Toward the first experiments of T-violation search in neutron-induced compound nuclear reaction

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NOPTREX
Neutron Optical Parity and Time-Reversal EXperiment

2025.9.23(Mon) Spin2025, Qingdao, China

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13. Kyushu University

Publication

- Spin dependence in the *p*-wave resonance of ^{139}La $+n$

  Physical Review C **V109**, 044606, (2024)

- High sensitivity of a future search for effects of P-odd/T-odd interactions on the 0.75 eV p-wave resonance in $n+{}^{139}$La forward transmission determined using a pulsed neutron beam

  Physical Review C **V109**, L041602, (2024)

- Combination of crystal growth with optical floating zone and evaluation of $Nd^{3+}:LaAlO_3$ crystals with the dynamic nuclear polarization of ^{139}La and ^{27}Al

  Review of Scientific Instruments **V95**, 063301, (2024)

(Recent progress on a polarized La target)

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2025/07/17

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Outline

1. Motivation
2. T-violation search with neutron-induced compound nuclear reaction
3. Current status of Phase-I experiment
4. Summary

Significance of CP violation research

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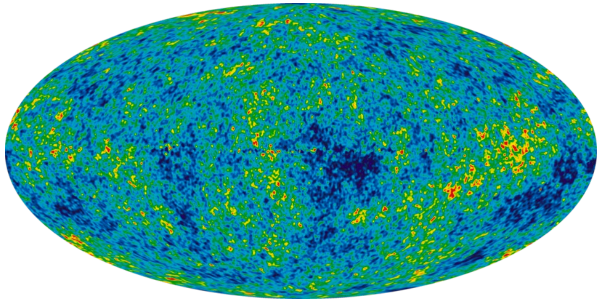
Matter-Antimatter Asymmetry in universe $\eta \equiv N_{baryon}/N_{photon}$

Observation

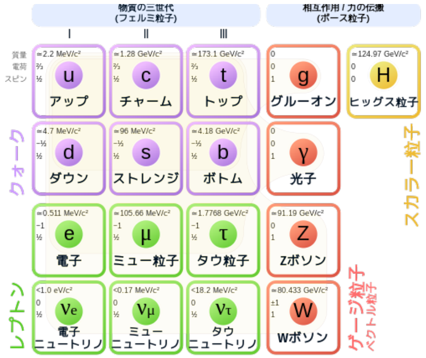
CMB https://map.gsfc.nasa.gov/media/121238/index.html



$\eta = (6.05 \pm 0.07) \times 10^{-10}$ Planck13

E. O. Zavarygin and A. V. Ivanchik, J. Phs.: Con. Ser. 661, 012016, (2015)

Standard Model



W. Bernreuther, in CP violation in Particle, Nuclear and Astrophysics, Springer, 2022

Unexplained !!

$\eta \sim 10^{-18}$ (CP violation in the Standard Model)

Low energy region ⇒ **Unknown CP violation** ⇐ **High energy region**

T-violation search

- unnecessity of production of anti-particles
- Connection between low and high energy phenomena

T-violation in low energy region

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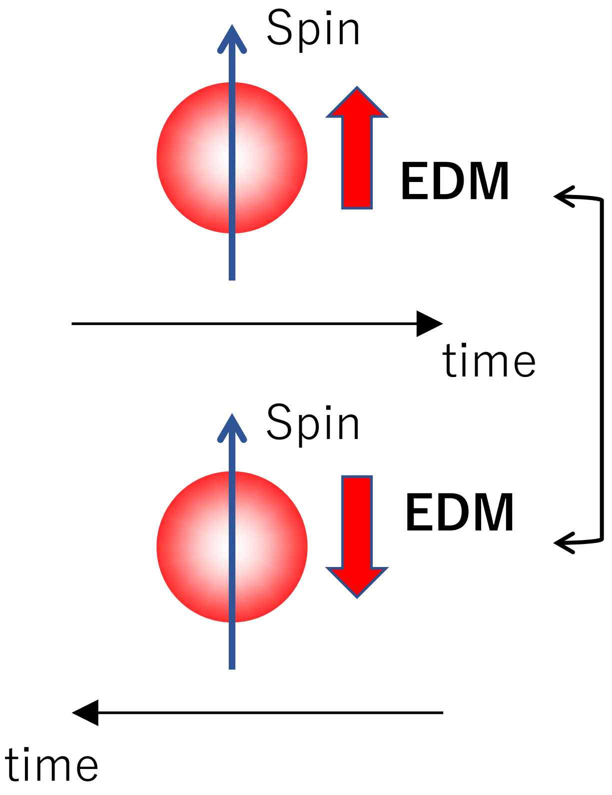
No final state interaction (two methods)

Approximate method

Electric Dipole Moment (EDM)

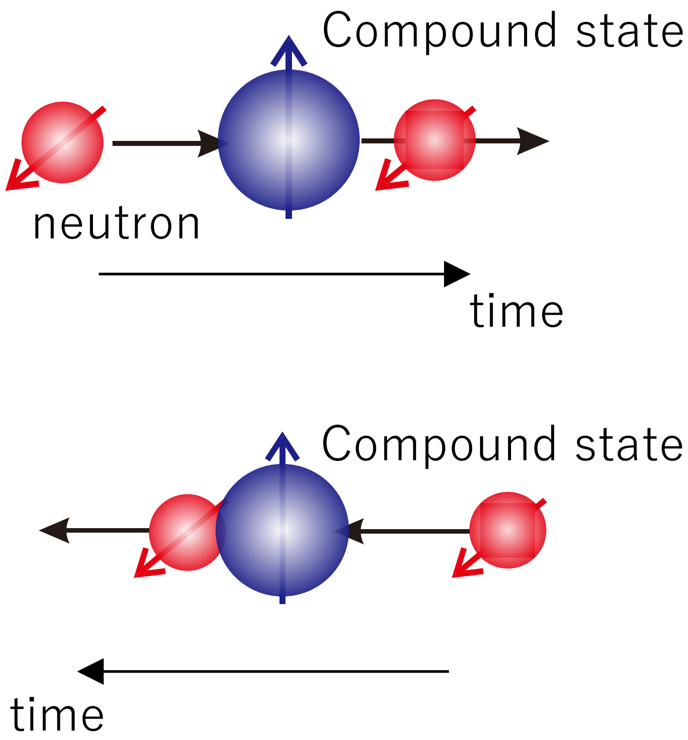
Static state



Distinguishable
in steam of time

Compound state

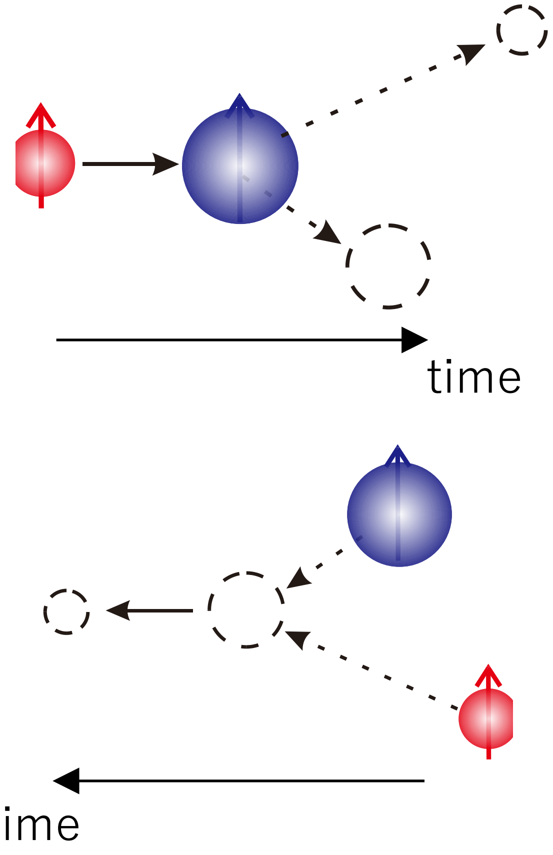
Initial state = final state



Difference of transmission

Normal scattering

Initial state ≠ final state



Connection to high energy region

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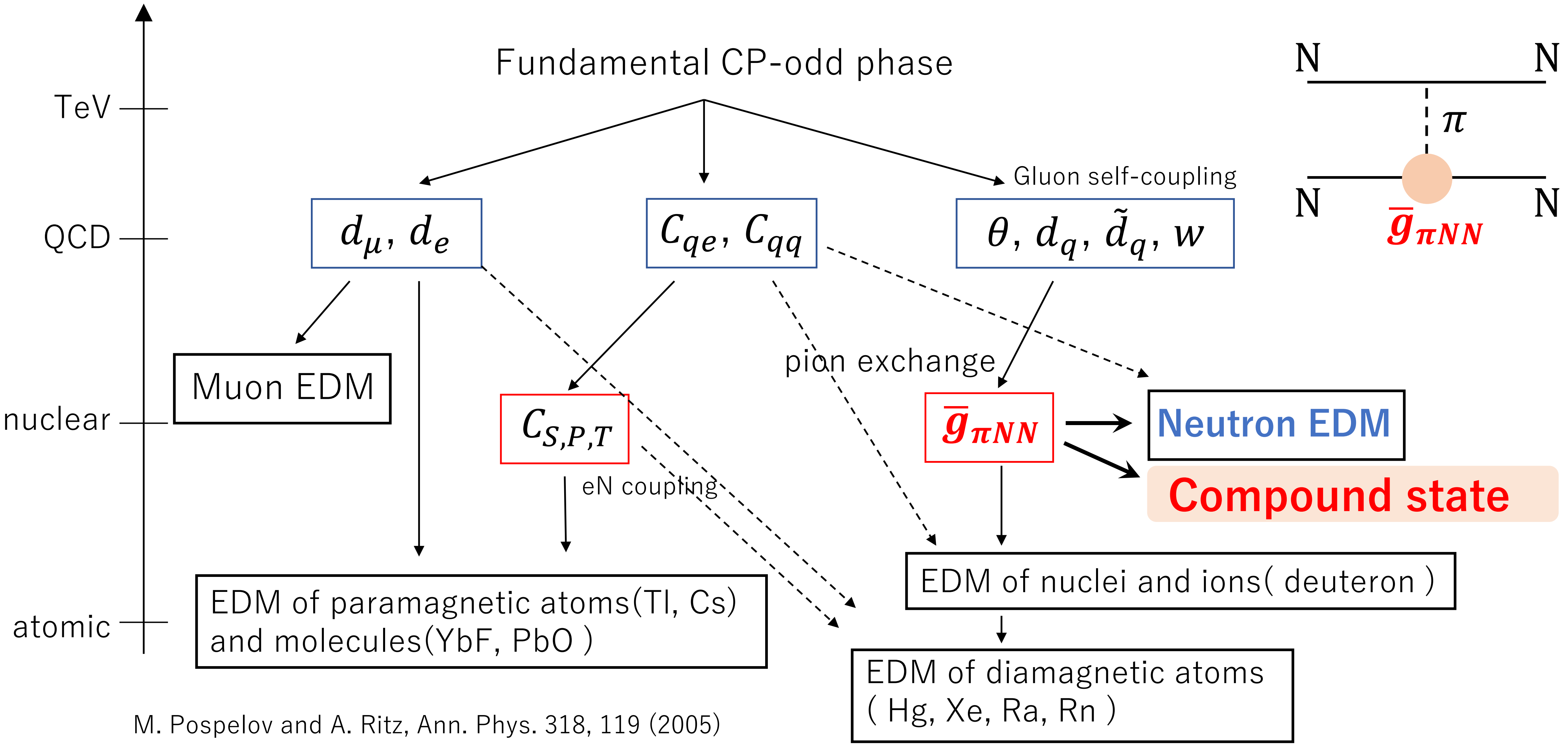

M. Pospelov and A. Ritz, Ann. Phys. 318, 119 (2005)

Relation to n-EDM

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n-EDM

J. Eagal, et al., Prog. Part. Nucl. Phys. **71**, 21 (2013)

$$d_n = -(1.5 \times 10^{-14}) \cdot \left(\underline{\bar{g}_{\pi NN}^{(0)}} - 0.93 \times 10^{-2} \cdot \bar{g}_{\pi NN}^{(1)} \right)$$

Sensitive

Compound state

Y.-H. Song, et al., Phys. Rev. C **83**, 065503 (2011)

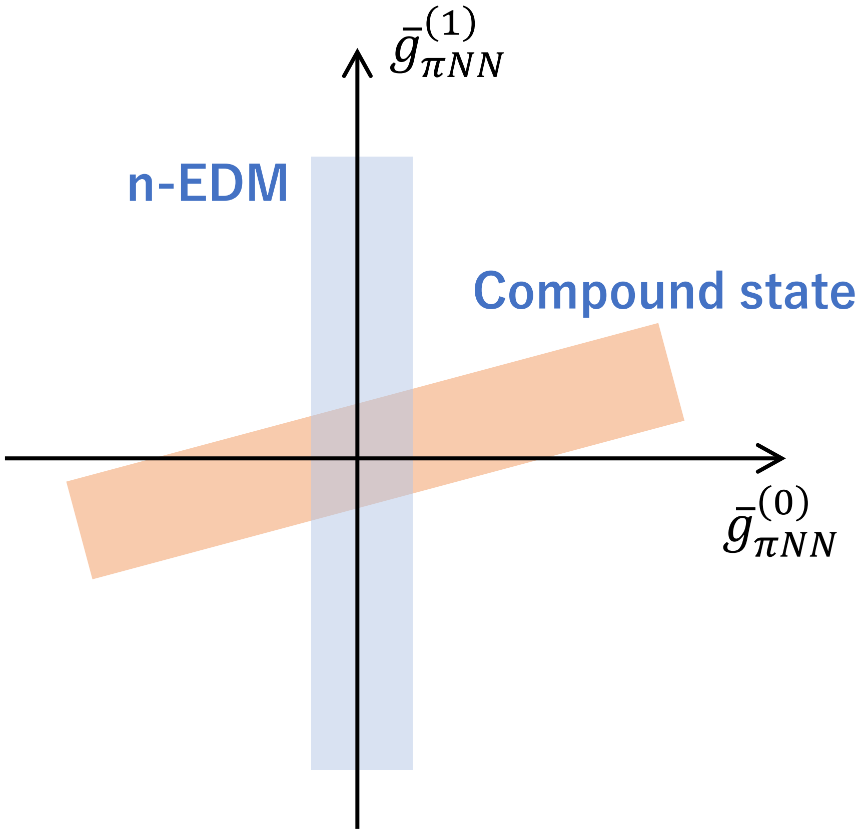
$$\frac{W_T}{W} = \frac{\Delta\sigma^{TP}}{\Delta\sigma^{P}} \cong \left(\frac{-0.47}{h_\pi^1} \right) \left(\underline{\bar{g}_{\pi NN}^{(0)} + 0.26 \cdot \bar{g}_{\pi NN}^{(1)}} \right)$$

Both sensitive

Reference:

$$n + p \rightarrow d + \gamma \quad h_\pi^1 = (2.6 \pm 1.2) \times 10^{-7}$$

D. Blyth, et al., Phys. Rev. Lett. **121** 242002 (2018)



Complimentary to n-EDM

Parity violation in Compound state

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Helicity Asymmetry

neutron Nucleus

$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

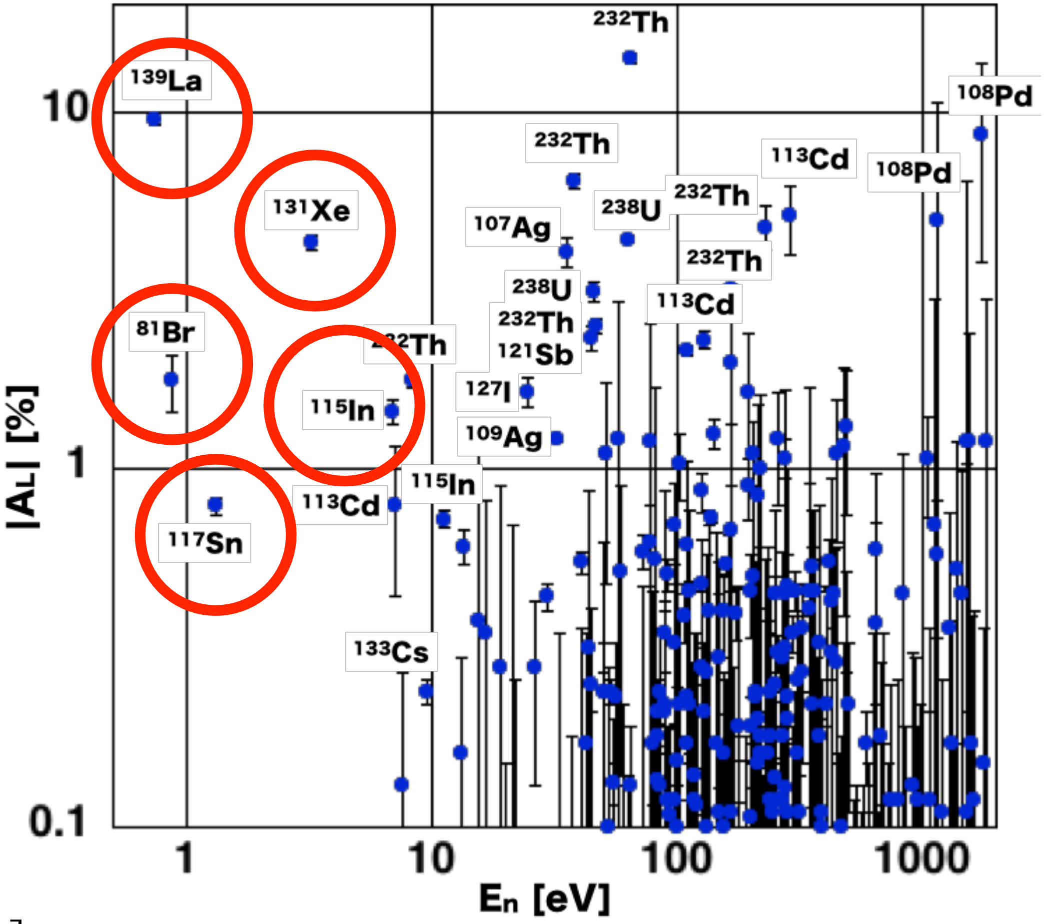
Ex) ^{139}La : $E_P = 0.734$ eV $\quad A_L = 9.7 \pm 0.3$ [%]

