (ASRC, JAEA)

Experiment


E. Saitoh

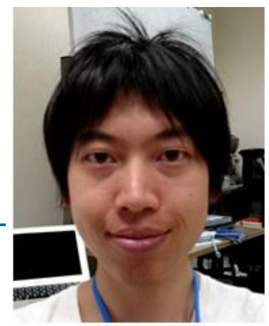

S. Okayasu


M. Ono


H. Chudo


K. Harii

→ **U. of Tokyo** (E. Saitoh)


Y. Ogata

Toshiba ← (Y. Ogata)


M. Imai


R. Takahashi

→ ***Ochanomizu U.*** (R. Takahashi)

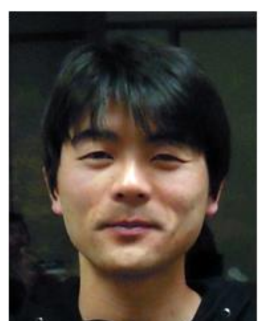
Theory

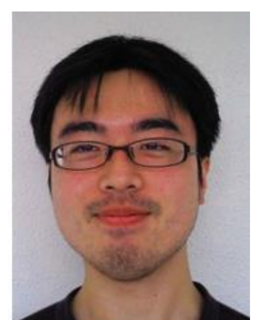
Riken, Kavli ↑ (S. Maekawa)

Kavli ↑ (M. Matsuo)


S. Maekawa


M. Matsuo


J. Ieda


Y. Ohnuma

→ ***Kavli*** (Y. Ohnuma)

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1. Introduction to spin mechatronics;
   Einstein-de Haas effect (1915) and Barnett effect (1915).
   New application of these effects.
   (M.Ono et al., Phys. Rev. B92, 174424(2015), Y. Ogata et al.,
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2. Spin hydrodynamic generation in liquid metals.
   New electric generation based on spintronics.
   (R.Takahashi et al., Nature Phys. **12**,52 (2016)),
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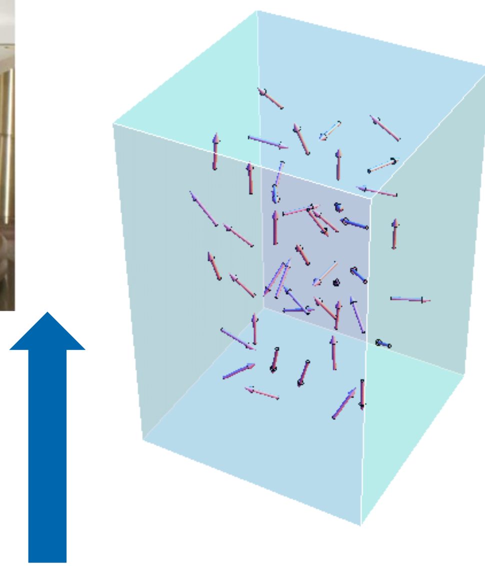
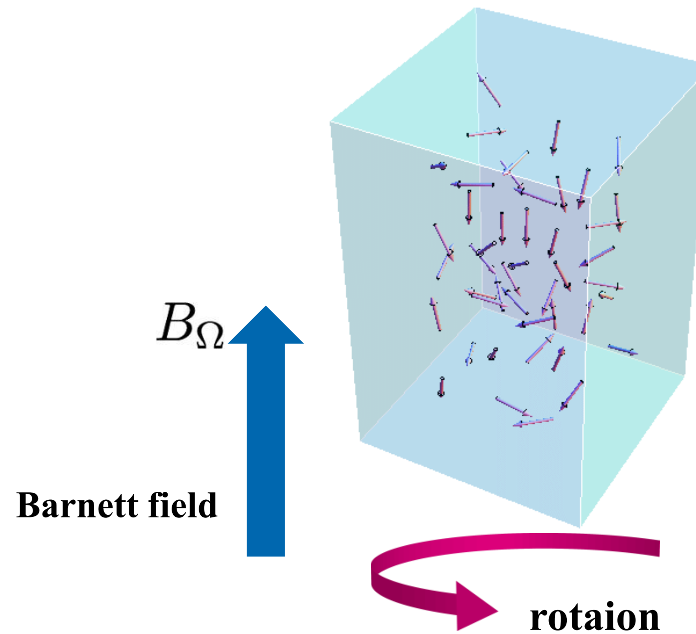
Angular momentum conservation between electrons and mechanical motion:

Einstein-de Haas effect(1915)



magnetism → rotation

Barnett effect(1915)



rotation → magnetism

Derivation of spin-rotation coupling

Dirac equation

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

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

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

Non-relativistic limit

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

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

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

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

spin-rotation coupling
due to angular momentum conservation:

Non-relativistic limit

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

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

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

No coupling constant!
Different from the spin Orbit coupling, which is of $1/m^2$

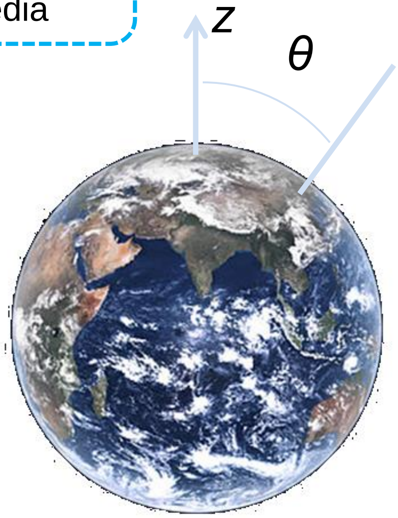
Rotation couples to Angular momentum!!
Magnetic field couples to Magnetic moment!!

