NOPTREX project (overview)

Masataka Iinuma（NOPTREX collaboration）
Hiroshima University

NOPTREX
Neutron Optical Parity and Time-Reversal EXperiment

2022.9.2(Fri) 19th QCD Workshop, Yamagata, Japan

Outline

1. Motivation
   - Search of T-violating effects in a low-energy region -

2. Enhancement of PNC and T-violation in compound state

3. Plan of NOPTREX project

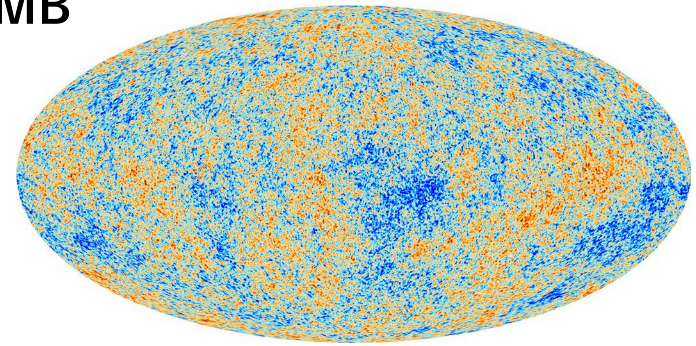
4. Summary

Search of unknown CP violation

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

Observation

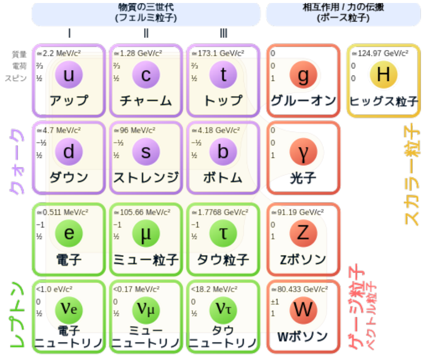
CMB



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

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

the Standard Model



Unexplained !!

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

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

Existence of unknown CP violation ?

T-violation

- Possible in low energy region（unnecessity of anti-particles）
- Investigation of connection between low and high energy phenomena

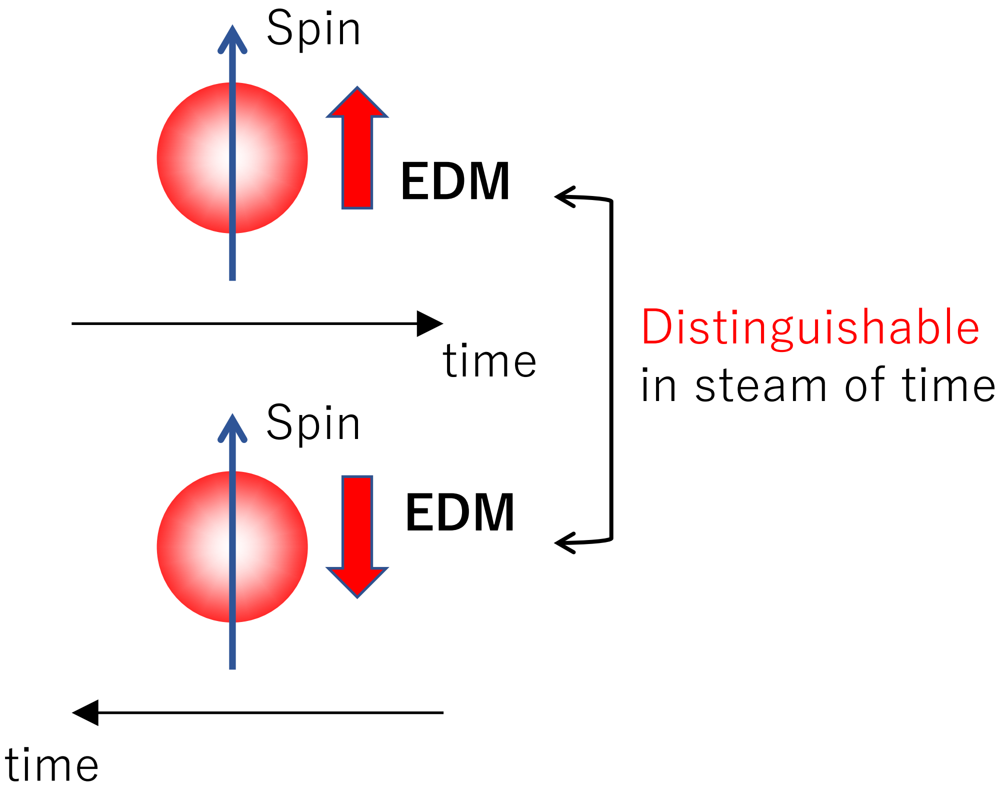
T-violation in low energy region

Two methods only without final state interaction (fake effects)

unrealistic

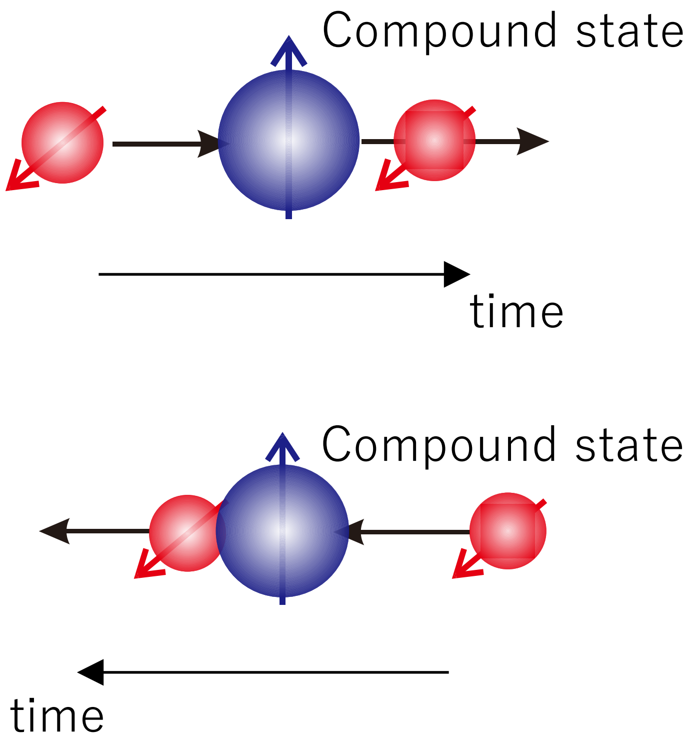
Electric Dipole Moment (EDM)

Static state



Neutron transmission

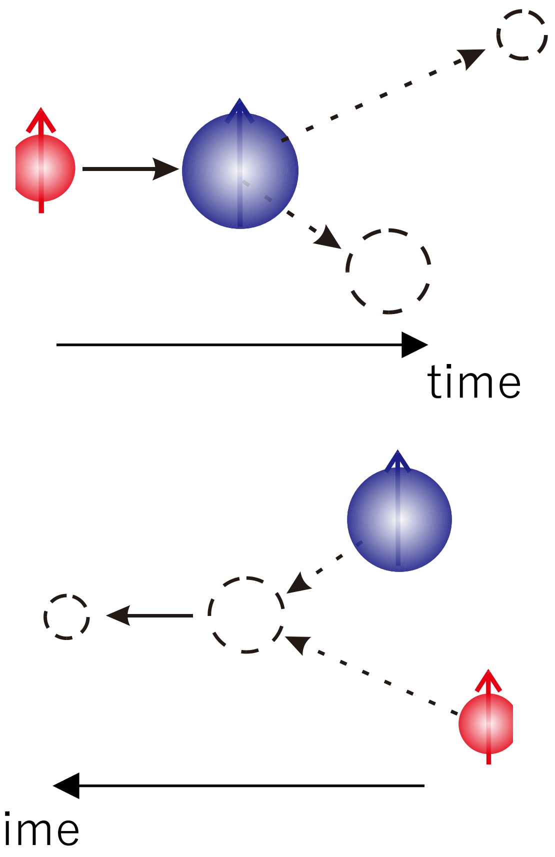
Initial state = final state



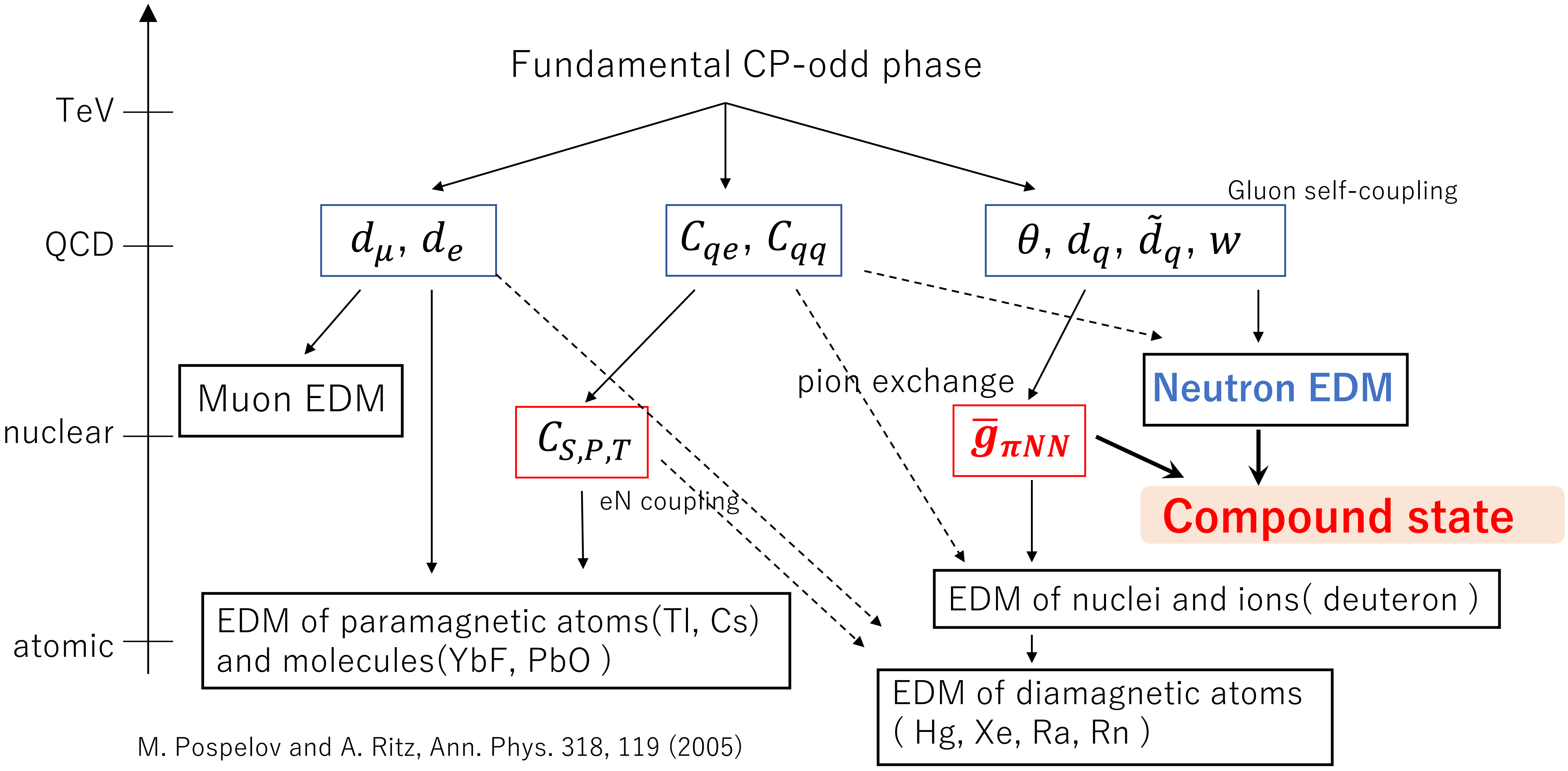
Difference of transmission

Normal scattering

Initial state ≠ final state



Connection to high energy region



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

Search region

n-EDM

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

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

Sensitive

Compound state

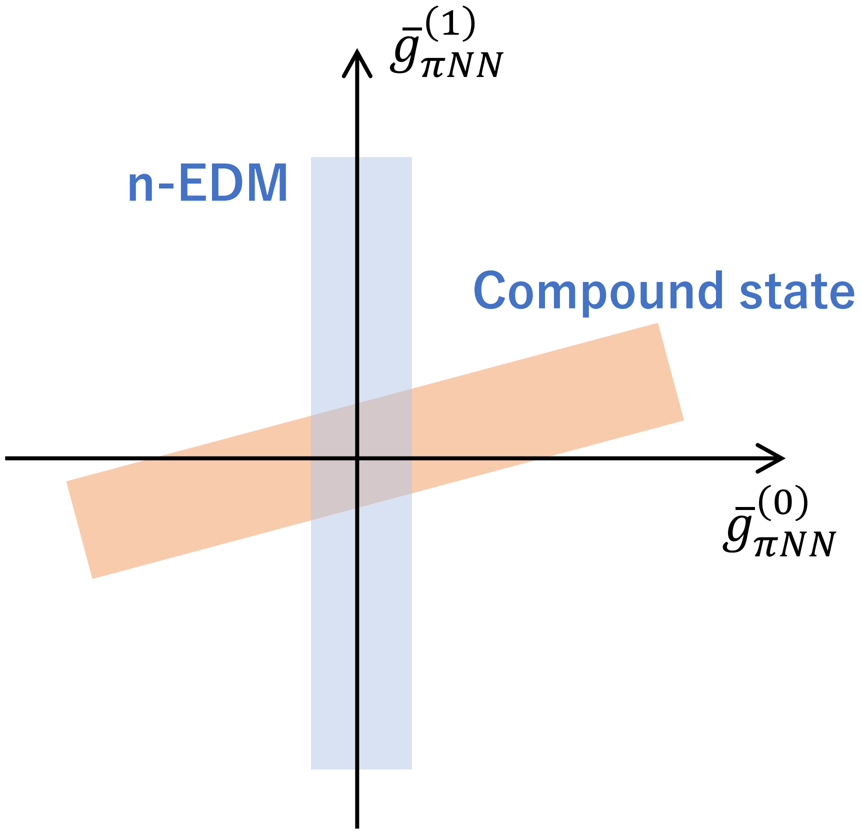
Y.-H. Song, et al., Phys. Rev. C 83, 065503 (2011)

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

Both sensitive

Reference: $n + p \to d + \gamma$

$$h^1_\pi = (3.04 \pm 1.23) \times 10^{-7}$$



Complimentary to n-EDM

Enhancement of Parity violation in Compound state

Helicity Asymmetry

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

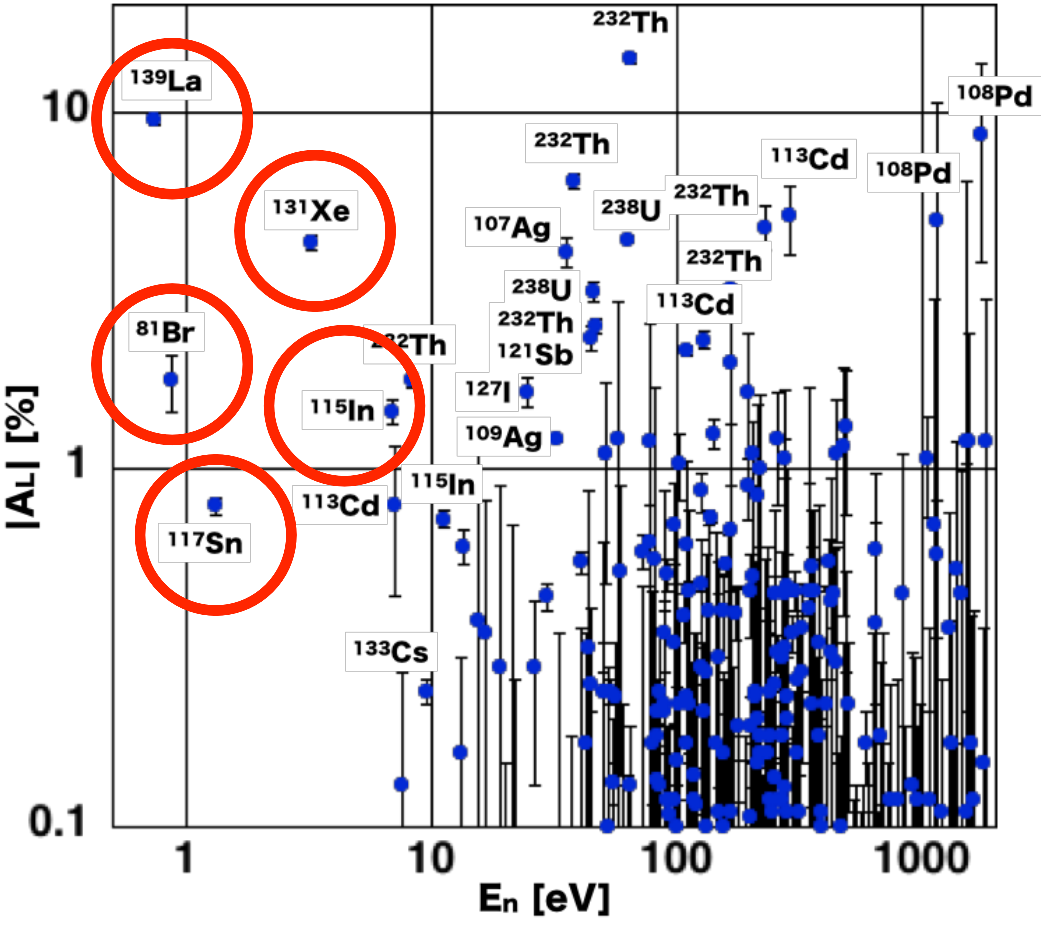
Ex) ^{139}La : $E_P = 0.734$ eV $\quad A_L = 0.097 \pm 0.003$