10^6 enhancement

Proton-proton scattering

proton proton

$E = 13.6$ MeV $\quad A_L = -(1.5 \pm 0.5) \times 10^{-5}$ [%]



P.D. Eversheim, et al., Phys. Lett. B **256**, 11-14, (1991)

S-P mixing model

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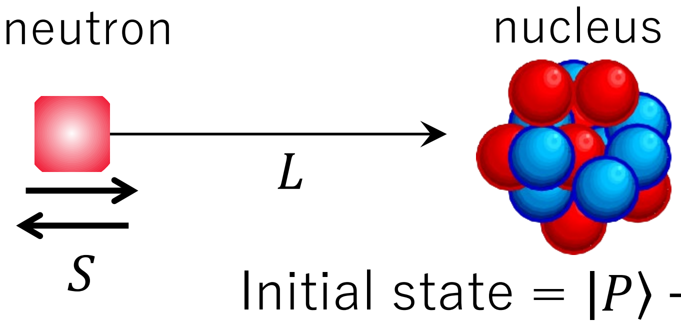
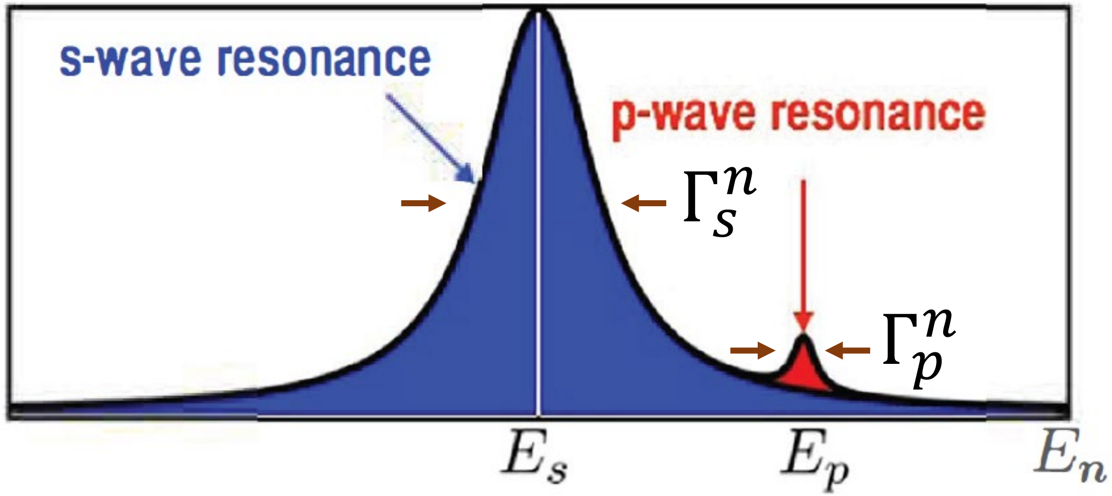
Generation of compound state



Initial state $= |P\rangle + \varepsilon|S\rangle$

$J = L + S \quad j = 1/2\ ,\ 3/2$



$$A_L = -2x \frac{W}{E_p - E_s} \sqrt{\frac{\Gamma_s^n}{\Gamma_p^n}}$$

Dynamical enhancement: $10^2 \sim 10^3$

structural enhancement: 10^3

$$x \equiv \sqrt{\frac{\Gamma_{p,j=1/2}^n}{\Gamma_p^n}} \quad y \equiv \sqrt{\frac{\Gamma_{p,j=3/2}^n}{\Gamma_p^n}}$$

$$\Gamma_p^n = \Gamma_{p,j=1/2}^n + \Gamma_{p,j=3/2}^n$$

Unknown parameters (partial neutron width)

T-violation in Compound state

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T-violating matrix element

T-violation

$$\Delta\sigma_T = \kappa(J)\frac{W_T}{W}\Delta\sigma_P$$

P-violation

P-violating matrix element

Angular momentum factor

$\boldsymbol{x}, \boldsymbol{y}$: unknown parameters

$$\kappa(J) = \begin{cases} \frac{I}{I+1}\left(1+\frac{1}{2}\sqrt{\frac{2I+3}{I}}\frac{\boldsymbol{y}}{\boldsymbol{x}}\right) & J = I+\frac{1}{2} \\ 1-\frac{1}{2}\sqrt{\frac{2I-1}{I+1}}\frac{\boldsymbol{y}}{\boldsymbol{x}} & J = I-\frac{1}{2} \end{cases}$$

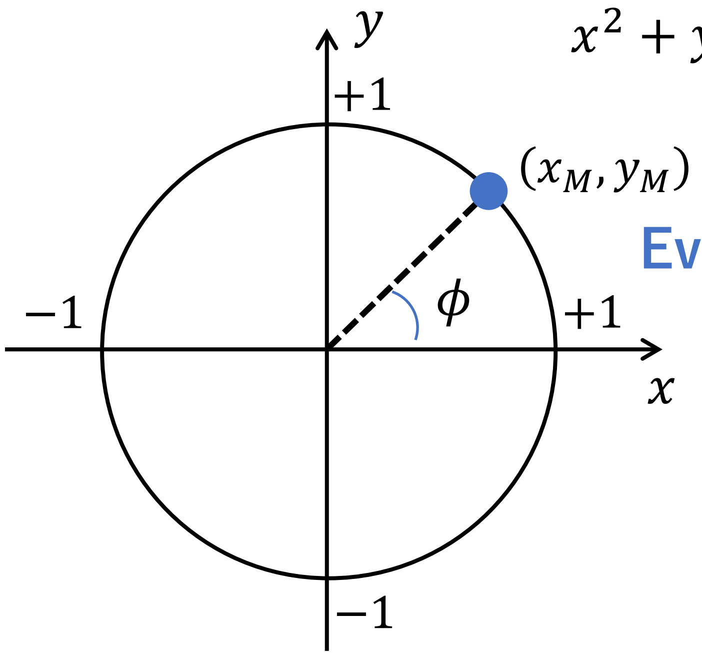
Candidate target：^{139}La, ^{131}Xe, ^{81}Br, ^{117}Sn, etc…

Interference between different channel spins

Gudkov, Phys Rep **212**, 77 (1992)

$$x^2 = \frac{\Gamma^n_{p,j=1/2}}{\Gamma^n_{p,j=1/2}+\Gamma^n_{p,j=3/2}} \quad y^2 = \frac{\Gamma^n_{p,j=3/2}}{\Gamma^n_{p,j=1/2}+\Gamma^n_{p,j=3/2}}$$

$$x^2 + y^2 = 1$$



Evaluation of $\kappa(J)$

Necessity of evaluation of x, y

Toward T-violation experiments

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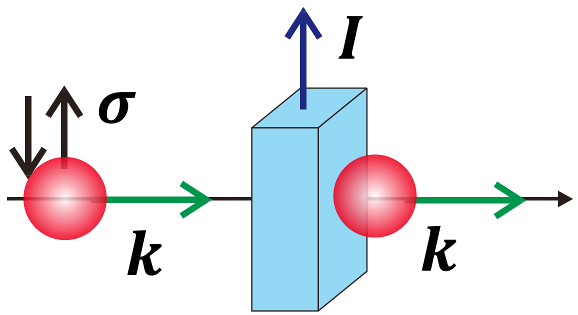
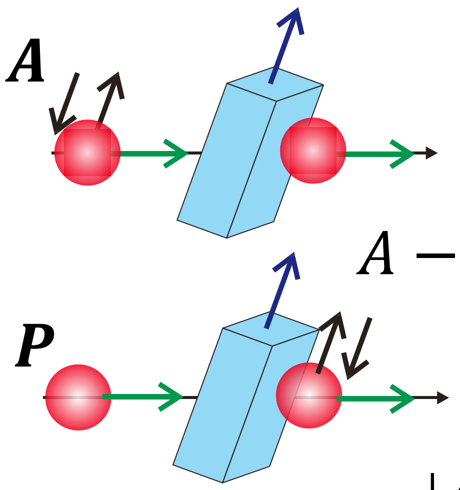
Phase-0



$Asymmetry \propto \mathrm{Im}[B']$

Constraint from A', B', C' terms
First step to spin control

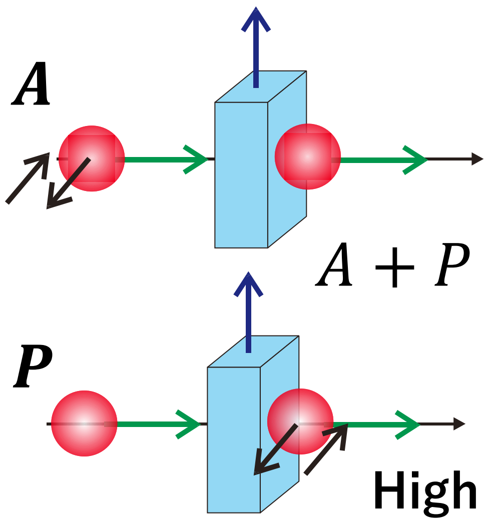
Phase-1



$A - P \propto \mathrm{Im}[K'^{*}D']$

Low sensitivity
Easy spin control

Phase-2



$A + P \propto \mathrm{Im}[D']$

High sensitivity
Not easy control

forward scattering amplitude

polarized ^{139}La($\boldsymbol{I} = 7/2$)

$$f = A' + P_1 H'(\boldsymbol{k}\cdot\boldsymbol{I}) + P_2 E'\{(\boldsymbol{k}\cdot\boldsymbol{I})^2 - 1/3\}$$
$$+ (\boldsymbol{\sigma}\cdot\boldsymbol{I})\,[P_1 B' + P_2 F'(\boldsymbol{k}\cdot\boldsymbol{I}) + P_3\, B'_3/3\,\{(\boldsymbol{k}\cdot\boldsymbol{I})^2 - 1\}]$$
$$+ (\boldsymbol{\sigma}\cdot\boldsymbol{k})[C' + P_1 K'(\boldsymbol{k}\cdot\boldsymbol{I}) - P_2\, F'/3 + P_3\, 2B'_3/3\,(\boldsymbol{k}\cdot\boldsymbol{I})]$$
$$+ \boldsymbol{\sigma}\cdot(\boldsymbol{k}\times\boldsymbol{I})[P_1 D' + P_2 G'(\boldsymbol{k}\cdot\boldsymbol{I})]$$

T-odd

Target

Target polarization

- P_1: vector polarization
- P_2: 2nd rank tensor polarization
- P_3: 3rd rank tensor polarization

B' term : x , y constraint

D' term : T-odd, P-odd

Phase-0 experiment

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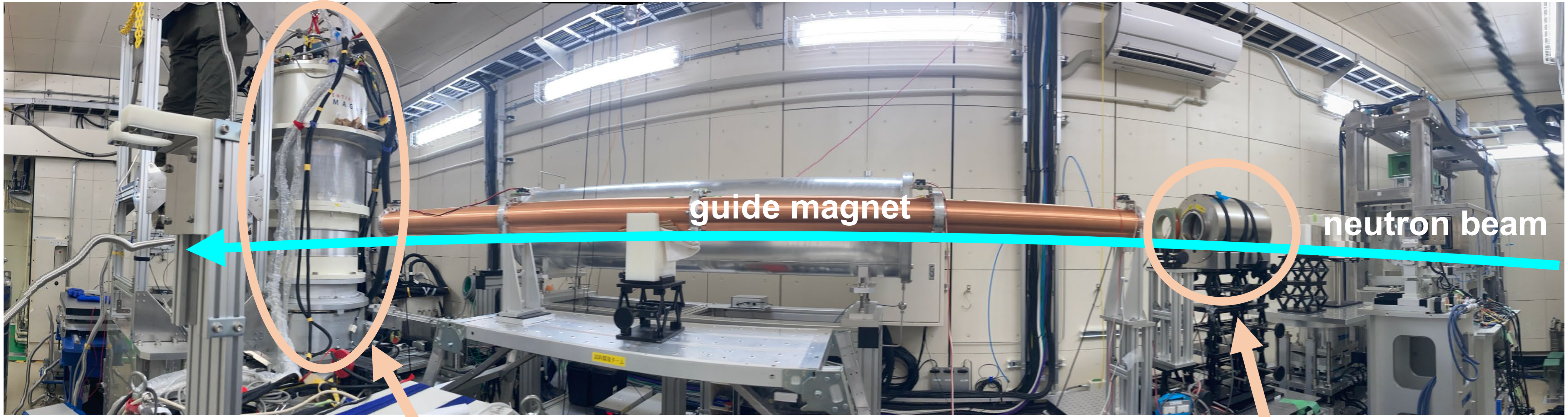
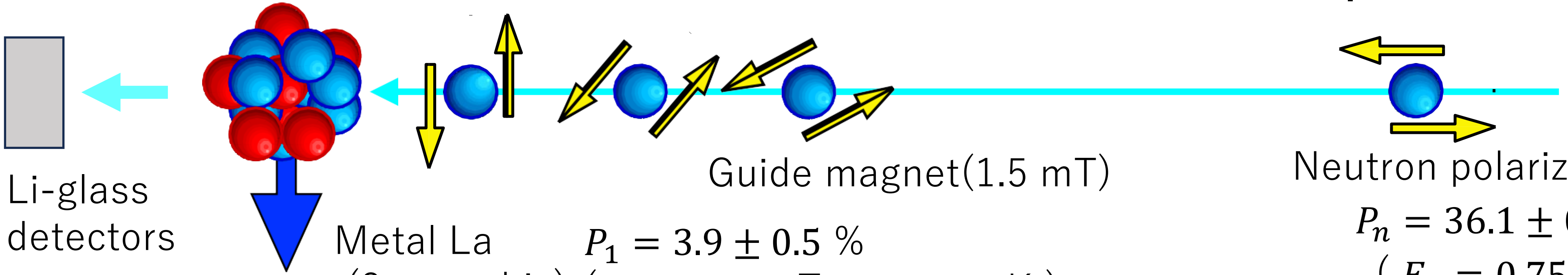
Measurement of B' term

J-PARC BL22 RADEN



Polarized La in the dilution refrigerator

^{3}He polarizer



Li-glass detectors

Metal La (2 cm cubic)

Guide magnet(1.5 mT)

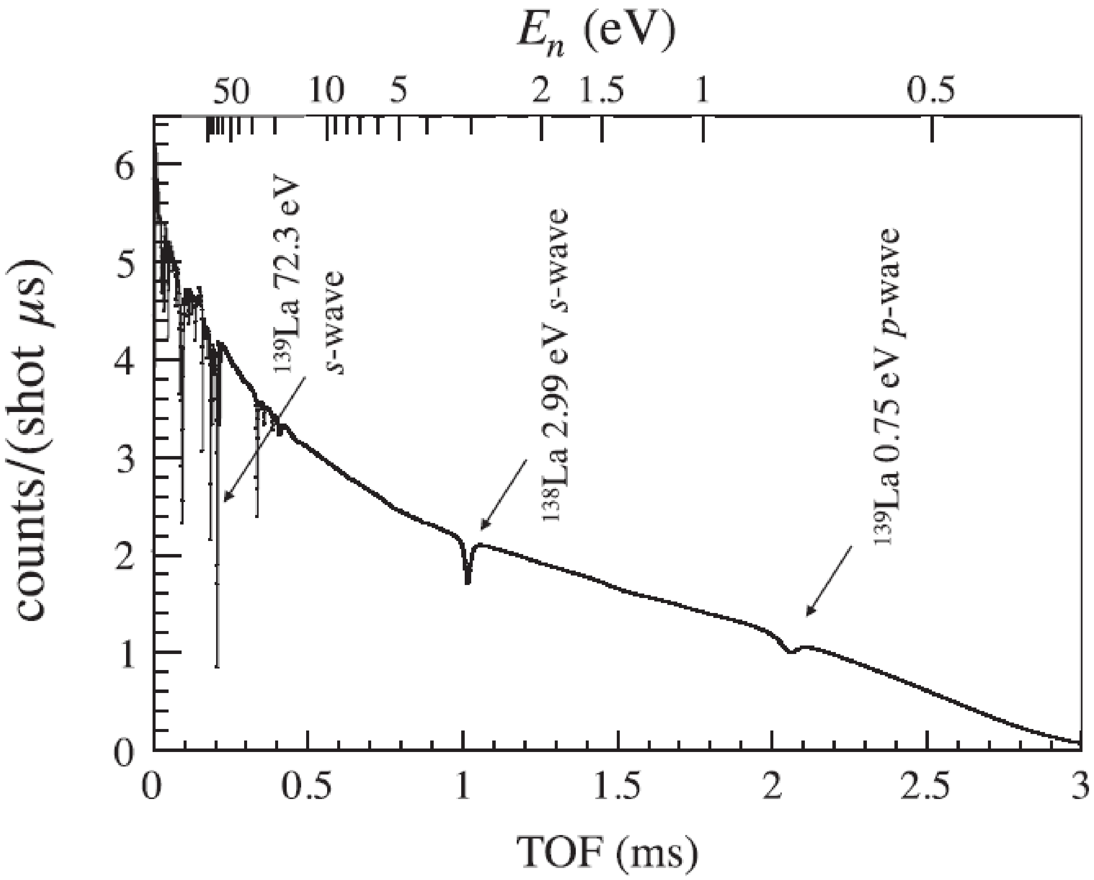
$P_1 = 3.9 \pm 0.5$ %
($B_{exp} = 6.8$ T, $T = 67$ mK)