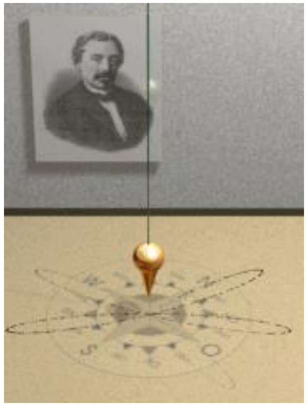
Foucault Pendulum

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

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

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



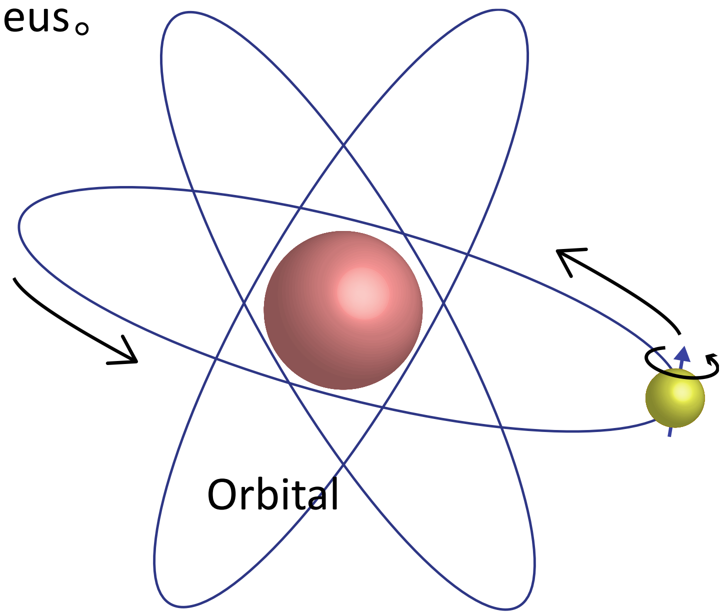


Foucault pendulum in the Southern Hemisphere
（Reverse in the Northern Hemisphere）

Electron：

Spin（S）：internal motion。

Ofrbital（L）：motion around a nucleus。



Total angular momentum of electron：

$\langle J \rangle = \langle S \rangle + \langle L \rangle$

Magnetic moment of electron：

$\langle \mu \rangle = \mu_B \langle 2S + L \rangle$

$2\mu_B \langle S \rangle$：

Spin magnetic moment

$\mu_B \langle L \rangle$：Orbital magnetic moment

$\mu_B = he/4\pi m_e$

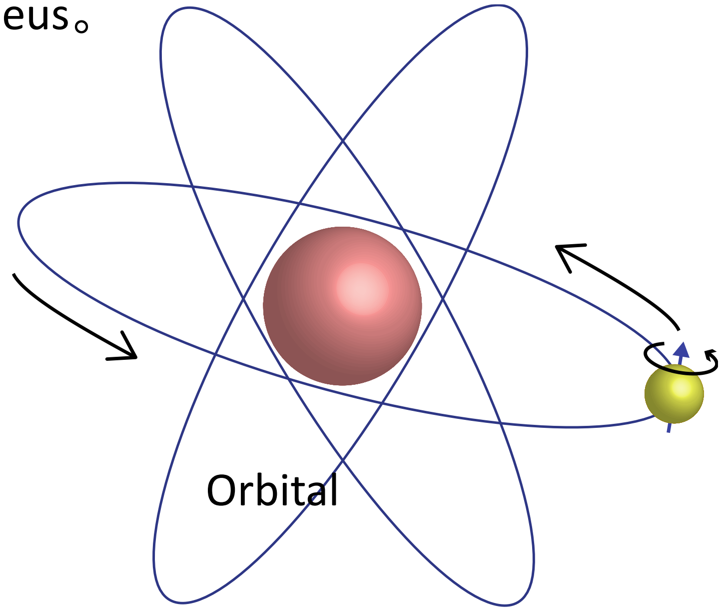
In 3d materials、the orbital angular momentum (L) is quenched by the crystal field.

↓

<L> recovers by the spin-orbit interaction！！

Application of Barnett effect:

Electron：
Spin（S）：internal motion。
Ofrbital（L）：motion around a nucleus。



Total angular momentum of electron：
$\langle J\rangle = \langle S\rangle + \langle L\rangle$

Magnetic moment of electron：
$\langle \mu\rangle = \mu_B\langle 2S + L\rangle$

$2\mu_B\langle S\rangle$：
Spin magnetic moment

$\mu_B\langle L\rangle$：Orbital magnetic moment

$\mu_B = he/4\pi m_e$

In 3d materials、the orbital angular momentum (L) is quenched by the crystal field.

