The KITS 2017 Forum in Beijing (March 29, 2017)

"Mechanical Effects on Spintronics"

-Spin Mechatronics-

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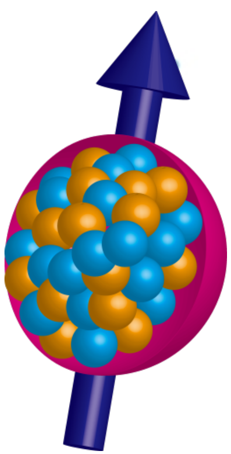

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3. Spin hydrodynamic generation in liquid metals.
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   News & Views; Nature Phys. **12**,24 (2016),
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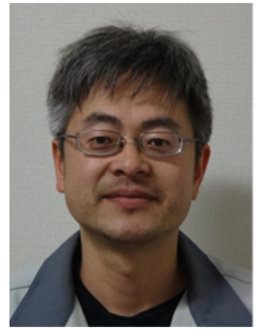
   Science **350**, 925 (2015)).

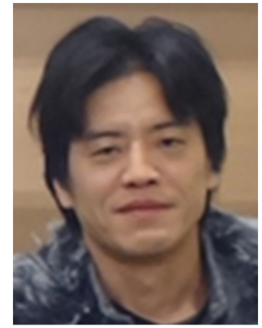
Collaborators (AERC, JAEA)

Experiment

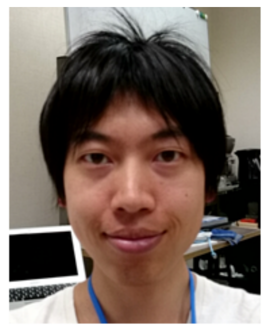

E. Saitoh


S. Okayasu


M. Ono


H. Chudo


K. Harii


Y. Ogata

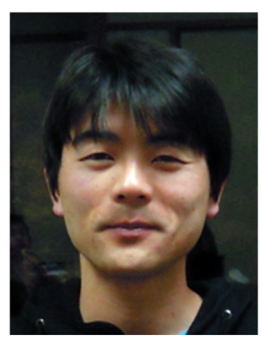

M. Imai

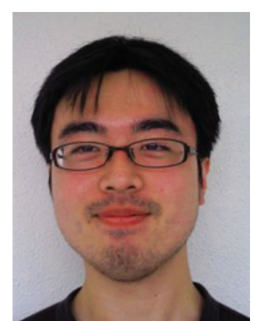

R. Takahashi

Theory


S. Maekawa


M. Matsuo


J. Ieda


Y. Ohnuma

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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

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

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

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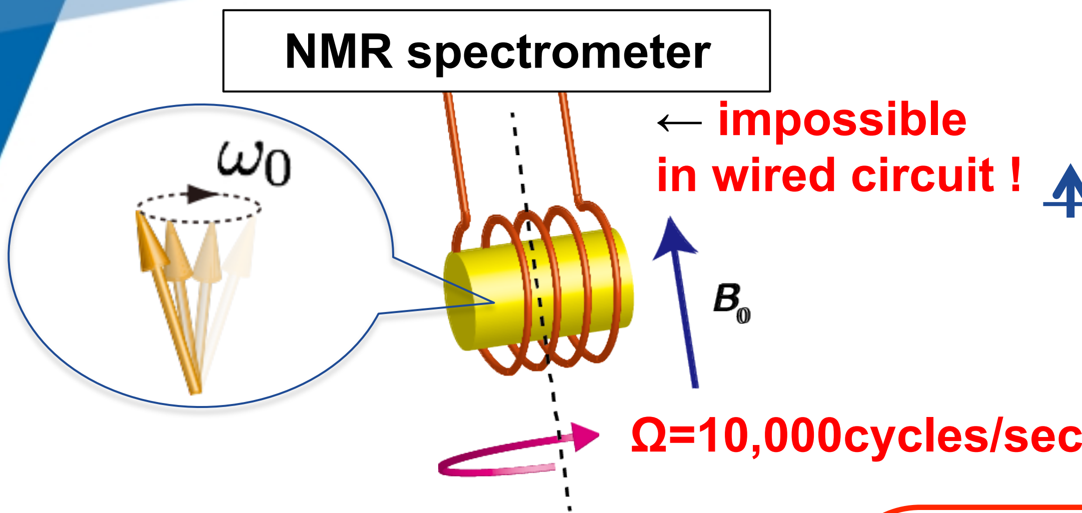
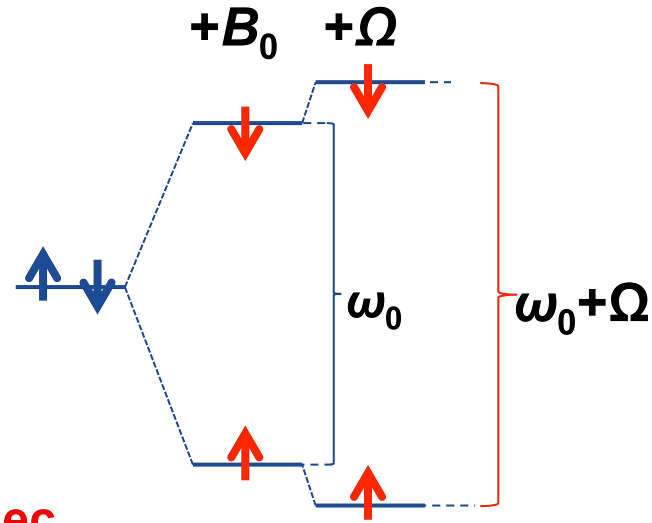
NMR measurement