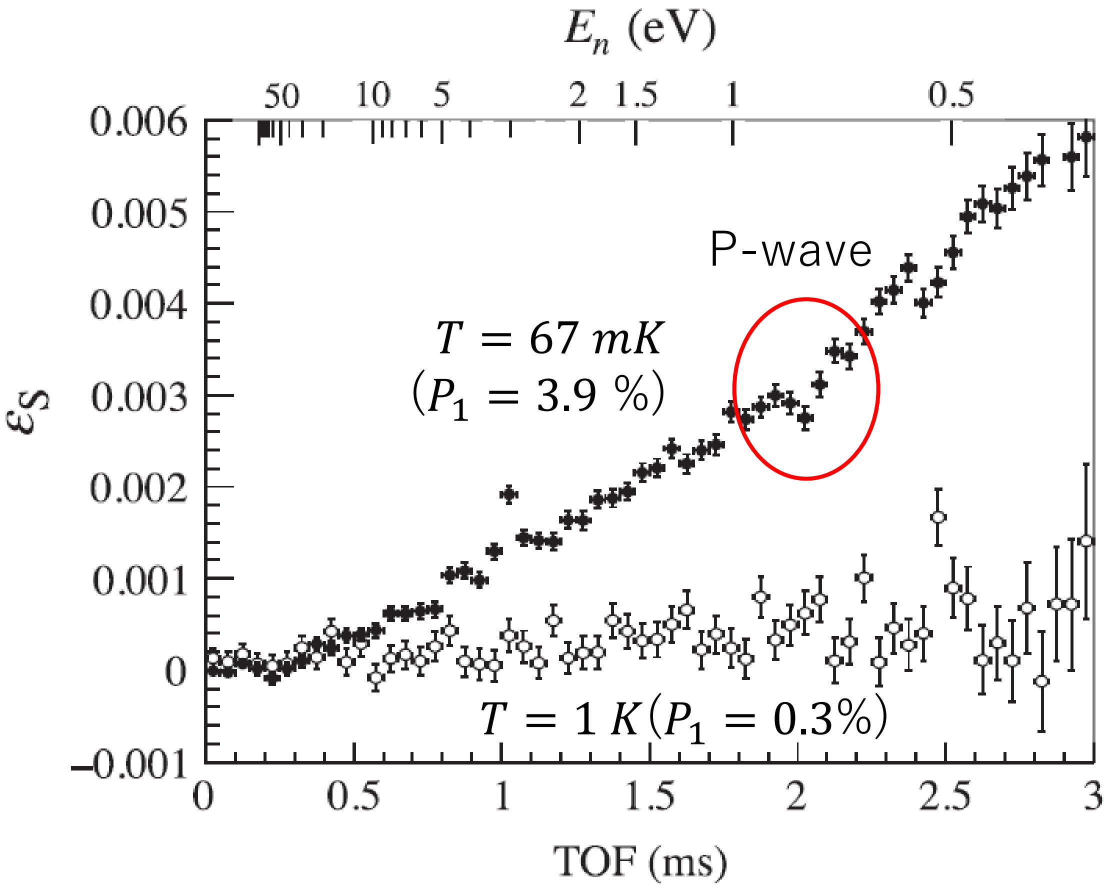
Neutron polarization
$P_n = 36.1 \pm 0.5$ %
($E_n = 0.75$ eV)

Measurement results

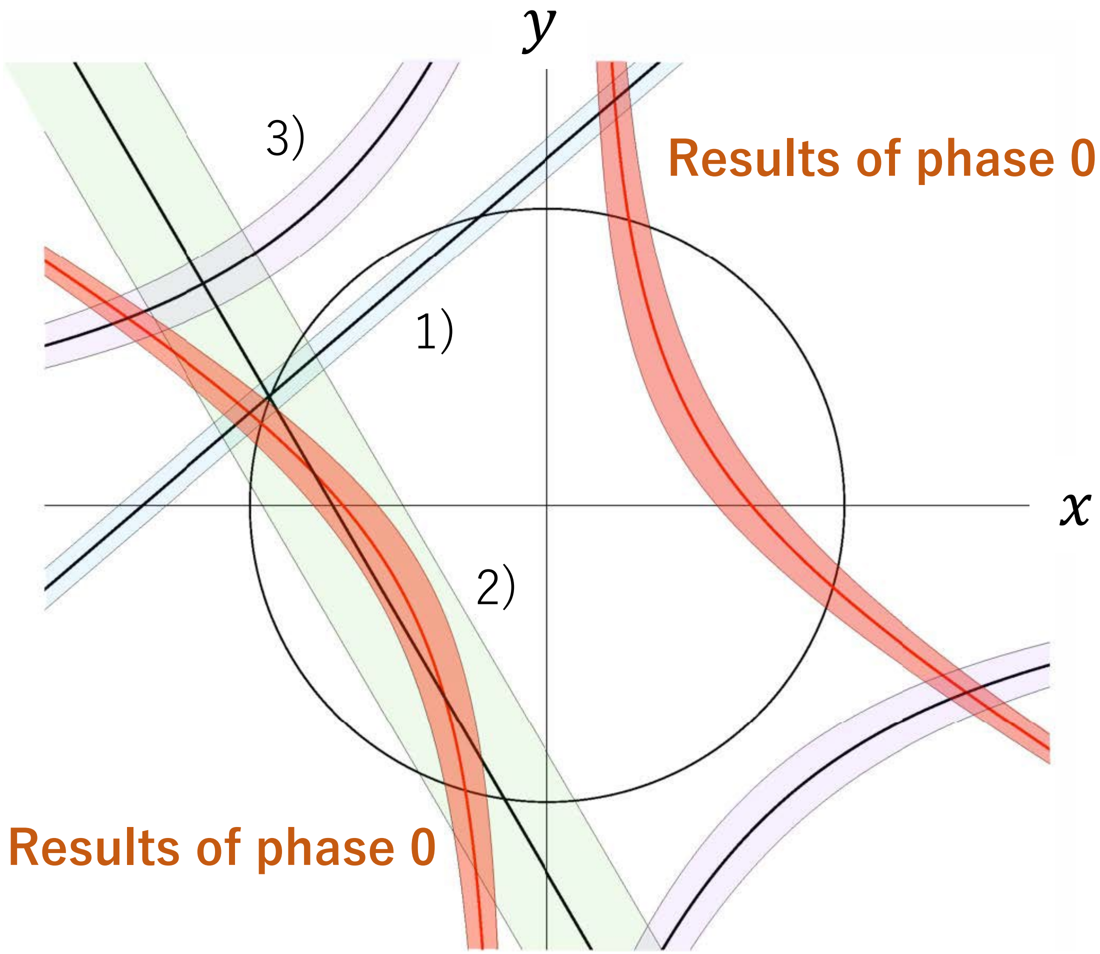
$\sigma_{\pm} = \sigma_0 \pm \sigma_S$ $\quad$ $\varepsilon_S = \dfrac{N_- - N_+}{N_- + N_+}$

$\sigma_{S,p}^{exp} = -0.26 \pm 0.08$ b

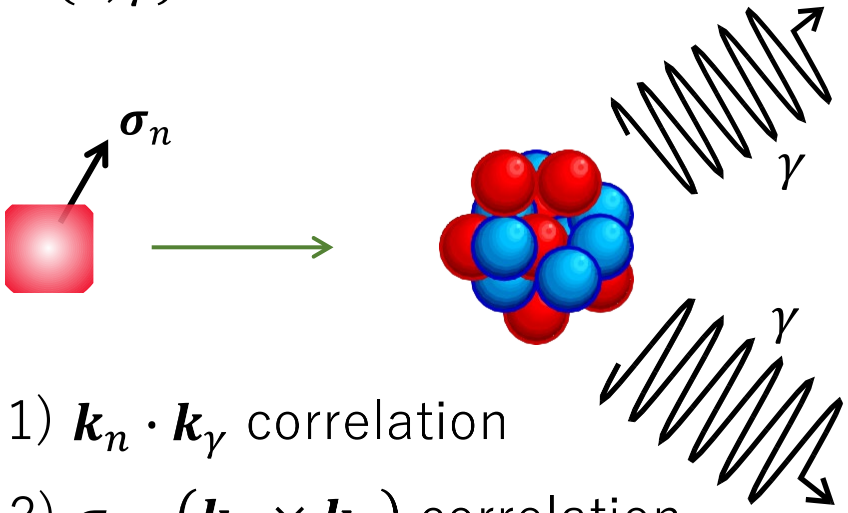




Evaluation of $\kappa(J)$



Other correlation measurements in (n,γ) reaction



1) $\boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma$ correlation

2) $\boldsymbol{\sigma}_n \cdot (\boldsymbol{k}_n \times \boldsymbol{k}_\gamma)$ correlation

3) $(\boldsymbol{k}_n \cdot \boldsymbol{k}_\gamma)^2 - 1/3$ correlation

$$\kappa(J) = 0.59 \pm 0.05$$

$$\Delta\sigma_{TRIV} = (0.17 \pm 0.02)\frac{W_T}{W}\ \text{b}$$

Preparation of Phase-1 experiments

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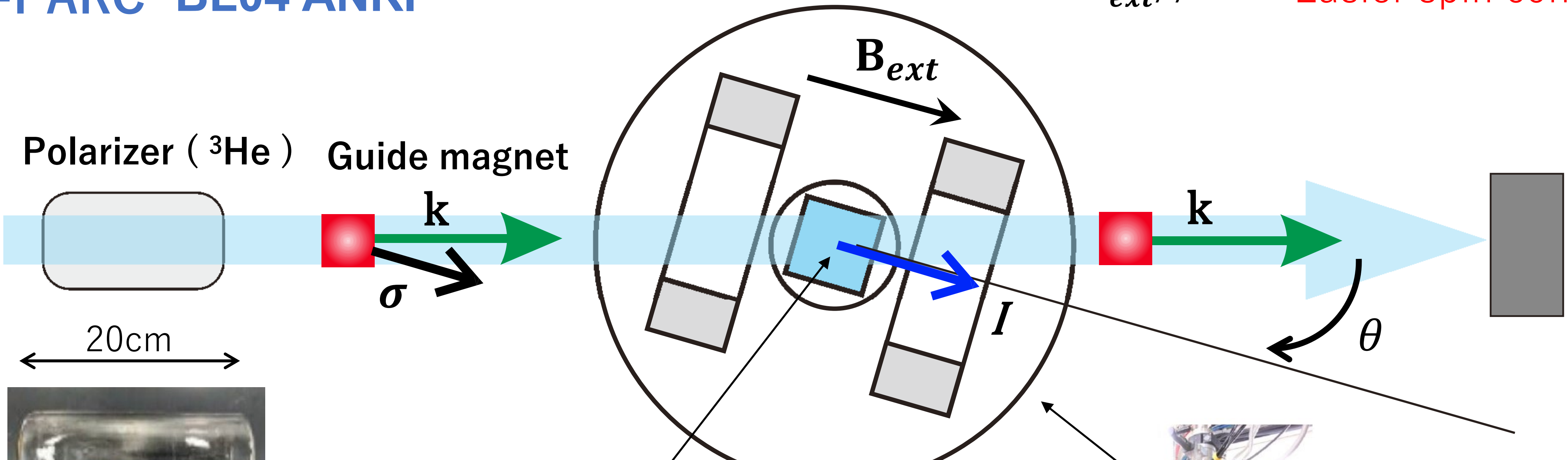
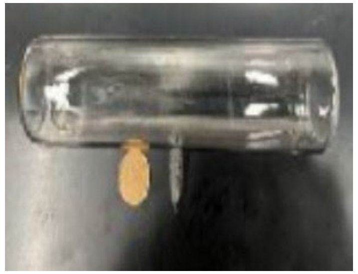
J-PARC BL04 ANRI

$\mathbf{B}_{ext} // \boldsymbol{\sigma}$ Easier spin control





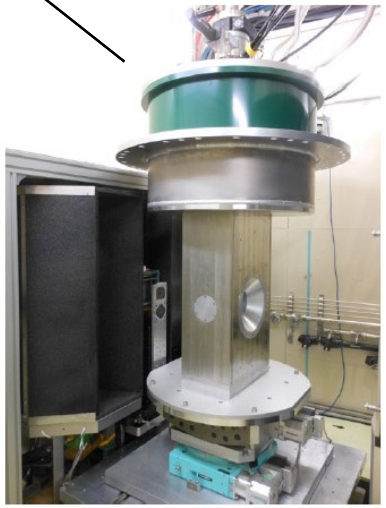
New big cell

P_n~85% at 0.74 eV

Polarized La Target

$LaAlO_3$ crystal
(Nd 0.03 mol%)

1.5cm cubic



4T superconducting magnet

Target assembly (preparation)

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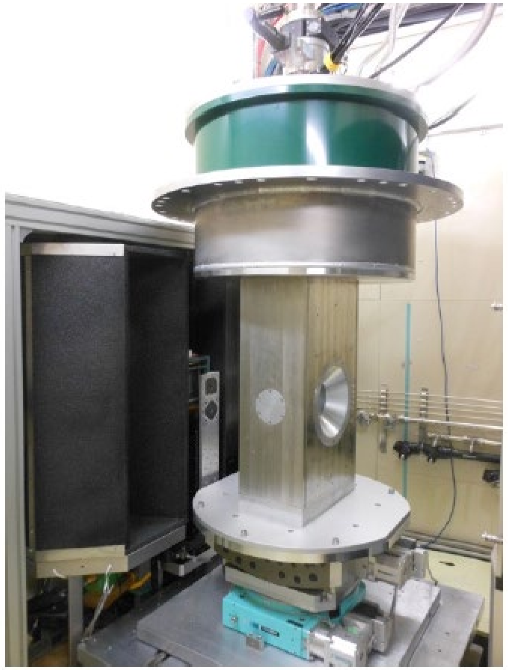
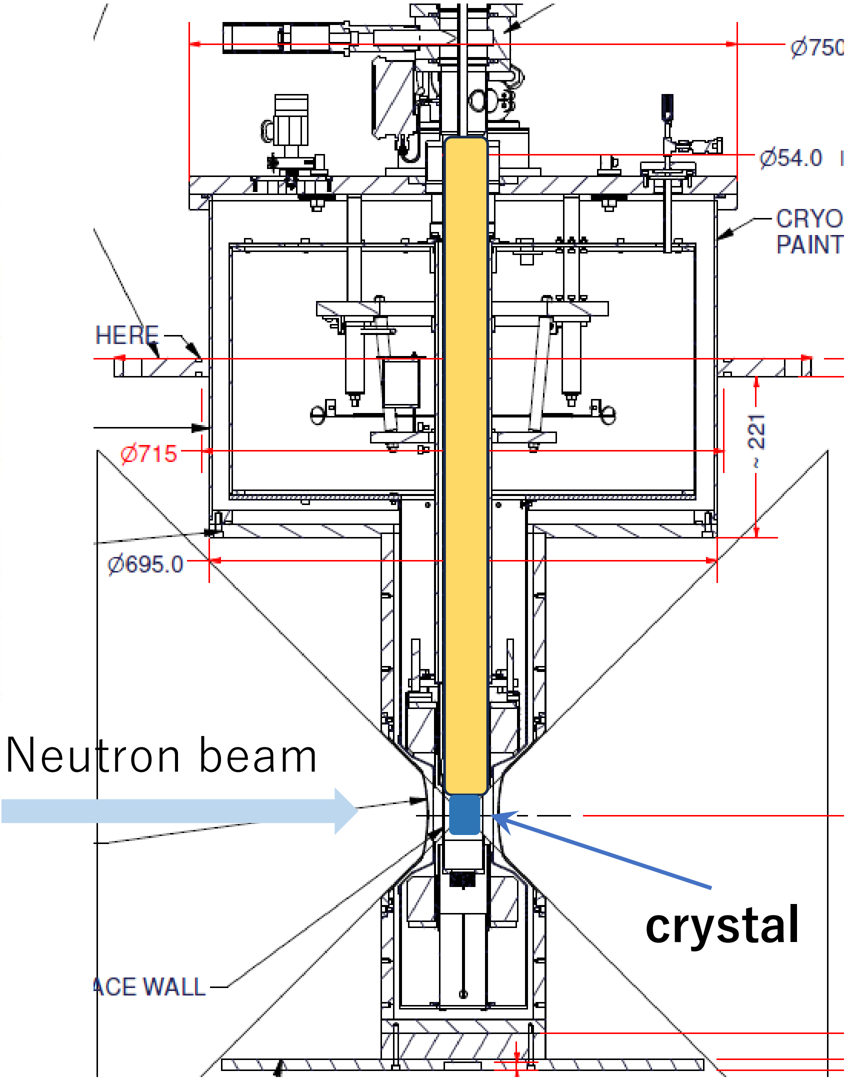
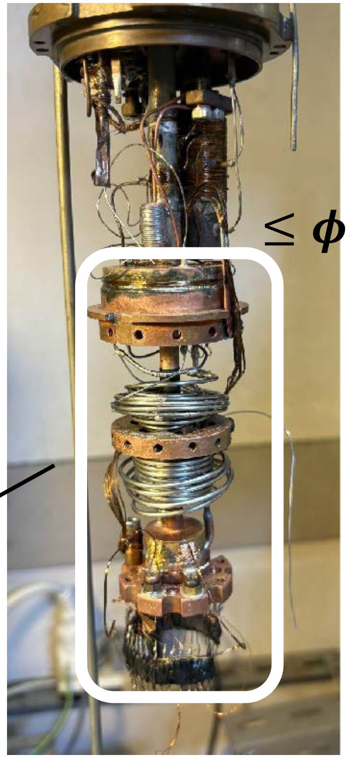