↓

<L> recovers by the spin-orbit interaction！！

<u>This is observed by the Barnett effect</u>.

g and g' in 3d metals

Magnetic field couples to magnetic moment and gives g,
Rotation couples to angular momentum and gives g'!!

$$\langle L \rangle \approx \epsilon \langle S \rangle$$

ESR

spectroscopic g factor

$$\langle \mu \rangle = \mu_B \langle L + 2S \rangle = \mu_B \underbrace{(2 + \epsilon)}_{=:\, g} \langle S \rangle$$

Barnett effect, Einstein-de Haas effect

gyroscopic g factor

$$g' = \frac{\langle \mu \rangle}{\mu_B \langle J \rangle} = \frac{2 + \epsilon}{1 + \epsilon} \sim 2 - \epsilon$$

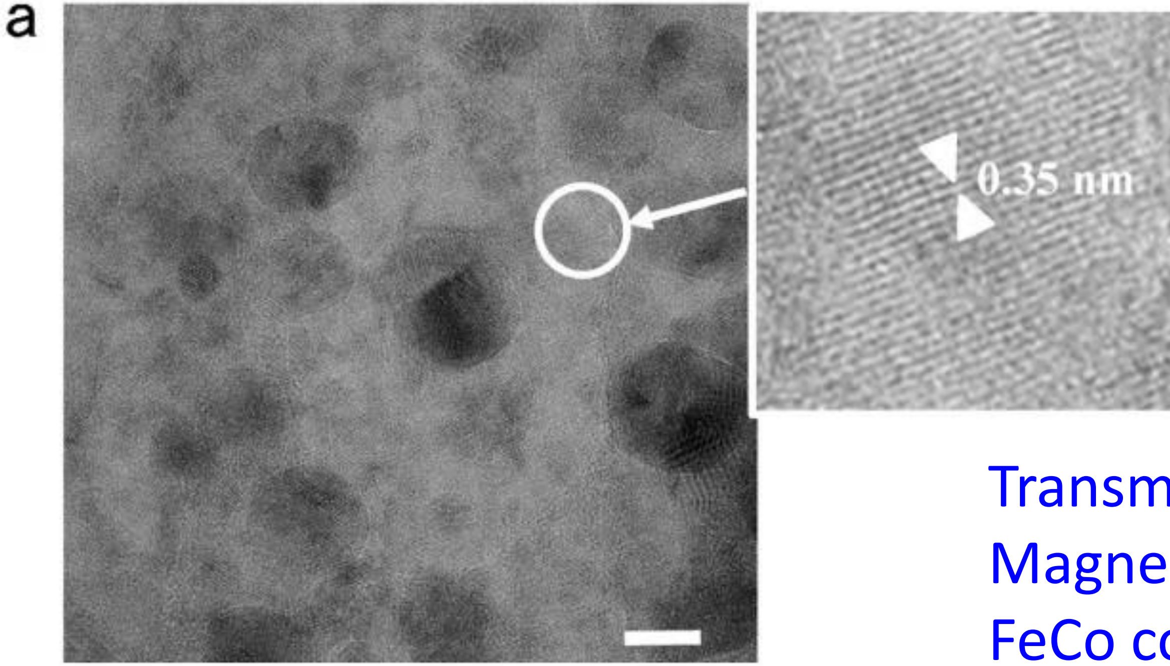
$$\langle J \rangle = \langle L + S \rangle = (1 + \epsilon) \langle S \rangle$$

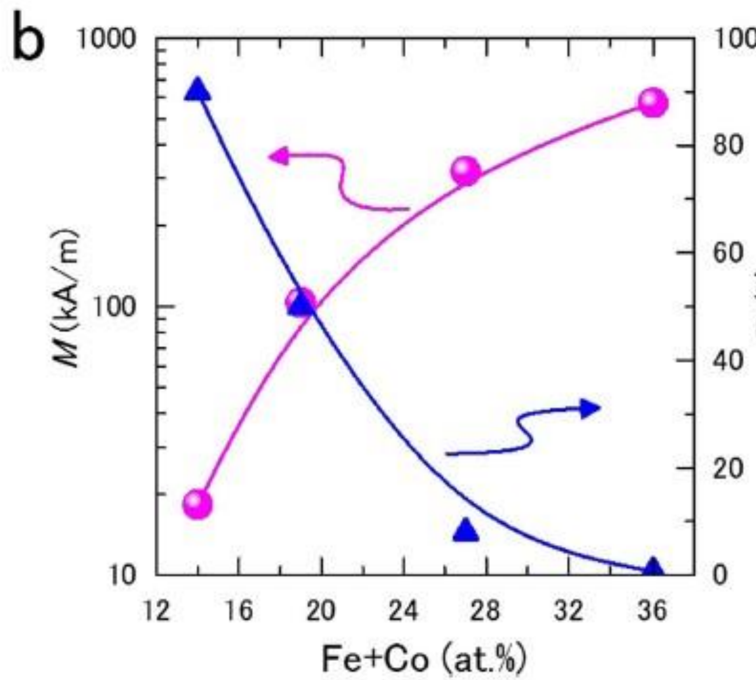
ε = 0.1 (Fe) and 0.21 (Co)

	Fe	Co
g	2.1	2.21
g'	1.92	1.85

C. Kittel, PR **76**, 743 (1948), D. Polder, PR **73**, 1116(1948), J. H. Van Vleck, Physica **15**, 197 (1949), J. H. Van Vleck, PR **78**, 266 (1950).