Proton-proton scattering

10^6 enhancement

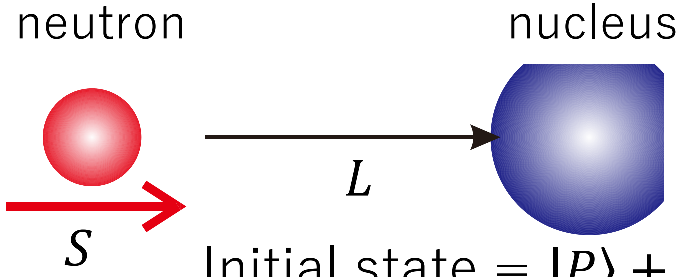
$E = 15$ MeV

$A_L = -(1.7 \pm 0.3) \times 10^{-7}$



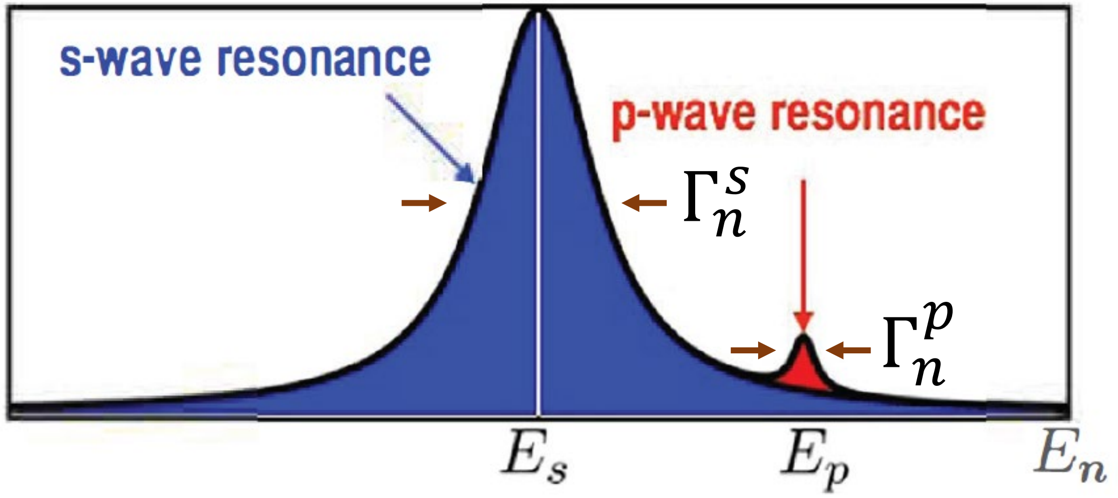
S-P mixing model

Generation of compound state



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

$J = L + S \qquad j = \frac{1}{2}, \frac{3}{2}$



$$A_L = -2x \frac{\langle s|W|p\rangle}{E_p - E_s} \sqrt{\frac{\Gamma_n^s}{\Gamma_n^p}} \qquad x = \sqrt{\frac{\Gamma_n^{p,j=\frac{1}{2}}}{\Gamma_n^p}} \qquad y = \sqrt{\frac{\Gamma_n^{p,j=\frac{3}{2}}}{\Gamma_n^p}}$$

Unknown parameters

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

$$\langle s|W|p\rangle = \sum_{i,j}^{N} a_i^* b_j \langle \psi_i|W|\psi_j\rangle \sim W\sqrt{N} \qquad |p\rangle = \sum_{i=1}^{N} b_i|\psi_i\rangle \quad |s\rangle = \sum_{i=1}^{N} a_i|\psi_i\rangle$$

$$N \sim \frac{\Delta E}{D} \sim 10^5$$

ΔE: 10^6 eV

D: 10 eV

P-violating
Weak matrix element

T-violation in Compound state

T-violation

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

T-violating matrix element

P-violation

P-violating matrix element

Angular momentum factor

T-violation Gudkov, Phys Rep 212, 77 (1992)

Interference between different channel spins

$$\Gamma_n^{s=I+\frac{1}{2}} \qquad \Gamma_n^{s=I-\frac{1}{2}}$$

P-violation

Interference between s and p waves

$$\Gamma_n^s \qquad \Gamma_n^{p,j=\frac{1}{2}}, \Gamma_n^{p,j=\frac{3}{2}}$$

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

Depending on x and y

Necessity of measurements of $\kappa(J)$

Candidates of target nuclei

	^{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

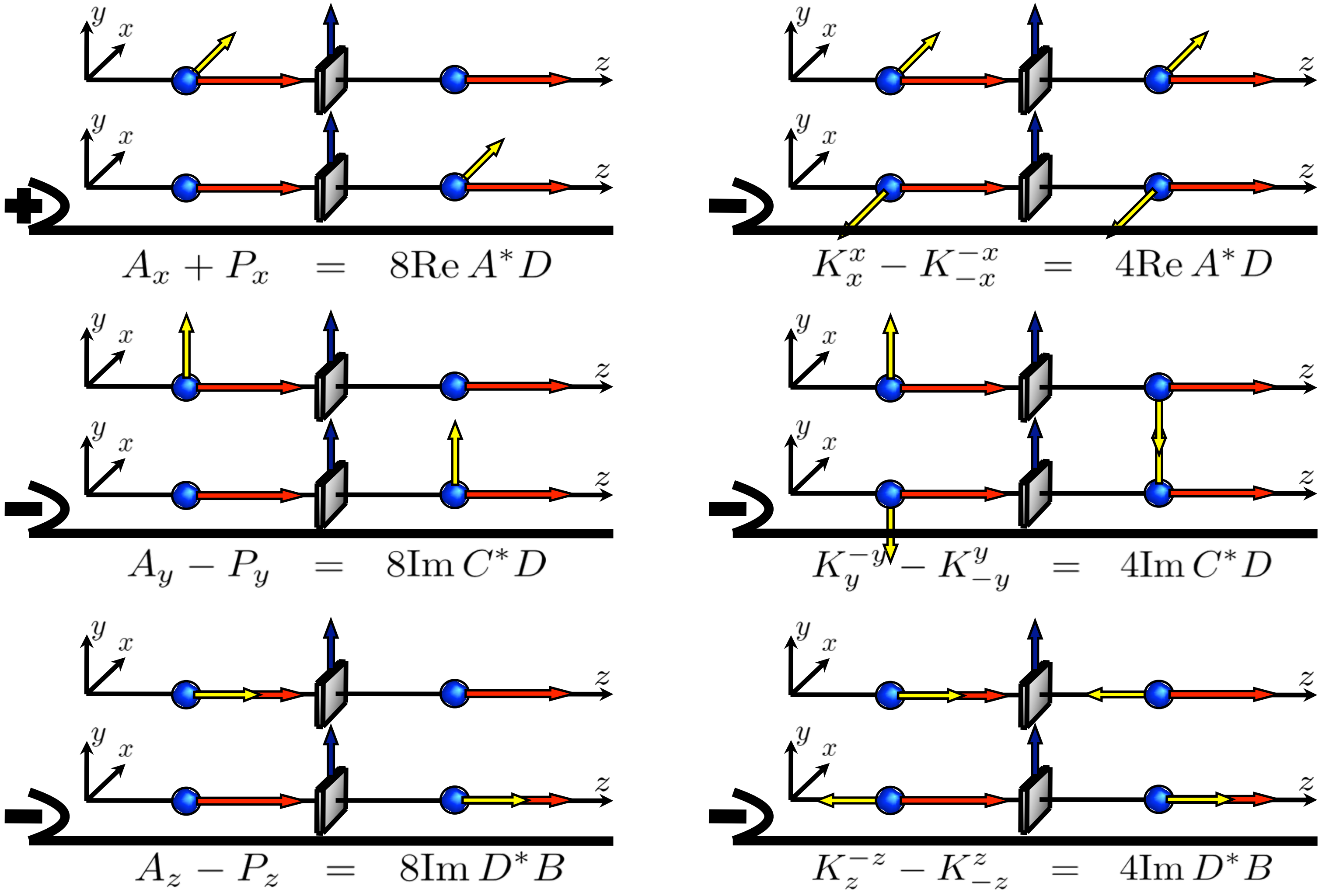
Configurations

Pseudomagnetic effects

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

P-odd T-even

T-odd P-odd



T-violation experiment at J-PARC

NOPTREX
Neutron Optical Parity and Time-Reversal EXperiment

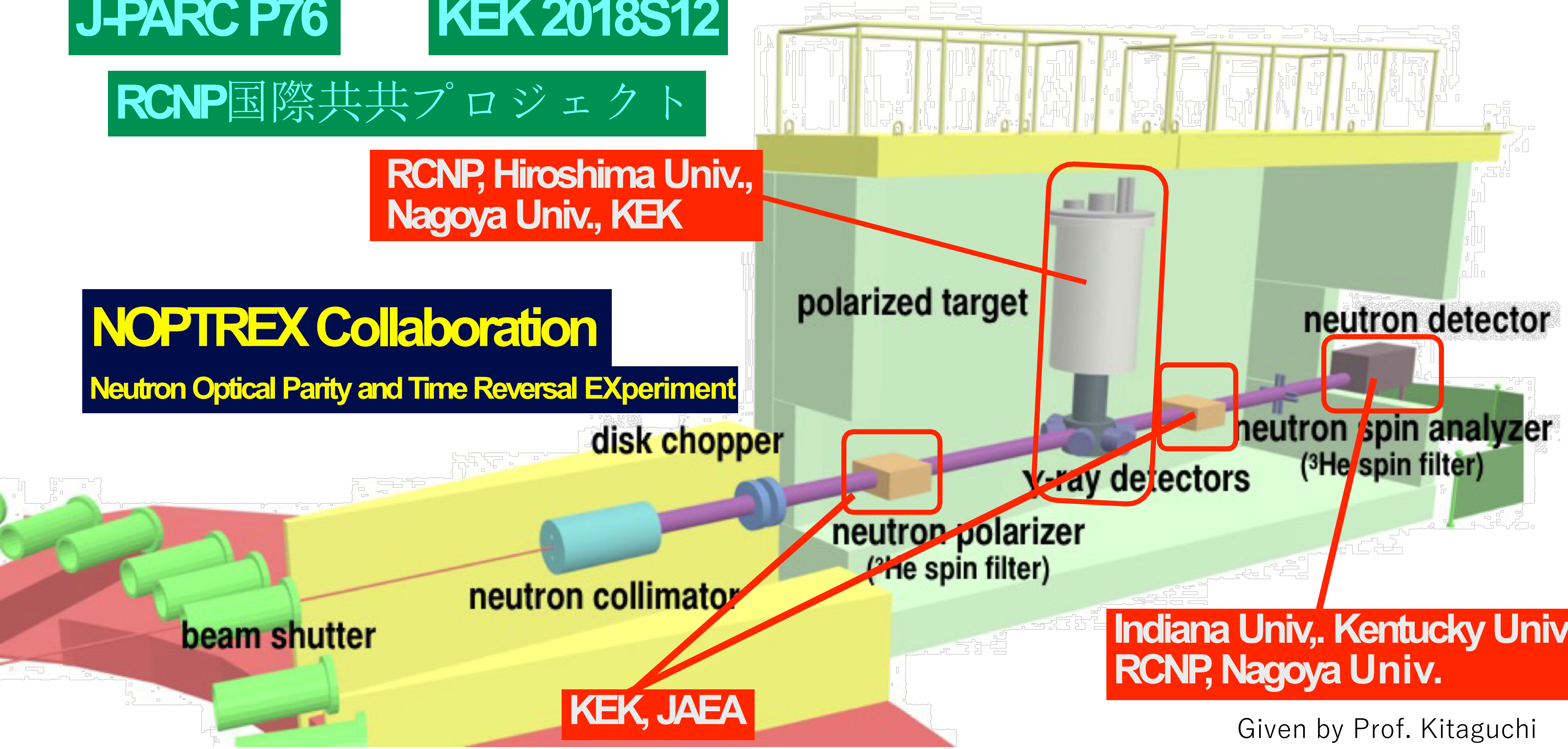
J-PARC P76

KEK 2018S12

RCNP国際共共プロジェクト

NOPTREX Collaboration

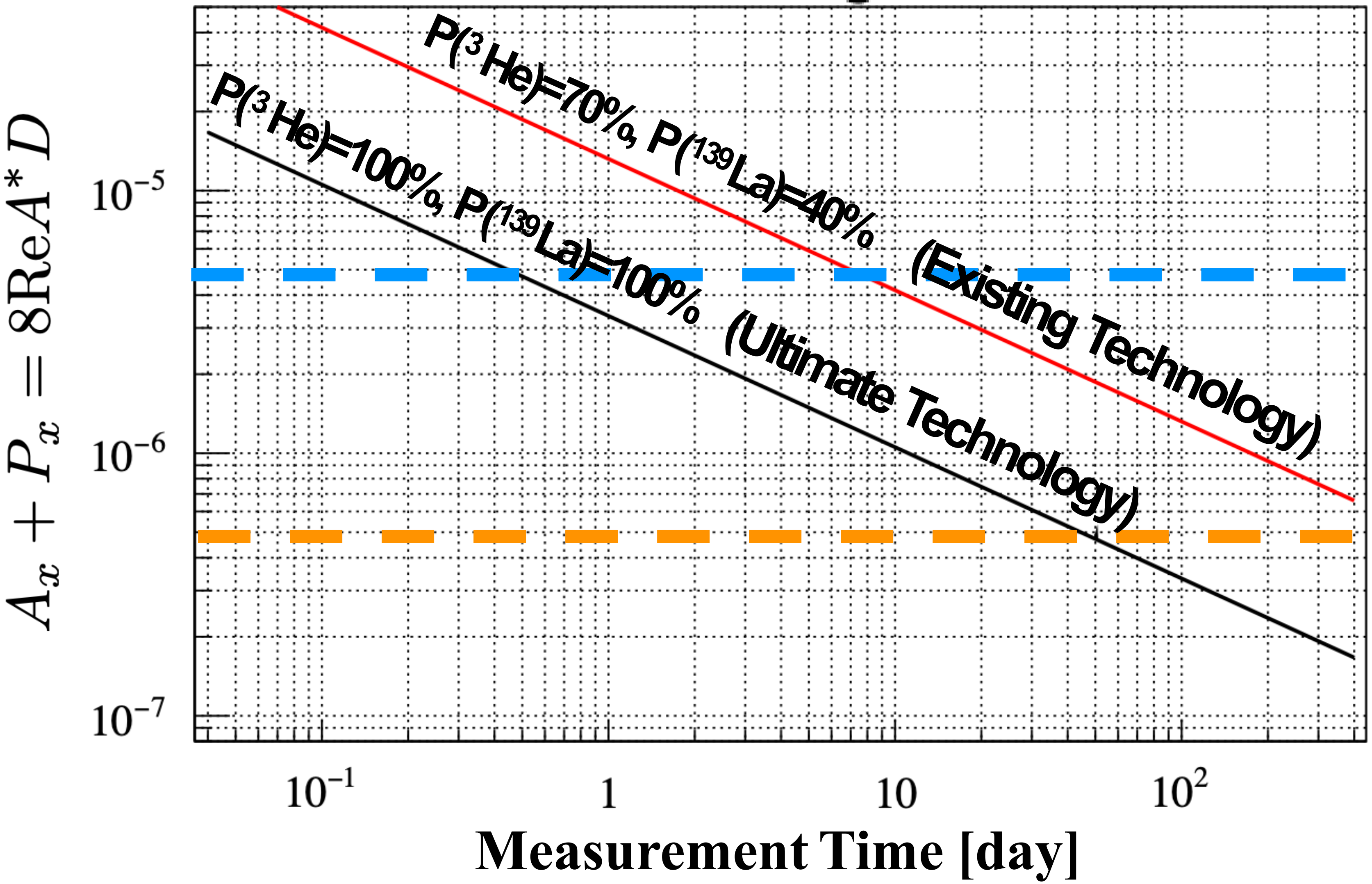
Neutron Optical Parity and Time Reversal EXperiment



Given by Prof. Kitaguchi

$\overrightarrow{^{139}\mathrm{La}}$ $\mathrm{LaAlO_3}$

$P(^{139}La) \geq 0.4$, $V \geq 4cm \times 4cm \times 2.8cm$
$B_0 \leq 0.1T$



$$\left|\frac{\langle W_T \rangle}{\langle W \rangle}\right| < 3.9 \times 10^{-4}$$

$$8\mathrm{Re}A^*D = 5.3 \times 10^{-5}$$

discovery potential corresponding to $d_n = 3.0 \times 10^{-26}$ e cm

discovery potential corresponding to $d_n = 3.0 \times 10^{-27}$ e cm

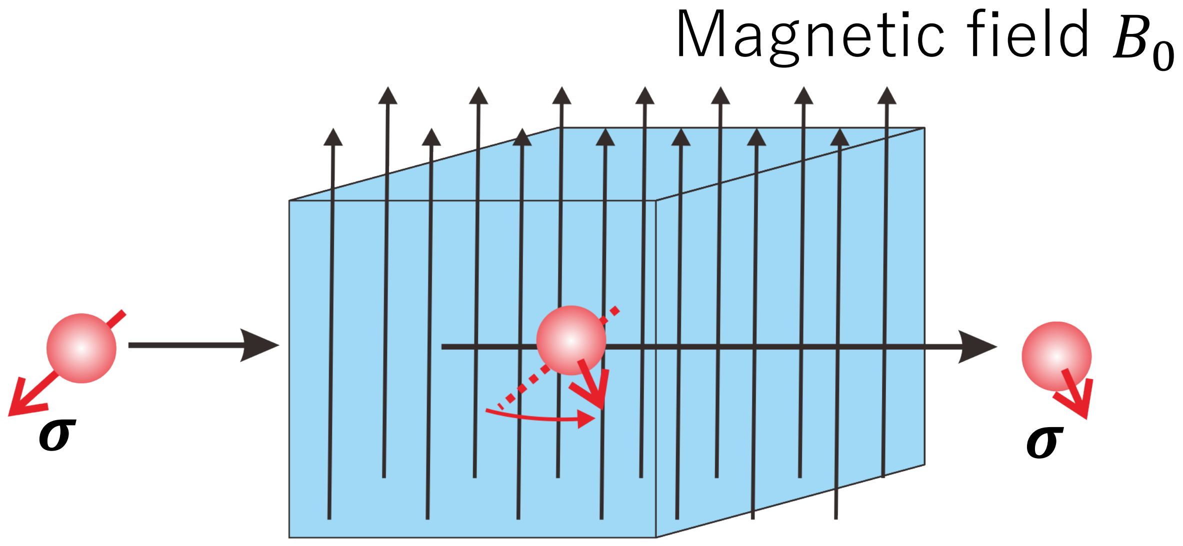
Given by Prof. Kitaguchi

Major systematic effects

D term $D\boldsymbol{\sigma}\cdot(\boldsymbol{k}\times\boldsymbol{I})$ Three vectors : orthogonal