HM insert

For both of
DNP and **brute-force**

Compact
HM dilution



≤ ϕ50mm

Polarized La targets

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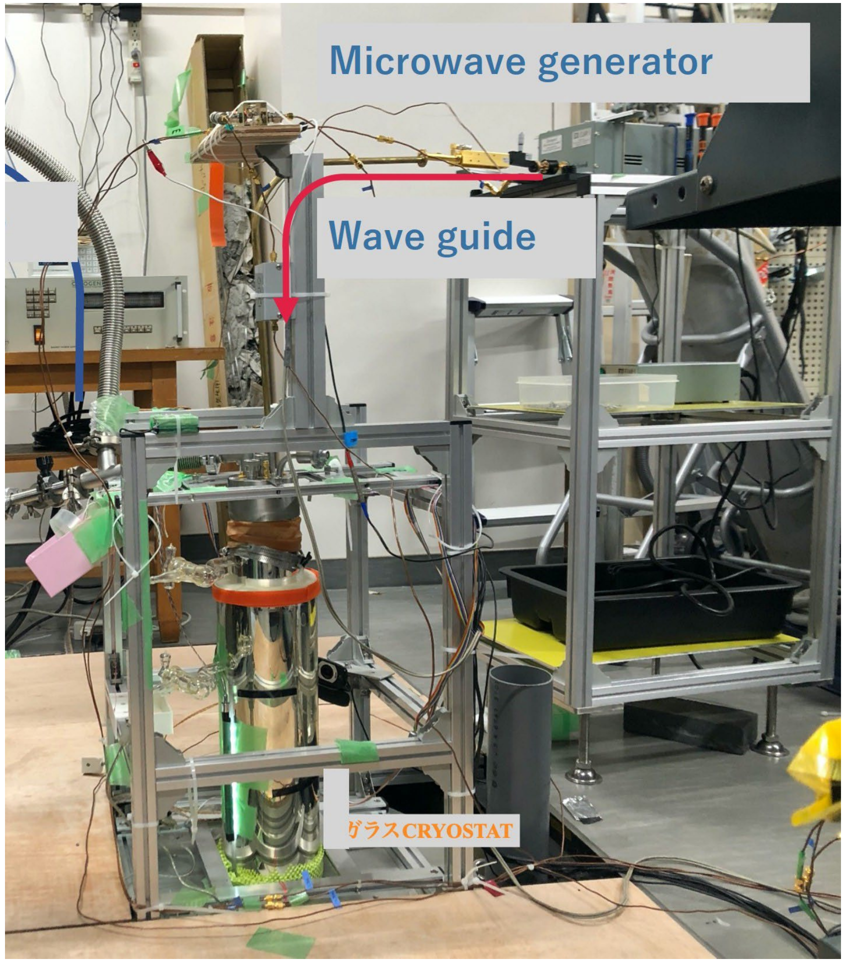
Dynamic Nuclear Polarization in $LaAlO_3$ crystals (Nd-doped) at Yamagata University



Condition : 2.3 T, 1.33 K

Apparatus : Glass dewar

Microwave: 69-71GHz, 200mW, 2W

NMR detection :
Al 25.915 MHz La 14.505 MHz

Nd : 0.01 mol%
Grown by ourselves

ϕ4mm, height 5 mm

$P_1 = 26 \pm 1\%$
(M.W. power : 0.2 W)

Nd : 0.03mol%
Grown by company

15 mm cubic

First use (large size)

$P_1 \sim 35\%$
(M.W. power : 2 W)

Optimization of Nd ions

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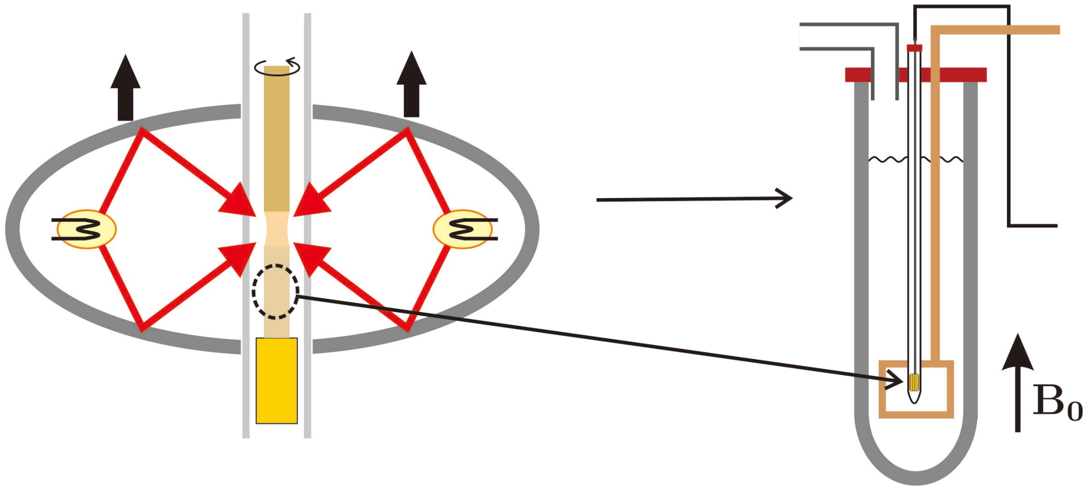
Crystal growth (Floating Zone) ➡ DNP tests



(Tohoku Univ. IMR) **(Yamagata Univ.)**

Crystalline part 40 mm

Direction of crystal axis

B_0= 2.3 T, Microwave power : 0.2 W

Nd mol%	Temp.	P_1 (saturated)	T_1 min.	size
0.03 [2]	1.5K	small	–	15mm cubic
0.05	1.3K	0.2 %	15	ϕ4mm × 5mm
0.03 [1]	**1.5K**	**20 %**	**80**	**15mm cubic**
0.01	**1.3K**	**52%**	**> 110**	**ϕ4mm × 5mm**

[1] : T. Maekawa, et al., NIM A V366, 115 (1995)
[2] : T. Maekawa, Kyoto Univ. Master thesis (1995) unpublished

Necessity of studies on growth for a large size

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Summary

- The T-violation search in neutron-induced compound nuclear reaction is quite attractive because of no final state interaction and availability of the huge enhancement similar to the PNC. In addition, this search is complementary to the neutron EDM.

- We have performed the Phase-0 experiments to measure the imaginary B' term, which demonstrate the realization of spin control. The results leads to $\kappa(J) = 0.56 \pm 0.05$ in La target by considering the other constraints on x and y, which means the same order enhancement as the PNC

- Now, the preparation is ongoing for starting the Phase-I experiments in Jan/Feb, 2026, particularly, our making efforts on ^{3}He polarizer, target cryogenics, spin control, etc.

Backup

Sensitivity

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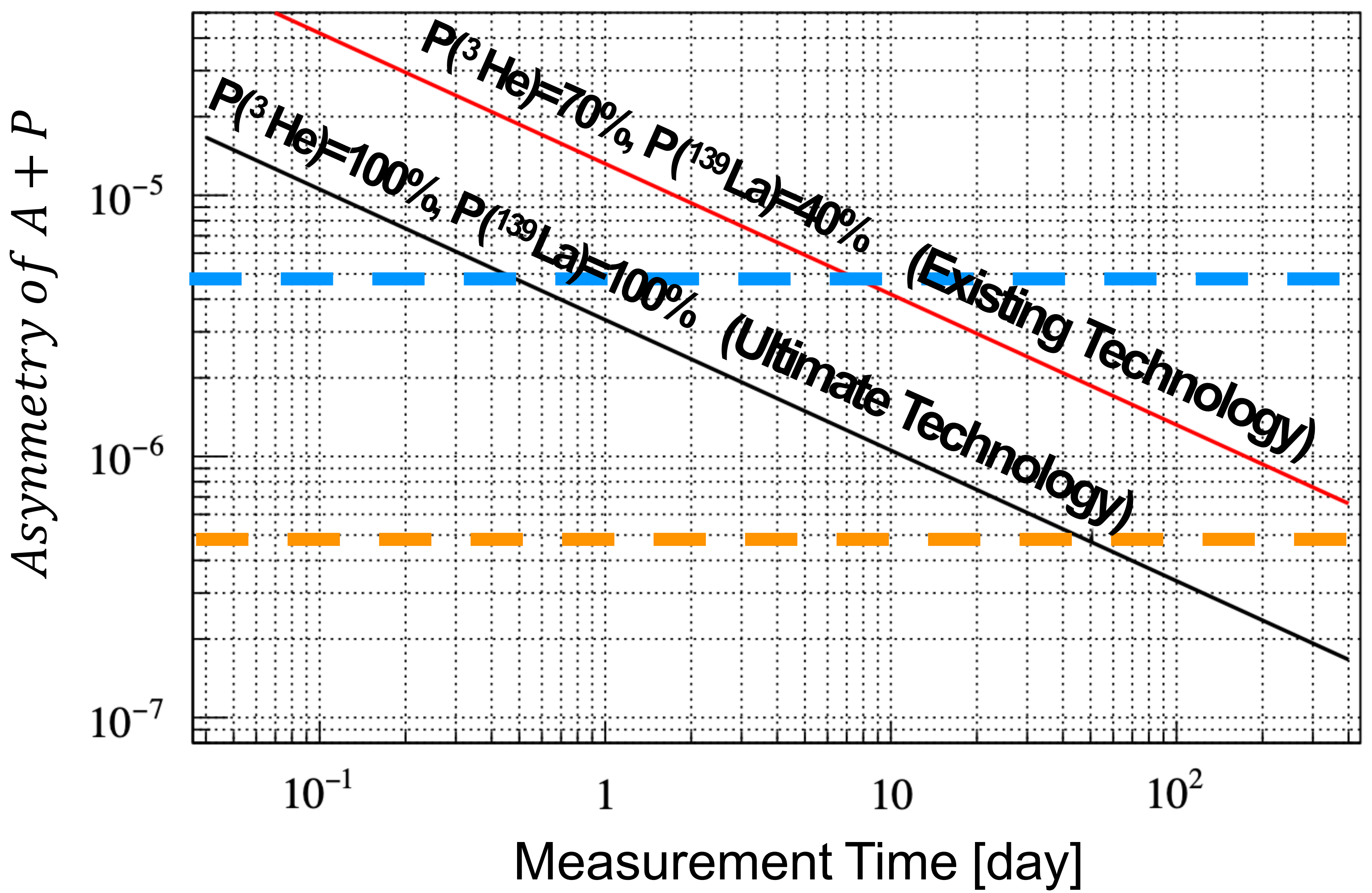
LaAlO$_3$ crystal $V \leq 40mm \times 40mm \times 28mm$ $B_0 = 0.1\,T$



J-PARC neutron source

$\frac{d\Phi}{dE} = 2 \times 10^{11} \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{eV}^{-1}$ @ 0.74 eV

$\Omega = 2.5 \times 10^{-5}$ sr

Discovery potential corresponding to $d_n = 3.0 \times 10^{-26}$ ecm

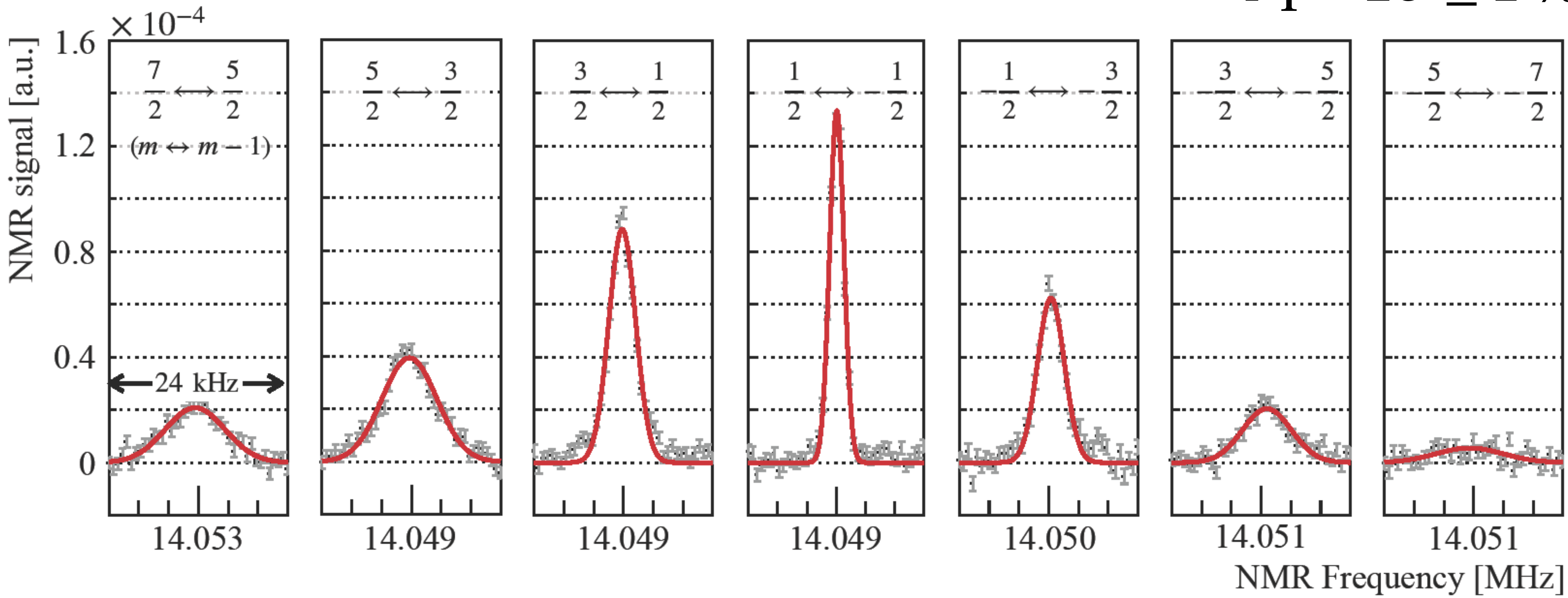
Discovery potential corresponding to $d_n = 3.0 \times 10^{-27}$ ecm

Enhancement of La (0.01 mol%)

Observation of 7 transitions ($I = 7/2$)

Microwave power : 200 mW $T_s = 3.782$ mK, B=2.35 T

$\boldsymbol{P_1 = 26 \pm 1\,\%}$



Not saturated !!

Buildup curve (0.01mol%)

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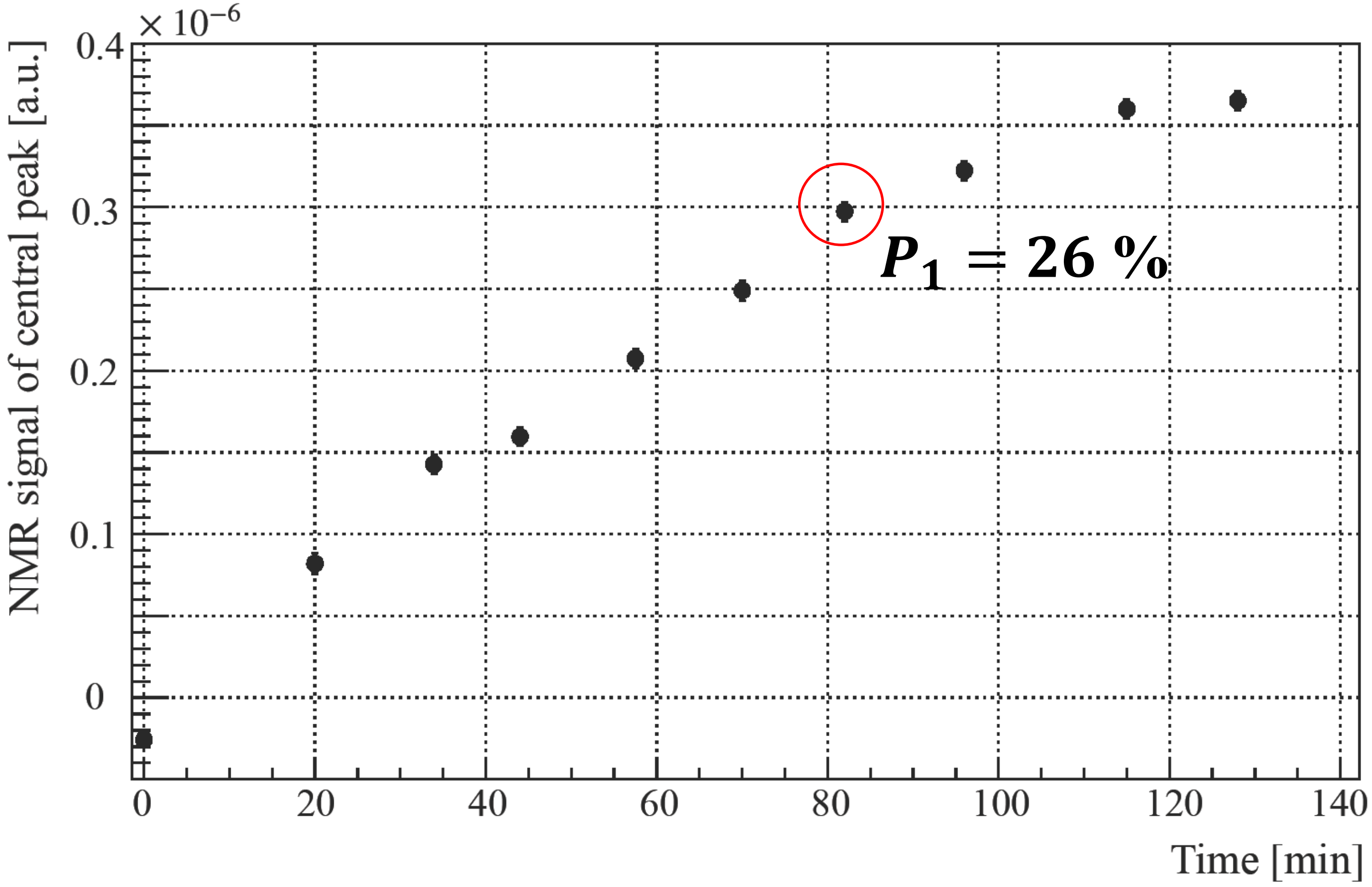
Monitoring of NMR signals in the transition $-1/2 \leftrightarrow +1/2$