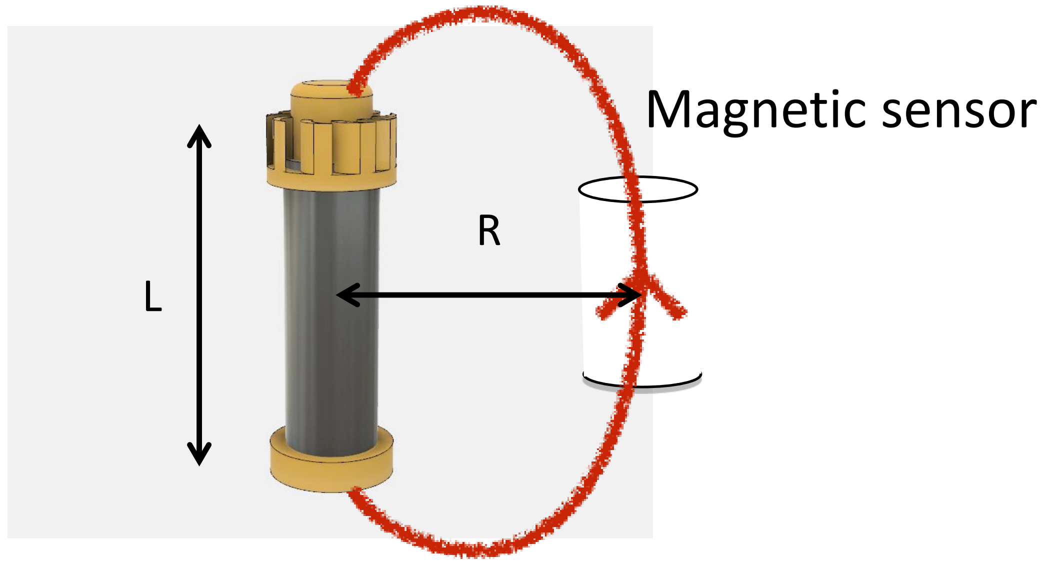
Transmittance and Magnetization vs. FeCo concentration In AlF_3:





Nano-Granuler magnets:
FeCo dispersed in MgF_2, AlF_3,etc.

Experimental set-up



Dipole model for the stray field

$$\Delta B = \frac{VM}{-4\pi\mu_0(R^2 + (L/2)^2)^{3/2}} \qquad M = \chi B_\Omega \qquad B_\Omega = \frac{\Omega}{\gamma}$$

V sample volume

χ susceptibility

Ω Rotation freq.

μ_0 : Bohr magneton

R : distance to sensor

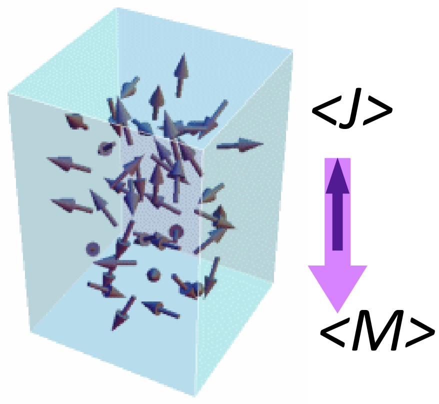
γ : gyromagnetic ratio

L : length of sample

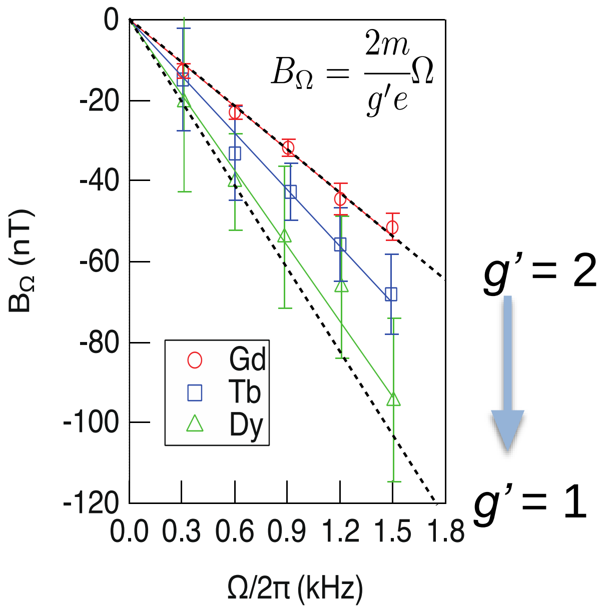
Barnett effect:

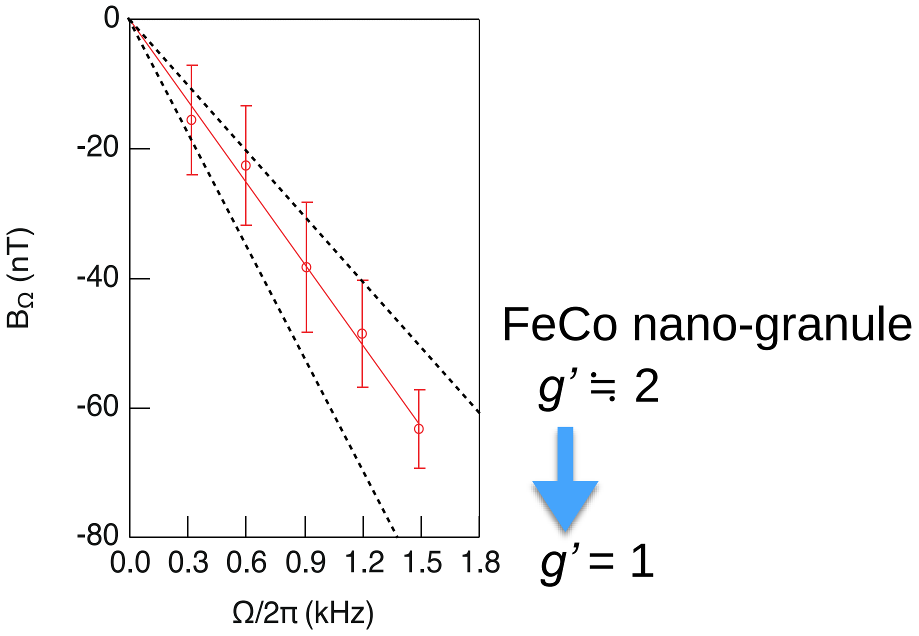
S. J. Barnett, Phys. Rev. 6, 239-270 (1915).

$$H_{\mathrm{SR}} = -\mathbf{J} \cdot \mathbf{\Omega}$$



Induced magnetic moment by rotation:





Rare earth metal:

Ogata *et al.*, APL(2017)

Nano-granular magnet: g' =1.76

Ogata *et al.*, JMMM (2017).

Contribution of Orbital : ε

	Fe(bulk)	Co(bulk)	FeCo-MgF
g	2.1	2.21	2.31
g'	1.92	1.85	1.76

Fe(bulk)

$$\epsilon = 0.1$$

Co(bulk)

$$\epsilon = 0.21$$

Spin Physics

FeCo-MgF

ESR

spectroscopic g factor

$$\langle \mu \rangle = \mu_B \langle L + 2S \rangle = \mu_B (2 + \epsilon) \langle S \rangle$$

$$(2+\epsilon) =: g$$

Barnett effect

gyroscopic g factor

$$g' = \frac{\langle \mu \rangle}{\mu_B \langle J \rangle} = \frac{2 + \epsilon}{1 + \epsilon}$$

FeCo-MgF:

$$g = 2.31 \qquad \epsilon = 0.31 \qquad g' = 1.76$$

Orbital is not a byplayer.

Orbital Physics!!

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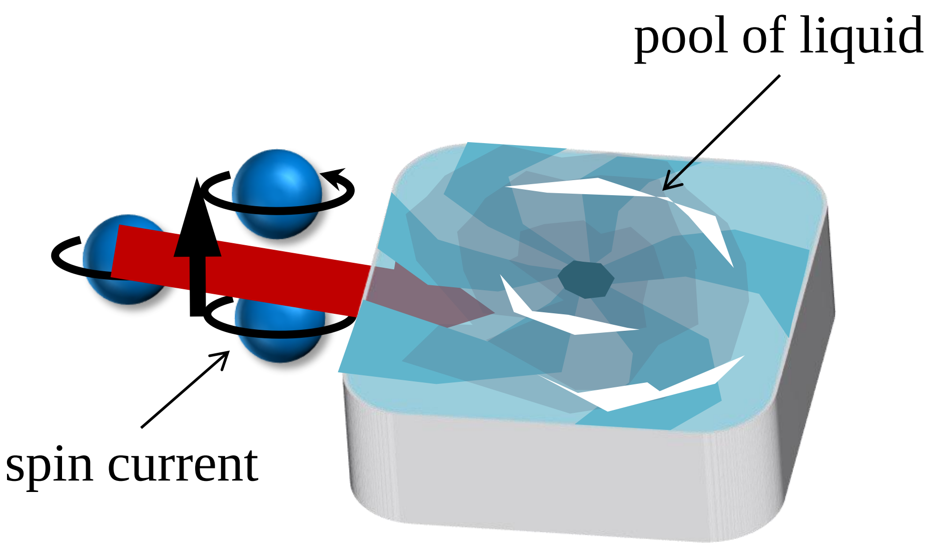
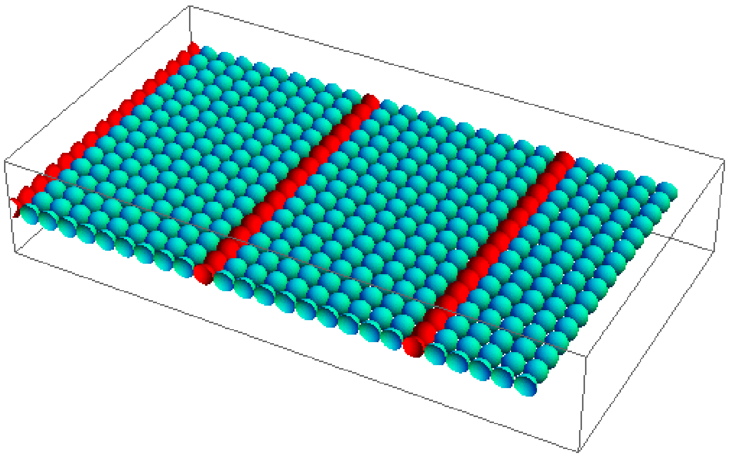
   (M.Matuo et al.,Phys. Rev. B (2017)).