Zeeman interaction

$$\mathcal{H} = -\gamma S \cdot B_0$$

Resonance condition

$$\omega_0 = \gamma B_0$$

Zeeman int.＋ Barnett effect

$$\mathcal{H} = -\gamma S \cdot (B_0 + B_\Omega)$$

Shift of resonance frequency = Ω

$$\omega_0 = \gamma B_0 + \Omega$$

Rotate together the coil and the sample

$$B_\Omega = \frac{\Omega}{\gamma}$$

electron $= \frac{2m_e}{g_e e}\Omega$ ~0.001 Oe/kHz

m_e : electron mass
e: charge
g_e: g-factor

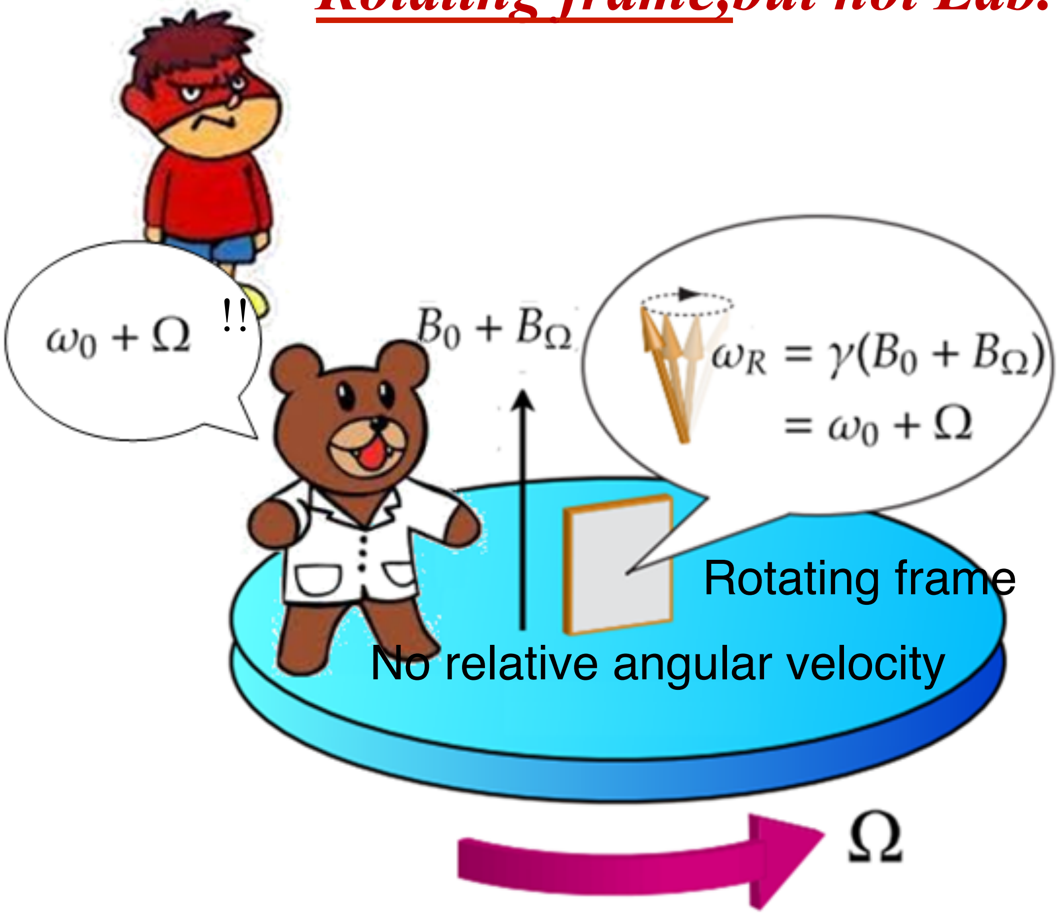
nucleus $= \frac{2m_P}{g_N e}\Omega$ ~1 Oe/kHz

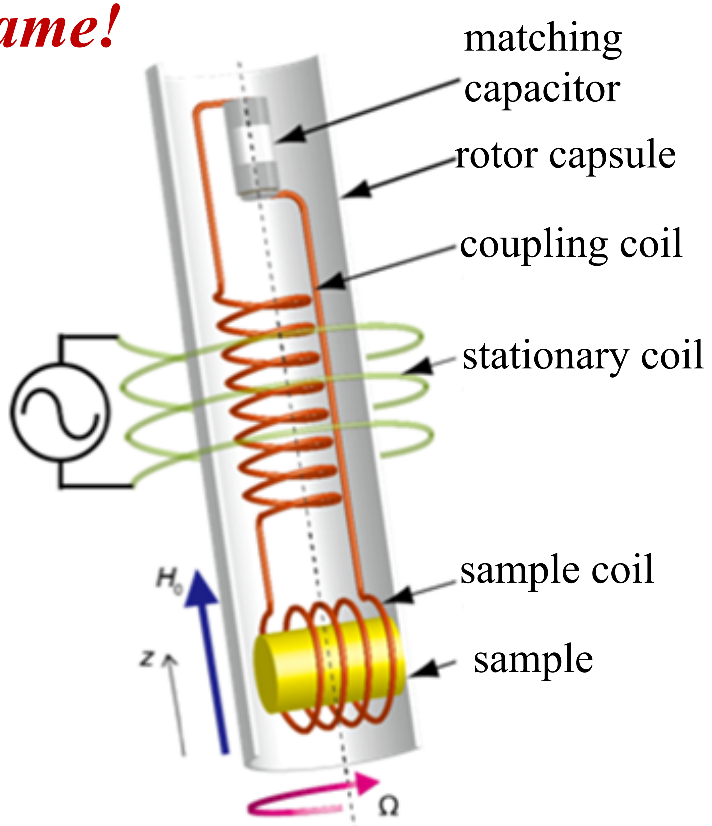
m_p : proton mass
e: charge
g_N: g-gactor

Ω couples to angular momentum,
B couples to magnetic moment.