Vector polarization in saturation

$P_1 = 52 \pm 3\ \%$

Evaluated buildup time

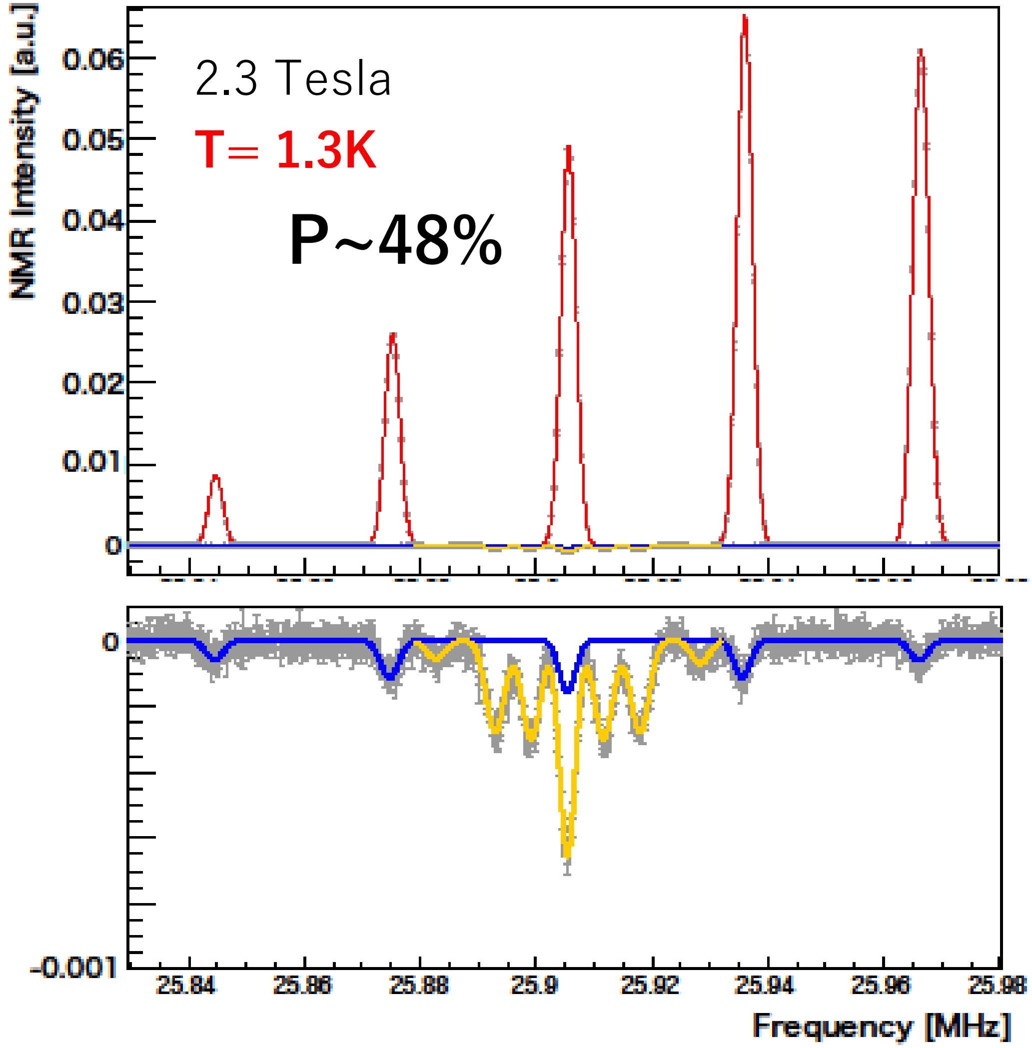
$T_b = 111.2 \pm 8.7\ [\mathrm{min}]$

Estimation of T1

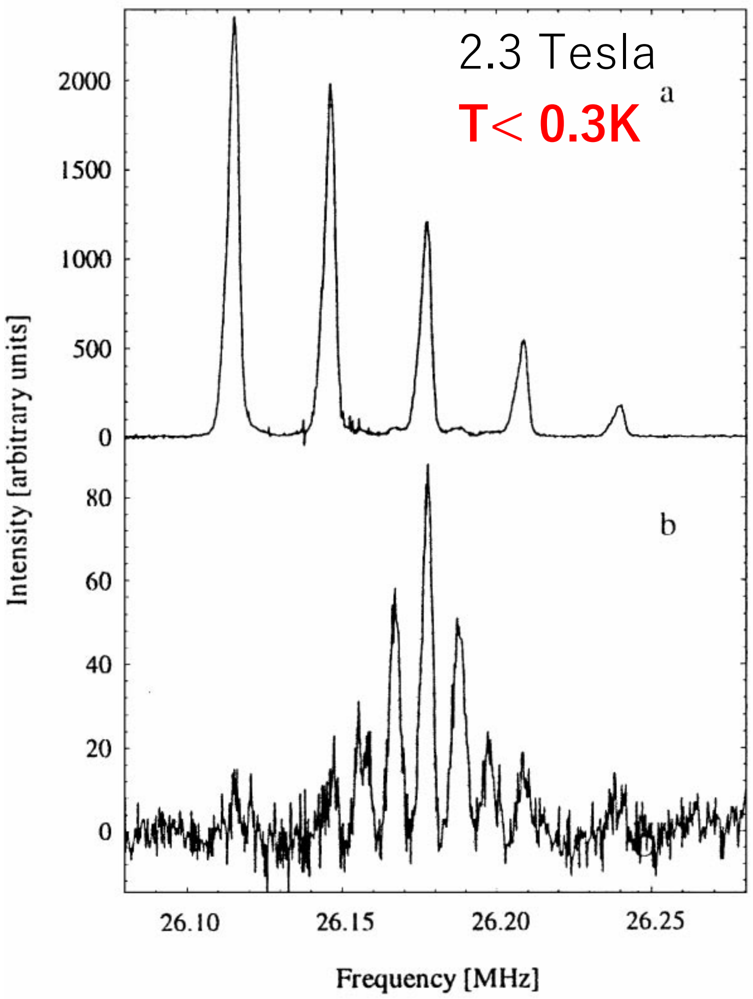
$\boldsymbol{T_1 > 110\ [\mathrm{min}]}$

Enhancement of Al (0.01mol%)

Microwave power : 2 W

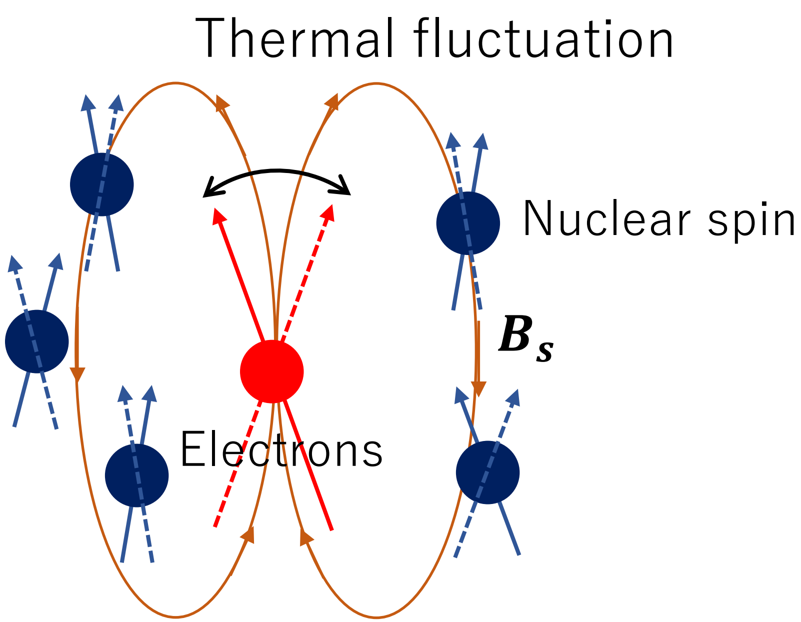


P.Hautle and M. Iinuma, *NIM* **A** 440, 638 (2000)



Relaxation process

Dipole-dipole interaction

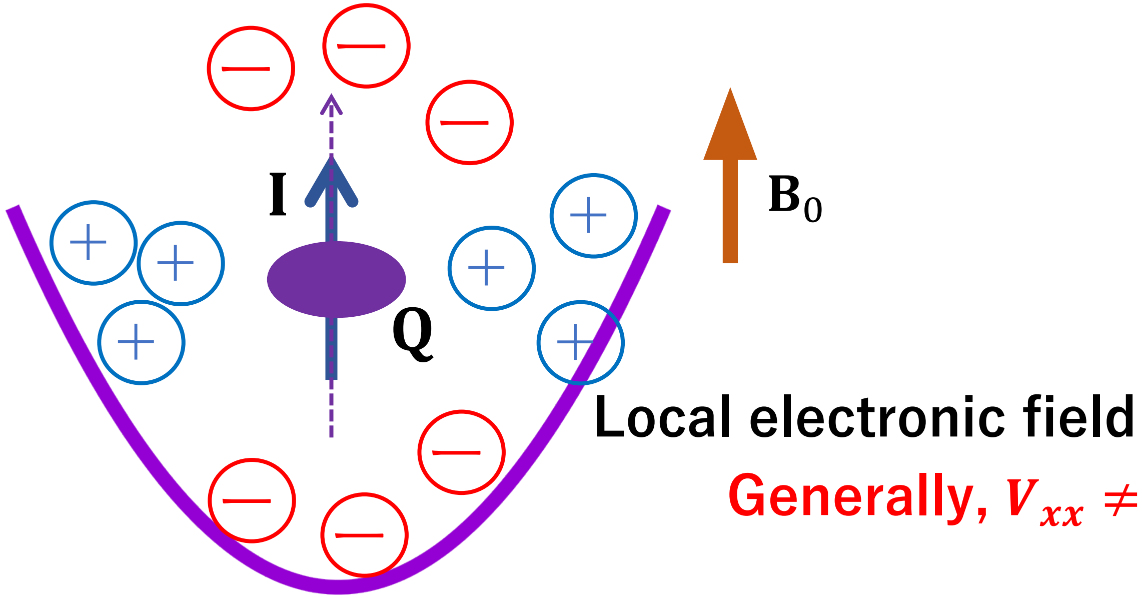


$$\mathbf{B}_s(\mathbf{r}) = -\frac{\mu_0}{4\pi}\hbar\gamma_e\left(\frac{\mathbf{S}}{r^3} - 3\frac{(\mathbf{S}\cdot\mathbf{r})\mathbf{r}}{r^5}\right)$$

Reduction of electron's number

Suppression of relaxation

Quadrupole interaction



Generally, $V_{xx} \neq V_{yy}$

$$\mathcal{H} = \frac{qQV_{zz}}{4I(2I-1)}\left[(3I_z^2 - I^2) + \underline{\frac{V_{xx}-V_{yy}}{V_{zz}}(I_x^2 - I_y^2)}\right]$$

Mixing between Zeeman sublevels

(in low magnetic field) not maintaining high polarization

Use of Nd^{3+}:$LaAlO_3$ crystals

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Perovskite structure

Paramagnetic ions for the DNP

Nd^{3+}: $LaAlO_3$ crystal

Perovskite crystal

Partially replacement of La with Nd

$$N_{La} : N_{Nd} \sim 10000 : 1$$

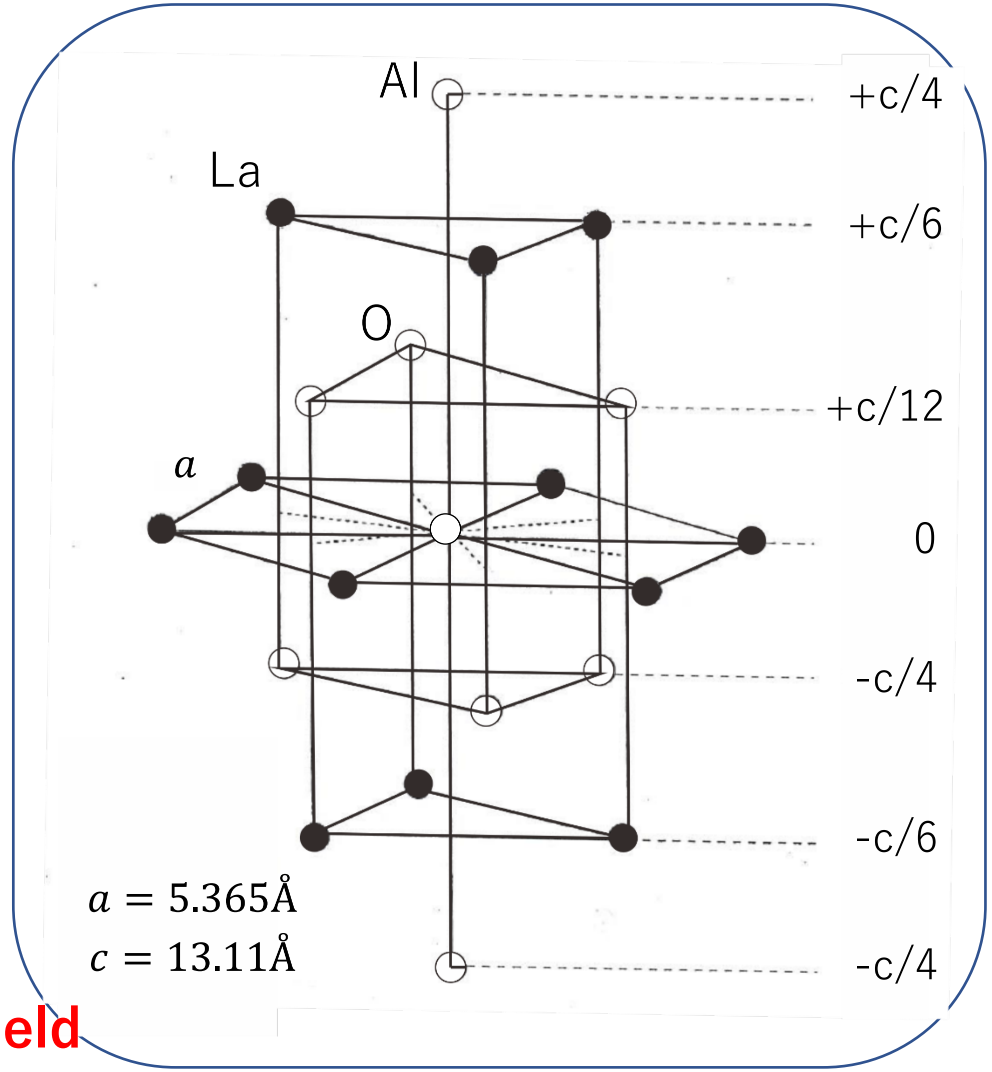
g-factor of Nd^{3+} : $g_{//} = 2.12 \quad g_{\perp} = 2.68$

3fold rotational symmetry(C_3) $V_{xx} = V_{yy}$

$$\frac{eQV_{zz}}{4I(2I-1)}\left[(3I_z^2 - I^2) + \frac{V_{xx} - V_{yy}}{V_{zz}}(I_x^2 - I_y^2)\right]$$

Maintaining high polarization in a low magnetic field

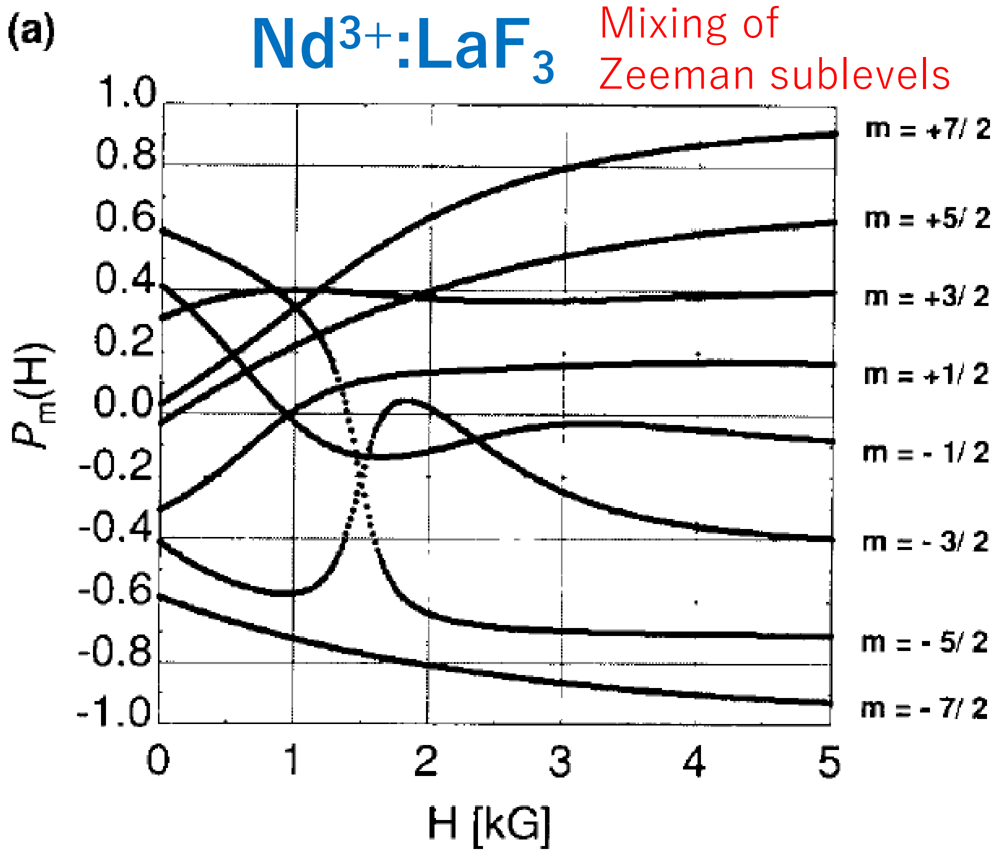
Y. Takahashi, et. al., NIM A 336, 583 (1993)