Neutron spin rotation in a magnetic field

Reduction of the sensitivity because of averaging



Neutron spin rotation per 1[T] and 1[s]

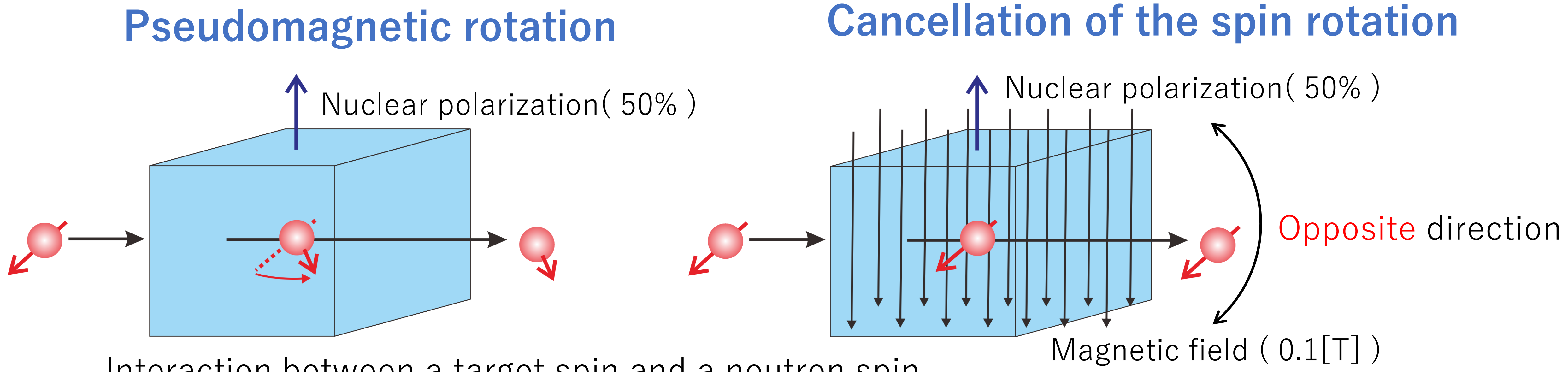
$\sim 2.91\times10^{7}$ rotation/Ts

At 2.3 [T] (La DNP exp)
and thickness of 4cm

Rotation angle : $8.1°$

Use of pseudomagnetic effect

B term $B(\boldsymbol{\sigma} \cdot \boldsymbol{I})$ ➡ Pseudomagnetic field for neutron spins



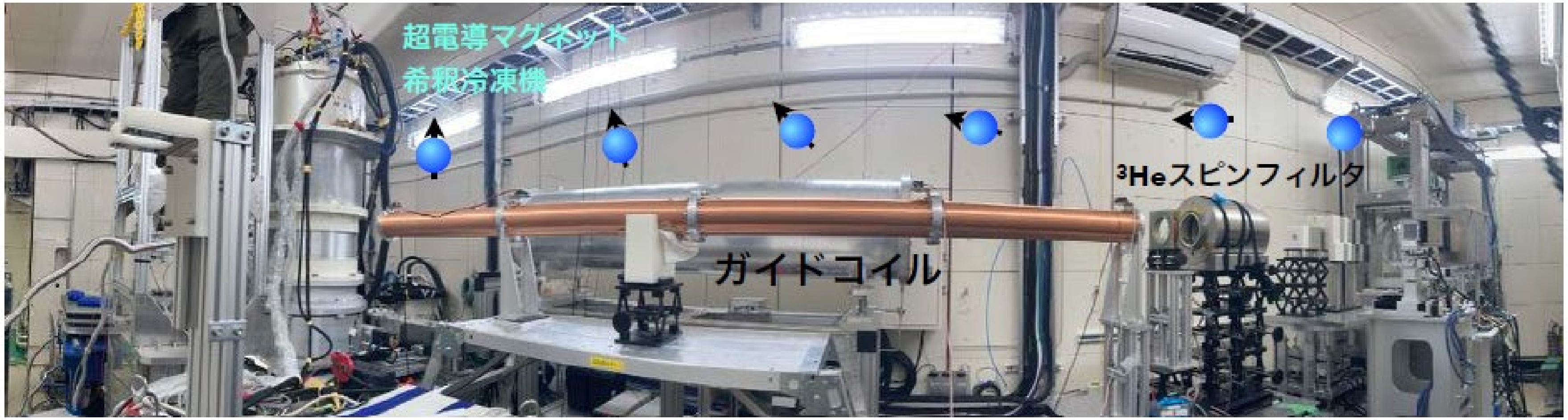
Interaction between a target spin and a neutron spin

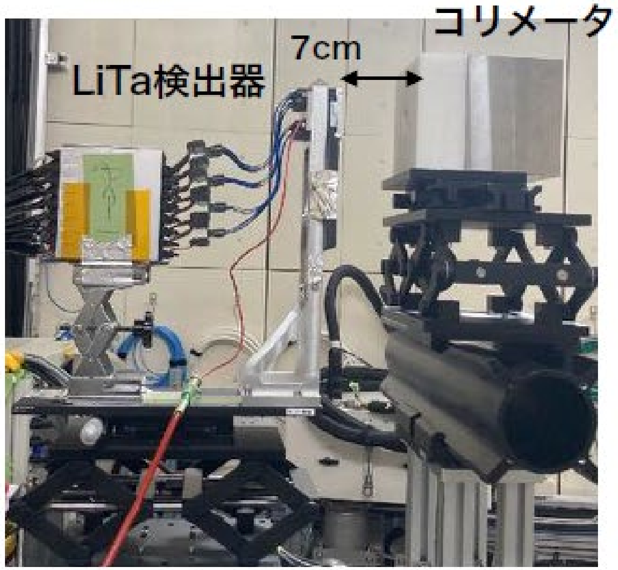
$LaAlO_3$ ： $H' = 0.1$ [T] for 50% polarization

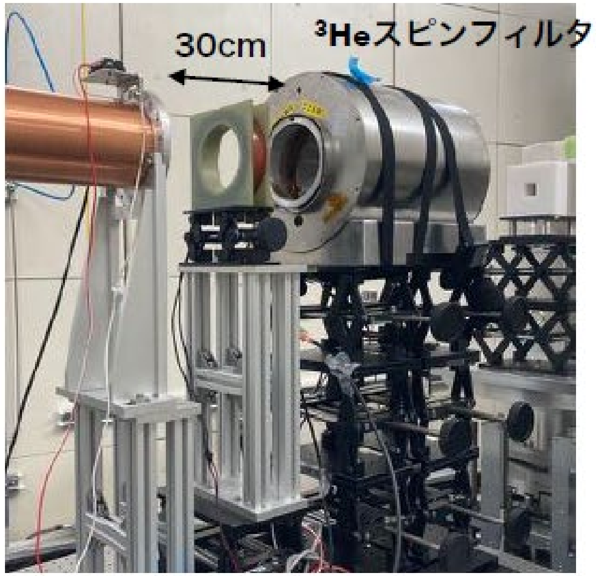
V. Gudkov and H. M. Shimizu, Phys. Rev. C **95** 045501, 2017

External field for the 50% polarized La target ~ 0.1 [T]
Necessity of measurements of B terms in advance

Setup for measurements of Im B term







Given by Prof. Okudaira

Research organization (polarized target)

Collaboration of 7 research institutes and 6 universities

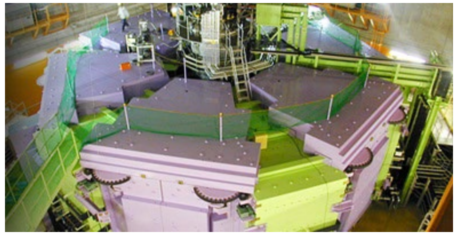
IMR(Tohoku University)

Nagoya University

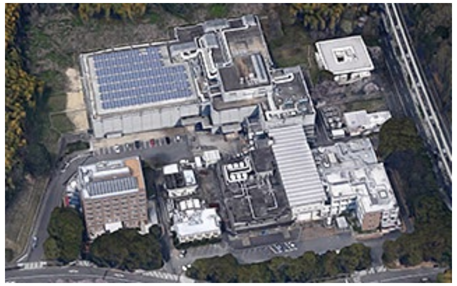
Hiroshima University
Kyoto University
Yamagata University
Ashikaga University
Japan Weman's University

PSI

RIKEN Nishina
RIKEN CEMS



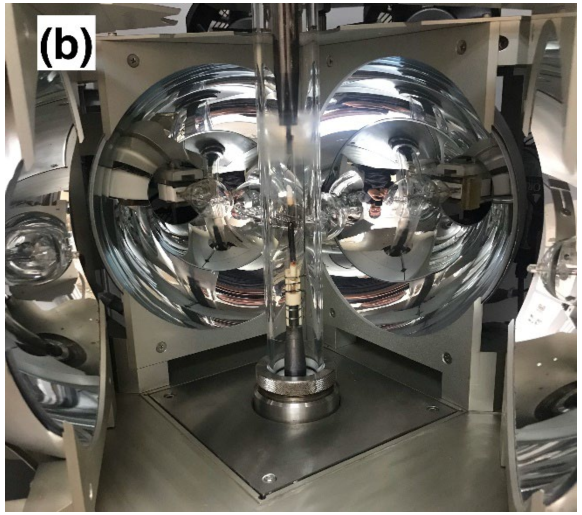
RCNP(Osaka University)

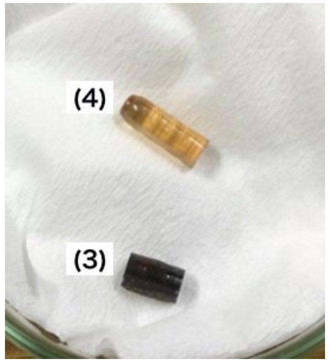


KEK IPNS, KEK CSC
KEK IMSS

Crystal growth

Tohoku Univ., IMR

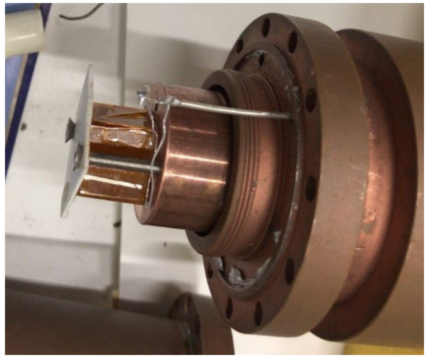




Tohoku Univ.
Nagoya Univ.
Hiroshima Univ.

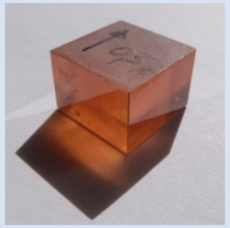
DNP & BF

Osaka Univ., RCNP



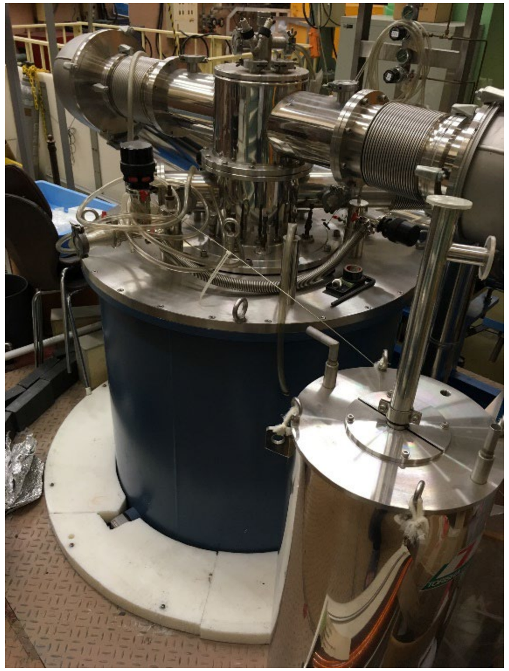
RCNP、Nagoya Univ.
Hiroshima Univ., RIKEN
Yamagata Univ., PSI

Polarized target



$LaAlO_3$ crystal
Nd doped (DNP)
pure (BF)

Cryogenic



Nagoya Univ.,
Riken, JWU,
Ashikaga Univ.,
Hiroshima Univ,
KEK, KEK CSC, RCNP

Development of
Cryogenic system

Active control of relaxation

Hiroshima Univ., N-BARD

Hiroshima Univ.
Nagoya Univ.

Control of nuclear relaxation
with aromatic molecules

Summary - activity toward T-violation -

Selection of target nuclei

Measurements of $\kappa(J)$ ^{139}La, ^{131}Xe, ^{81}Br, ^{117}Sn, $\cdots$

T. Okudaira, et al., Phys. Rev. C97, 034622, (2018)
J. Koga, et al., Phys. Rev. C105, 054615, (2022)

Verification of S-P mixing model

Measurements of angular correlations in (n, γ)

T. Yamamoto, et al., Phys. Rev. C101, 064624, (2020)
T. Okudaira, et al., Phys. Rev. C104, 014601, (2021)

Neutron polarizer

^3He spin filer

T. Okudaira, et al., NIM A977, 164301 (2020)

Neutron detector

D. Schaper, et al., NIM A969, 163961 (2020)

U.S. NOPTREX
RCNP

Polarized target

La polarization by the DNP and BF

K. Ishizaki, et al., NIM A1020, 165845 (2021)

RCNP, Nagoya, Yamagata, Tohoku IMR, Hiroshima, KEK CSC, etc.

Investigation of pseudomagnetic effects

Imaginary B term of ^{139}La
First attempt of using polarized ^{139}La target

NOPTREX collaboration

(Neutron Optical Party & Time Reversal Experiment)

Nagoya Univ.
H. M. Shimizu, M. Kitaguchi, K. Hirota, T. Okudaira, T. Yamamoto, K. Ishizaki, Y. Niinomi, I. Ide, H. Tada, H. Hotta, T. Hasegawa, Y. Ito, R. Nakabe, Y. Kiyanagi, N. Wada, T. Matsushita

Kyushu Univ.
T. Yoshioka, J. Koga,

JAEA
S. Endoh, A. Kimura, H. Harada, K. Sakai, T. Oku

Osaka Univ.
T. Shima, H. Yoshikawa, K. Ogata, H. Kohri, M. Yosoi

Tokyo Inst. Tech.
H. Fujioka, Y. Tani, K. Kameda

Hiroshima Univ.
M. Iinuma, M. Abe, S. Wada

Yamagata Univ.
T. Iwata, Y. Miyachi, Y. Takanashi

Tohoku Univ.
M. Fujita, Y. Ikeda, T. Taniguchi, S. Takada

KEK
T. Ino, S. Ishimoto, K. Taketani, K. Mishima, G. Ichikawa

RIKEN
Y. Yamagata, H. Ikegami, T. Uesaka, K. Tateishi, D. Miura

Kyungpook Univ.
G. N. Kim, S. W. Lee, H. J. Kim

Kyoto Univ.
K Hagino, Y. I. Takahashi, M. Hino

Ashikaga Univ.
D. Takahashi

Japan Women's Univ.
R. Ishiguro

Univ. British Columbia
T. Momose

IHEP-CSNS
J. Tang, X. Tong

Indiana Univ.
W. M. Snow, C. Auton, J. Carini, J. Curole, K. Dickerson, J. Doskow, H. Lu, G. Otero, J. Vanderwerp, G. Visser

Univ. of South Carolina
V. Gudkov

Oak Ridge National Lab.
J. D. Bowman, S. Penttila, P. Jiang

Univ. Kentucky
C. Crawford, B. Plaster, H. Dhahri

Los Alamos National Lab.
D. Schaper

NIST
C. C. Haddock

Southern Illinois Univ.
B. M. Goodson

Ohio Univ.
P. King

Middle Tennessee State Univ.
R. Mahurin

Eastern Kentucky Univ.
J. Fry

Western Kentucky Univ.
I. Novikov

UNAM
L. Barron-Palos, A. Perez-Martin

Berea College
M. Veillette

Paul Scherrer Institut
P. Hautle

Juelich
E. Babcock

Nottingham
M. Barlow

Depauw
A. Komives

Current states of R & D

- **Estimation of spin-lattice relaxation time (T_1) at 0.1 K and in 0.1 T（RCNP）**

（K. Ishizaki ,et al., NIM A V1020, 165845, 2021）

Extrapolation with the measurement results of T_1 at various conditions
Assumption of electronic spin-spin reservoir (SSR)

$$T_1(0.1T, 0.1K) \geq 1[\mathrm{h}]$$

- **Necessity of optimization of Nd concentration**

- **Observation of enhancements with the crystals grown by ourselves（Yamagata Univ.）**

Nd condition：0.01mol%
DNP condition：2.3T, 1.3K

Polarization ≥ 20 %
T_1 > 120 min.

Long T_1

- **Establishment of our basic method for the crystal growth**

- **Precise control of Nd concentration （Tohoku Univ. IMR）**

Establishment of precise control of 0.001 mol% level

- **Nd optimization : feasible**
- **Interesting region : ≤ 0.01 mol%**

Current status of Nd optimization

We have achieved the technological level for studying the Nd optimization.

Crystal growth

Control of Nd concentration

Tohoku Univ. IMR

→ provided

← feedback

Evaluation through the DNP

Simple tests at 1.3 K in 2.3 T

Yamagata Univ.