Tuning circuit

The observation must be done in
<u>Rotating frame,</u>but not Lab. frame!

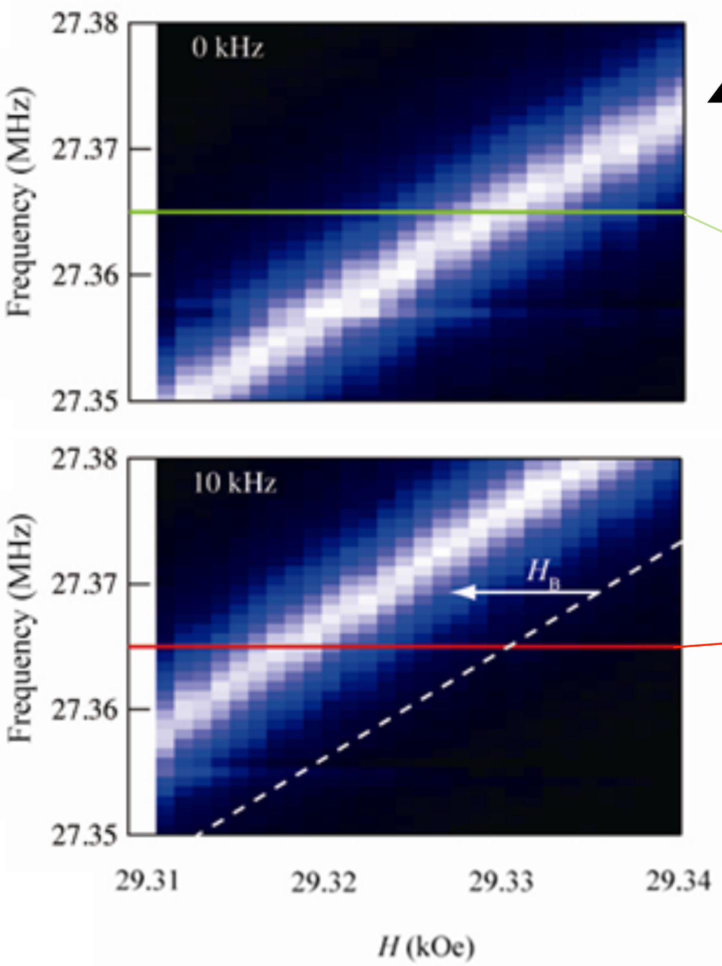




sample and coil are put inside of the rotor

Observation of Barnett field

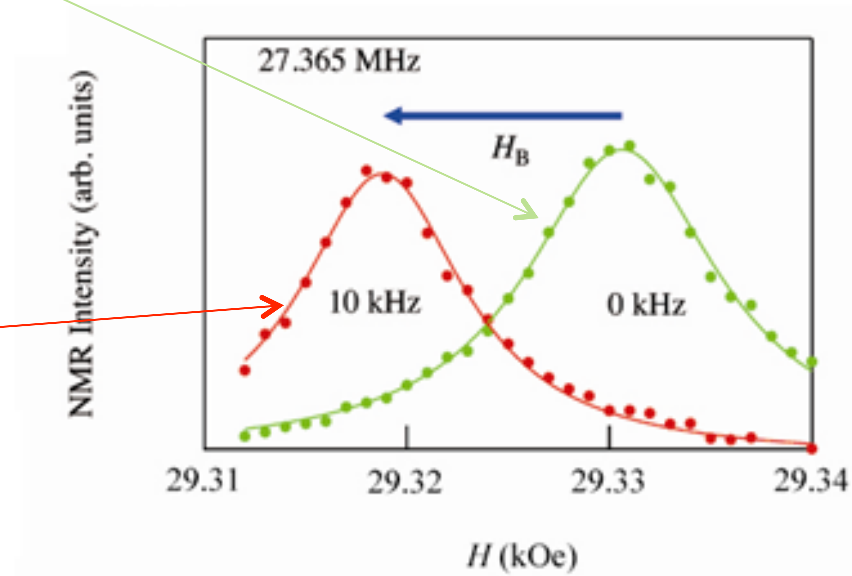
without rotation



with rotation

^{115}In : γ~9.330MH/10kOe
(reported value: 9.3858 MHz/10kOe)

cross section



B_Ω~10.7 Oe at Ω/2π=10kHz

Sign of gyromagnetic ratio、 γ :