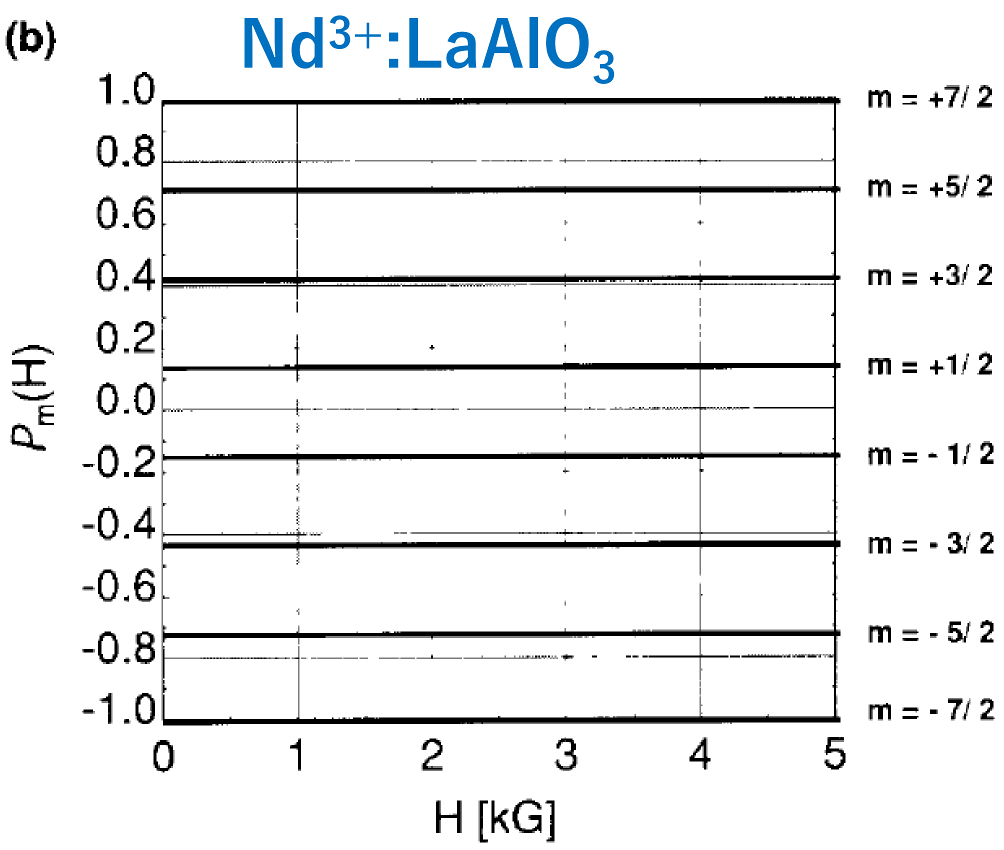
Characteristics in a low field

Y. Takahashi, et. al., NIM A 336, 583 (1993)

Population in Zeeman sublevel ψ_m : $P_m(H) \equiv \langle\psi_m|I_Z|\psi_m\rangle/I$ Field orientation : C_3 axis



Not easy for maintaining



Possible for maintaining in a low field

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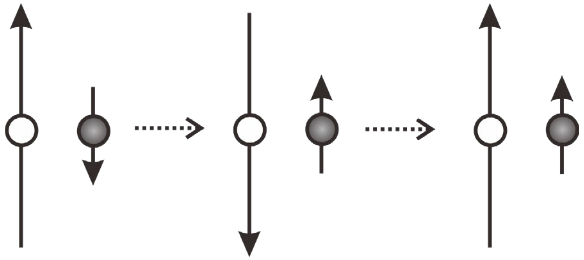
Typical preparation of polarized target

Low magnetic field (< 1 T) 2.3 T too high for a typical beam experiment

Achievement of high polarization

Low temperature (~ 0.5 K)
High magnetic field (> 2.3 T)

DNP

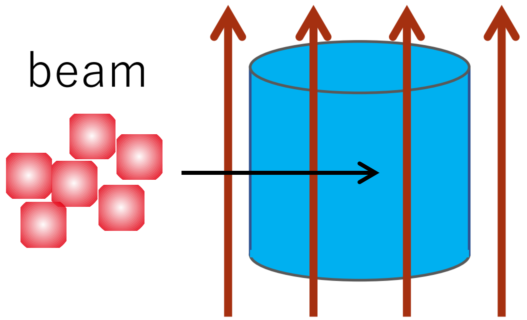


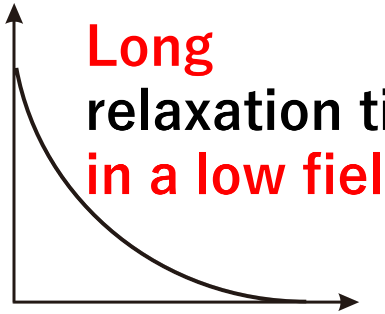
Microwave irradiation

Switch

Spin frozen target

Very low temperature (< 0.1 K)
Low magnetic field (< 1 T)





Long relaxation time in a low field

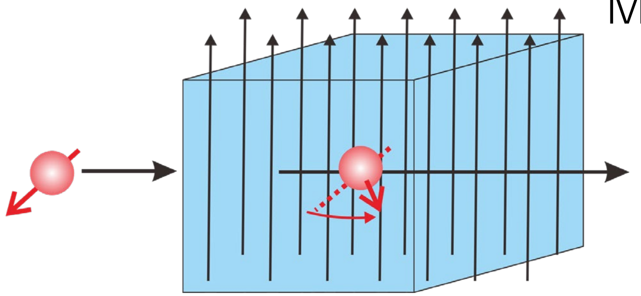
Reduction of the field after freezing spins

Practical polarized target : only proton and deuteron

Systematic effects

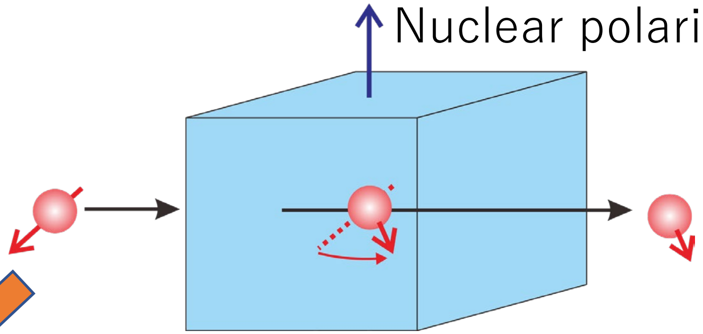
Neutron spin rotation ➡ Reduction of the sensitivity of the D term $D\boldsymbol{\sigma}\cdot(\boldsymbol{k}\times\boldsymbol{I})$

Spin rotation by external magnetic field



At 2.3[T] (DNP exp)
and thickness of 4cm
Rotation angle : $8.1°$

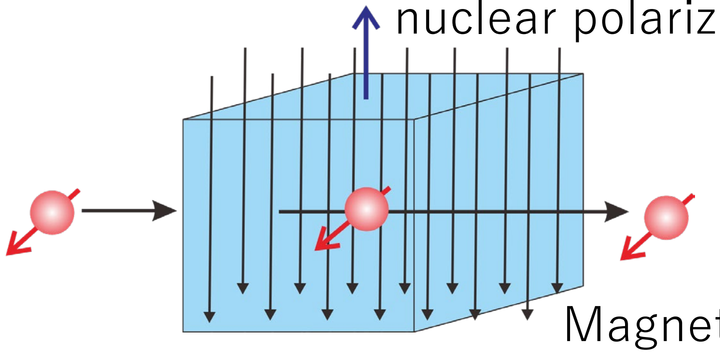
Spin rotation by pseudomagnetic effect



$LaAlO_3$: $H' = 0.1$ [T] for 50% La polarization

V. Gudkov and H. M. Shimizu, Phys. Rev. C **95** 045501, 2017

Cancellation of spin rotation



Opposite direction

Dynamic Nuclear Polarization (DNP)

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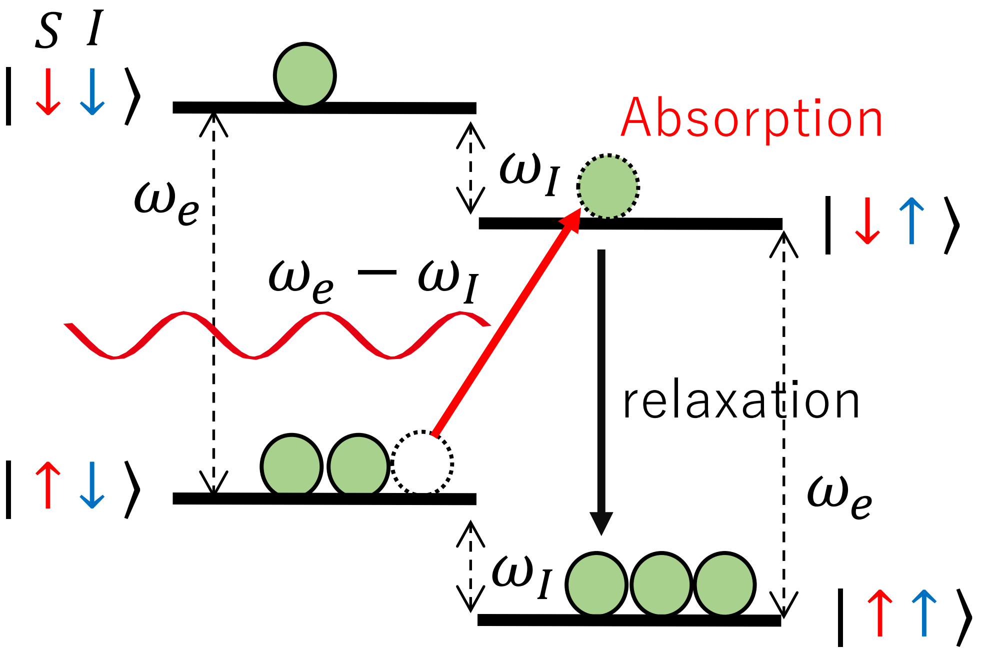
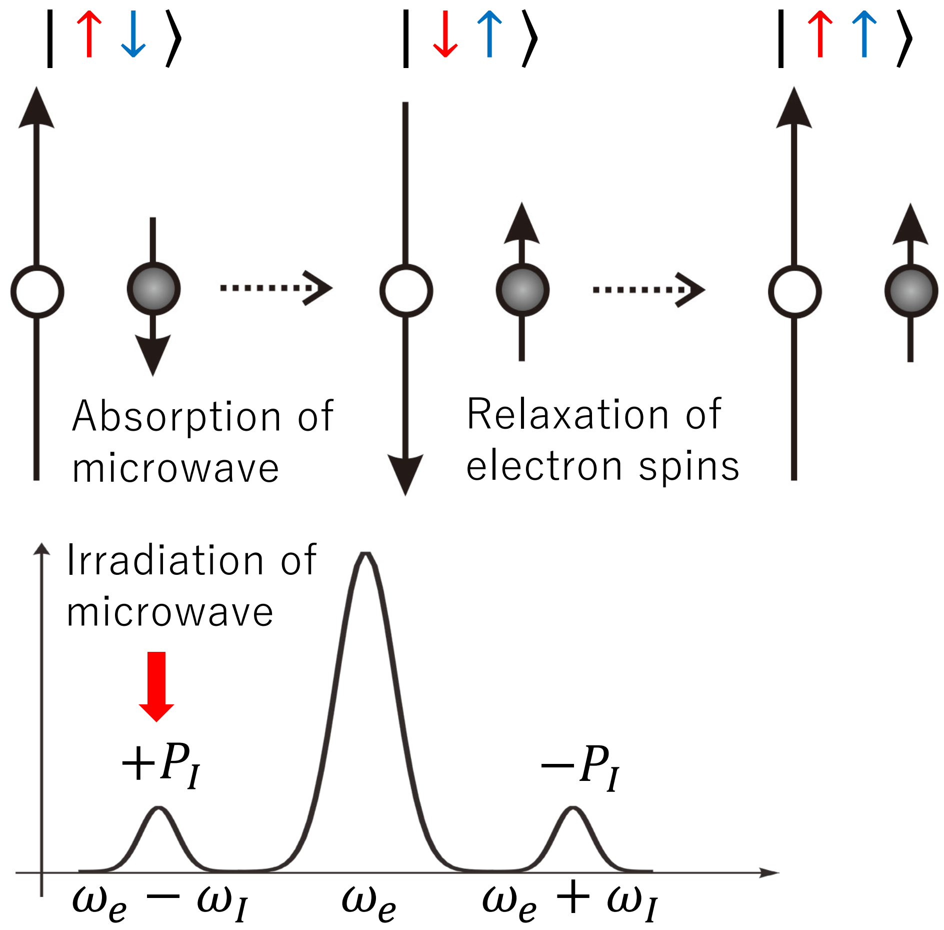
Electron (paramagnetic ions) polarization ⇒ Transfer into nuclear spins

(Method: solid effect, thermal mixing, etc...)

Ex) Solid effect($I = 1/2$)



microwave ($\omega_e - \omega_I$) irradiation



Candidates of target nuclei

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	^{139}La	^{81}Br	^{117}Sn	^{131}Xe
Large PNC effect	◎	○	◎	◎
Small resonance energy	◎	◎	○	○
Small nuclear spin	△ 7/2	○ 3/2	◎ 1/2	○ 3/2
Large natural abundance	◎	○	×	△
Large $\lvert\kappa(J)\rvert$	~1 T. Okudaira, et al., Phys. Rev. C97, 034622, (2018)			
Nuclear polarization	~50% DNP P. Hautle and M. Iinuma, NIM A440, 638, (2000)	–	–	~7% SEOP Molway et al., arXiv: 2105.03076 (2021) US NOPTREX

Configurations

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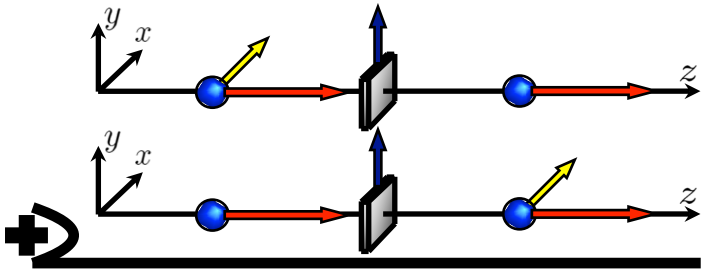
Forward scattering amplitude

Pseudomagnetic effects

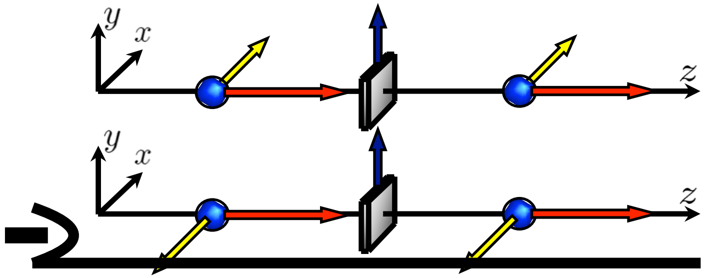
$$f = A + B(\boldsymbol{\sigma}\cdot\boldsymbol{I}) + C(\boldsymbol{\sigma}\cdot\boldsymbol{k}) + D\boldsymbol{\sigma}\cdot(\boldsymbol{k}\times\boldsymbol{I})$$

P-odd T-even

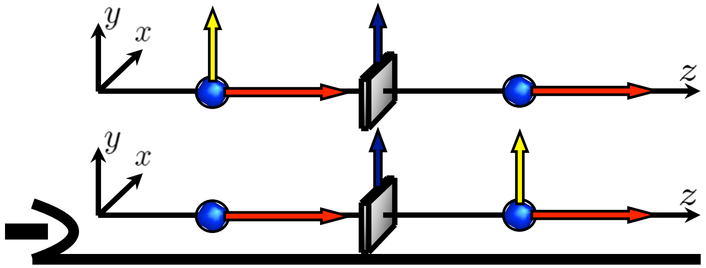
T-odd P-odd



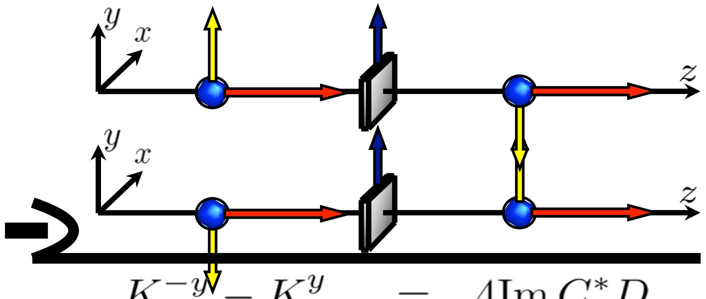
$$A_x + P_x = 8\mathrm{Re}\,A^* D$$



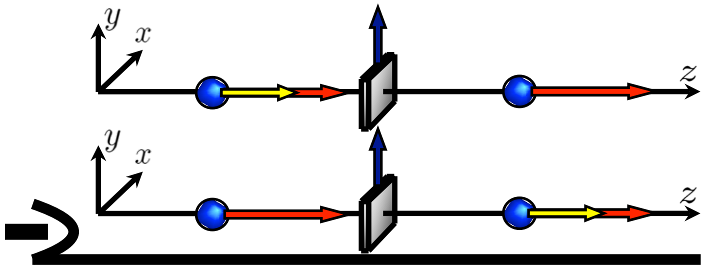
$$K^{x}_{x} - K^{-x}_{-x} = 4\mathrm{Re}\,A^* D$$