Current summary in various Nd concentration (blue color : our crystals)

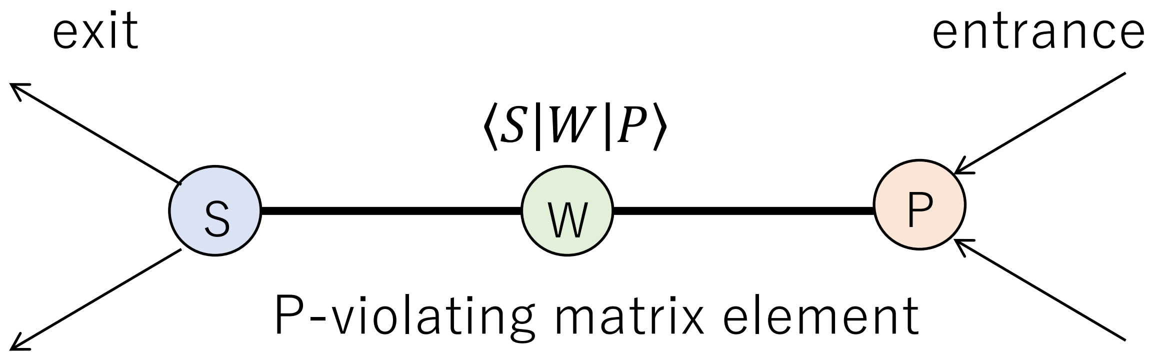
Nd concentration	condition	La enhancement	Al enhancement	Relaxation time
0.05 mol%	**2.3T, 1.3K**	**2.7**	**2.7**	**~ 15 min**
0.03 mol% [1]	2.3T, 1.5K	~ 100	> 50	~ 80 min
0.01 mol%	**2.3T, 1.3K**	**> 100**	**> 50**	**> 120 min**
0.003 mol% [2]	2.3T, 1.5K	1	1	

Best results

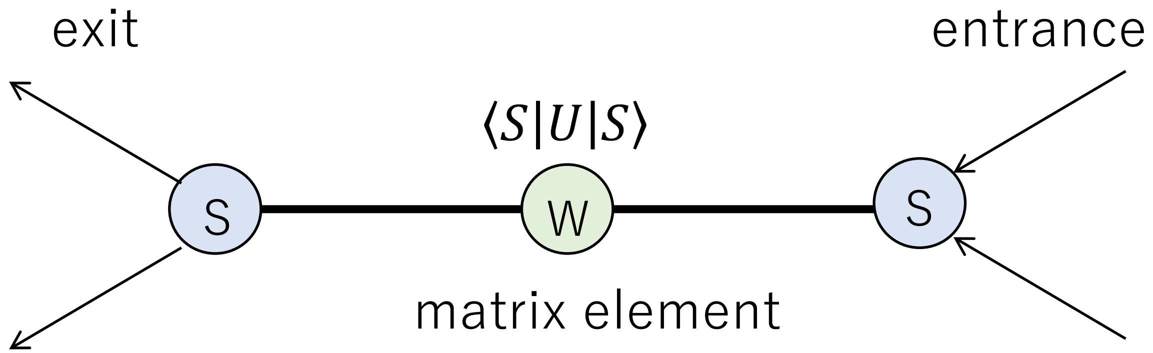
[1] : T. Maekawa, et al., NIM A V366, 115 (1995)
[2] : T. Maekawa, Kyoto Univ. Master thesis (1995) unpublished

Image of S-P mixing for P-violation

Initial state : $|P\rangle$

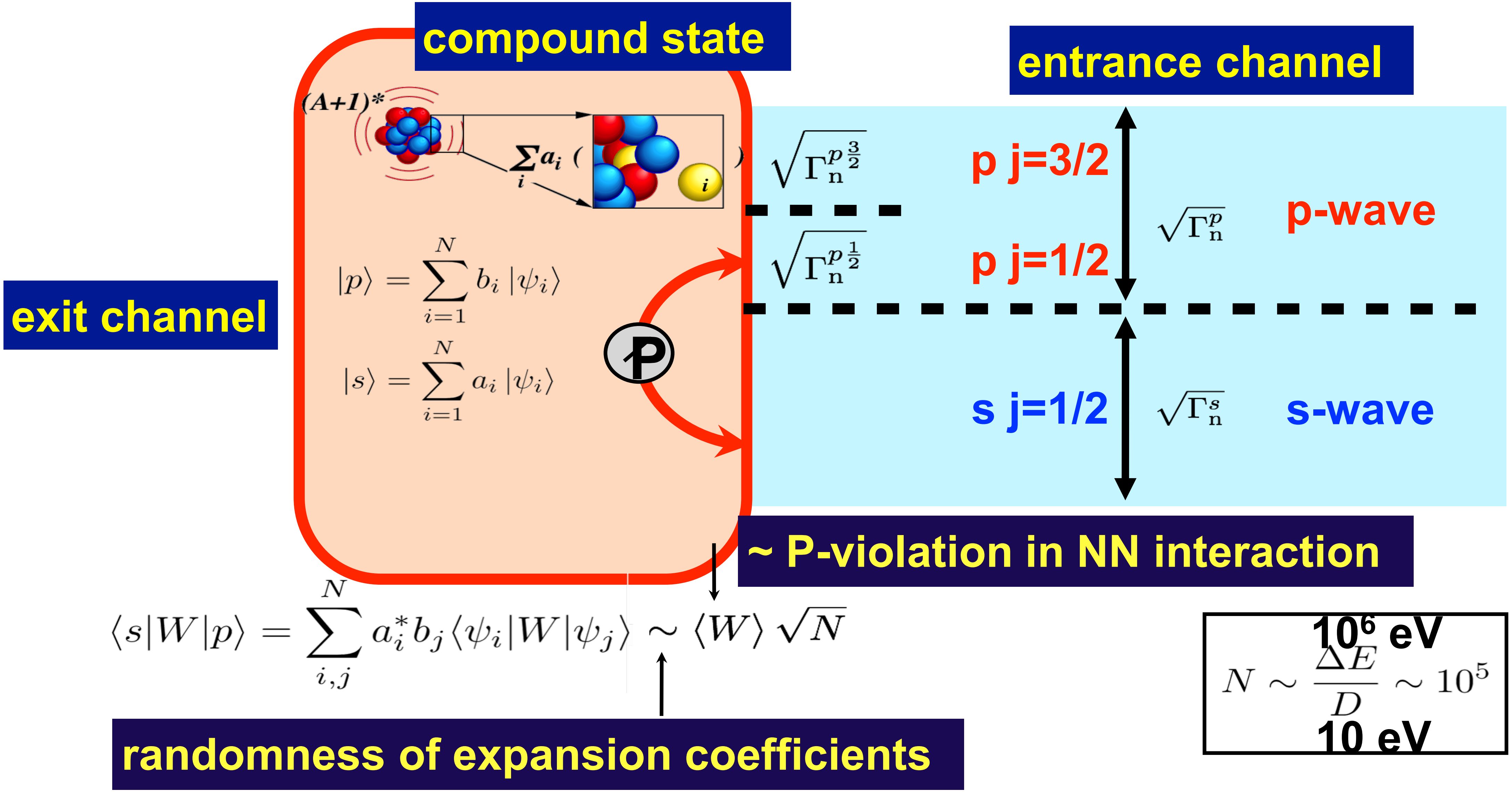


Initial state : $|S\rangle$

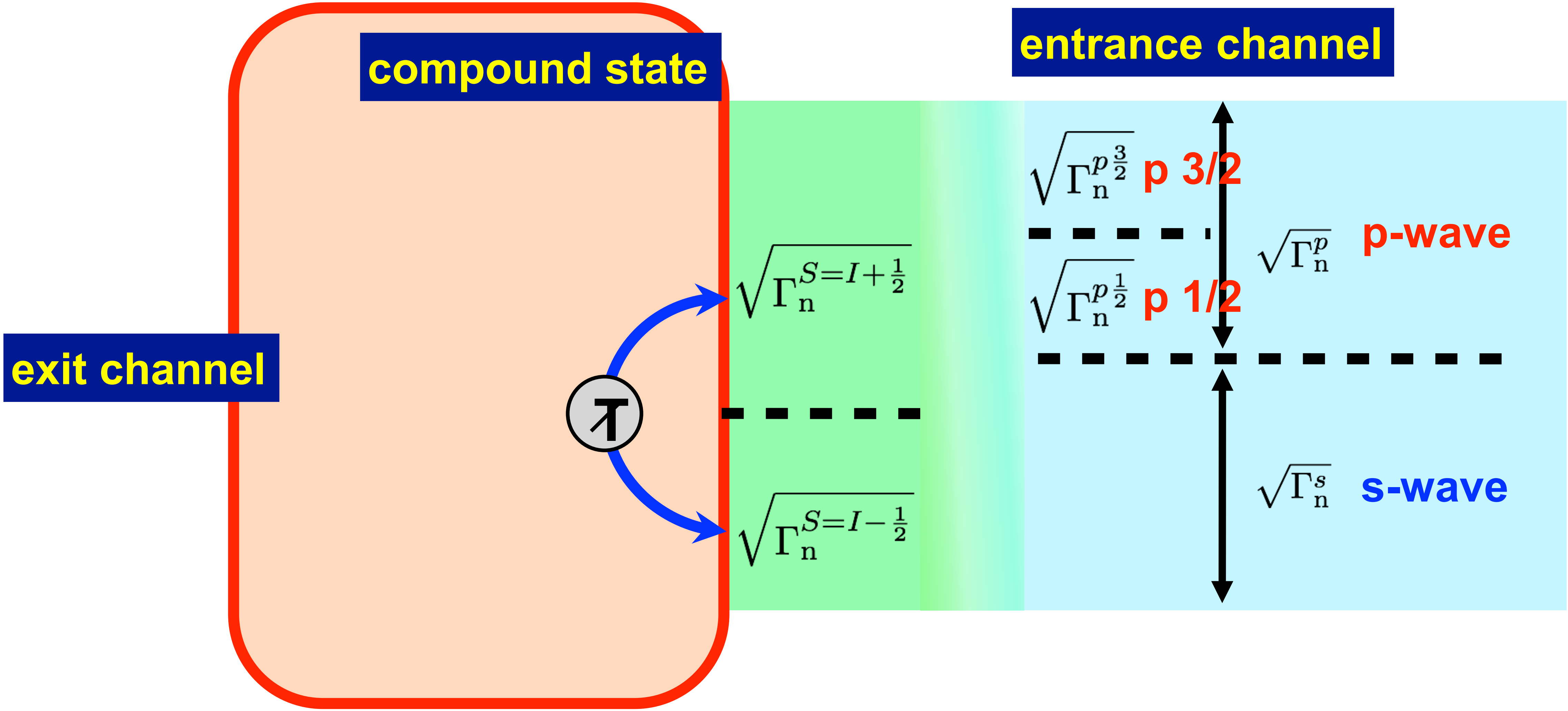


Superposition of two states

Enhancement of PNC



Enhancement of T-violation



Preparation of solid polarized target

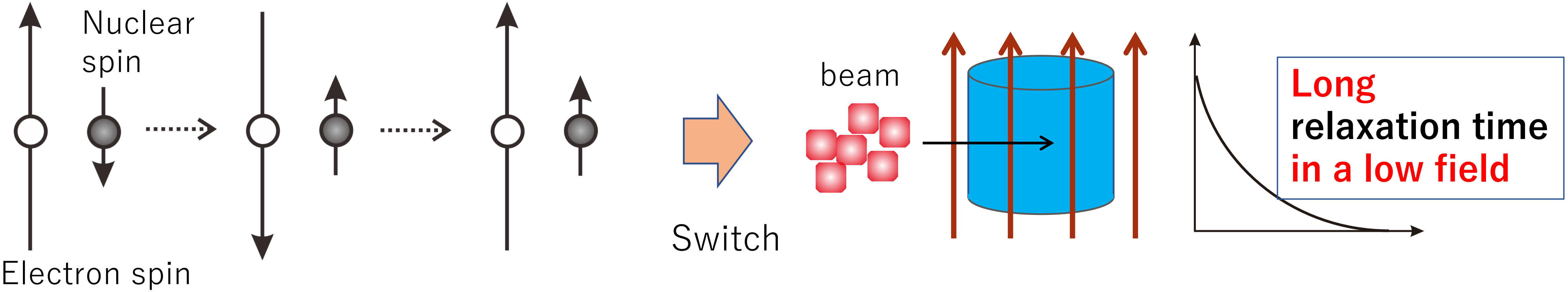
Dynamic Nuclear polarization (DNP)

Electron polarization ➡ Nuclear spins

Polarization transfer

Operation for spin frozen

Cooling down to very low temperature(< 0.1 K)
and reducing the field



Low temperature (~ 0.5 K)
High magnetic field (> 2.5 T)

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

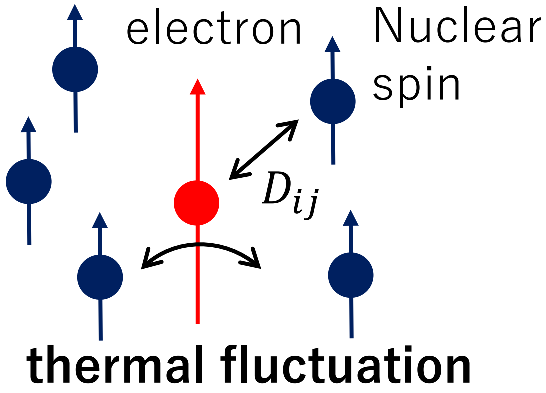
Too high for a typical beam experiment

Practical polarized target : only proton and deuteron

Relaxation process

Two major processes in a solid polarized target with high quadrupole moment

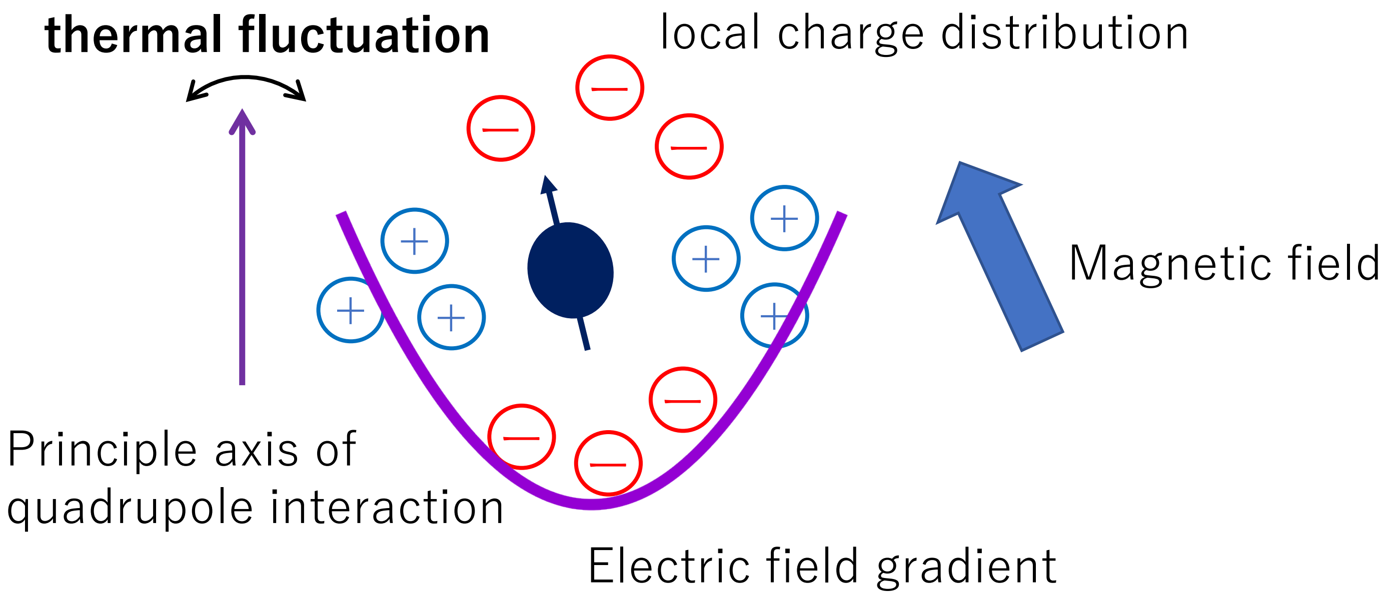
Dipole-dipole interaction



D_{ij} : Dipole-dipole interaction

Controllable by changing the number of electron spins

Quadrupole interaction



Mixing of Zeeman sublevels

Keeping the high polarization is not easy in a low magnetic field

Development of polarized La target

Metal La

Z = 57 A=139

Nuclear spin ：$I = 7/2$

Magnetic moment

$\mu = 2.783\mu_B$ (proton：$\mu = 2.793\mu_B$)

Quadrupole moment

$Q = 0.20$ [barn] (deuteron：$Q = 0.00286$ [barn])

Two order higher compared to deuteron

middle in whole nuclear species

First step for opening realization of new polarized target

Key device for the T-violation search with a slow neutron

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

Perovskite structure

Paramagnetic ions for the DNP

Nd^{3+}: $LaAlO_3$ crystal

Perovskite crystal

Partially replacement of La with Nd

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

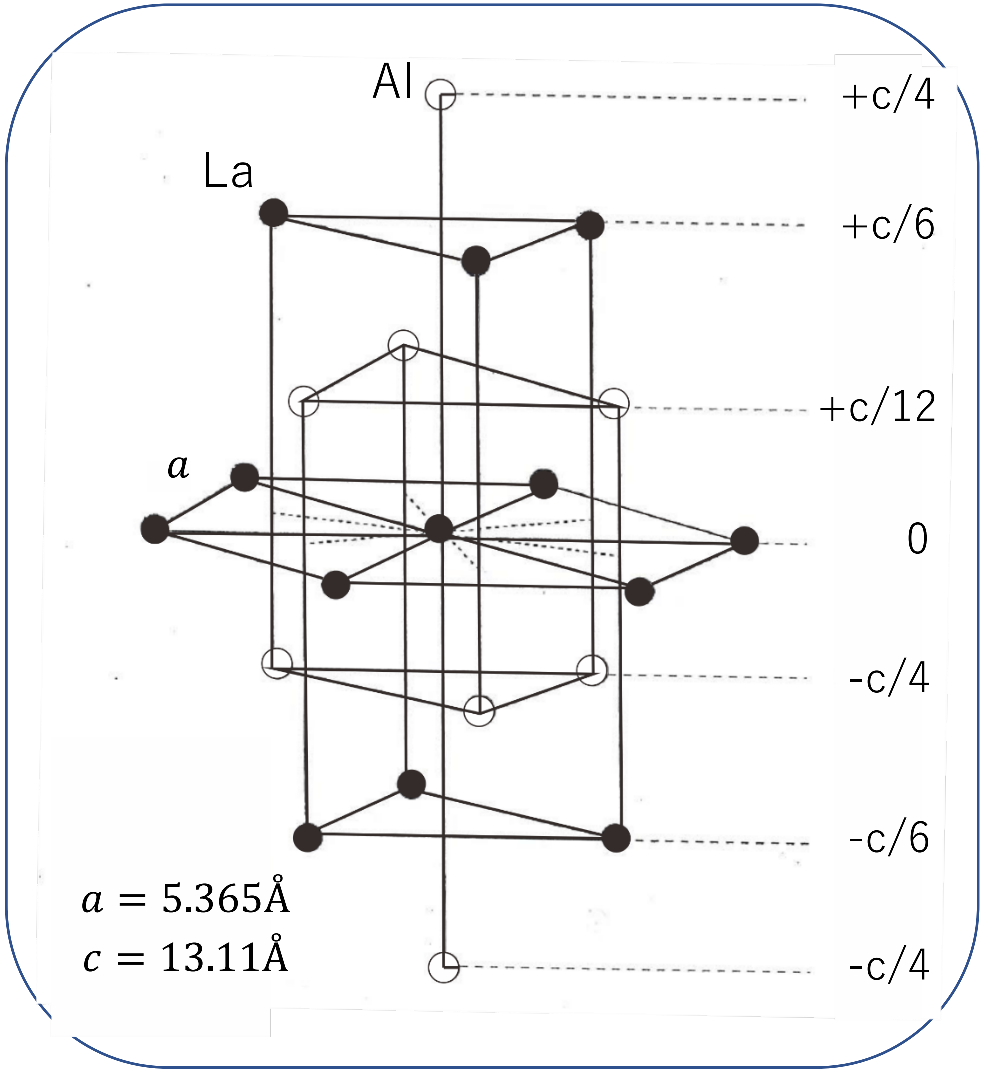
g-factor of Nd^{3+} : $g_{//} = 2.12 \quad g_{\perp} = 2.68$

Twining domain structure

Cubic ($Pm\bar{3}m$) ⟹ Pseudo-cubic

Phase transition at 813 [K]

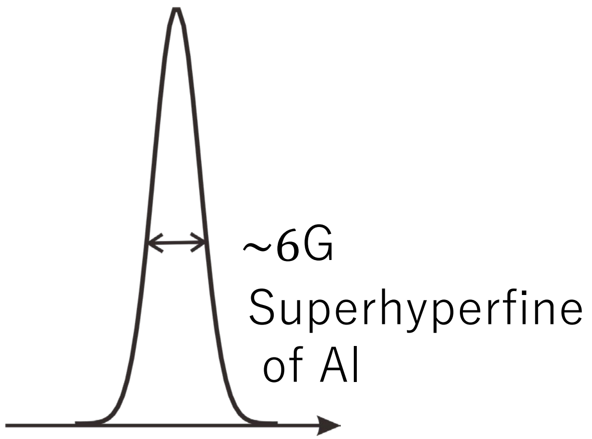
$LaAlO_3$ crystal



Advantage of crystal symmetry

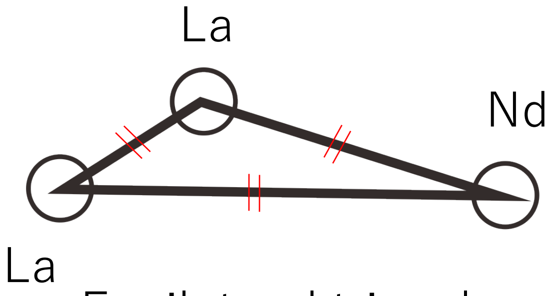
Y. Takahashi, et. al., NIM A 336, 583 (1993)

Narrow ESR linewidth



High efficiency of DNP

Magnetically equivalence



Equilateral triangle

C_3 symmetry

Equivalent efficiency for all sites

Diagonalization on C_3 axis

Electric field gradient $V_{xx} = V_{yy}$

Principle axis = C_3 axis

$$H_{total} = H_{Zeeman} + H_{quad}$$

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

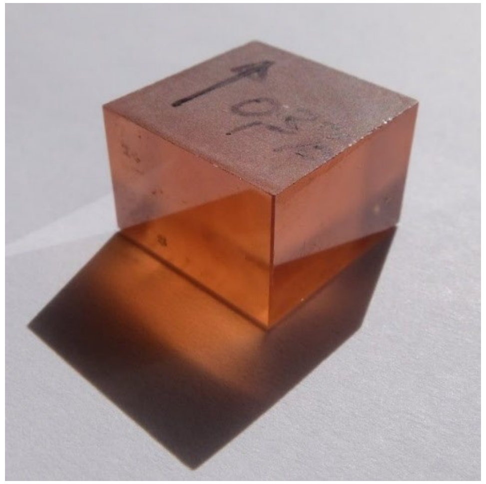
No mixing of Zeeman sublevels

Possibility of maintaining the polarization in a low magnetic field

DNP of La with $LaAlO_3$ at PSI

Spin transfer by SSR (Spin-Spin reservoir) (thermal mixing)

P.Hautle and M. Iinuma, NIM A 440, 638 (2000)　Results of reanalysis



	Spin temperature	Polarization
Al (positive)	+ 2.00 [mK]	+ 61.9 %
Al (negative)	- 1.58 [mK]	- 71.0 %
La (negative)	- 1.72 [mK]	- 49.8 %

- Sample:
  - Size : 15x15x4 [mm]
  - Concentration of Nd : 0.03 mol%
- Condition : B=2.35 T, T< 0.3 K

Possibility of realizing a practical polarized target
Necessity of studies on the relaxation in a low field(~ 0.1 [T])

Measurements of relaxation time at RCNP

(K. Ishizaki ,et al., NIM A V1020, 165845, 2021)

- **Project research in RCNP (2018/4 – 2022/3)**
- **COREnet proposal in RCNP (2020/4 – 2022/3)**

Purpose

Measurements at various conditions
Estimation at 0.1 T, 0.1 K based on the results

Measured crystal

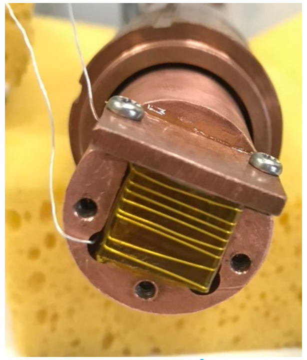
- 1.5cmX1.5cmX1.5cm
- Nd concentration：0.03mol%
- Direction of magnetic field：parallel to C_3 axis

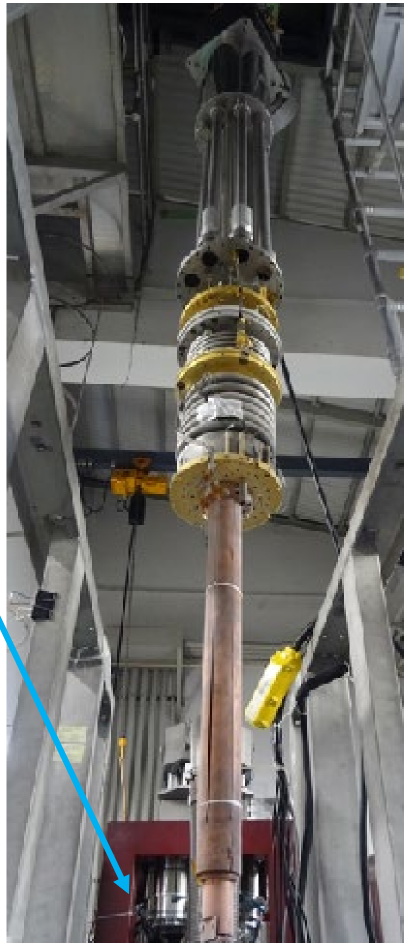
Measurement conditions

Use of thermal NMR signals without the DNP

	La	Al
Oct. – Dec. / 2019	0.5K (5.0 T)	0.5K (0.5, 1.0, 2.5 T)
Mar. – Apr. / 2020	0.5K (0.5, 1.0, 2.5 T) 0.1K (0.75 T)	1.5K (1.0, 2.0 T)

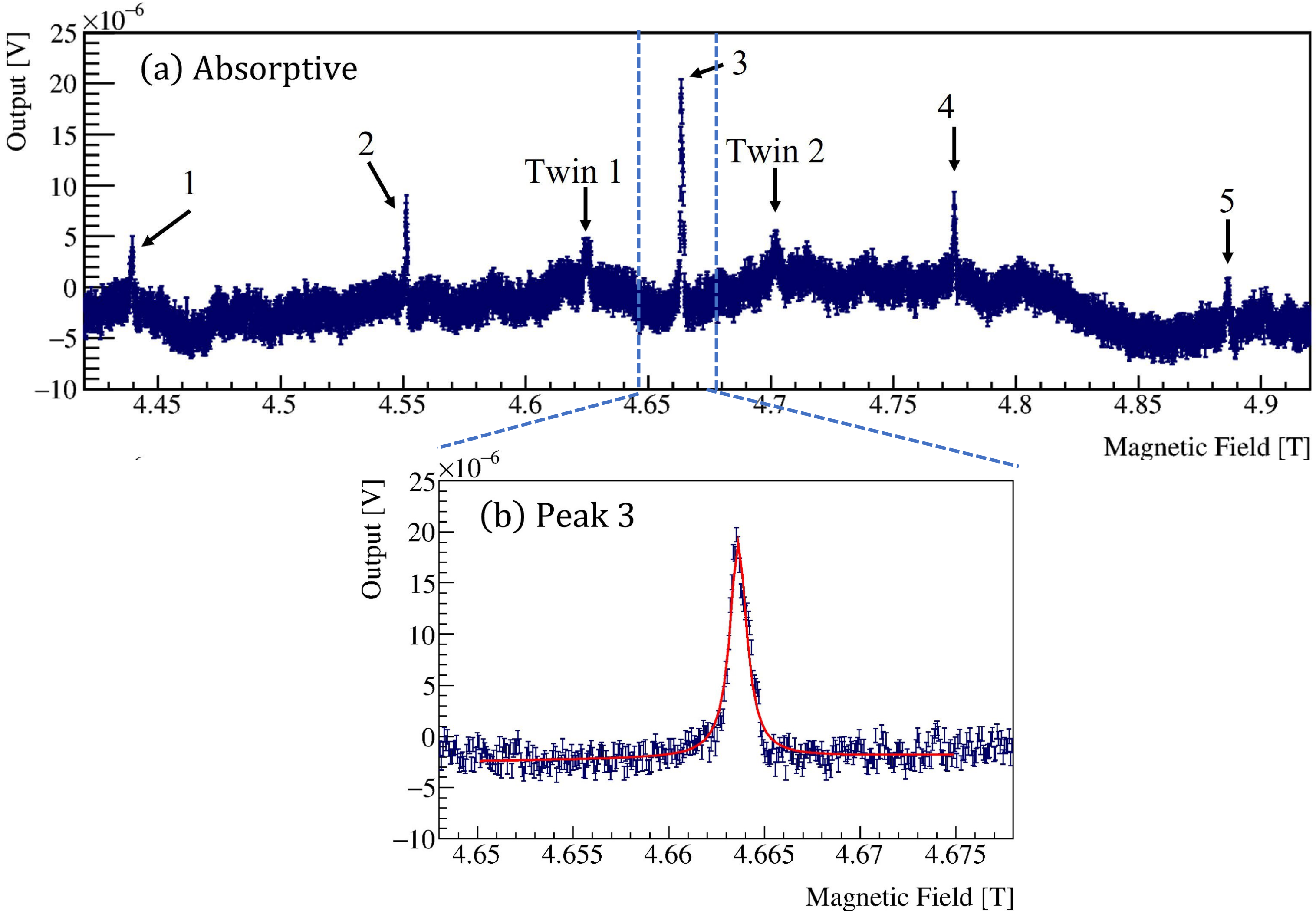
Refrigerator (17T、10mK)（DRS2500)



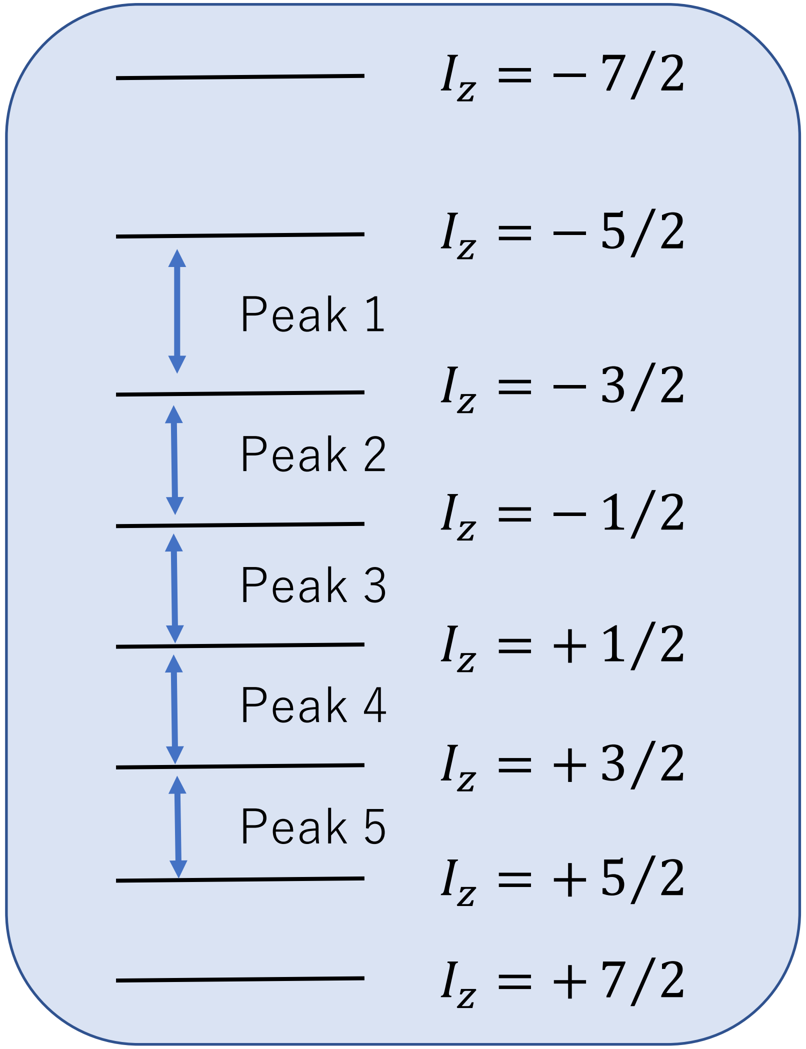


Thermal NMR spectra of La

Condition : 5 [T], 0.5[K]   Tuned frequency : 28.04 [MHz]