Hamiltonian

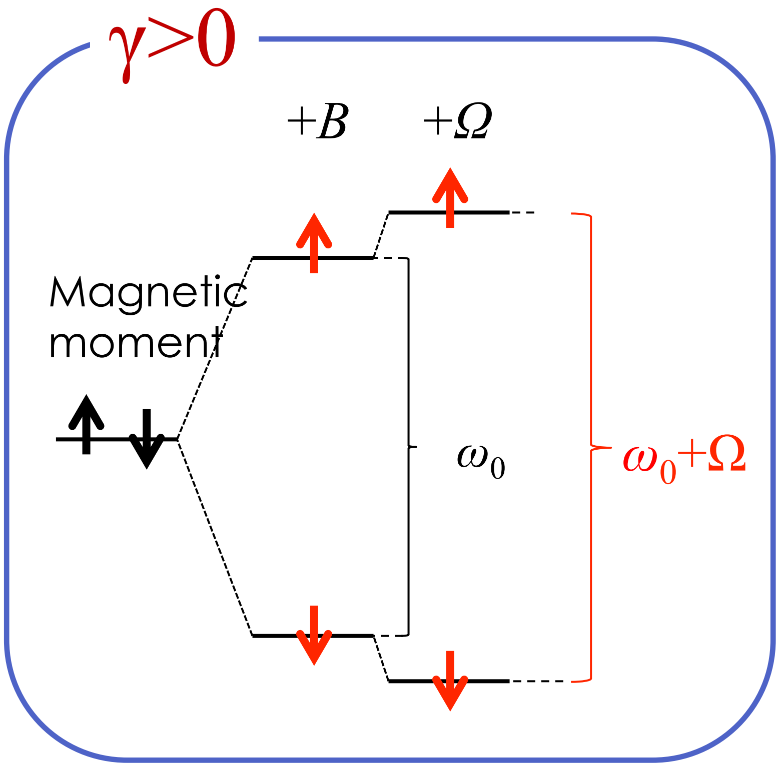
$$\hat{H} = -\gamma \boldsymbol{I} \cdot \left(\boldsymbol{B} + \frac{\boldsymbol{\Omega}}{\gamma} \right)$$

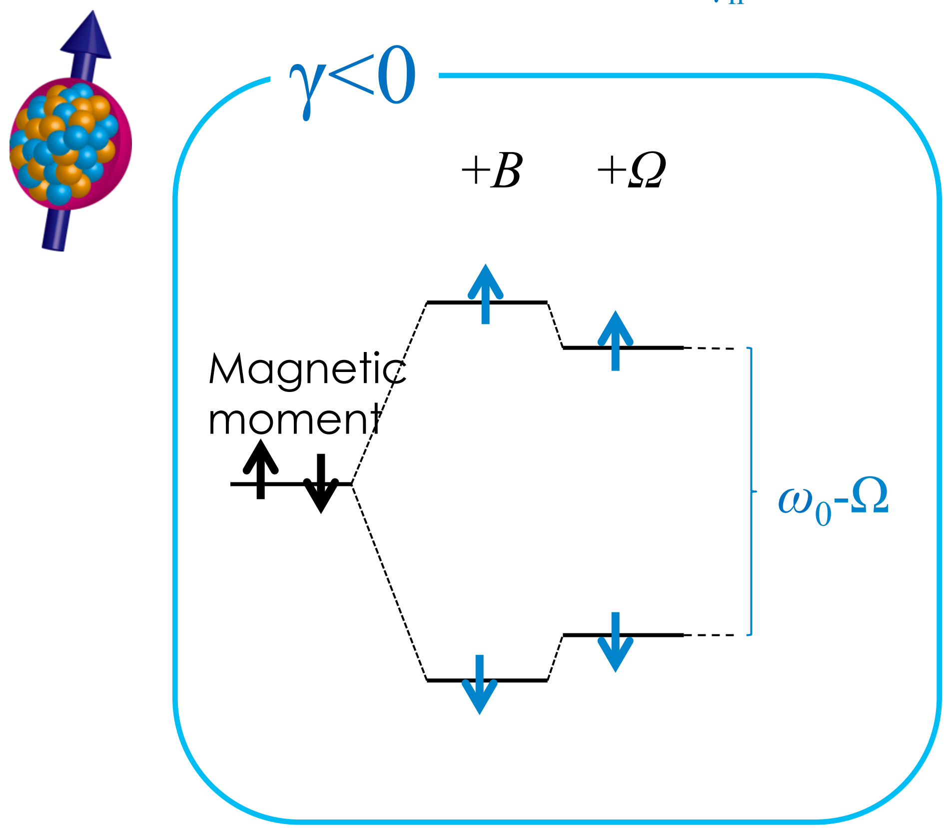
The sign of Barnett field depends on the sign of gyromagnetic ratio: γ

e.g.