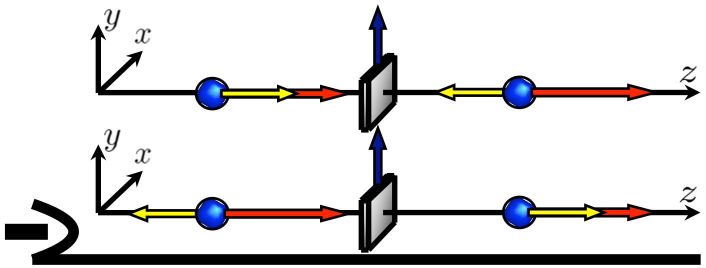
$$A_y - P_y = 8\mathrm{Im}\,C^* D$$



$$K^{-y}_{y} - K^{y}_{-y} = 4\mathrm{Im}\,C^* D$$



$$A_z - P_z = 8\mathrm{Im}\,D^* B$$



$$K^{-z}_{z} - K^{z}_{-z} = 4\mathrm{Im}\,D^* B$$

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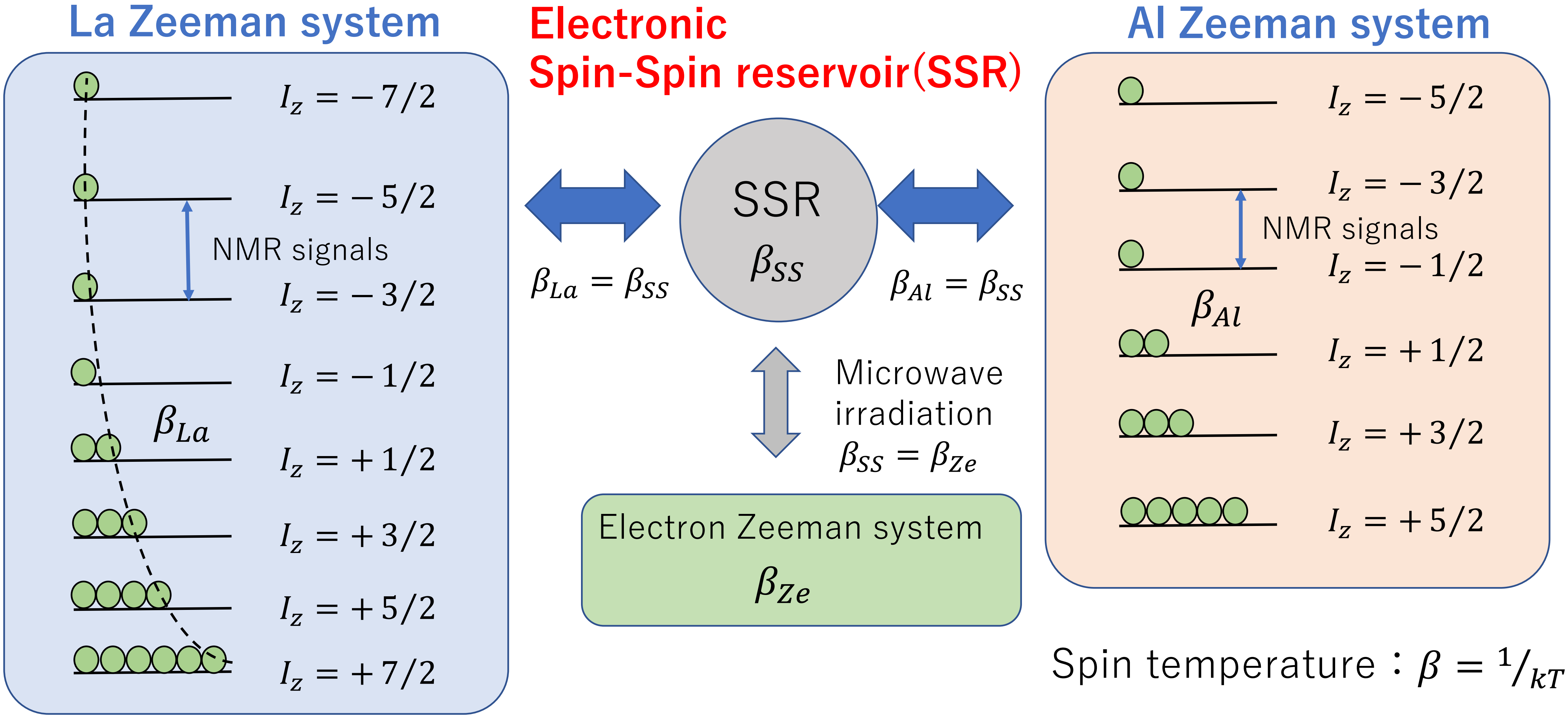
DNP mechanism



Evidence of SSR

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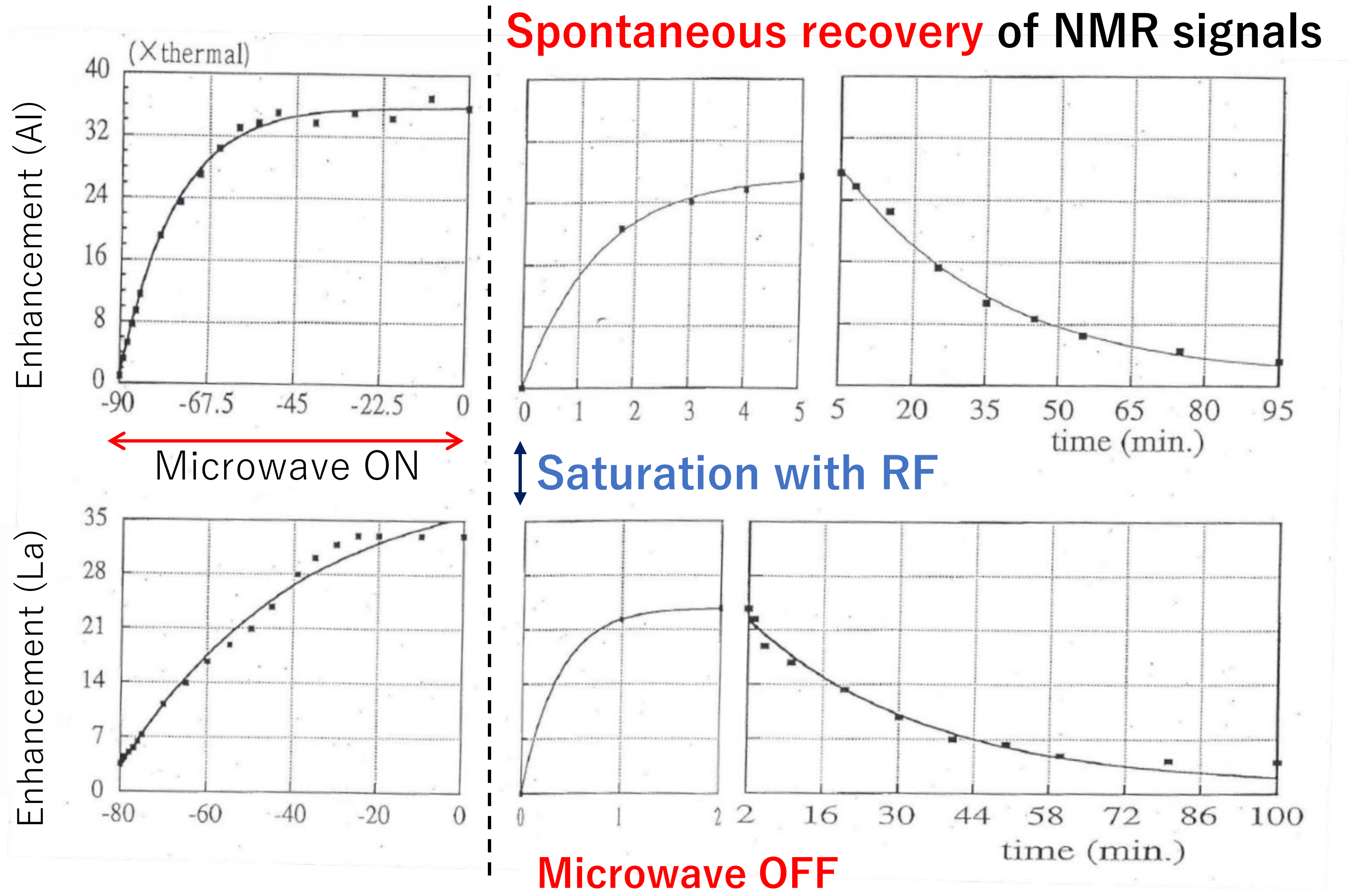
T=1.8K B=0.8T Microwave : 24GHz, 200mW



La transition

$I_z = -5/2 \leftrightarrow I_z = -3/2$

Al transition

$I_z = -1/2 \leftrightarrow I_z = +1/2$

Basic method for Nd optimization

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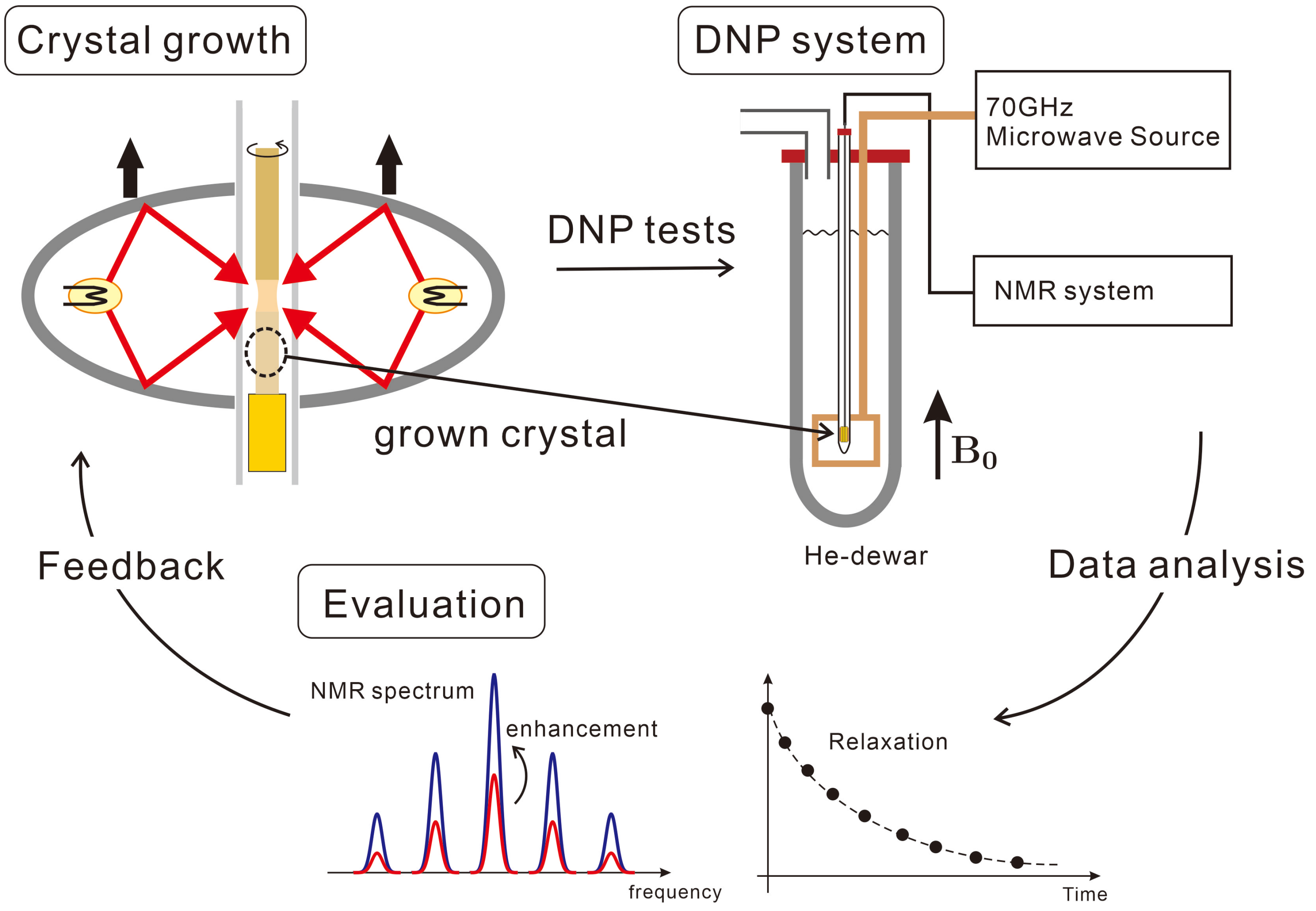
Neutron Optical Parity and Time-Reversal EXperiment

K. Ishizaki, et al., *Rev Sci Instrum* **95**, 063301 (2024)



Crystal growth
(Floating Zone(FZ) method)
in Tohoku University, IMR

Various Nd concentrations

DNP tests
(1.3 K, 2.3 Tesla)
in Yamagata University

Evaluation of crystals
for next crystal growth

Crystal growth in IMR, Tohoku Univ.

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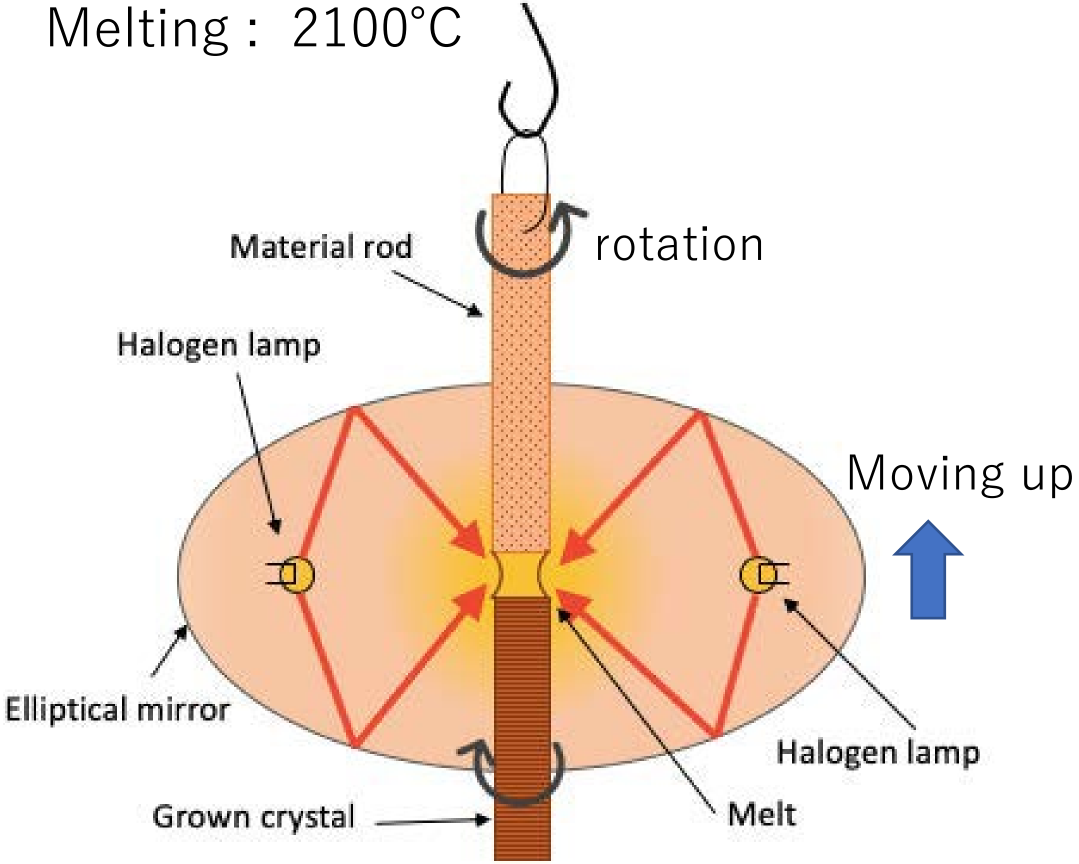
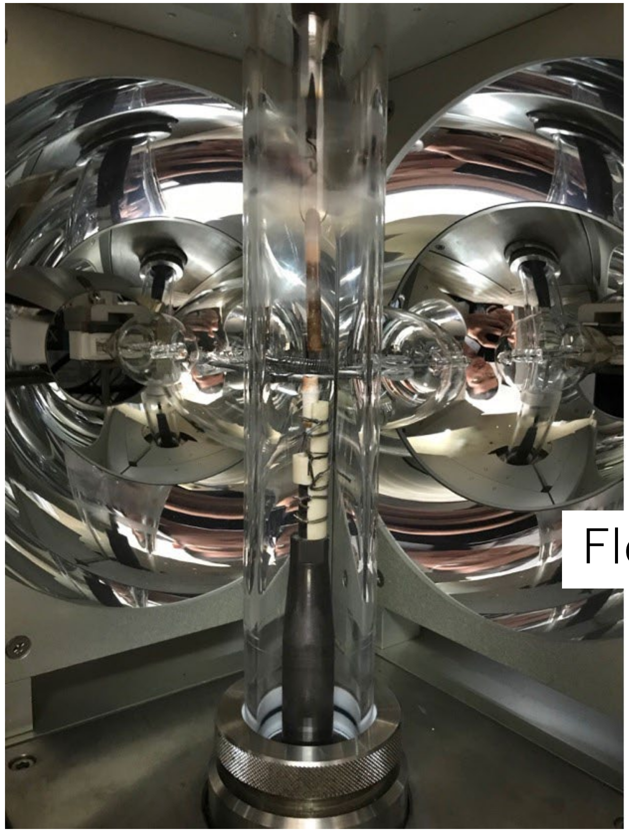
IMR cooperative program,
No. 18G0034, 19K0081, 19G0037, 202012-CNKXX-0001, 202012-CRKEQ-0015

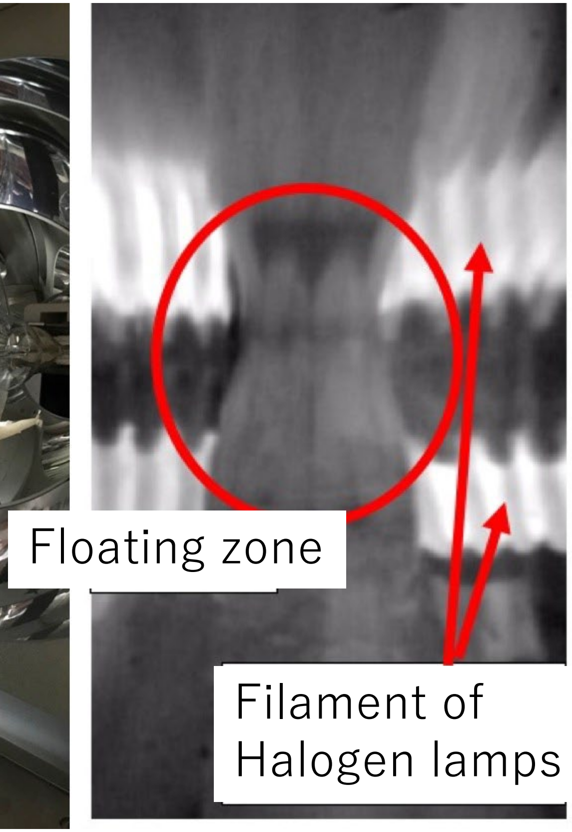
Floating-Zone(FZ) method

Melting : 2100°C



Mixed sample : powder of $La(OH)_3 + Al_2O_3$





Typical grown crystals

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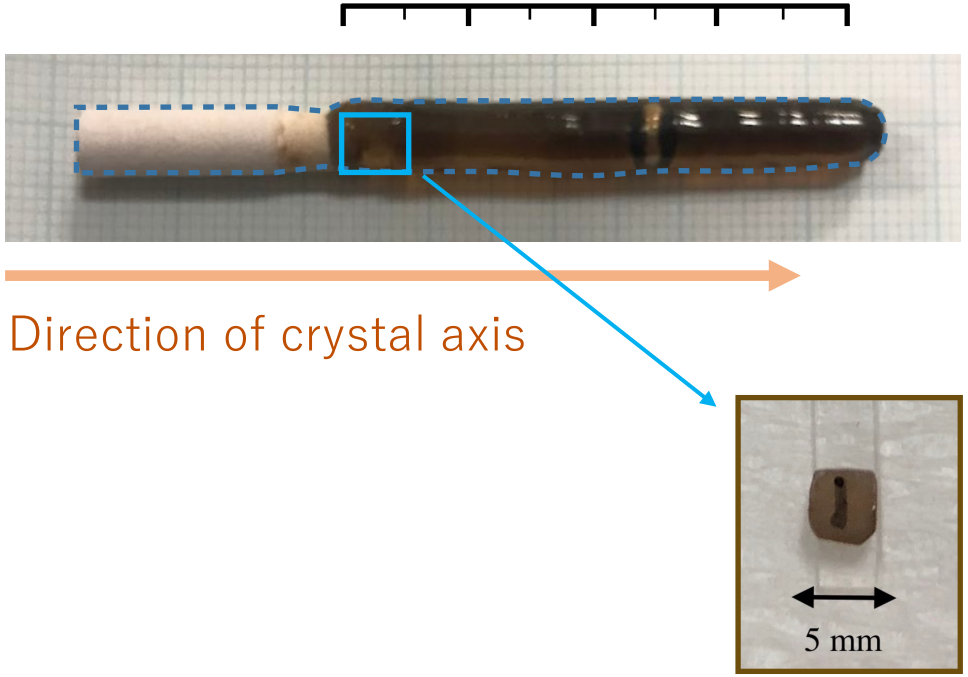
First crystal Nd : 0.05mol%

Dimension : Diameter 5 mm Length 40 mm

Crystalline part 40 mm

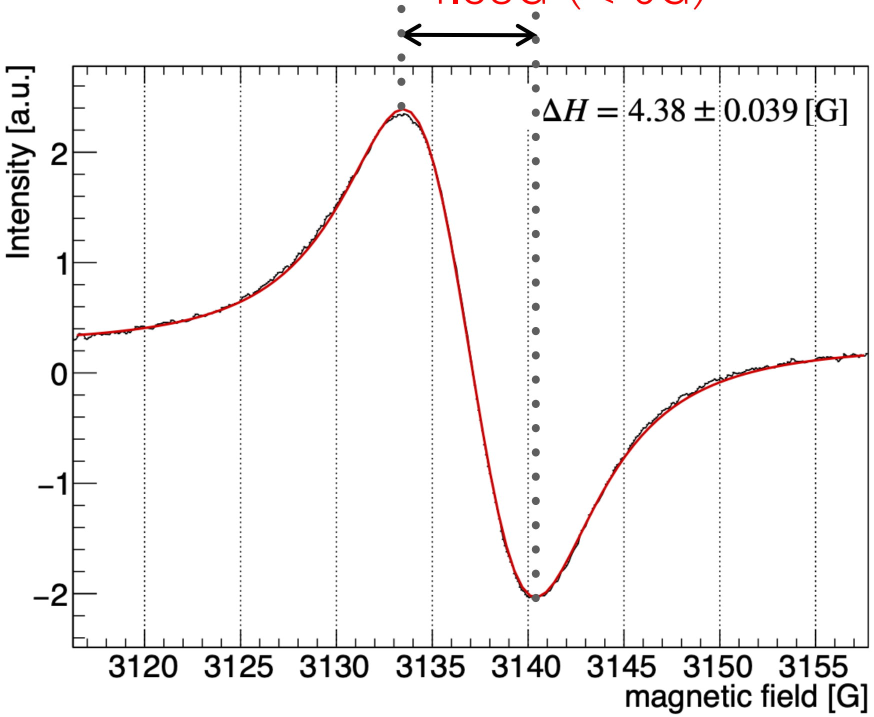


Direction of crystal axis

ESR measurements

Narrower

4.38G (< 6G)



First results with our grown crystal

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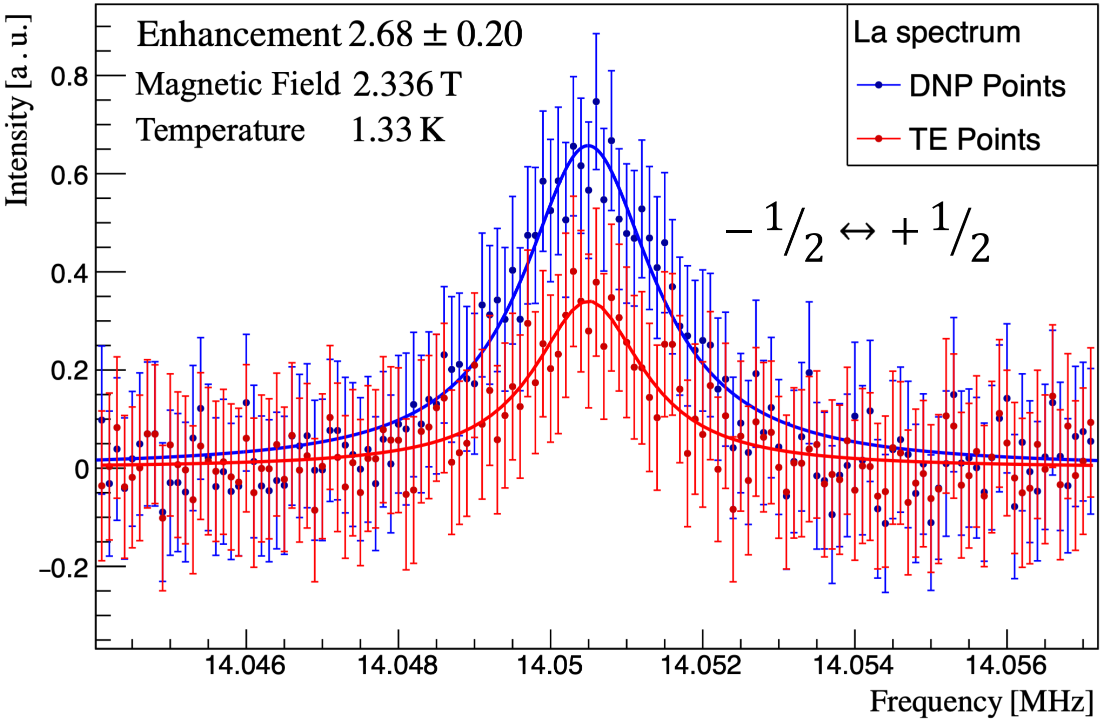
First observation of the enhancement with the crystal grown by ourselves.

0.05mol% crystal

La spectrum

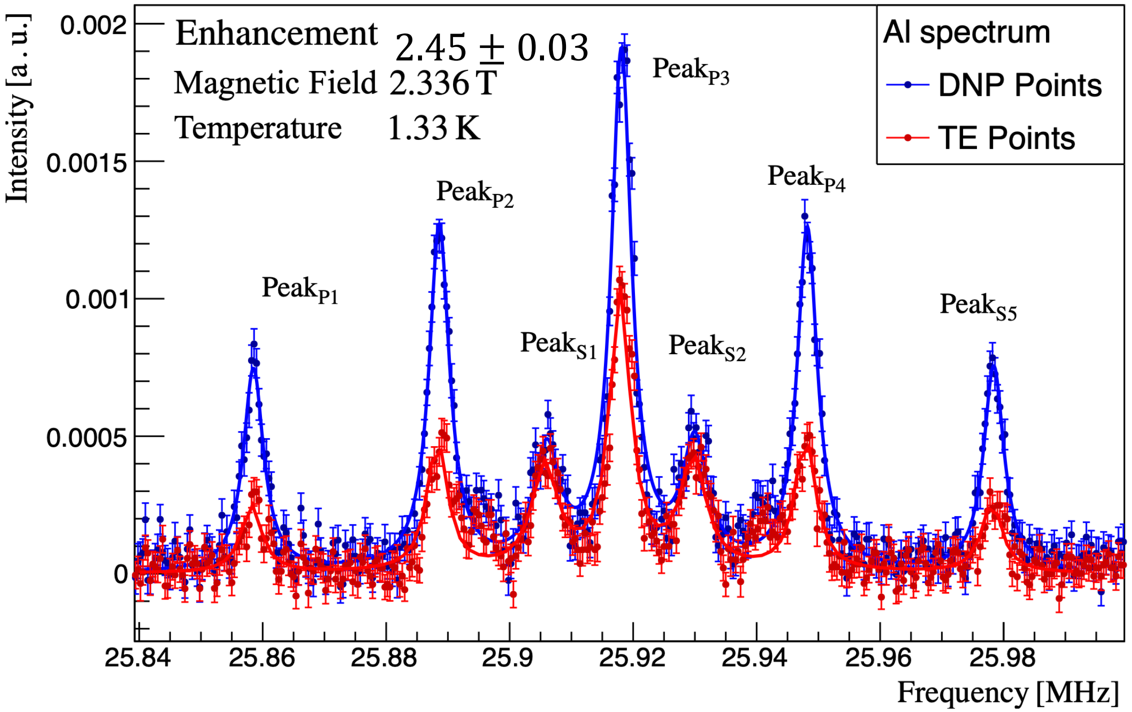


Enhancement $= \mathbf{2.68 \pm 0.20}$

$$P_{vector} = 0.202 \pm 0.011$$

Al spectrum

Condition: 2.3 T, 1.3 K



Enhancement $= \mathbf{2.45 \pm 0.03}$

Buildup & relaxation

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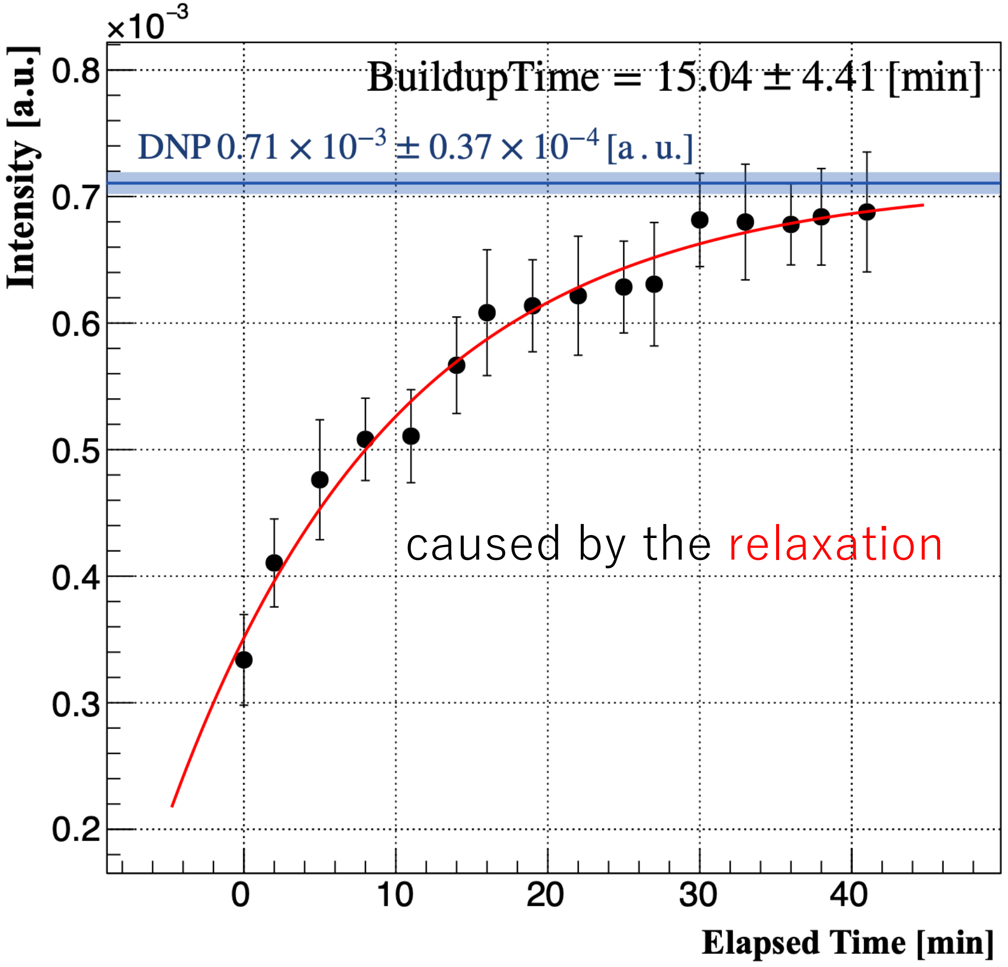
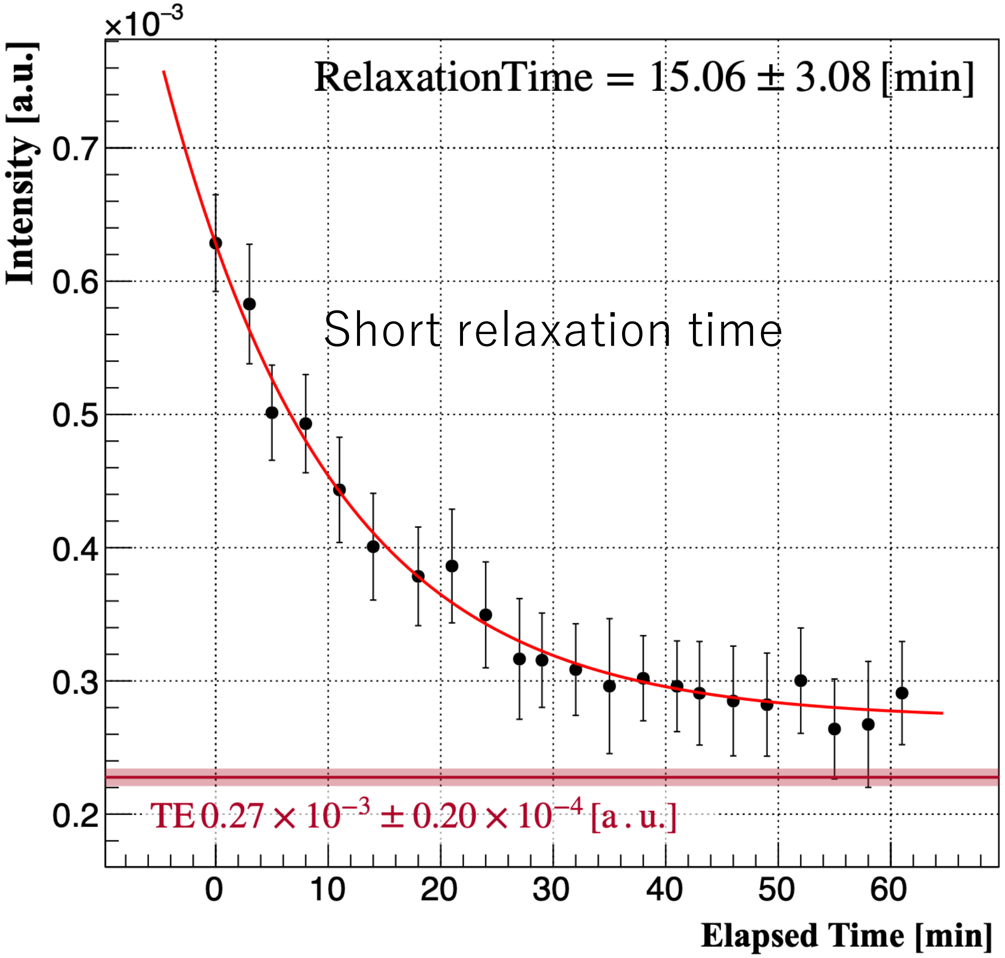
Neutron Optical Parity and Time-Reversal EXperiment

0.05mol% crystal La NMR signal $-1/2 \leftrightarrow +1/2$ transition

Buildup time ≅ Relaxation time

Condition: 2.3 T, 1.3 K





Present research organization

Collaboration of 7 research institutes and 6 universities

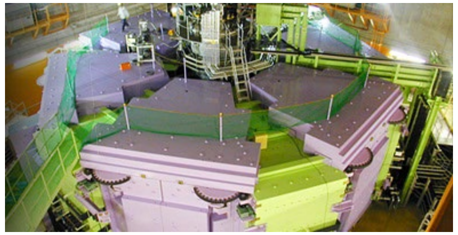
IMR(Tohoku University)

Nagoya University

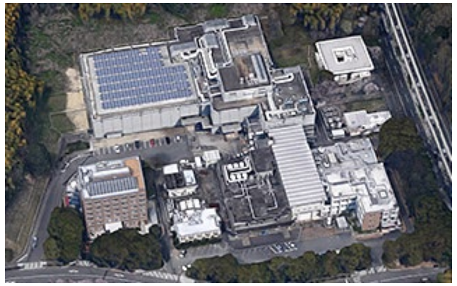
Hiroshima University
Kyoto University
Yamagata University
Ashikaga University
Japan Weman's University

PSI

RIKEN Nishina
RIKEN CEMS



RCNP(Osaka University)



KEK IPNS, J-PARC cryogenics section, KEK IMSS