spin current injection into liquid



An electron (spin) is a kind of rotor !!

spin current generation from fluid motion



empirical velocity distribution in a pipe

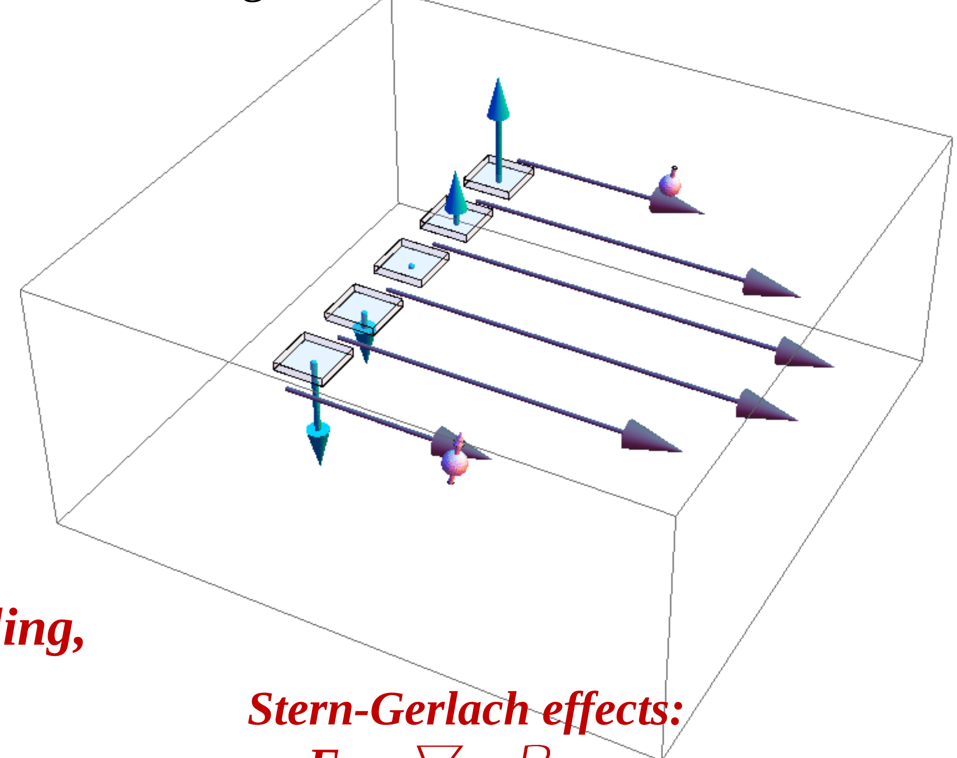
there are local rotational motions (vorticity)

$H = S \cdot \Omega$: spin-rotation coupling,

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

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

Spin current is induced parallel to gradient of local rotation.