proton: $\gamma_p = 42.8$ MHz/T

neutron: $\gamma_n = -29.1$ MHz/T

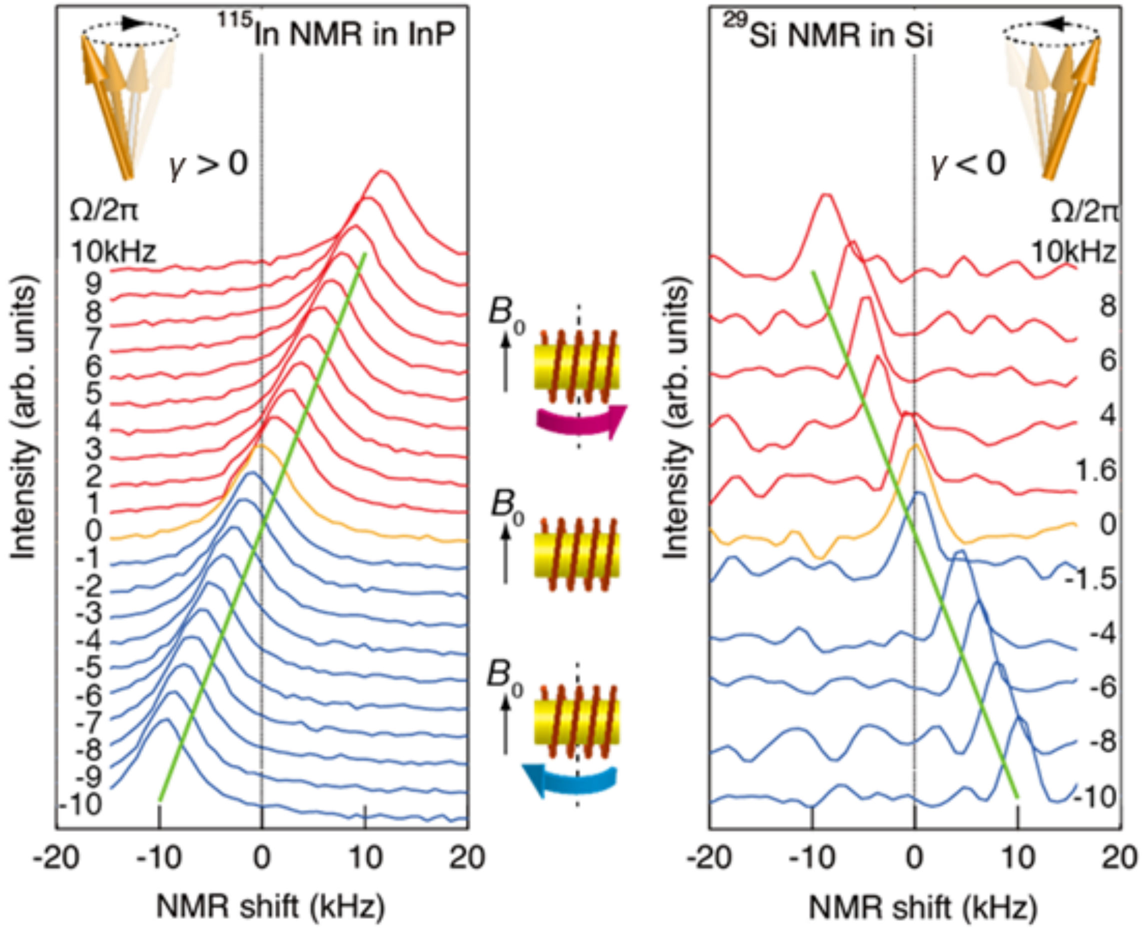


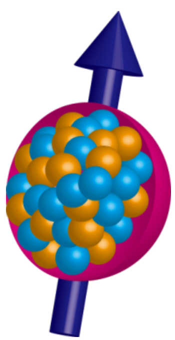


Ω couples to angular momentum,
B couples to magnetic moment.

Resonance shift direction changes by the sing of γ

Frequency shift and γ

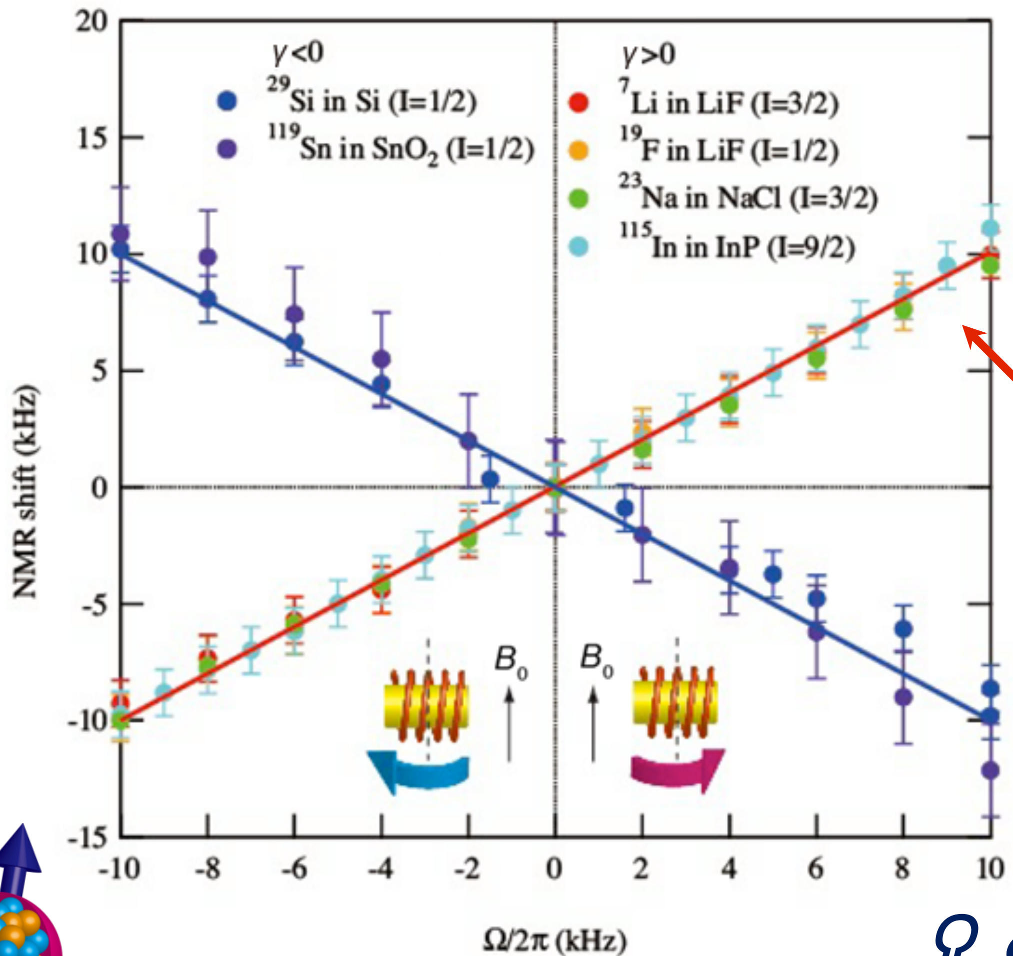




Indium-115: $\gamma_{In} = 9.33$ MHz/T
Silicon-29: $\gamma_{Si} = -8.45$ MHz/T

Using rotating NMR, we can easily determine the sign of gyromagnetic ratio of nuclei.