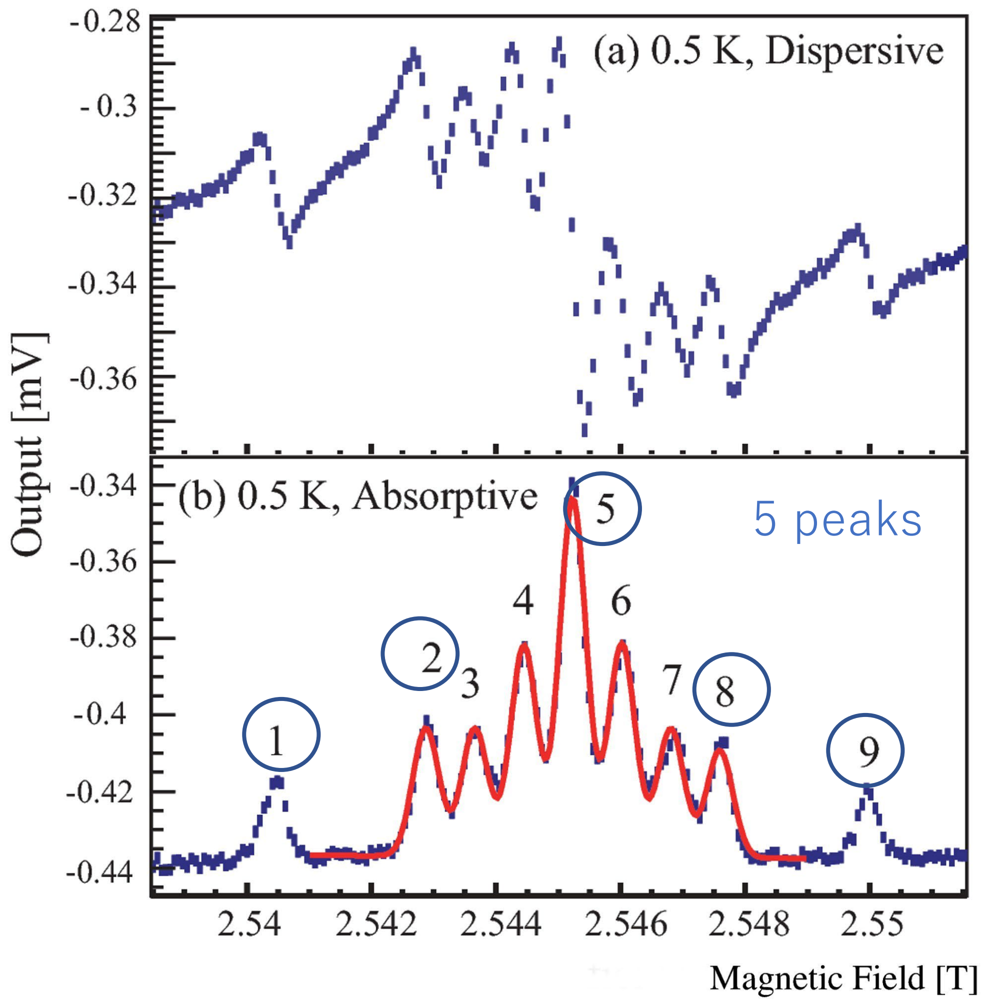


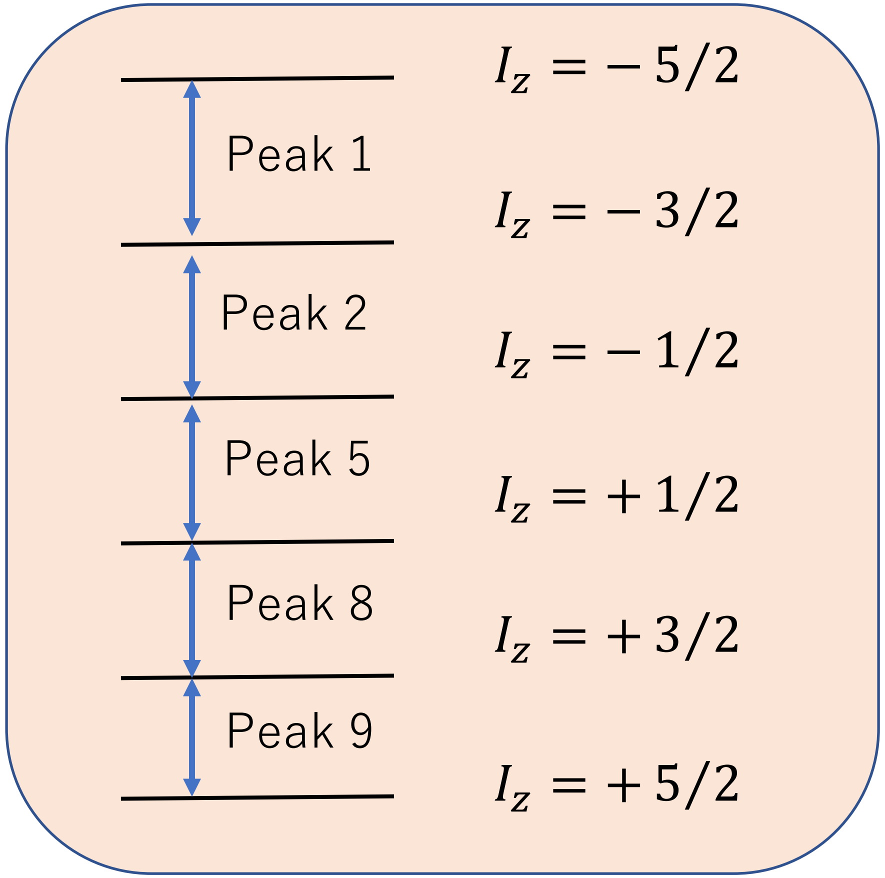
Zeeman system



Thermal NMR spectra of Al

Condition : 2.5 [T], 0.5[K]   Tuned frequency : 28.2 [MHz]



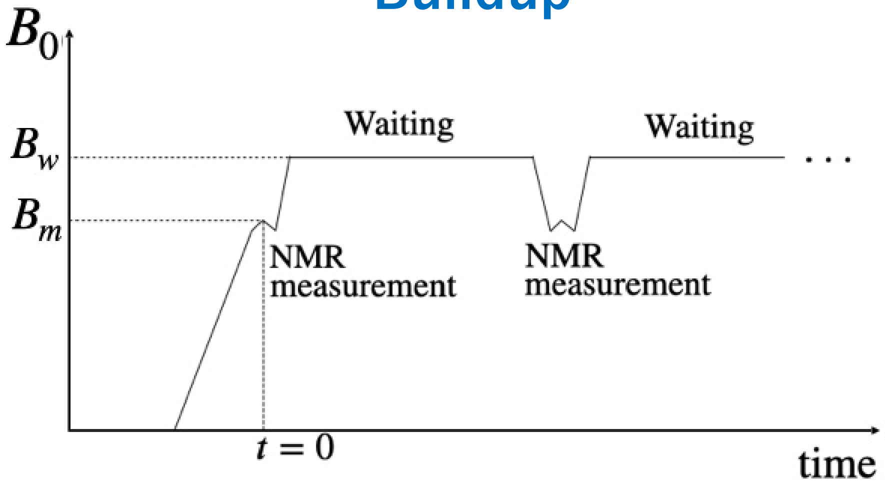


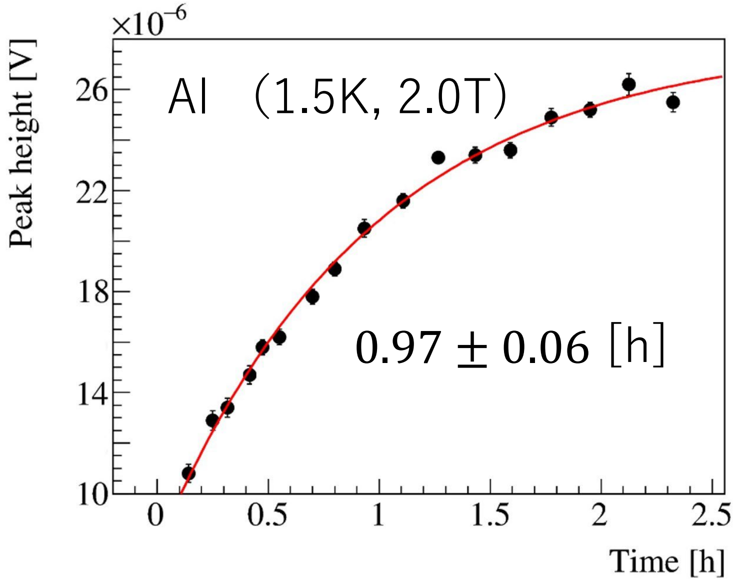
Peak 3, Peak 4, Peak 6, Peak 7 : from the other domain

Methods

Buildup

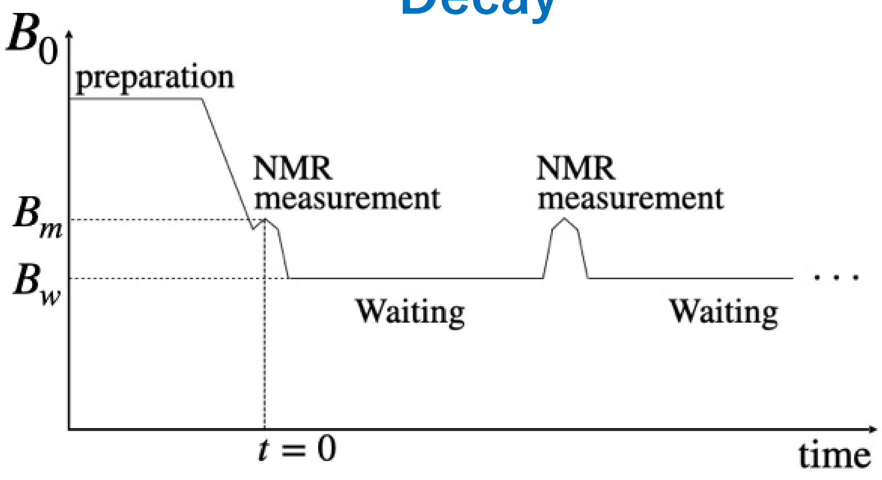
Condition

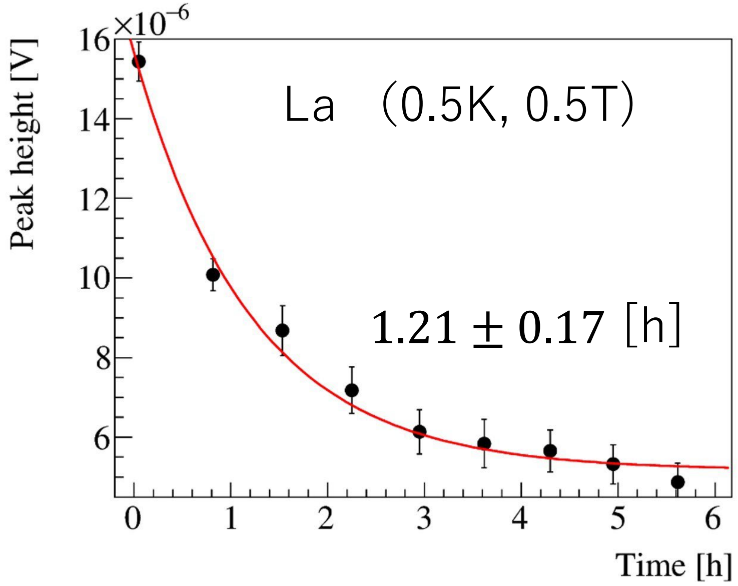




Decay

Condition





Estimation of relaxation time in a low field

Assumption of relaxation process via Electric Spin-Spin reservoir (SSR)

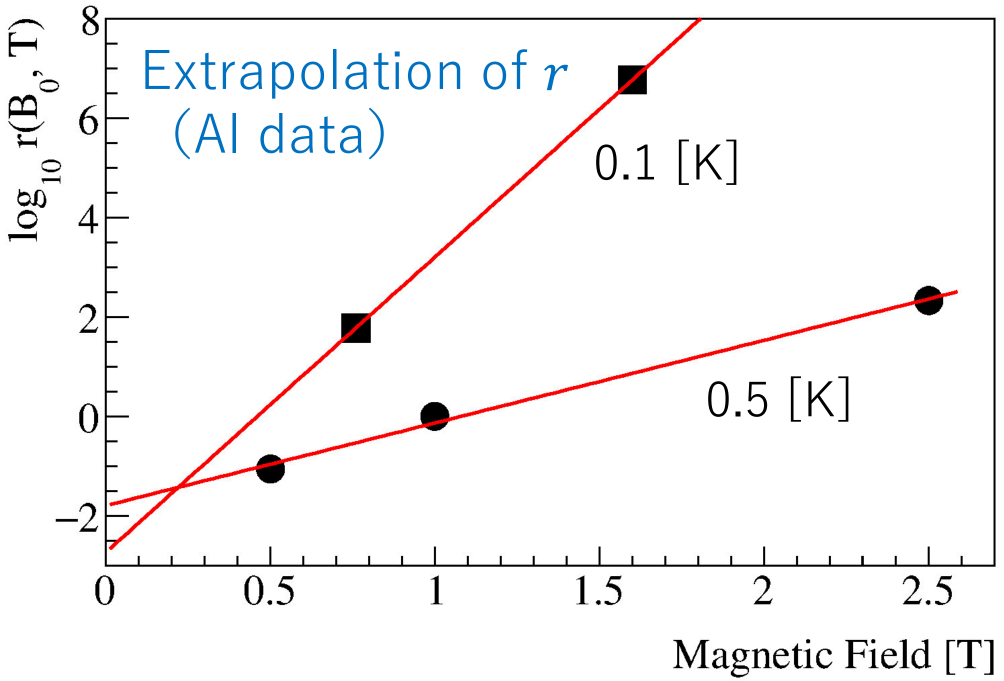
$$\frac{1}{T_{1n}} \propto \boxed{C^2} \frac{1}{H_0^2} \left(\frac{1}{T_{1SS}} \right) (1 - P_0^2)$$

Nd concentration

La relaxation time ≅ Al relaxation time

Extrapolation of ratio of T_{1SS}

$$r(B_0, T) \equiv \left(\frac{1}{T_{1SS}(B_0, T)} \right) \Big/ \left(\frac{1}{T_{1SS}(1.0T, 0.5K)} \right)$$



Estimation at 0.1T 0.1K

$$T_1(0.1T, 0.1K) \geq 1[\mathrm{h}]$$

Necessity of the optimization of Nd concentration

Current issues toward the development

1. Establishment of research environment for Nd optimization

Preparation of crystals various Nd concentration	Provided → ← feedback	Simple DNP tests at 1.3 K

Necessity of growing crystals by ourselves
Observation of the enhancement with our grown crystals

2. Fundamental studies on a polarized target at low temperature

Preparation of a test bench at RCNP

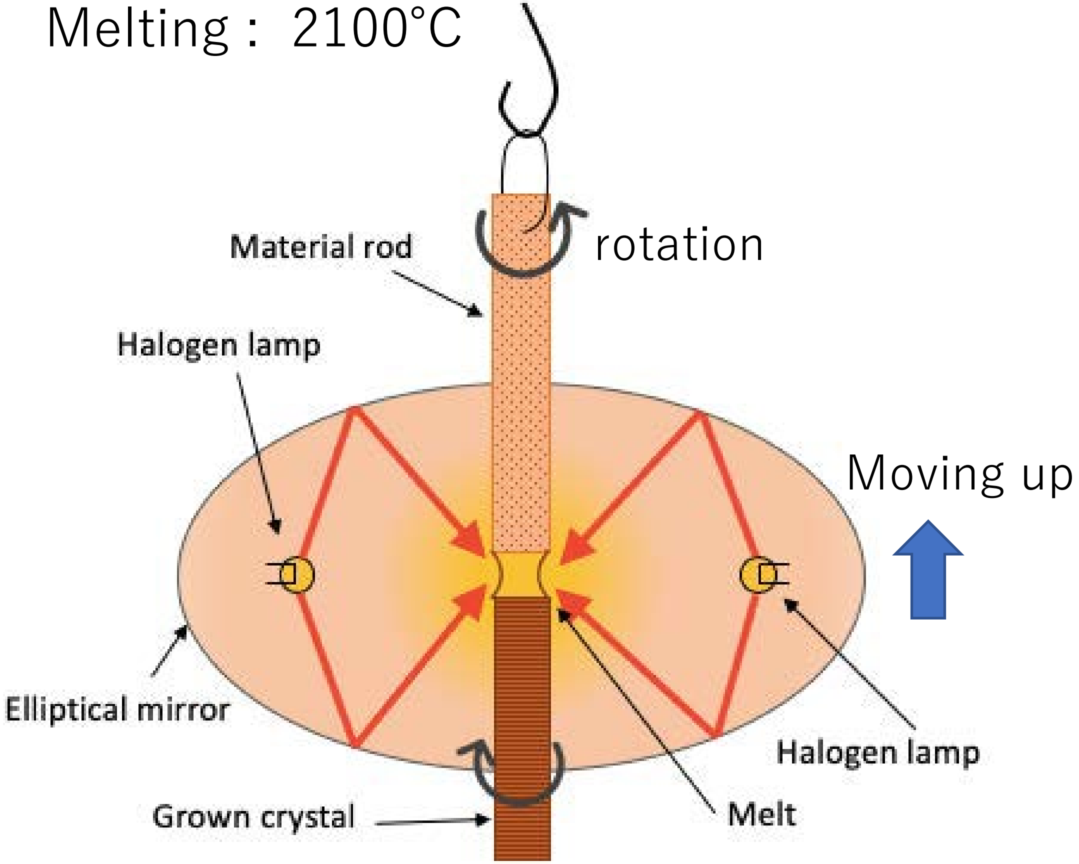
3. Development of cryogenic system toward the T-violation search

Studies on basic characteristics of $LaAlO_3$ at low temperature,
thermal conductivity, Kapitza resistance, etc..

Crystal growth in IMR, Tohoku Univ.

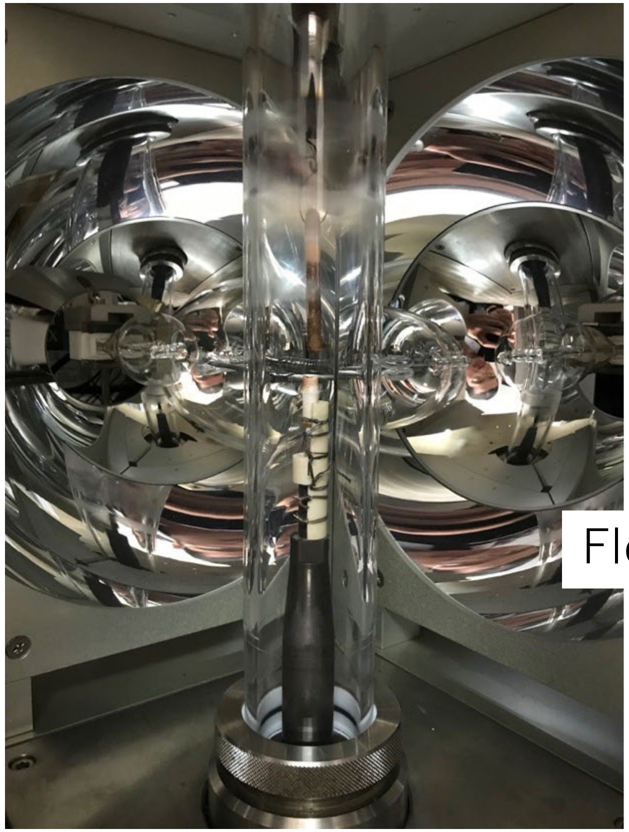
Floating-Zone(FZ) method

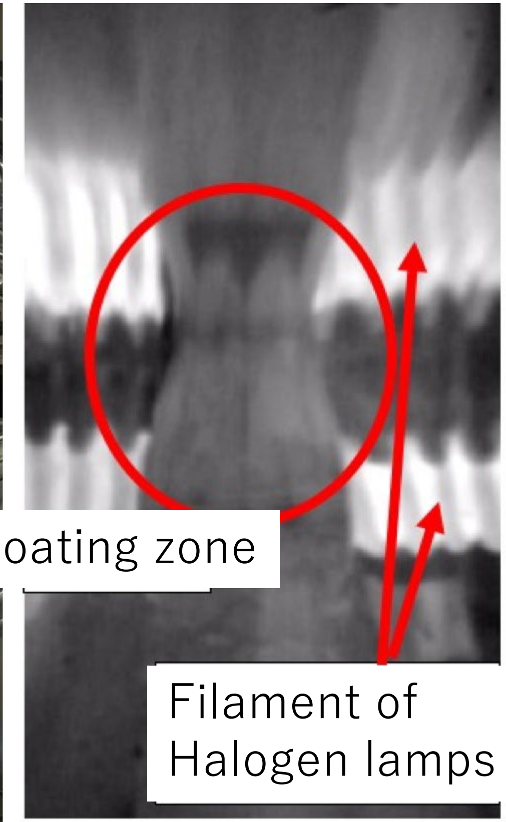
Melting : 2100°C



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

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

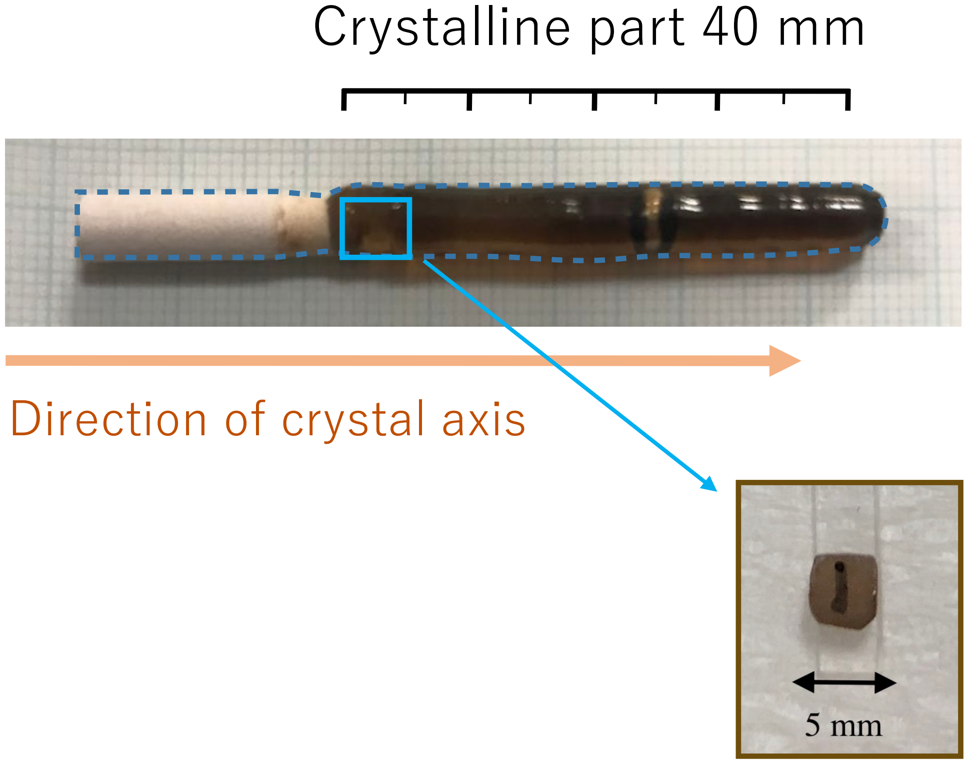




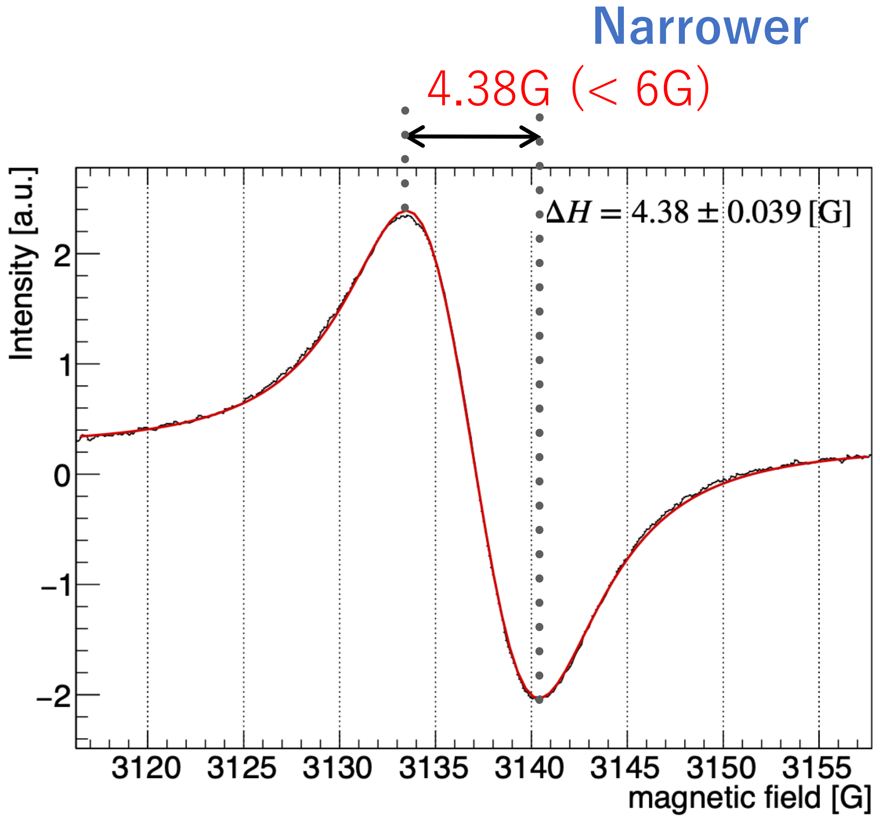
Typical grown crystals

First crystal　　Nd : 0.05mol%

Dimension : Diameter 5 mm Length 40 mm



ESR measurements



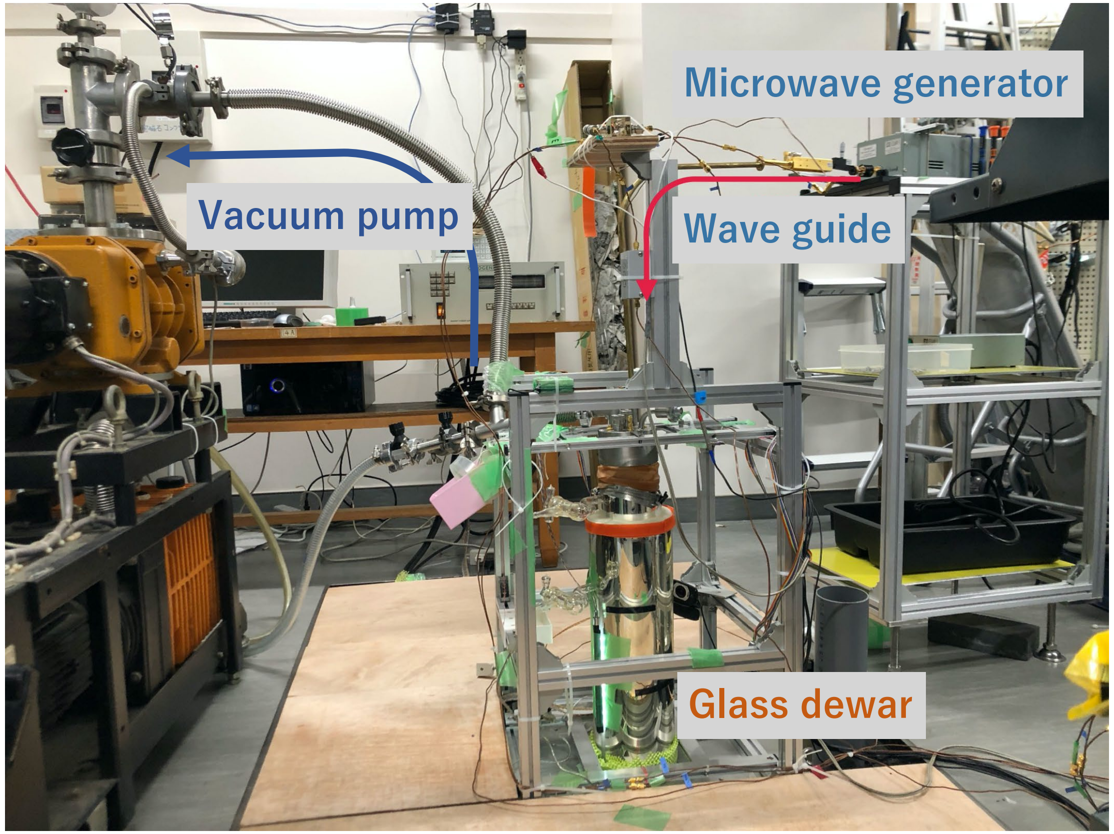
Simple DNP test at Yamagata Univ.

Condition：2.336 T, 1.33 K

Apparatus : Glass dewar

Microwave: 69-71GHz, 200mW

NMR detection :
Al 25.915 MHz La 14.505 MHz

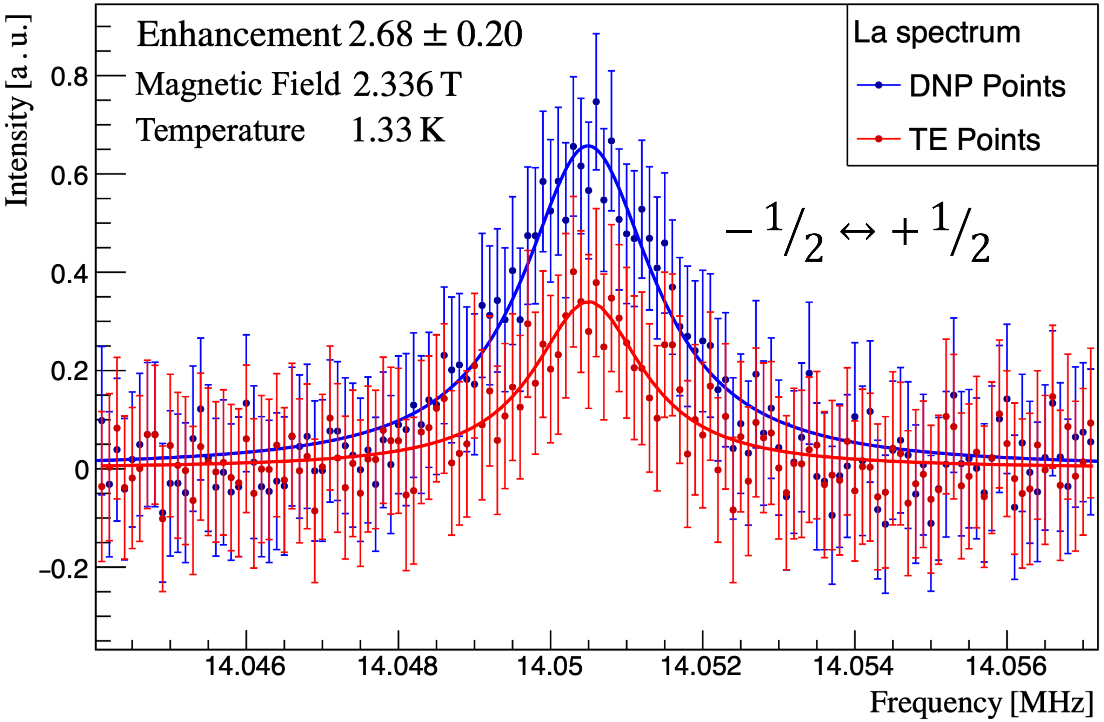


First results with our grown crystal

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

0.05mol% crystal

La spectrum

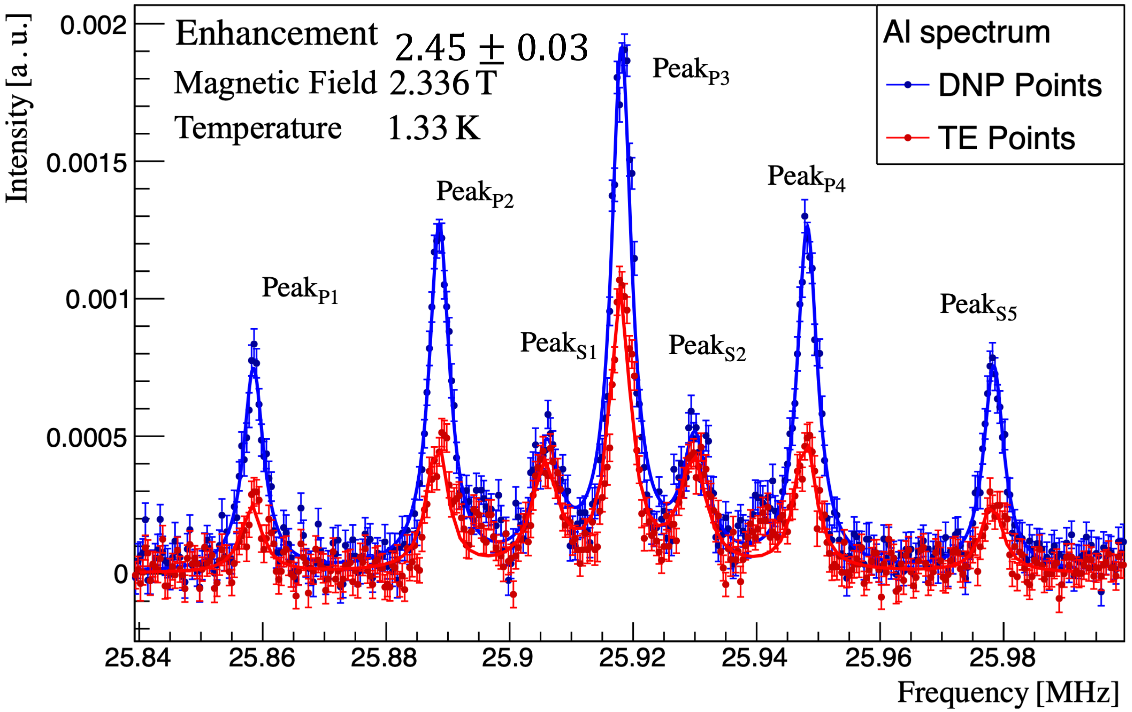


Enhancement $= \mathbf{2.68 \pm 0.20}$

$P_{vector} = 0.202 \pm 0.011$

Al spectrum

Condition: 2.3 T, 1.3 K



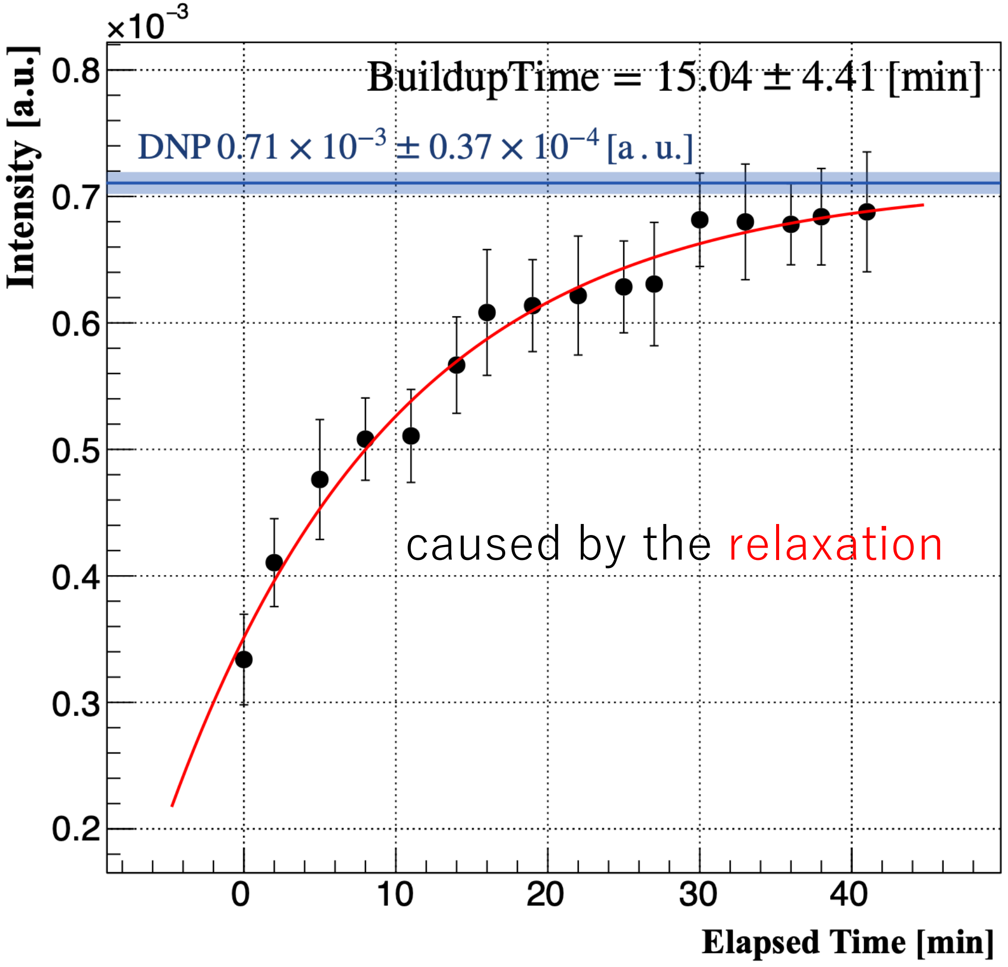
Enhancement $= \mathbf{2.45 \pm 0.03}$

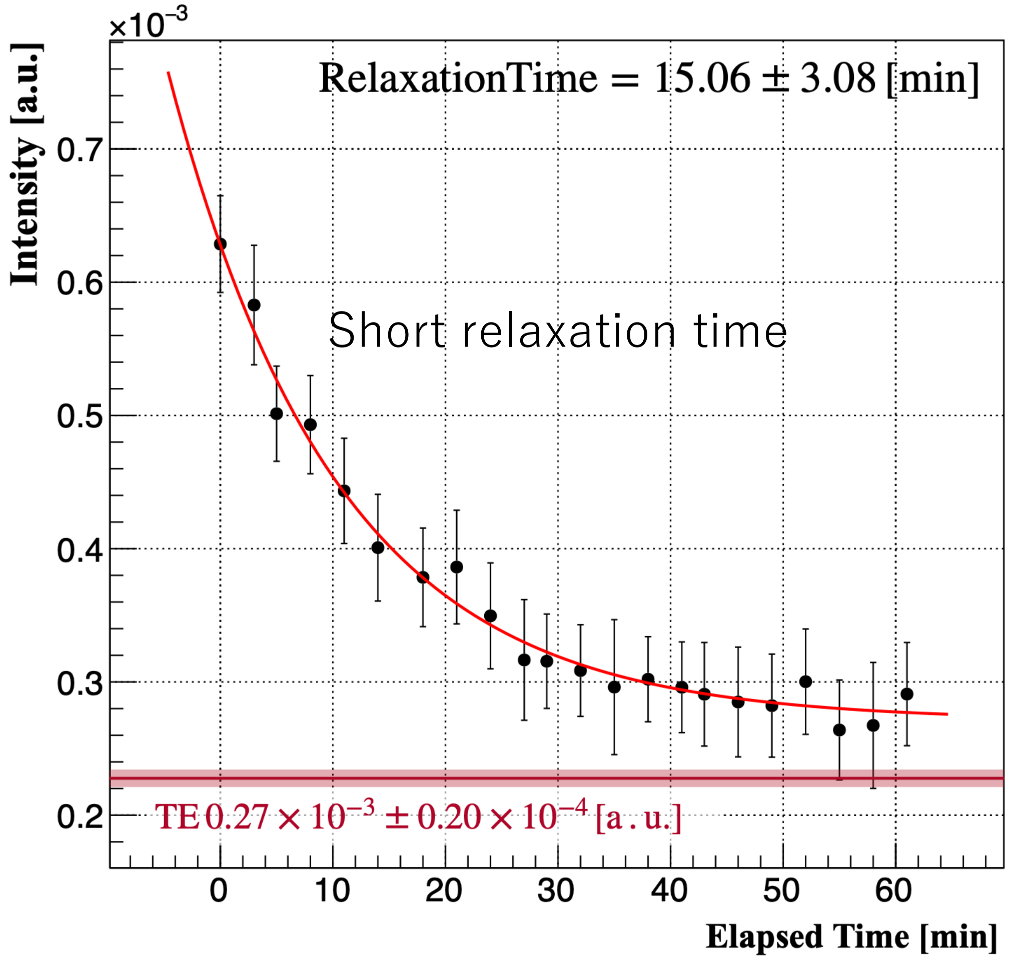
Buildup & relaxation

La NMR signal $-1/2 \leftrightarrow +1/2$ transition

Condition: 2.3 T, 1.3 K

Buildup time ≅ Relaxation time



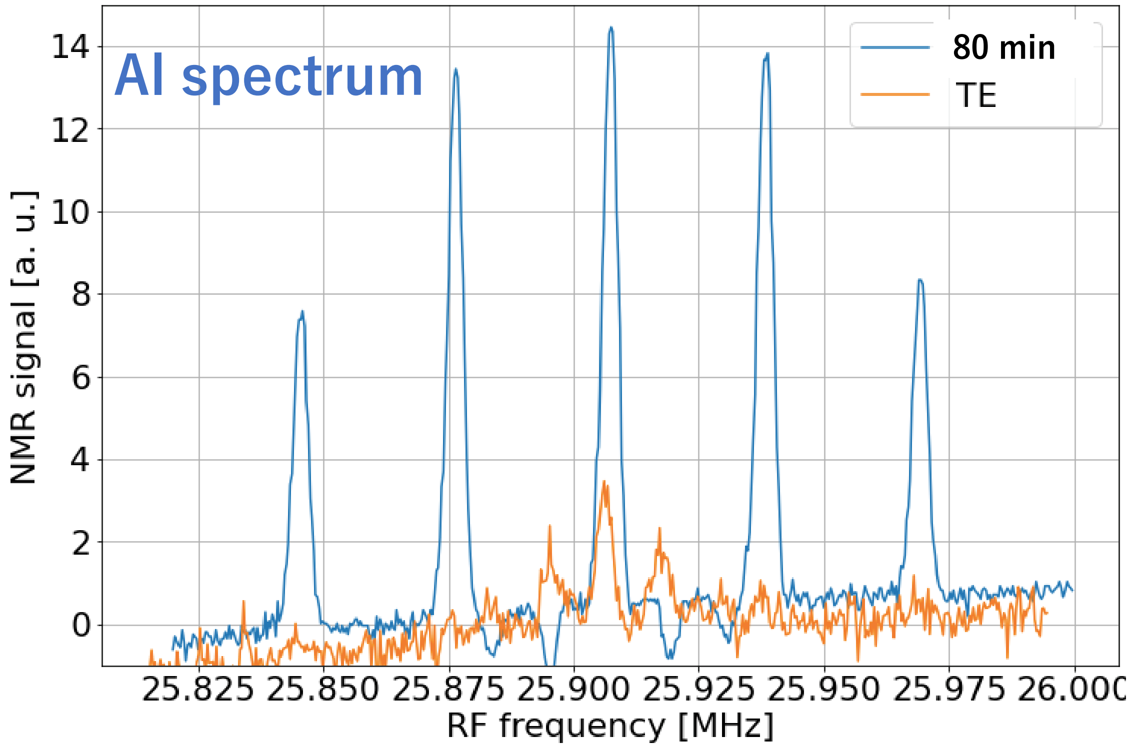


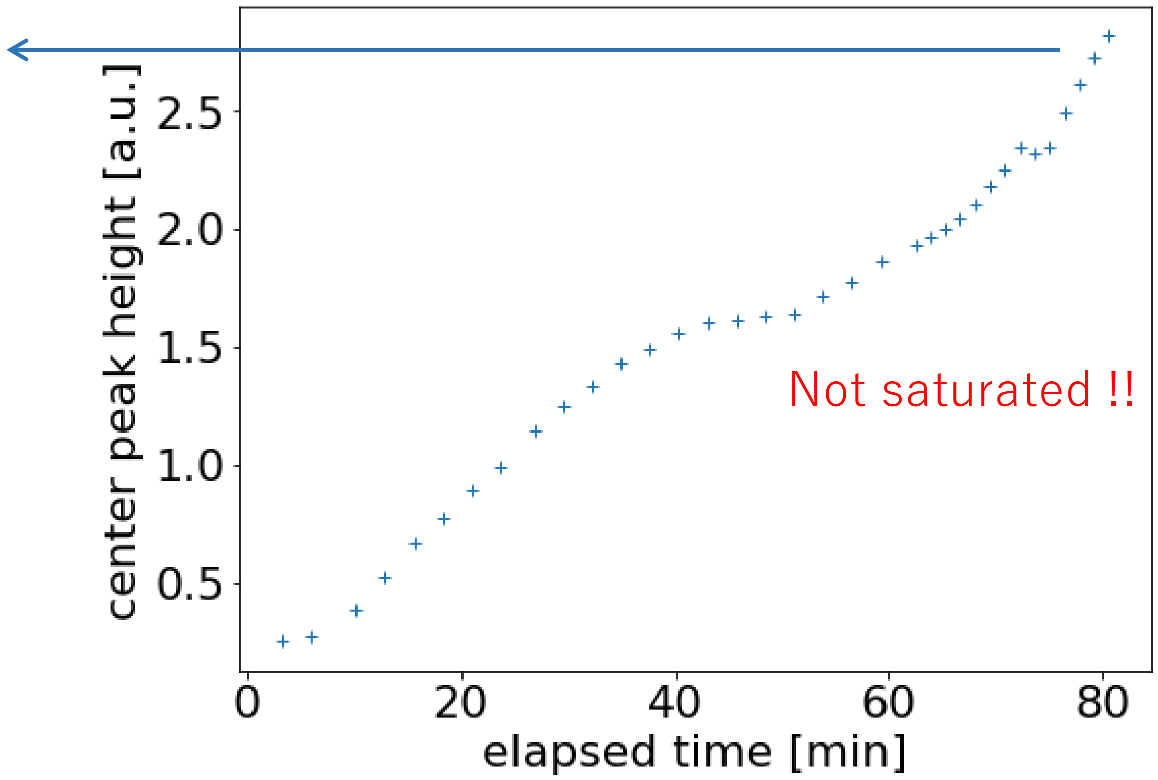
Second attempt

Condition: 2.3 T, 1.3 K

0.01 mol% crystal Expectation of longer relaxation time

Enhancement > 14

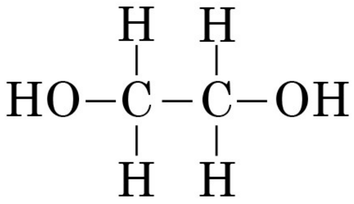




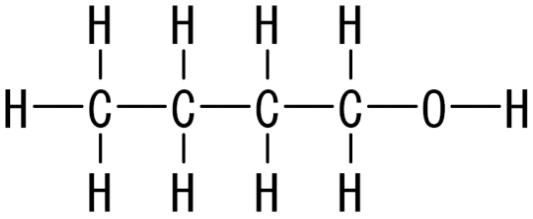
Target materials (DNP)

Chemically-doped Glassy materials

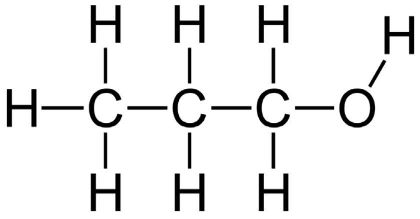
Paramagnetic ions : Cr(V) complex



Ethylene glycol



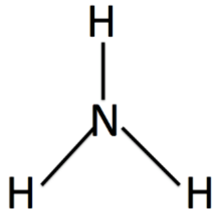
Butanol



Propanol

Irradiated materials

Paramagnetic ions: Radicals produced by irradiation



Ammonia

Li–H

Lithium hydride

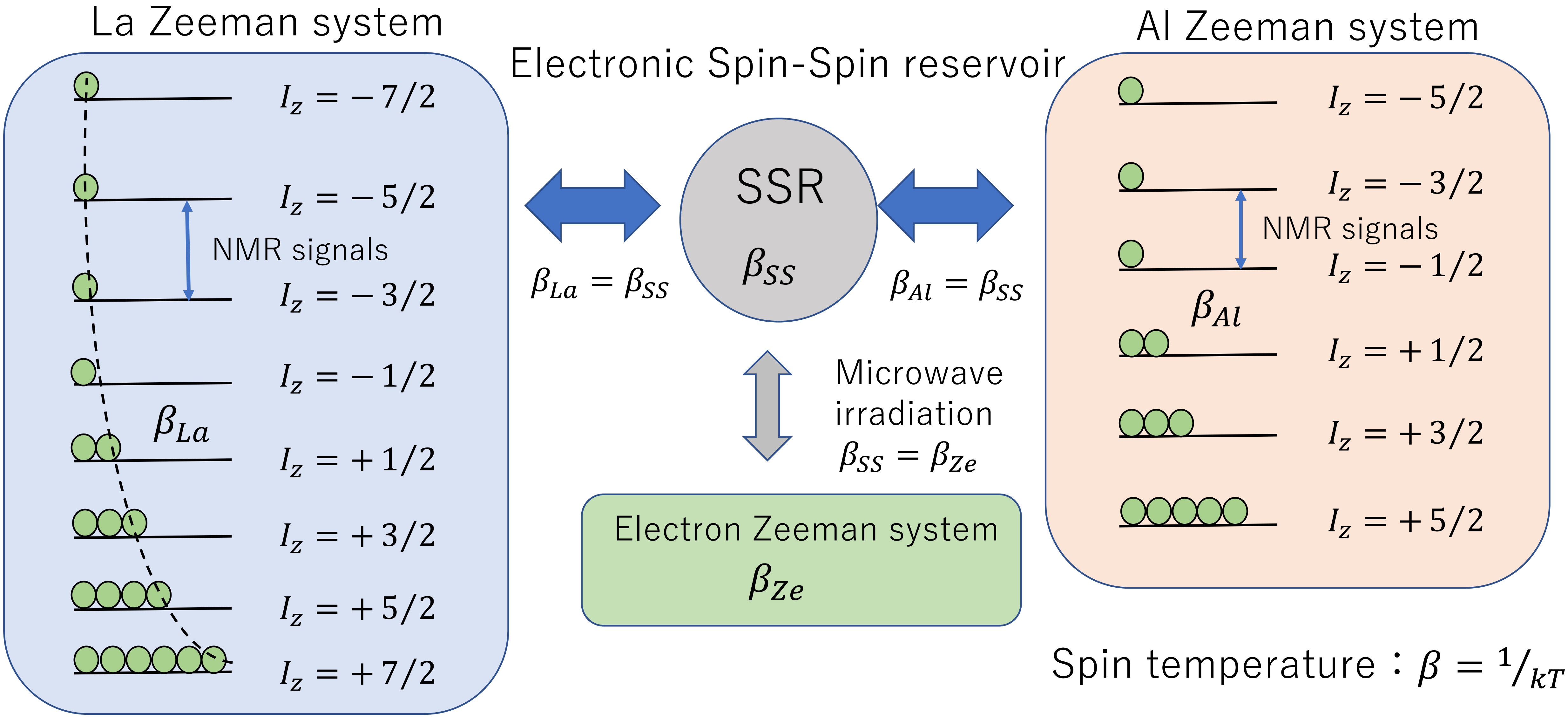
Li–D

Lithium deuteride

Flexible target size, high rate of contents

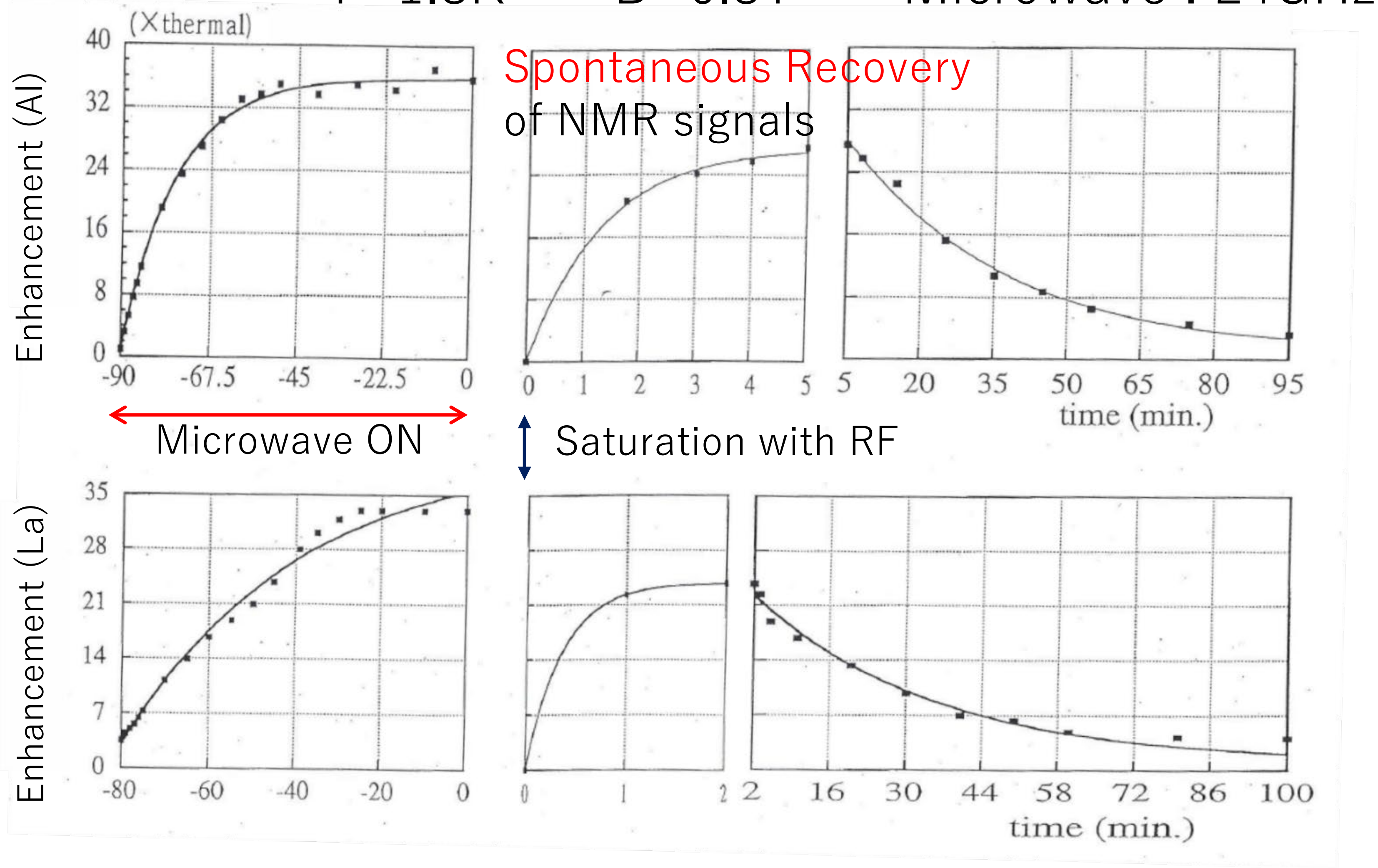
Practical target : only proton and deuteron typical P(p)>90%、p(d)>50%

DNP mechanism



Evidence of SSR

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



La transition

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

Al transition

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

Use of Nd:LaAlO$_3$ crystals

Symmetry of Perovskite structure

Paramagnetic ions : neodymium

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

- Narrow ESR linewidth : ~ 6G
- Magnetically equivalence of all La(or Nd) sites
- Diagonalization of quadrupole interaction in C$_3$ axis

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

Spin Hamiltonian

$$H = -\hbar\gamma_N \vec{I} \cdot \vec{H} + \hbar D_{zz}(I_z^2 - I(I+1)/3)$$

γ_N : gyromagnetic ratio ($\gamma_N/2\pi = 0.6$ kHz/G)

I : La nuclear spin (I = 7/2)

D_{zz}: quadrupole coupling constant ($D_{zz}/2\pi = 0.36$ MHz)