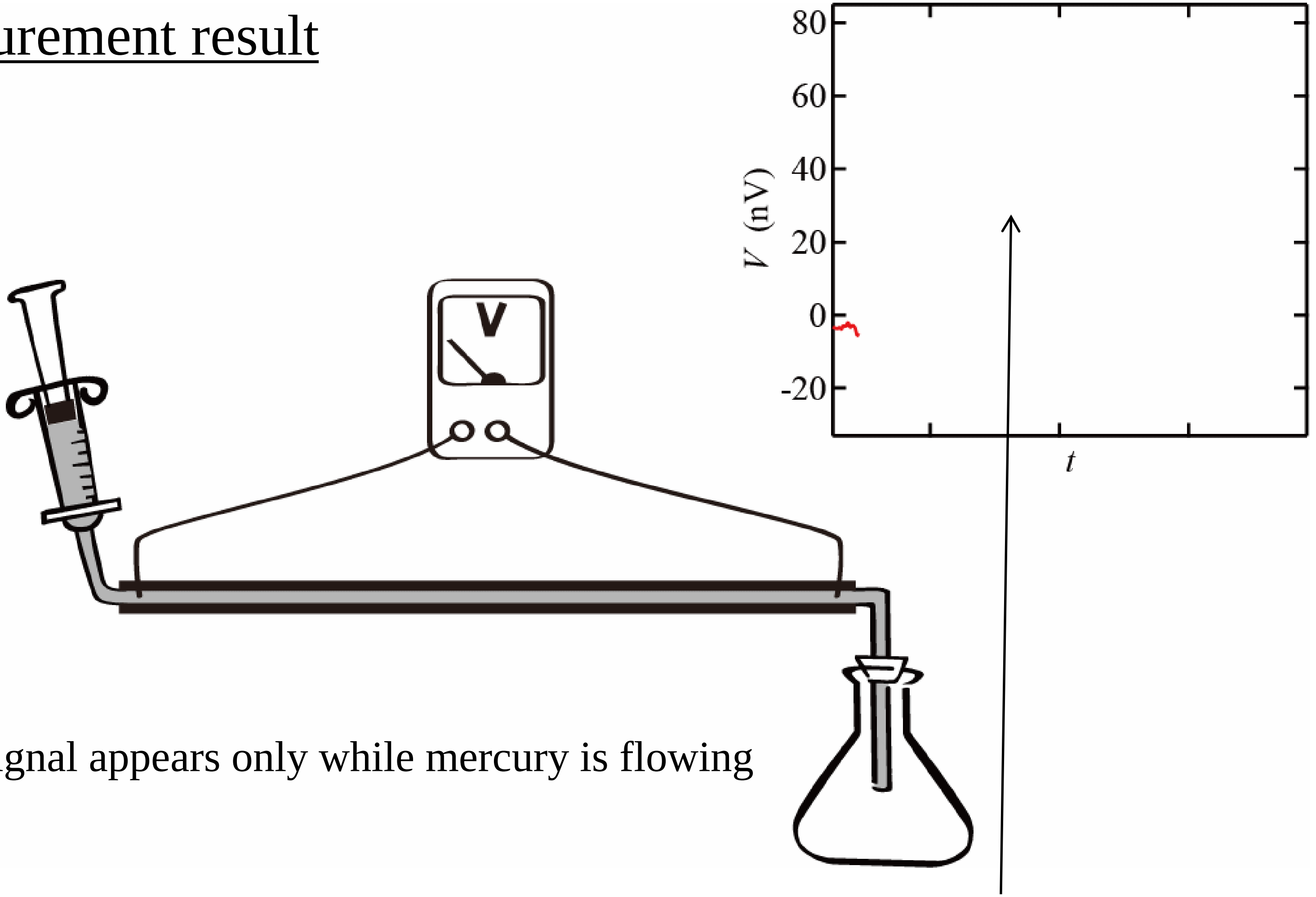


Stern-Gerlach effects:

$$F_s = \nabla \cdot B$$
$$= \nabla \cdot \Omega$$

overview

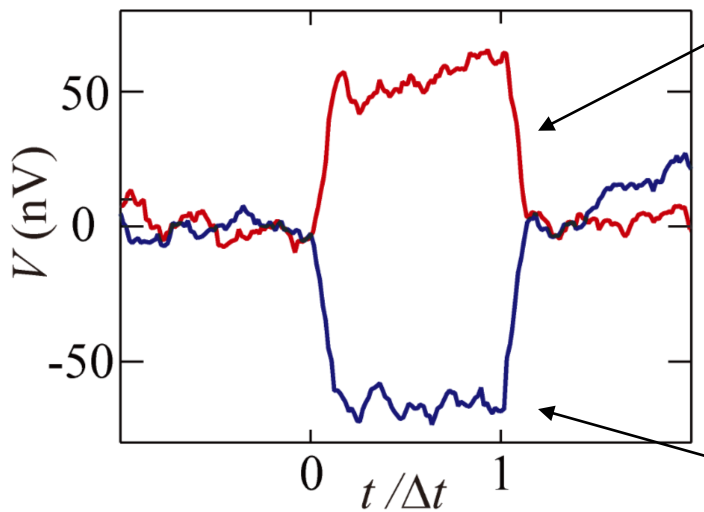
measurement result

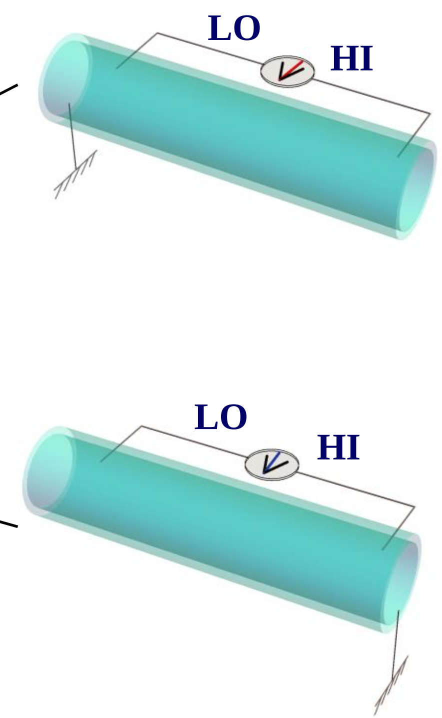


voltage signal appears only while mercury is flowing

"Spin Hydrodynamic Generation (SHD)"