Frequency shift in various ...



Zeeman + Barnett field

$$\hat{H} = -\gamma\hbar \boldsymbol{I} \cdot \left(\boldsymbol{B} + \frac{\boldsymbol{\Omega}}{\gamma} \right)$$

Lithium-7: $\gamma_{Li} = 16.5$ MHz/T
Fluorine-19: $\gamma_{F} = 40.1$ MHz/T
Sodium-23: $\gamma_{Na} = 11.3$ MHz/T
Indium-115: $\gamma_{In} = 9.33$ MHz/T

Silicon-29: $\gamma_{Si} = -8.45$ MHz/T
Tin-119: $\gamma_{Si} = -15.9$ MHz/T

Ω couples to angular momentum,
B couples to magnetic moment.

Frequency shift is universally observed !?

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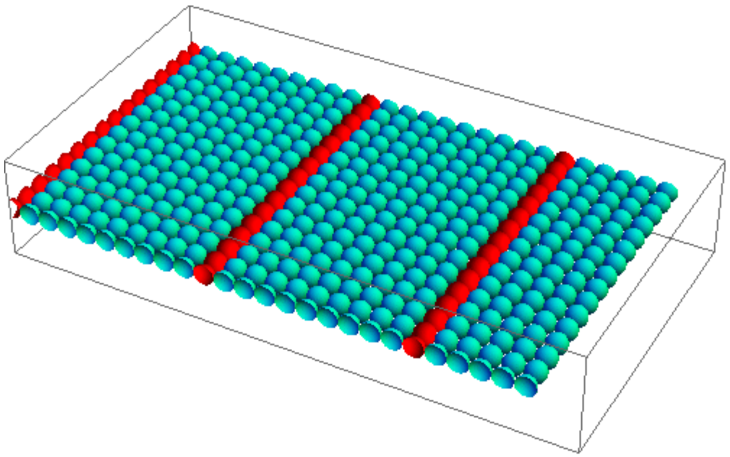
spin current generation from fluid motion



empirical velocity distribution in a pipe

⇓

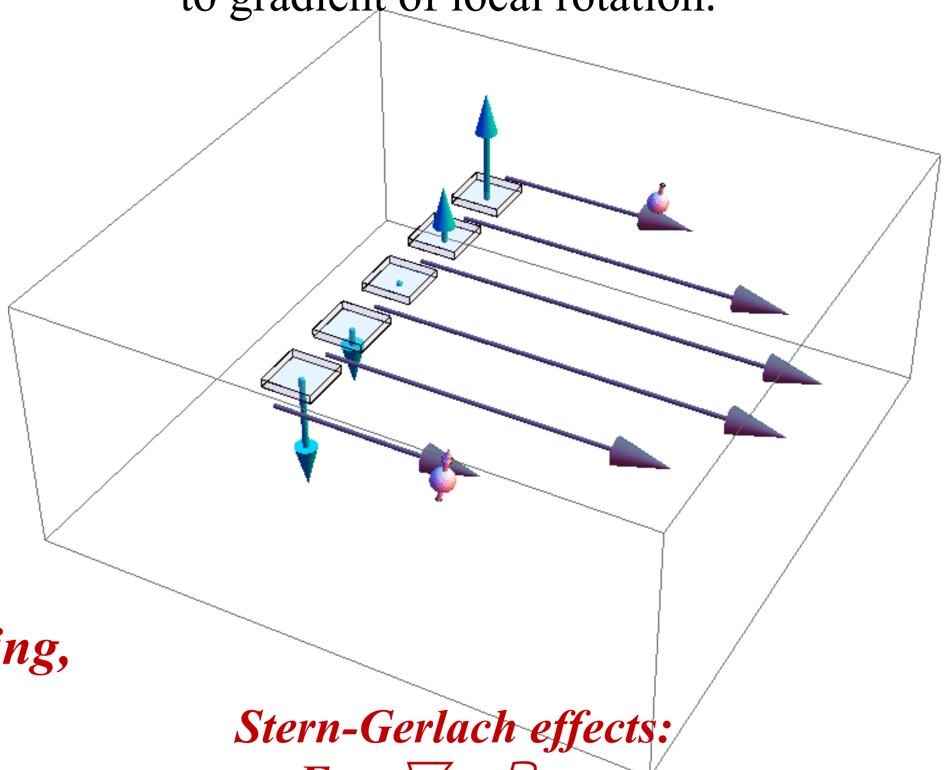
there are local rotational motions (vorticity)

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

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

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

Spin current is induced parallel to gradient of local rotation.