Result 1 -SHD Signal Measurement

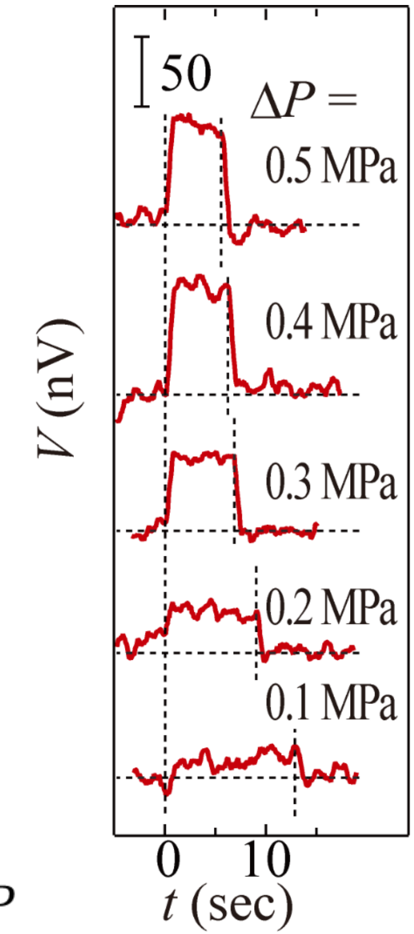




Δt 5.9 sec, 2.7 m/s

Internal Diameter ϕ 0.4 mm

Length L 80 mm



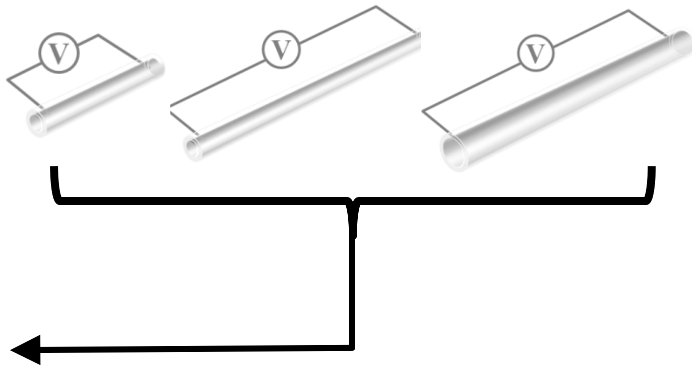
- Signal is reversed by reversing the flow direction
- Signal increases with increasing pulsed pressure ΔP

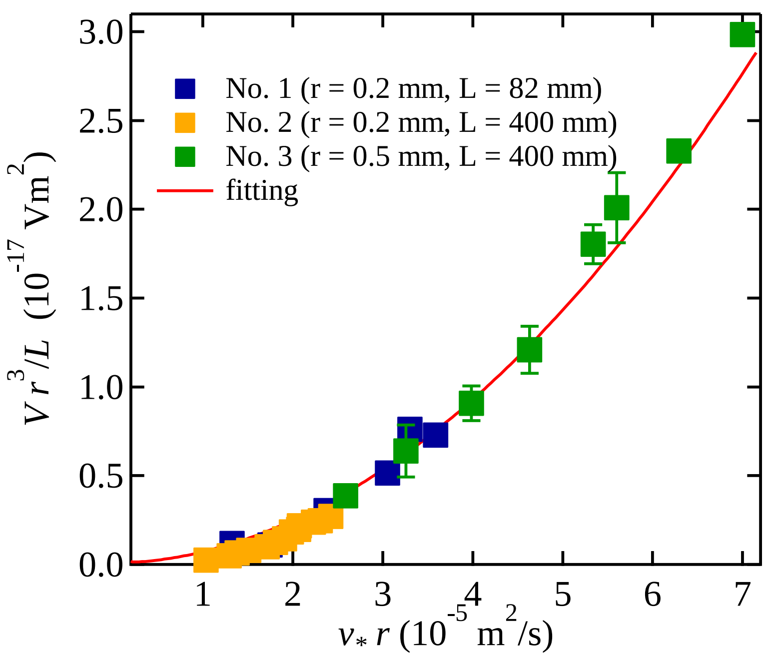
pipe size dependence measurement

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

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

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





All results can be fitted
by the same parameter set

$$V \propto v^2$$

In conclusion:

Spin Mechatronics!!

→ Electron (spin) is a rotor.

→ General relativistic quantum mechanics.

$H = S \cdot \Omega$: spin-rotation coupling

Mechanical rotation provides a new degree of freedom in quantum matter!!

c.f., Talk by M.Matsuo on May 6.