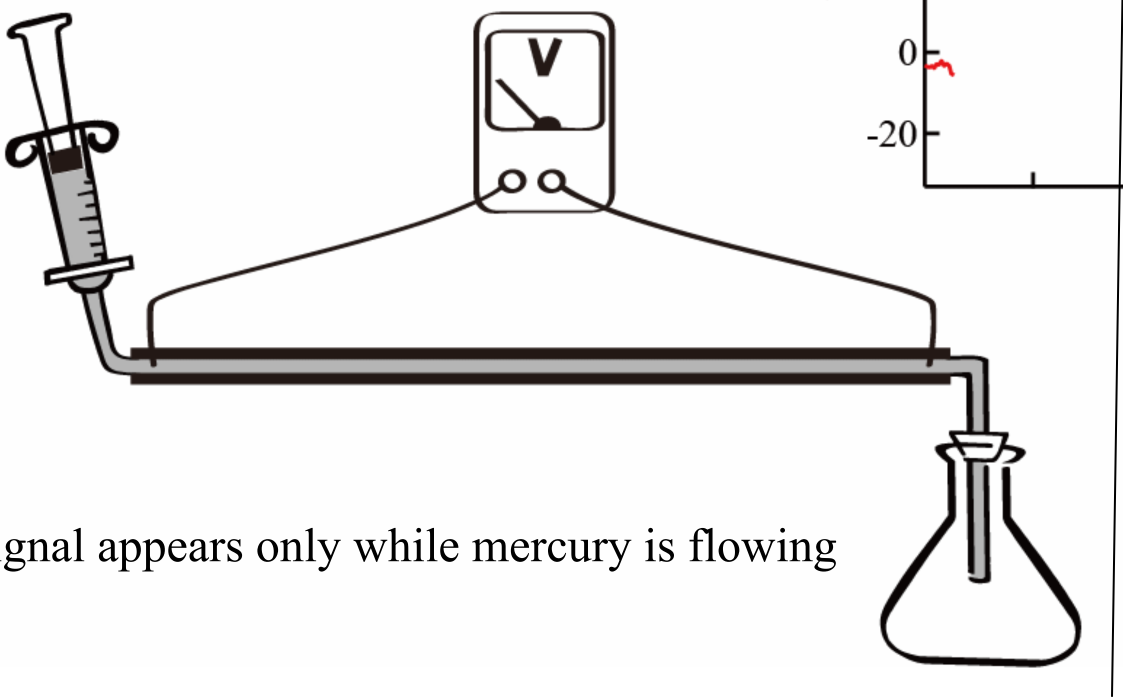
Stern-Gerlach effects:

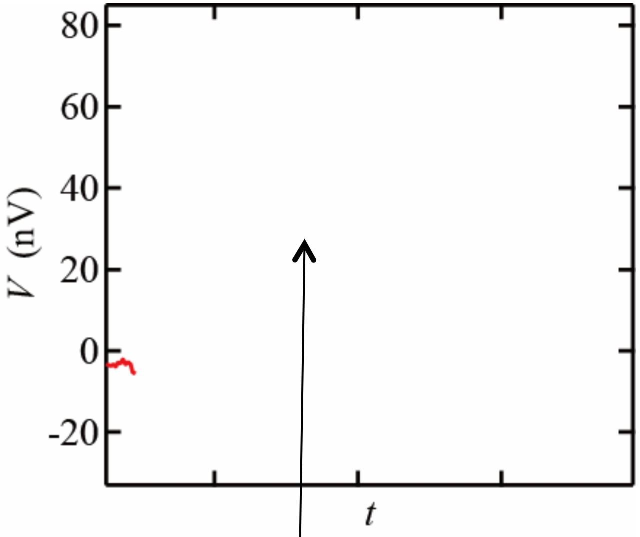
$Fs = \nabla \cdot B$

$= \nabla \cdot \Omega$

overview

measurement result

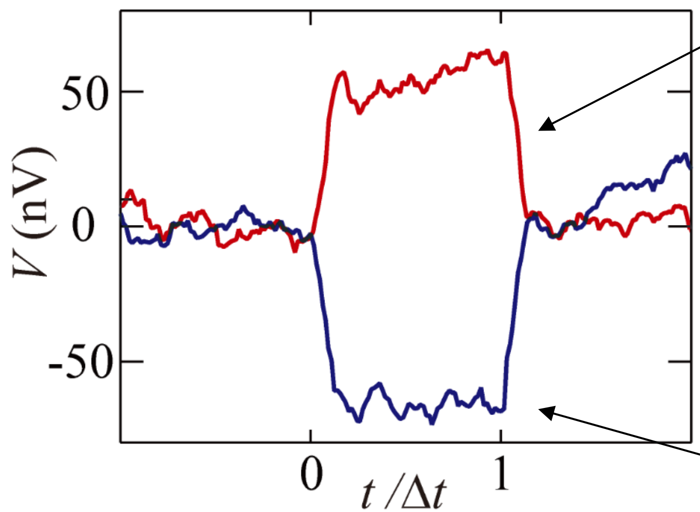


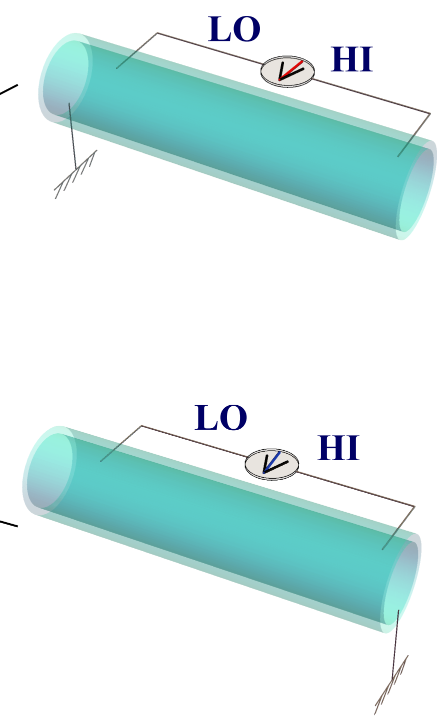


voltage signal appears only while mercury is flowing

"Spin Hydrodynamic Generation (SHD)"

Result 1 -SHD Signal Measurement

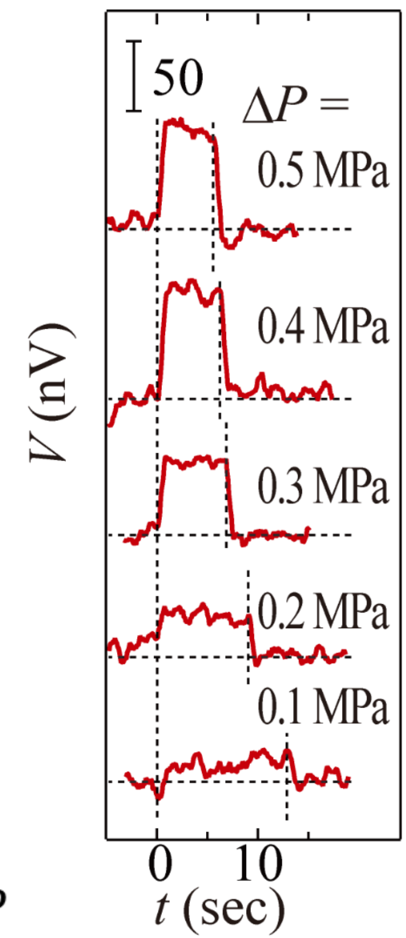




Δt 5.9 sec, 2.7 m/s

Internal Diameter ϕ 0.4 mm

Length L 80 mm



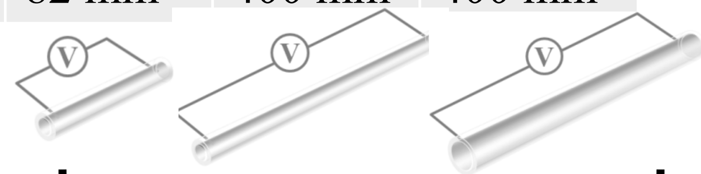
- Signal is reversed by reversing the flow direction
- Signal increases with increasing pulsed pressure ΔP

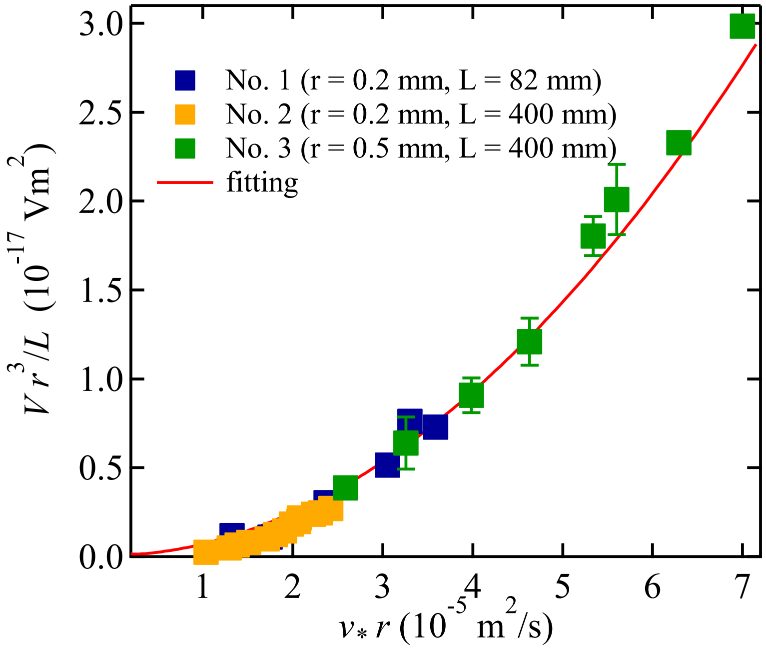
pipe size dependence measurement

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

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

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





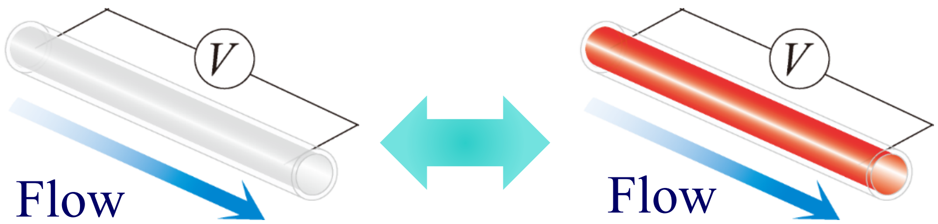
All results can be fitted
by the same parameter set

$$V \propto \nu^2$$

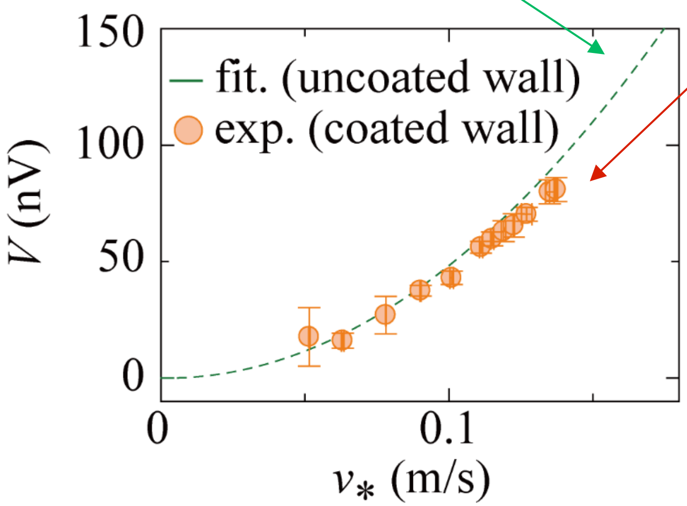
Result 3 -Absence of Contact Electrification of Wall

Uncoated Quartz Pipe

Quartz Pipe
with Resin-coated Inner Wall



Resin and Quartz exhibit different electrification properties



Flow-induced signal in resin-coated pipe is the same as that in uncoated pipe

→ ruling out the contribution of the charging effect between pipe wall and fluid

In summary:

Angular momentum conservation and Energy conservation: