“Present status of development of a polarized La target in the T-violation search with a slow neutron”

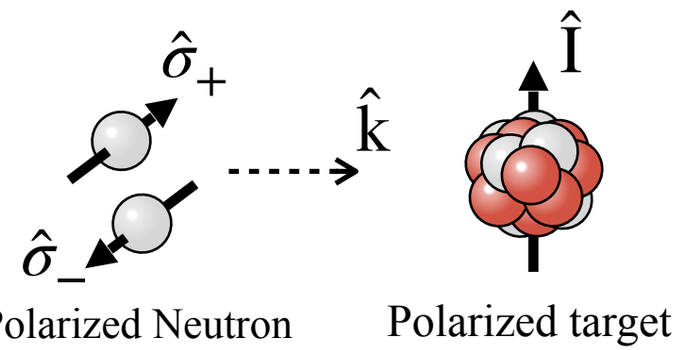
Ikuo IDE

Φ Lab. Department of Physics
Nagoya University

and **NOPTREX Collaboration**

T-violation search at J-PARC

compound nuclear resonance



Forward scattering amplitude

Spin Independent
P-even, T-even

P-violation
P-odd, T-even

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

Spin Dependent
P-even, T-even

T-violation
P-odd, T-odd

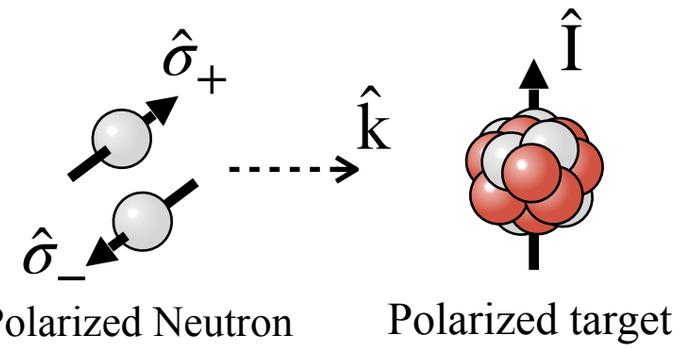
Discovery T-violation

↓

Measurement of the difference in cross section between Up and Down (neutron spins)

T-violation search at J-PARC

compound nuclear resonance



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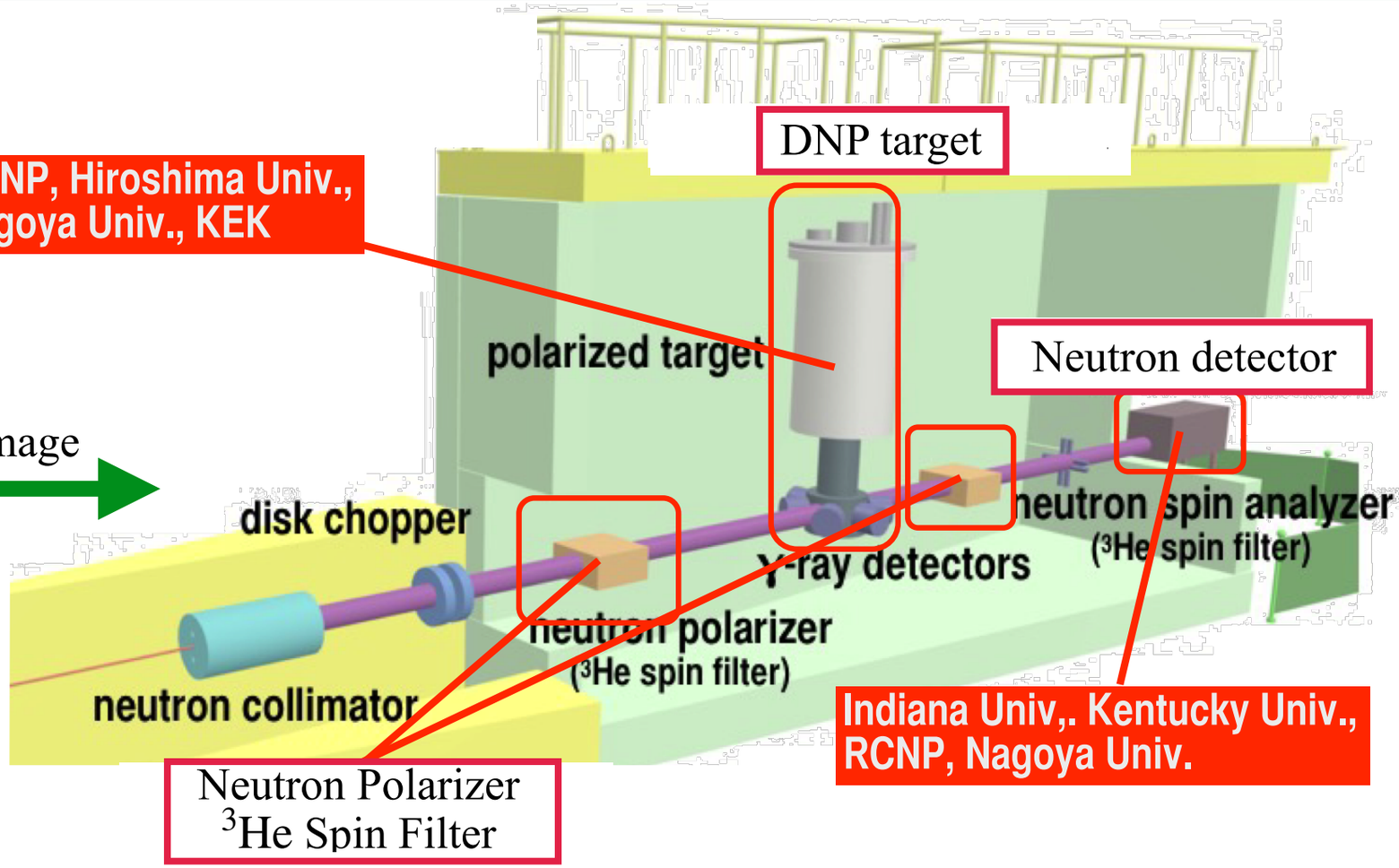
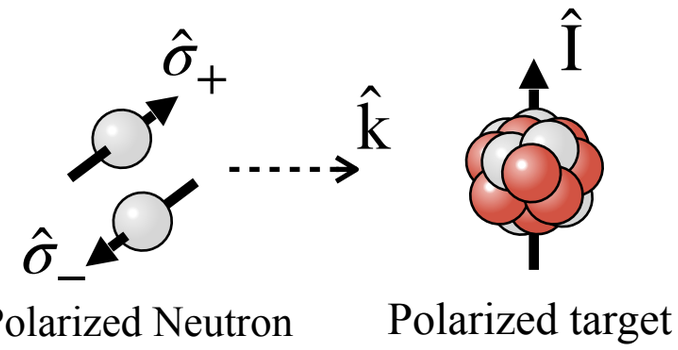


T-violation search at J-PARC

compound nuclear resonance



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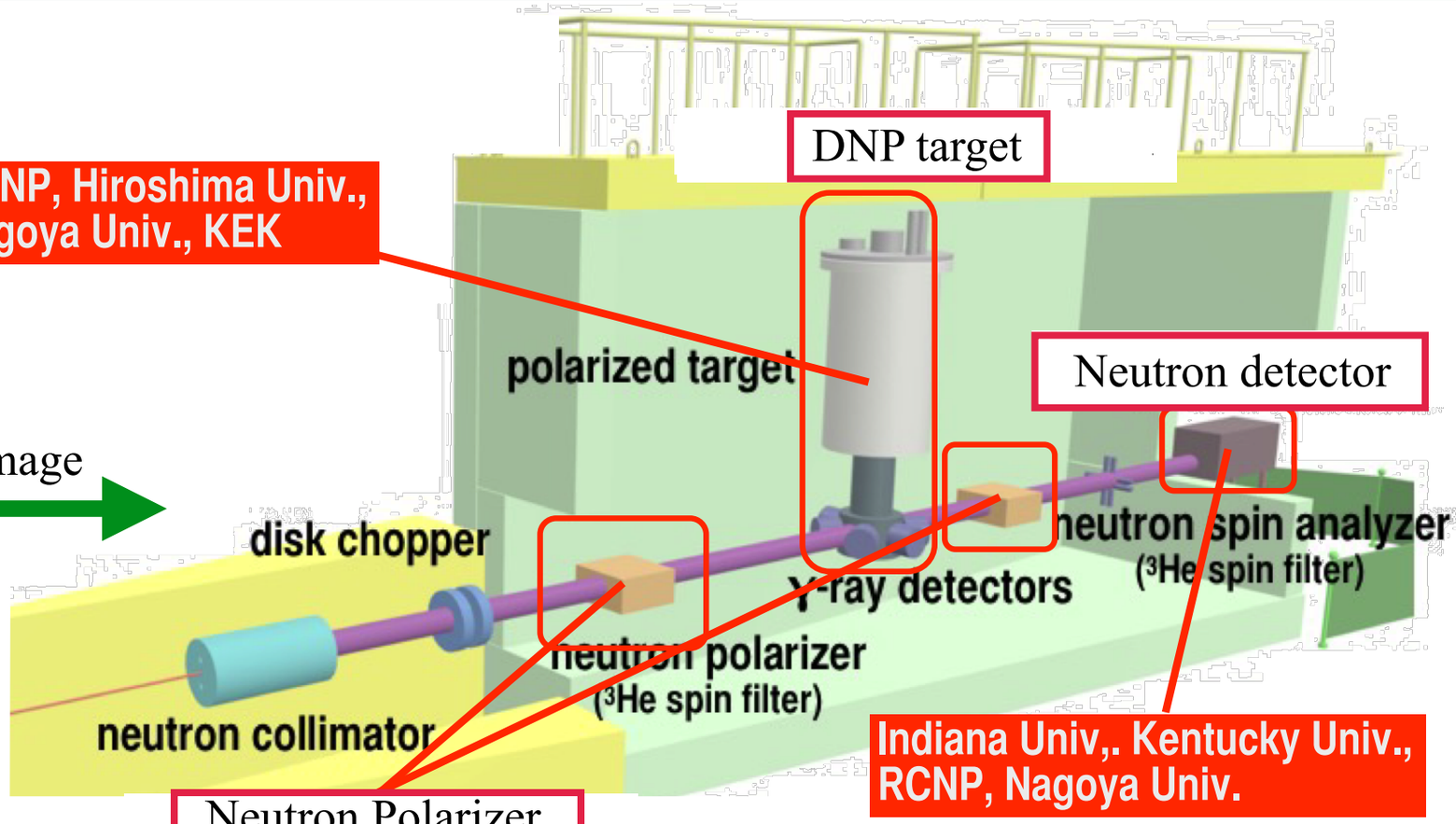
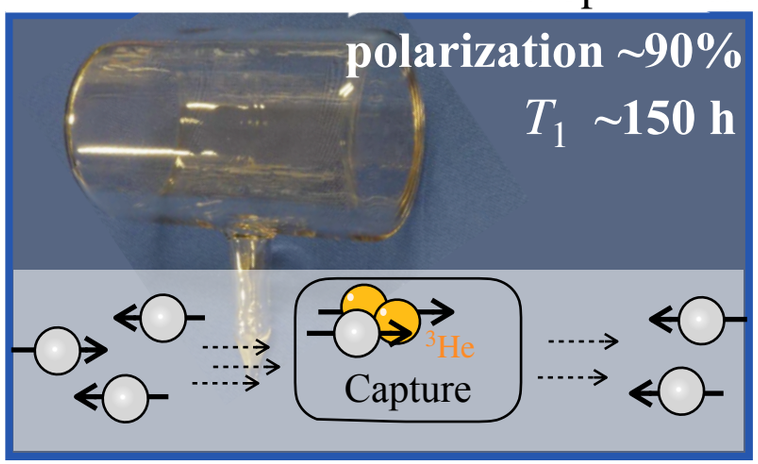


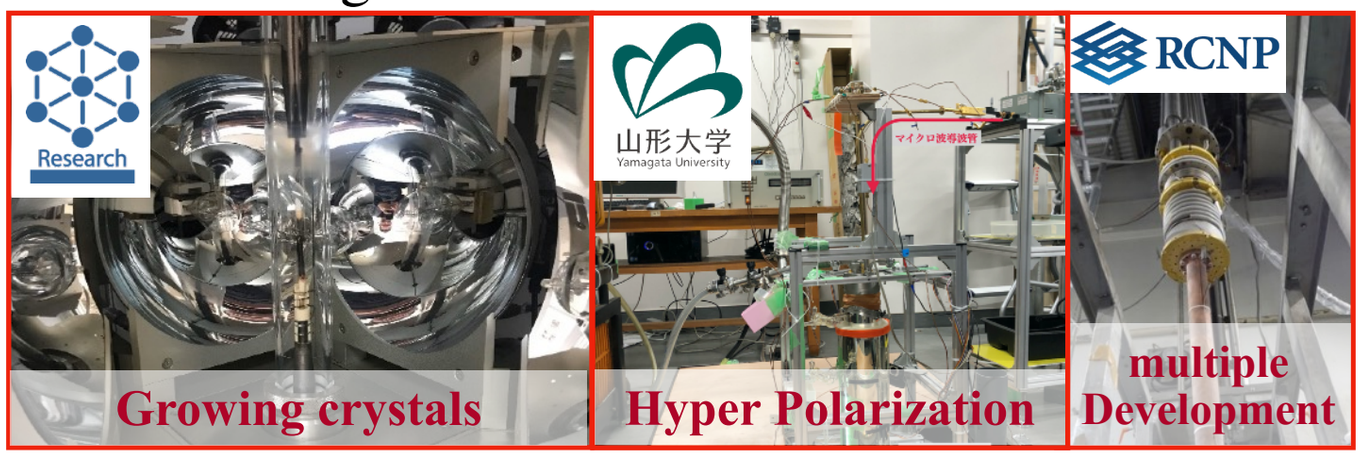
Developments

Neutron Polarizer　　^{3}He Spin Filter

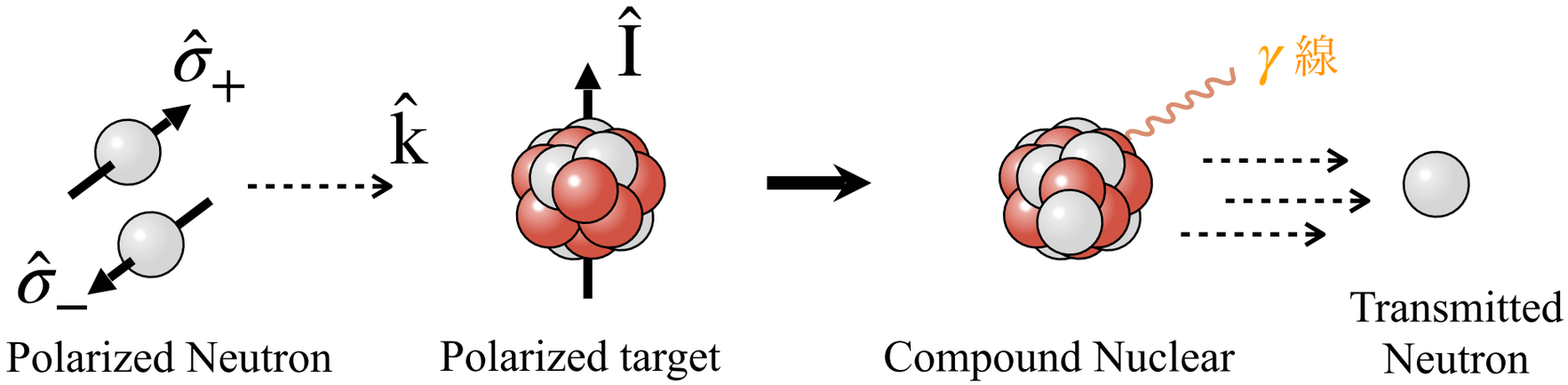


T. Okudaira et al., Phys. Rev. C (2018).

Polarized target



T-Violation search using compound nuclear resonance with slow newtron (NOPTREX)



Candidate nuclear ➤ ^{139}La, ^{131}Xe, ^{81}Br, ^{117}Sn, etc . . .

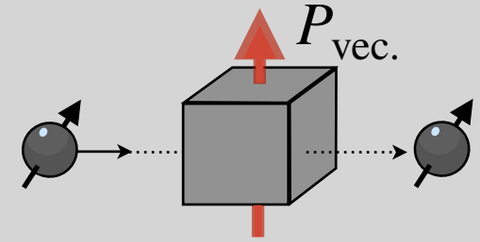
^{139}La nuclear

resonance Energy ◎	Natural Abundance ◎	$\lvert\kappa(J)\rvert$ Value ◎	Spin △	polarization Achievement ◎
0.74 eV	99.9 %	~1 $(0 \le \lvert\kappa(J)\rvert \le 1)$	7/2	DNP (~50 %)

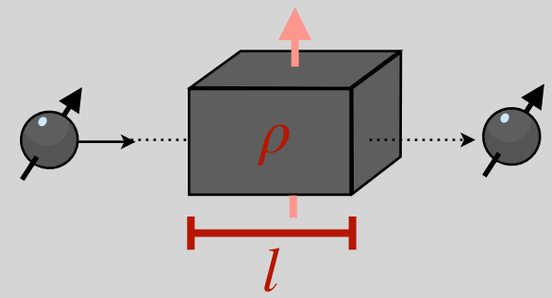
- The lower the neutron energy, the higher the luminosity @ **J-PARC** neutron source.
- $\lvert\kappa(J)\rvert$ Value is Factor for converting P-violation amplification to T-violation.
- La polarization reached 50% by DNP method (60 mK, 2.3 T).
  (P.Hautle and M. Iinuma, NIM A 440, 638 (2000))

Target Requirements

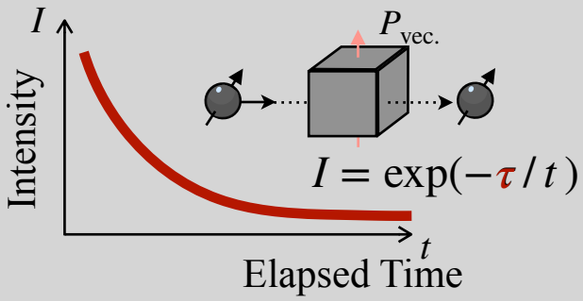
・Heigh Polarization (P > 40 %)



・Heigh density / Big size

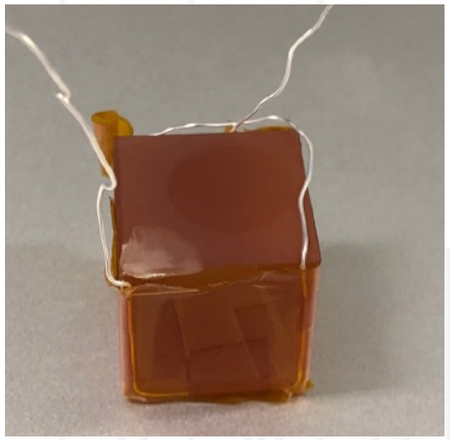


・Long Relaxation Time



Polarize Target

$LaAlO_3$ crystal (Nd^{3+} doped)



Merit

- Quadrupole interaction diagonalized on C_3 axis
- Proven polarization technology by DNP.
  (P. Hautle, M. Iinuma, 2000, NIM A)

Nd^{3+} conc . = 0.03 mol %

1. First DNP experiment (B = 2.35 T, T = 1.3 K)

   Polarization : 20 % (Positive)

   (T. Maekawa, et. al., NIM A 366, 115 (1995))

2. Experiment at PSI (B = 2.35 T, T < 0.3 K)

   Polarization : 47.5 % (Positive)

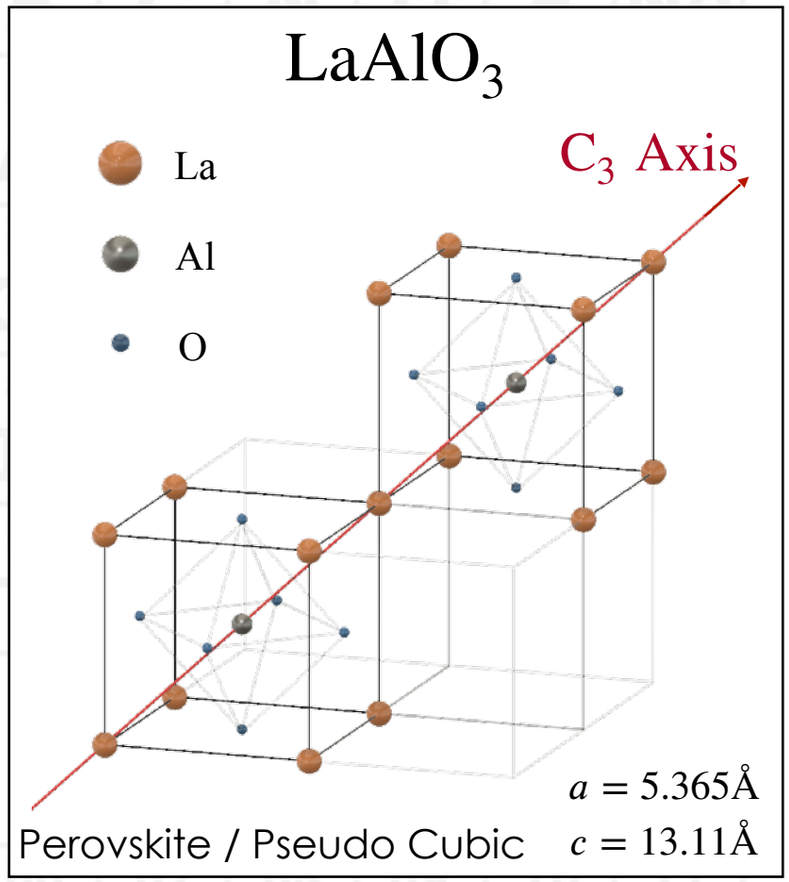
   (P.Hautle and M. Iinuma, NIM A 440, 638 (2000))

Attic number 57

^{139}La

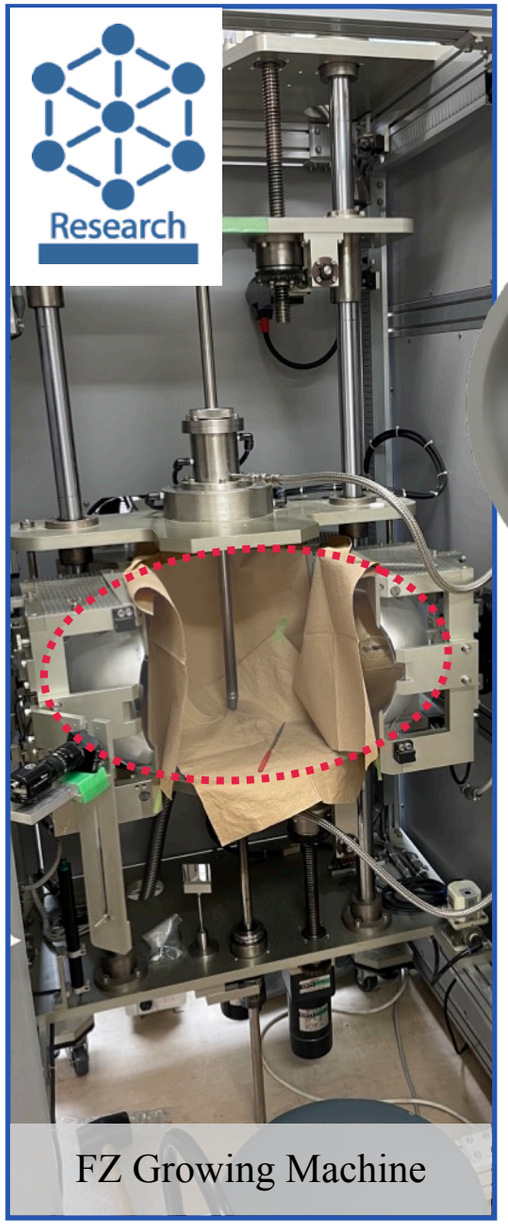
Spin I = 7/2

High Natural Abundance **99.91 %**

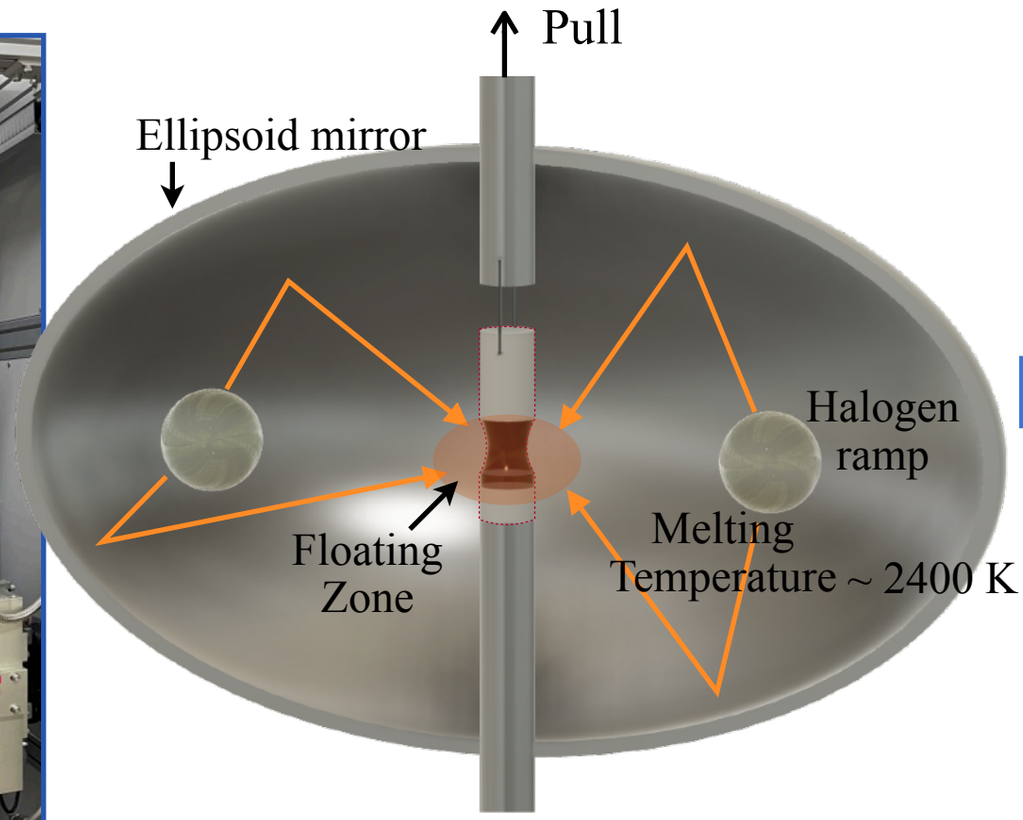


➤ Growth & Development of Nd doped $LaAlO_3$ crystals

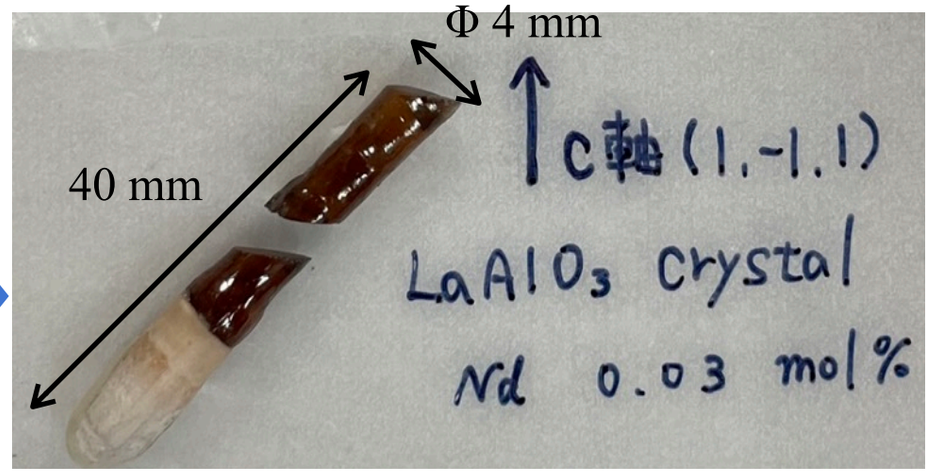
Growing $LaAlO_3$ Crystal (Doped Nd ion)
- Floating-Zone Method-



FZ Growing Machine



Grown crystals



Successful growth of multiple crystals with different Nd concentrations

Method

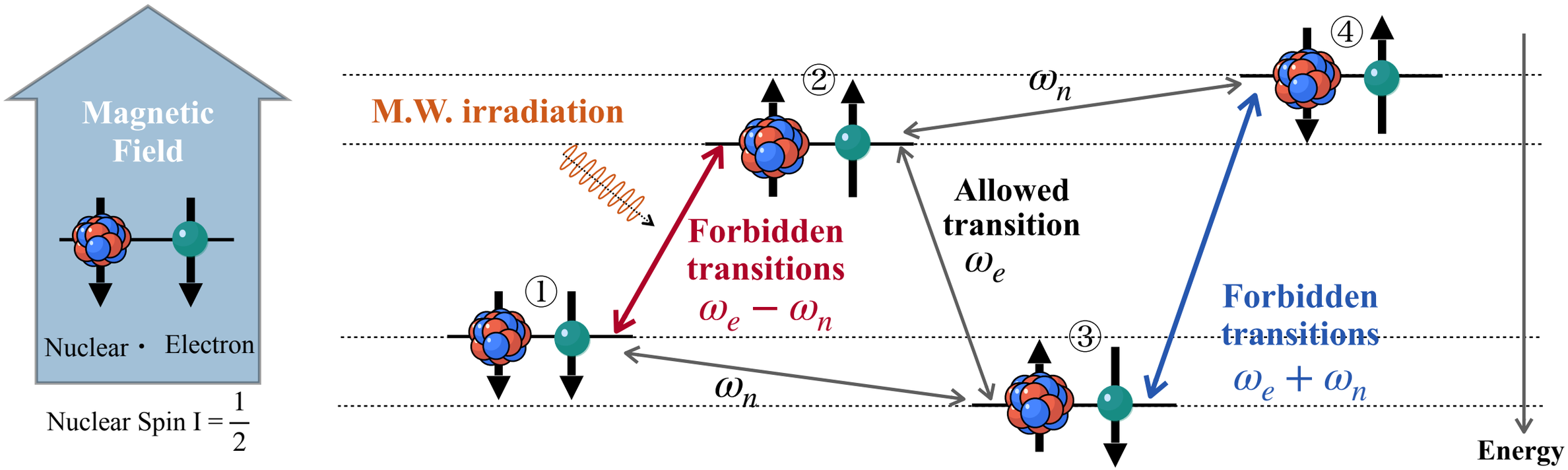
1. Condense light on the melting region using an ellipsoidal mirror, and melt raw material.
2. The crystals are pulled up while rotating, and cooled.

Crystal growth parameters

Method	Floating - Zone
Ingredient Material	Oxidized Lanthanum (La_2O_3) Alumina (Al_2O_3) Neodymium (Nd)
Nd concentration	0.01, 0.03, 0.05 mol%…

Dynamic Nuclear Polarization (DNP)

…transferring highly polarized electron spin to nuclear spin



ω_e ： Electron Spin Flip - flop

ω_n ： Nuclear Spin Flip - flop

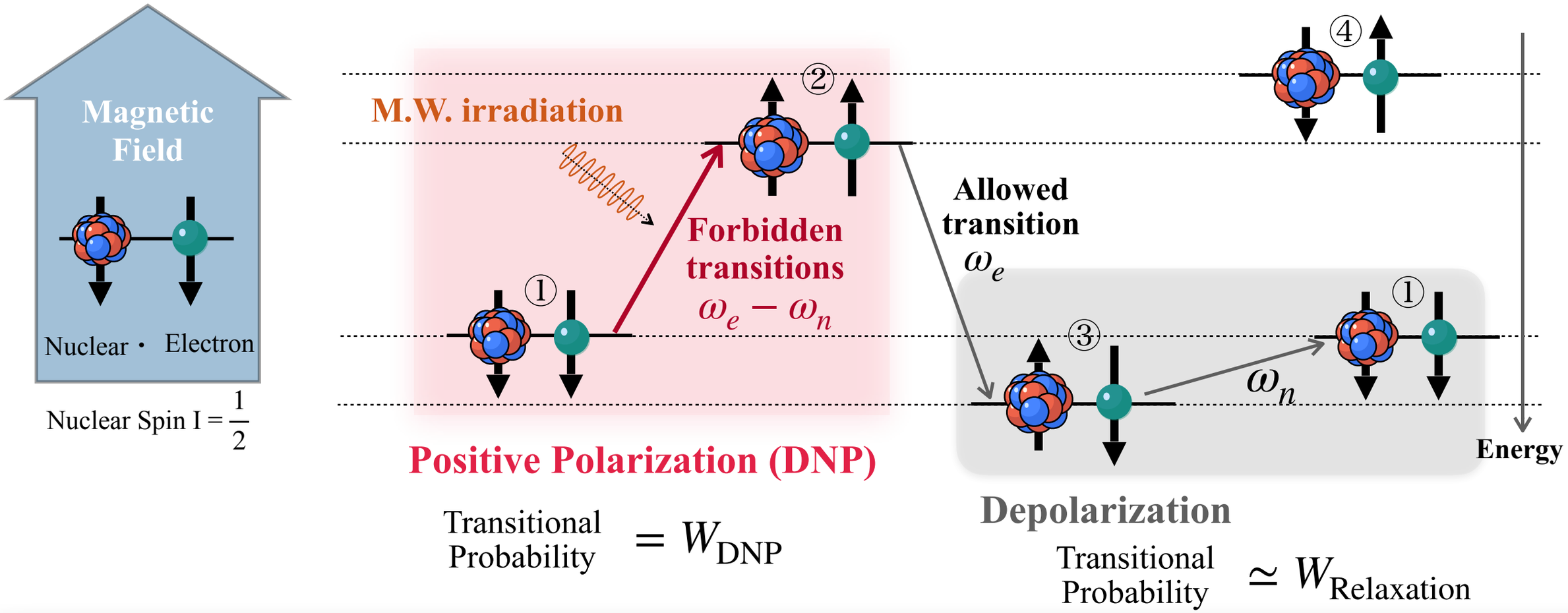
・Allowed transition： ω_e , ω_n

・Forbidden transitions： $\omega_e + \omega_n$, $\omega_e - \omega_n$

Forbidden transitions are permitted by irradiating M.W. (colored arrows)

Dynamic Nuclear Polarization (DNP)

…transferring highly polarized electron spin to nuclear spin



DNP mechanism: competing between forbidden and allowed transitional probability

→ The maximum polarization depends on … Transition probability of the allowed transition (T_1)

Microwave power, etc …

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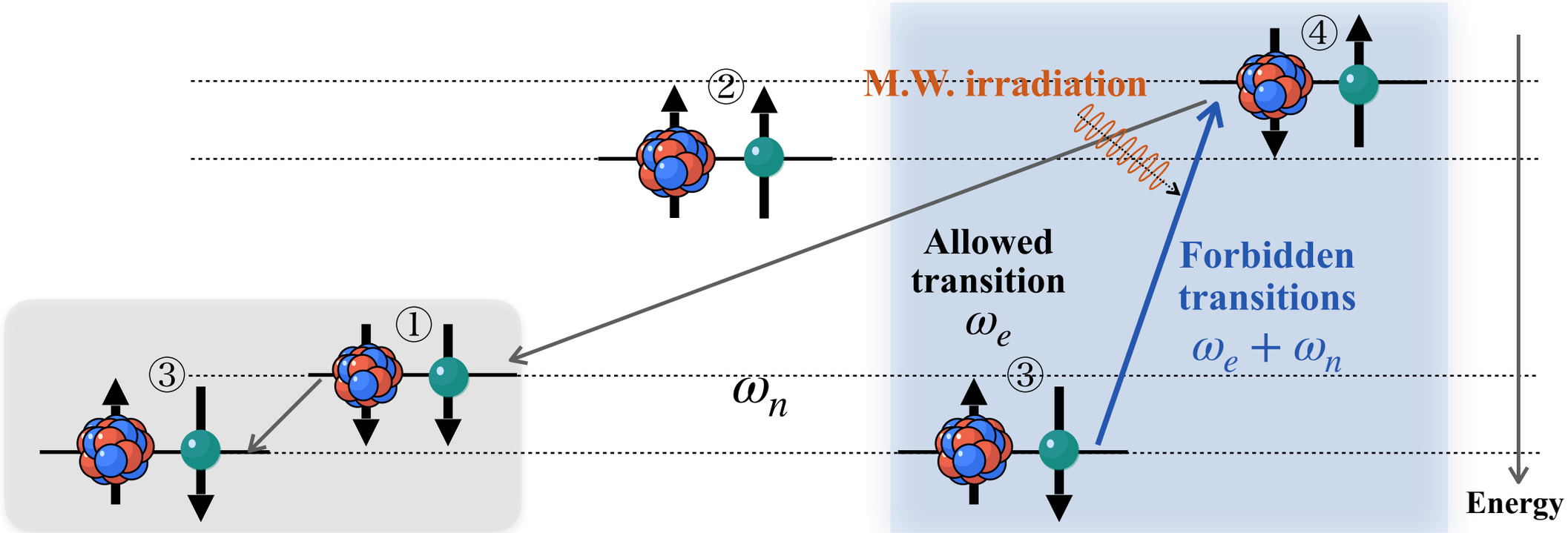
…transferring highly polarized electron spin to nuclear spin



Negative Polarization (DNP)

$$\text{Transitional Probability} = W_{\text{DNP}}$$

Depolarization

$$\text{Transitional Probability} \simeq W_{\text{Relaxation}}$$

DNP mechanism: competing between forbidden and allowed transitional probability

→ The maximum polarization depends on … Transition probability of the allowed transition (T_1)

Microwave power, etc …

Summary of past experiments

Measurement of polarization and relaxation time of ^{139}La nuclei (in Nd^{3+}: $LaAlO_3$ Crystal) hyperpolarized by DNP

Nd Conc. [mol %]	Polarization [%]	Relaxation Time [min]	Date of measurement
0.3	small	—	Kyoto Univ.
0.05	0.2%	15 min	2021 at Yamagata Univ. (Nagoya Univ.)
0.03	20%	82 min	Kyoto Univ. T. Maekawa, H. M. Shimizu, M. Iinuma, NIM A 366, 115 (1995)
0.003	—	—	

Don't made by Nagoya

Crystal made by Nagoya

- Best Nd concentration: 0.03 mol% (0.3, 0.03, 0.003 mol %)
- 0.03 mol % has Higher Polarization and longer Relaxation-time than 0.05 mol %

→ The appropriate amount of Nd concentration needs further study.

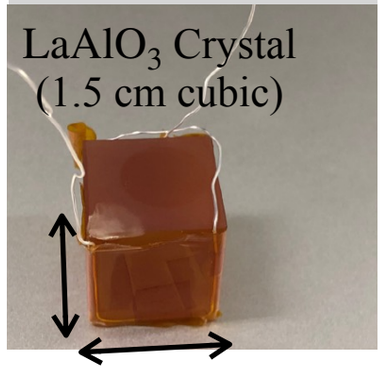
Summary of past experiments

T1 measurement at Al of the $LaAlO_3$ crystal

Nd Conc. [mol %]	Polarization [%]	Relaxation Time [min]	Date of measurement
0.03	—	T1 > 60 min	2019 at Osaka Univ. K.Ishizaki and I.Ide, et. al., NIM A (2021)

Don't made by Nagoya

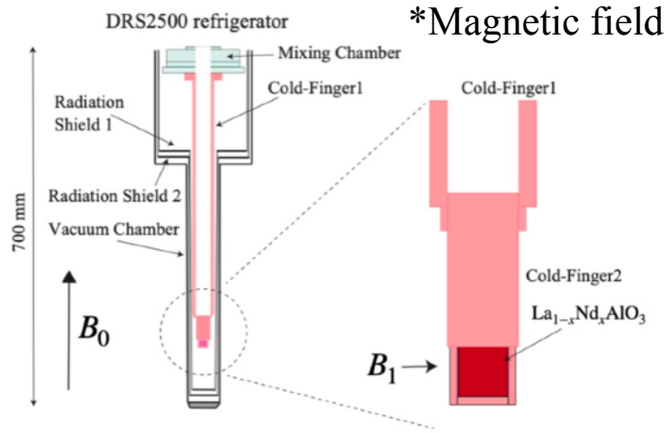
Sample Information

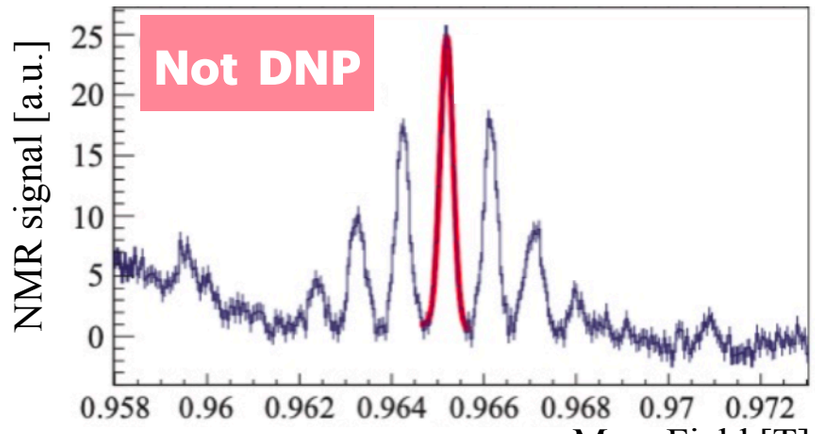


Nd conc. : 0.03 mol %

Condition T = 1.5 K, ν_{La} = 28.2 MHz

*Magnetic field sweep

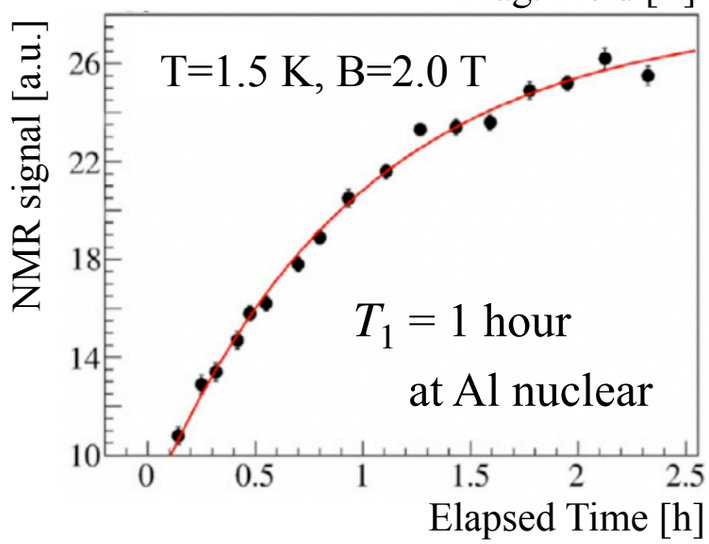




Result : Relaxation Time T1 at Al nuclear is more than **1 [hour]**

If… T1 mechanism: dominant electron spin relaxation
→ Al and La relaxation times are the same.

La nuclear similary, T_1 > **1 [hour]** → Not Good for use as a target



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Crystal made by Nagoya	**0.01**			2022 at Yamagata Univ. (Nagoya Univ.) ← This talk!
Don't made byNagoya	**0.003**	—	—	Kyoto Univ.

→ Measurement polarization and relaxation times with More dilute Nd conc.

DNP Experiment at Yamagata Univ. (2022.03)

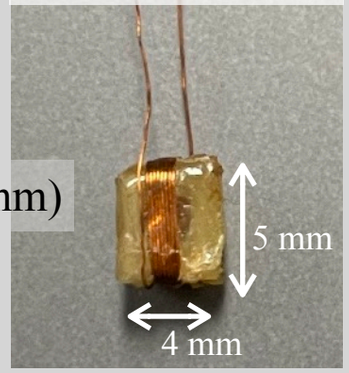
Sample Information

Nd^{3+} : $LaAlO_3$ Crystal

Sample size : Cylinder (φ4 × 5 mm)

Nd^{3+} conc. : 0.01 mol %

grown by Nagoya



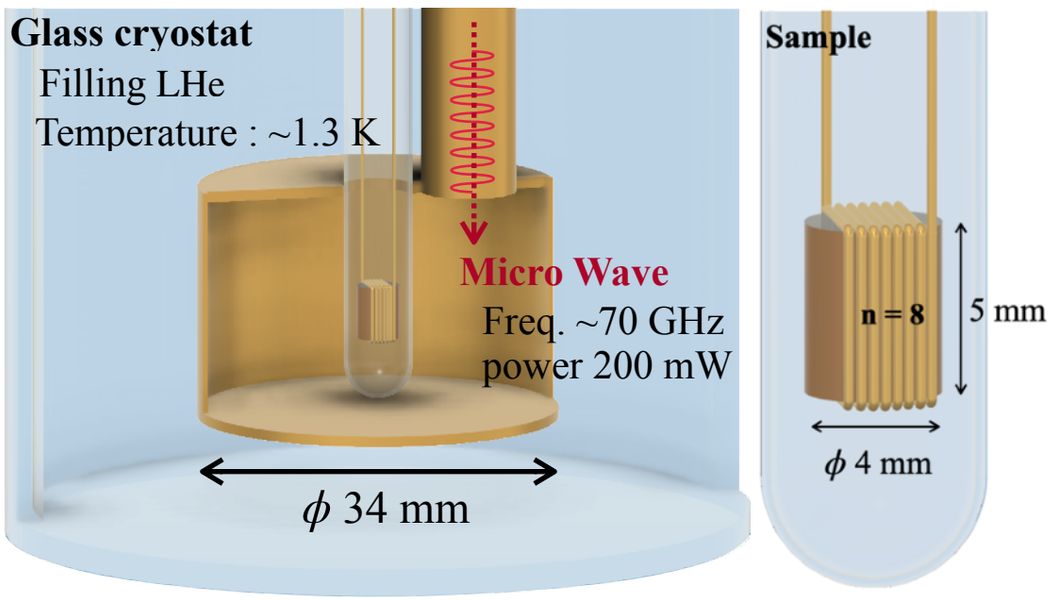
Experiment Condition

Temperature : 1.33 K

Magnetic field : 2.336 T

NMR Frequency : La - 14.505 MHz

Detail of mount method



Measurement details

[1] Frequency response of the M.W.

Scanning microwave frequencies polarized by DNP using the ^{27}Al nuclear

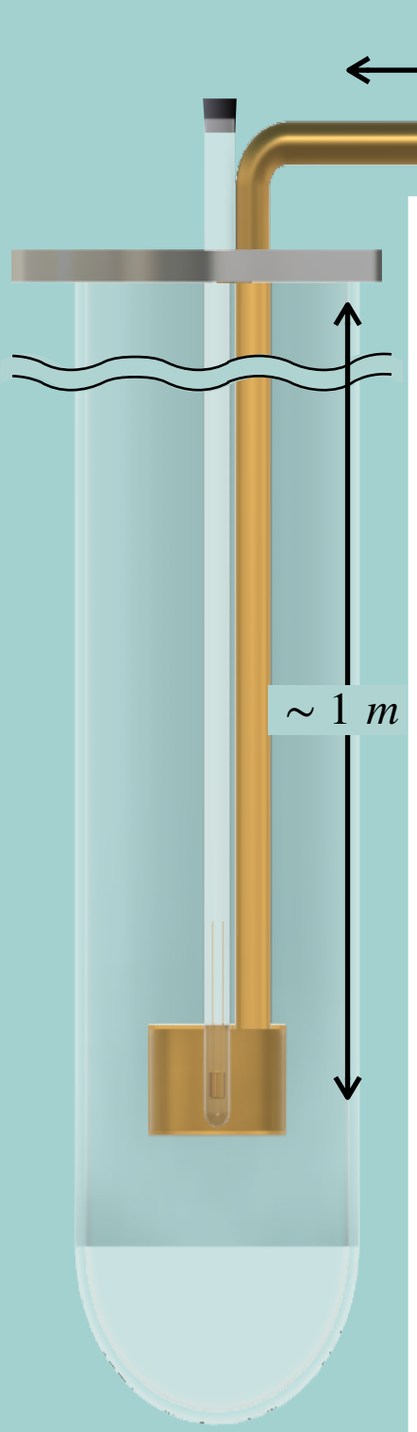
[2] Polarization of ^{139}La nucleus

@ Positive Polarization

Measures all NMR peaks (=7 peaks) of La nucleus

Buildup Time of ^{139}La nucleus

Estimates polarization relaxation time from BuildupTime



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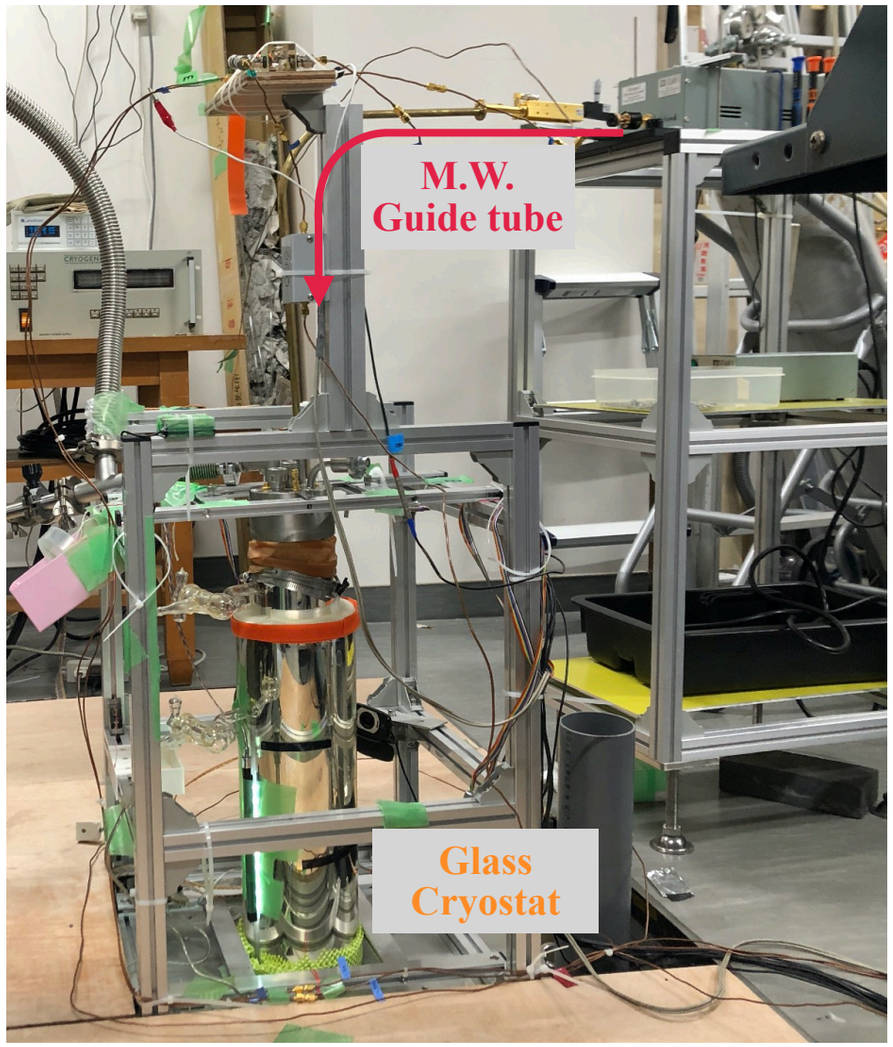

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M.W. Frequency

$$\nu_{\mathrm{M.W.}} = \hbar(\gamma_e + \gamma_N)H_0$$
$$\simeq \hbar\gamma_e H_0 \quad (\gamma_{\mathrm{Nuclear}} \ll \gamma_{\mathrm{electron}})$$

	Gyromagnetic rate γ [MHz/T]	Frequency [GHz] at B = 2.35 T
electron	1.76×10^{5}	68.97
Al	11.0	4.6×10^{-3}
La	6.0	3.5×10^{-3}

[1] Frequency response of the M.W.

Scanning microwave frequencies
using the ^{27}Al nuclear

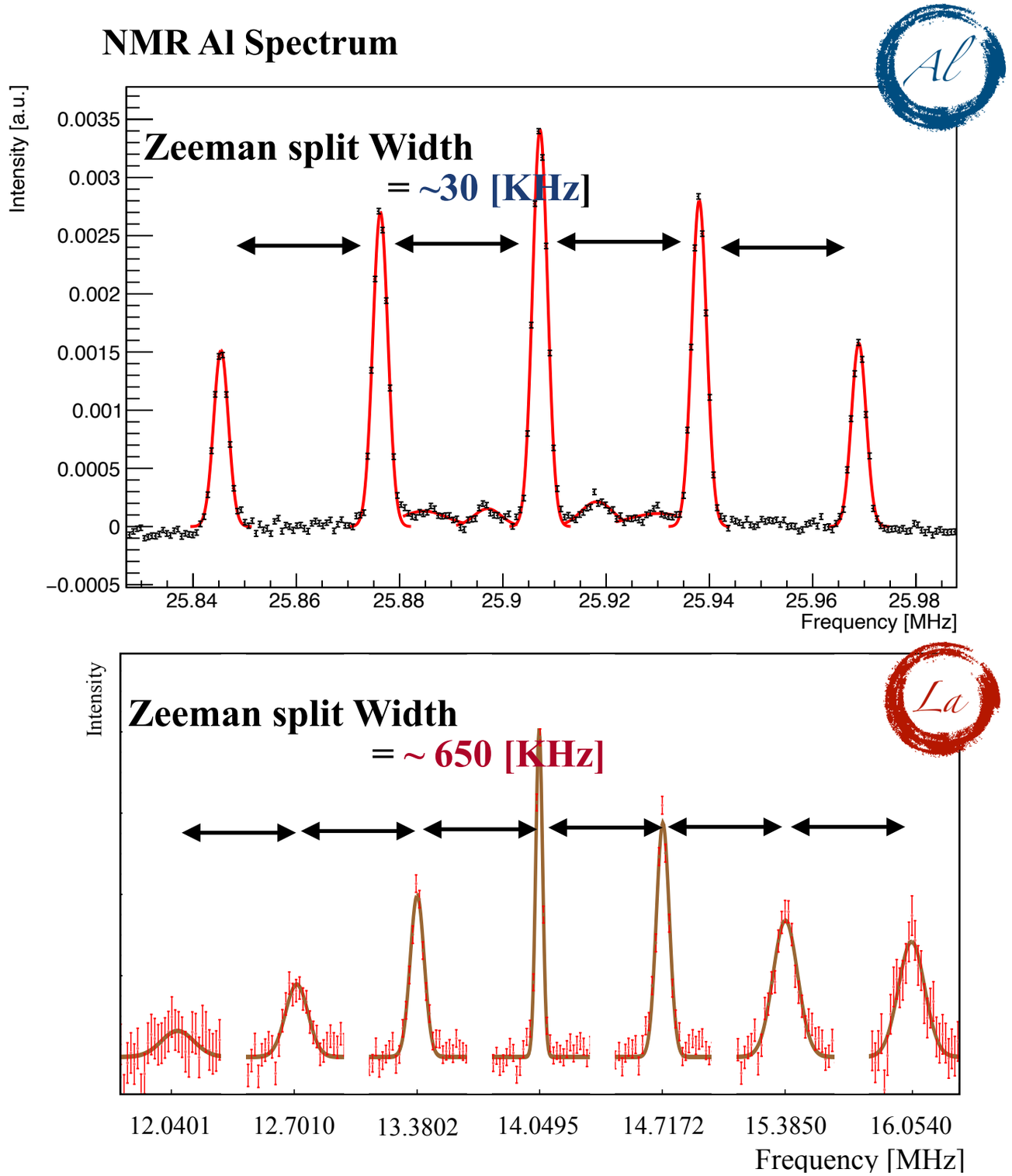
Method

1. Microwave irradiation around DNP conditions :
Frequency 70 GHz

Scan Freq. : 69.36, 69.38, 69.40, … 69.54 GHz

→ Search for Frequency to amplify polarization at the Maximum polarization

**The Zeeman split width of La is very long,
Not all peaks can be observed
in a single NMR measurement.**



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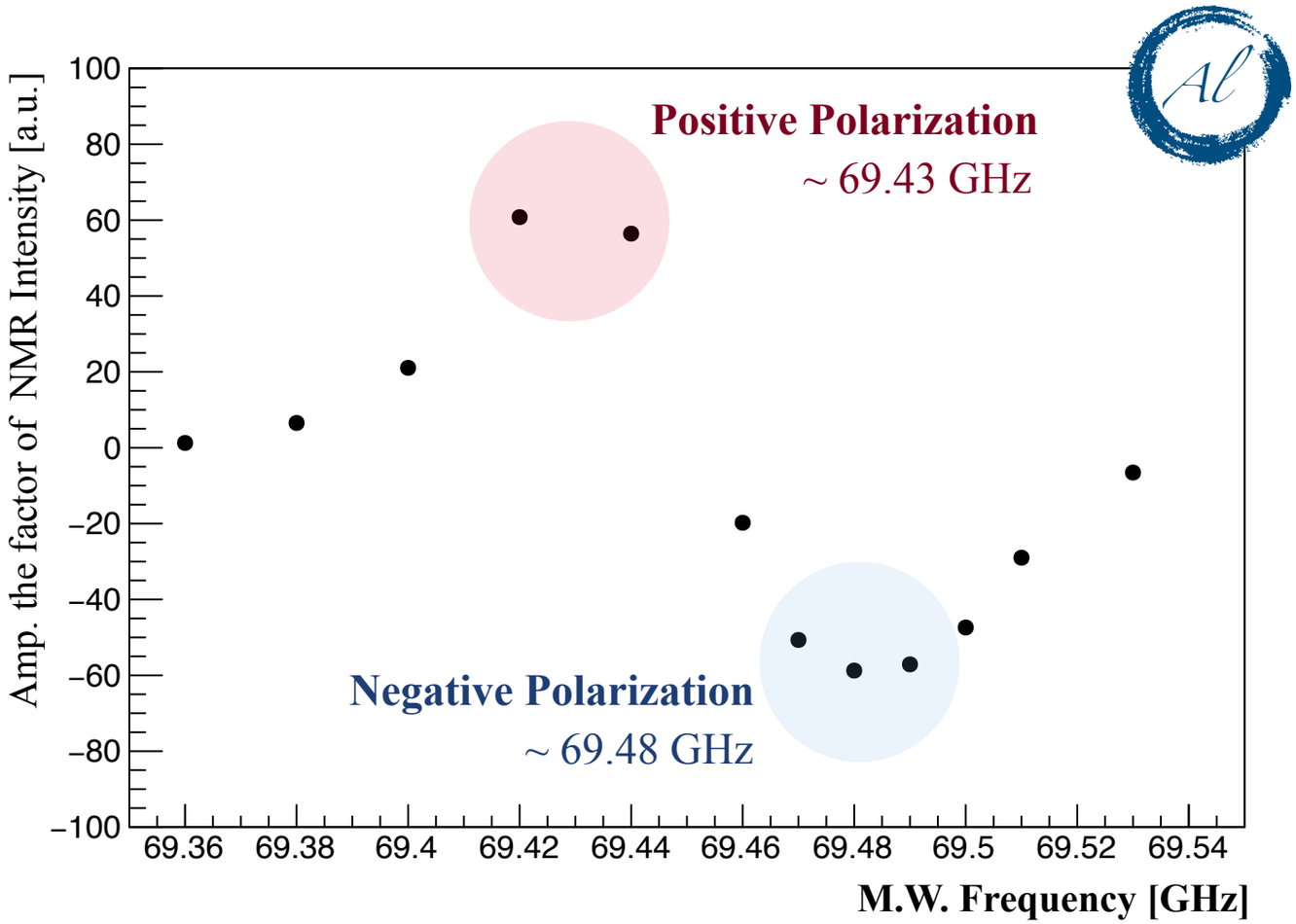


Microwave dependence at the Al nuclear

Result

Positive Polarization : 69.43 [GHz/2π]

Negative polarization : 69.48 [GHz/2π]

➤ Using this M.W. frequency,
measure the **Positive Polarization** of La nuclei.

[2.1] Polarization of ^{139}La nucleus

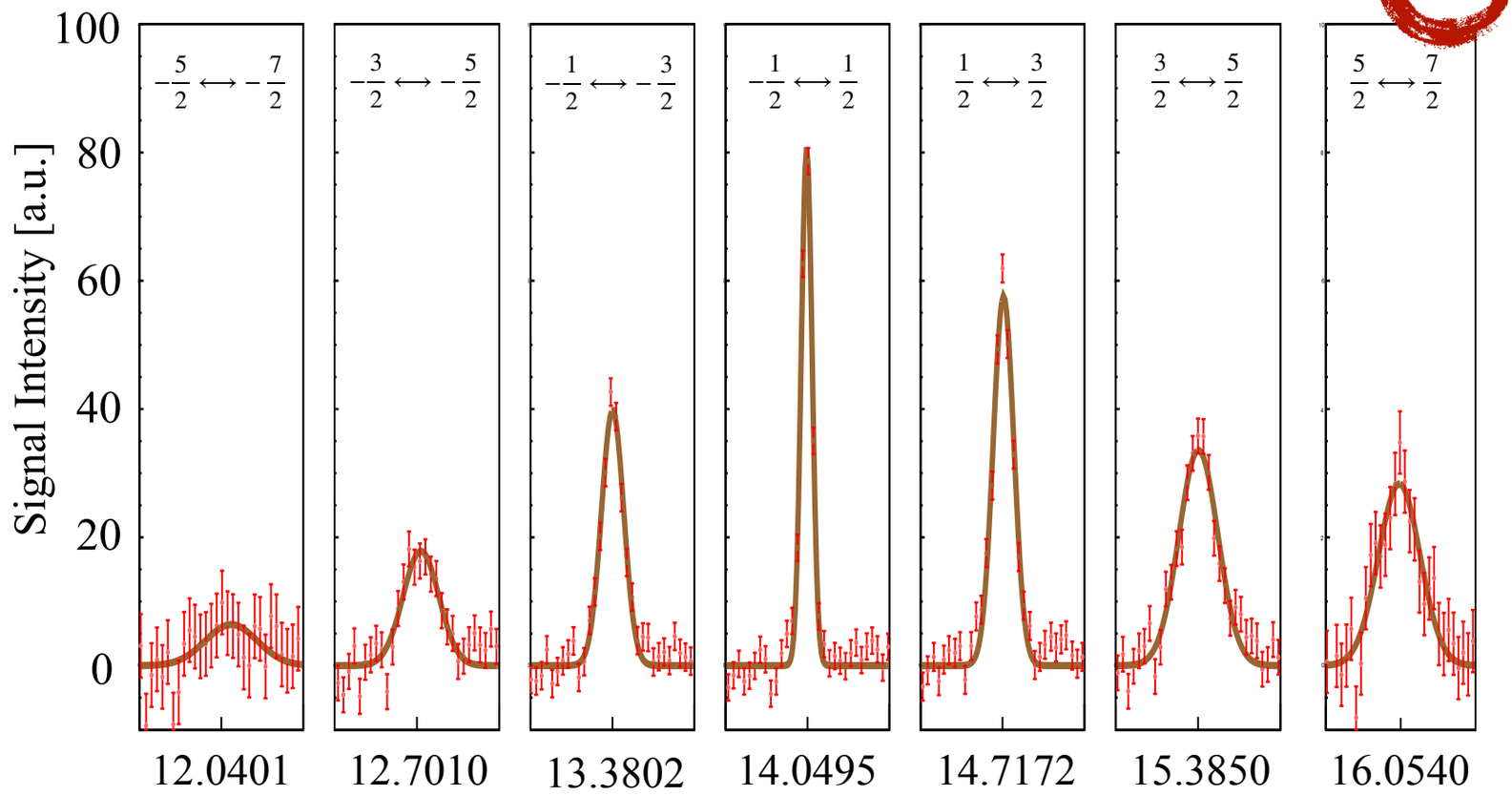
@ Positive Polarization

Measures all NMR peaks (=7 peaks) of La nucleus

Conditions : B = 2.336 [T] , T = 1.33 [K]

M.W. Freq. : 69.435 [GHz]

Irradiation Time : **2.5 [hour]**



Result

measured DNP spectrum

couldn't measure TE spectrum

→ **TE signal Intensity is Small.**

→ **impossible to conduct experiments for a long time due to lack of LHe**

[2.1] Polarization of ^{139}La nucleus

@ Positive Polarization

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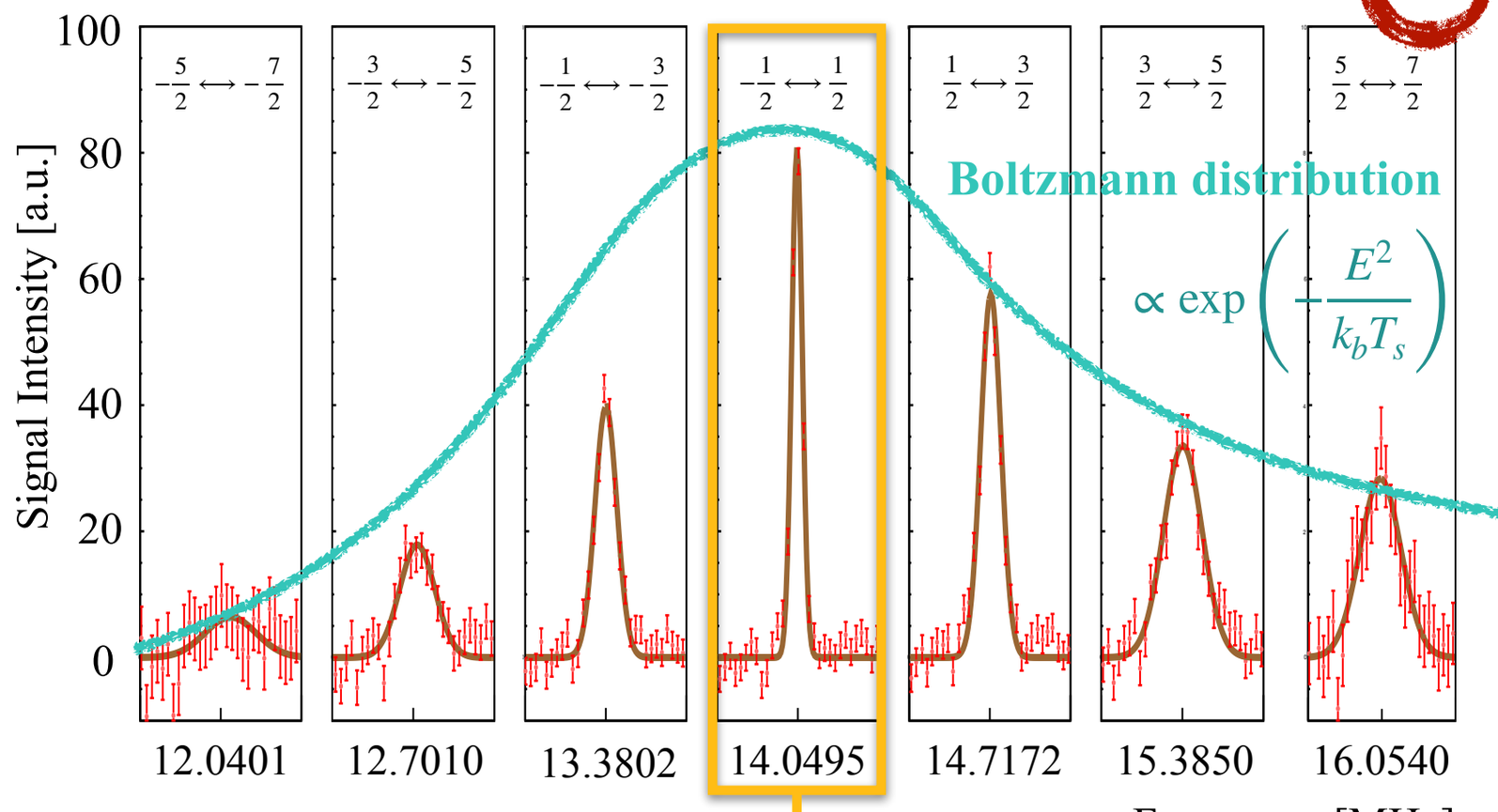

Result

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→ **TE signal Intensity is Small.**

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Spin Temperature : 3.782 mK

Polarization : 19.68 ± 0.98 [%]

Monitors only the Center Peak growing by microwave (DNP)
→ Measure Build-up Time.

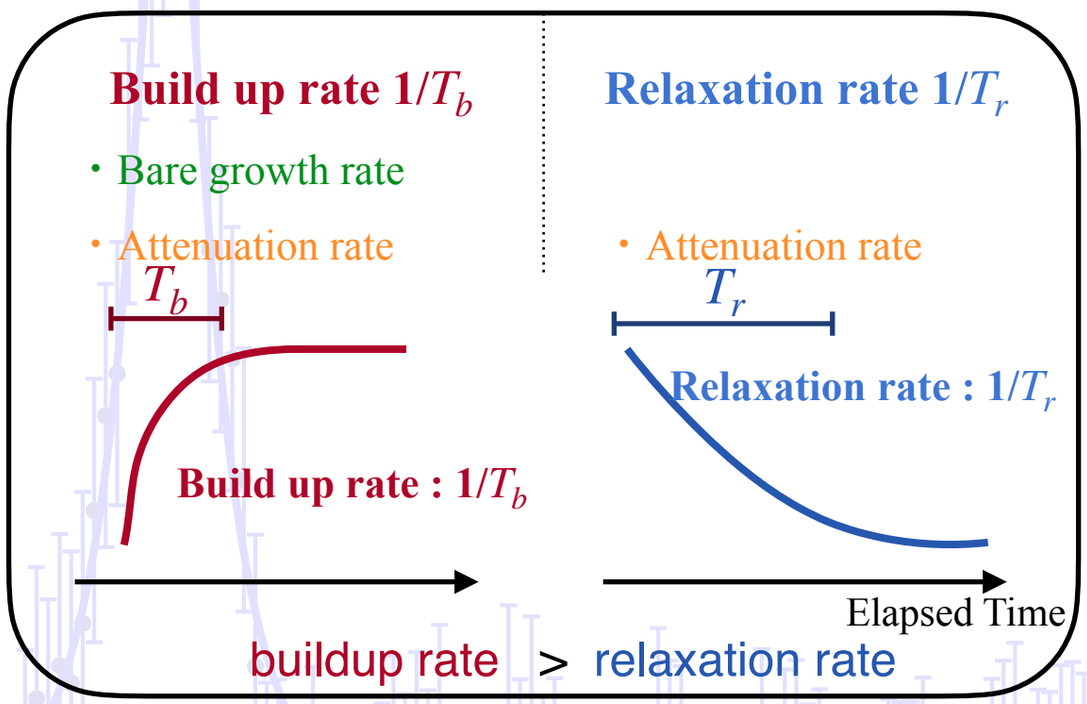
All signals are polarized according to the Boltzmann distribution.

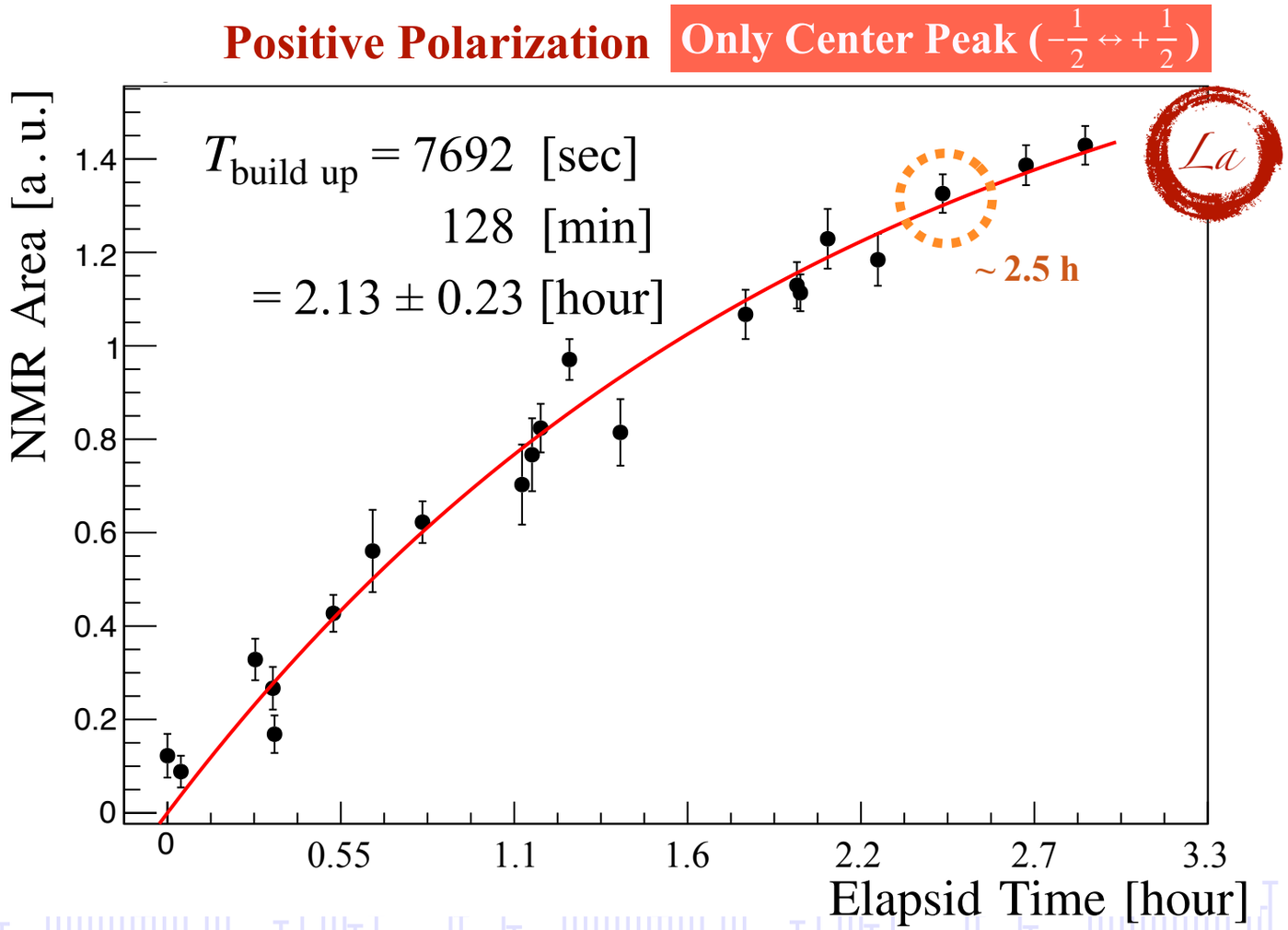
→ Polarization is calculated from the spin temperature.

[2.2] Buildup Time of ^{139}La nucleus

$T_{\text{build up}} = 2.13 \pm 0.23$ [hour]

…Relaxation Time could not be measured.
For time and other reasons.





Estimates polarization relaxation time from BuildupTime

$T_{\text{relaxation}} > T_{\text{build up}} = 2.13 \pm 0.23$ [hour]

Summary of past experiments

Measurement of polarization and relaxation time of ^{139}La nuclei (in Nd^{3+}: $LaAlO_3$ Crystal) hyperpolarized by DNP

	Nd Conc. [mol %]	Polarization [%]	Relaxation Time [min]	Date of measurement
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Don't made by Nagoya	**0.03**	20%	82 min	Kyoto Univ.
Crystal made by Nagoya	**0.01**	P > 19.6 %	T1 > 120 min	2022 at Yamagata Univ. (Nagoya Univ.) ← This talk!
Don't made byNagoya	**0.003**	—	—	Kyoto Univ.

→ Measurement polarization and relaxation times with More dilute Nd conc.

T-Violation search using compound nuclear resonance with slow newtron (NOPTREX)

Pseudomagnetism

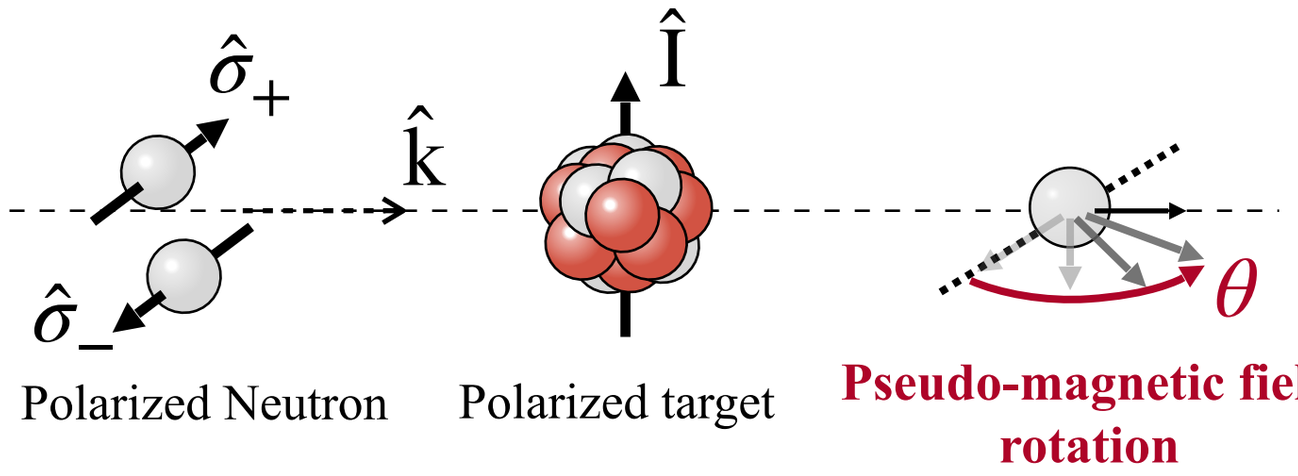
V.Gudkov and H.M.Shimizu, pays. Rev. C95 045501 (2017)

Pseudo-magnetic field effect

created by the nuclear potential of the target nucleus

→ Rotating neutron spin

(transmitted through the sample)

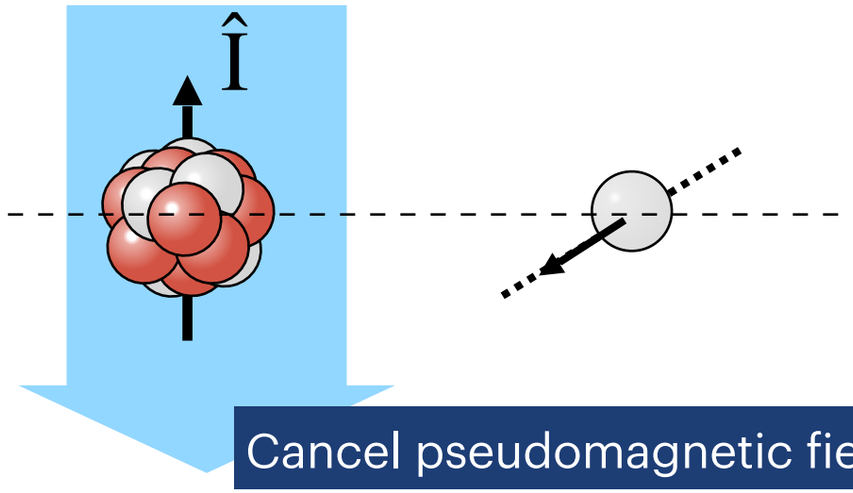


Solutions

Operation of the external magnetic field with $LaAlO_3$ crystal (3 cm cubic)

Apply a External magnetic field

≃ pseudo magnetic field of the $LaAlO_3$ crystal



Polarization of ^{139}La 100% → 0.23 [T]

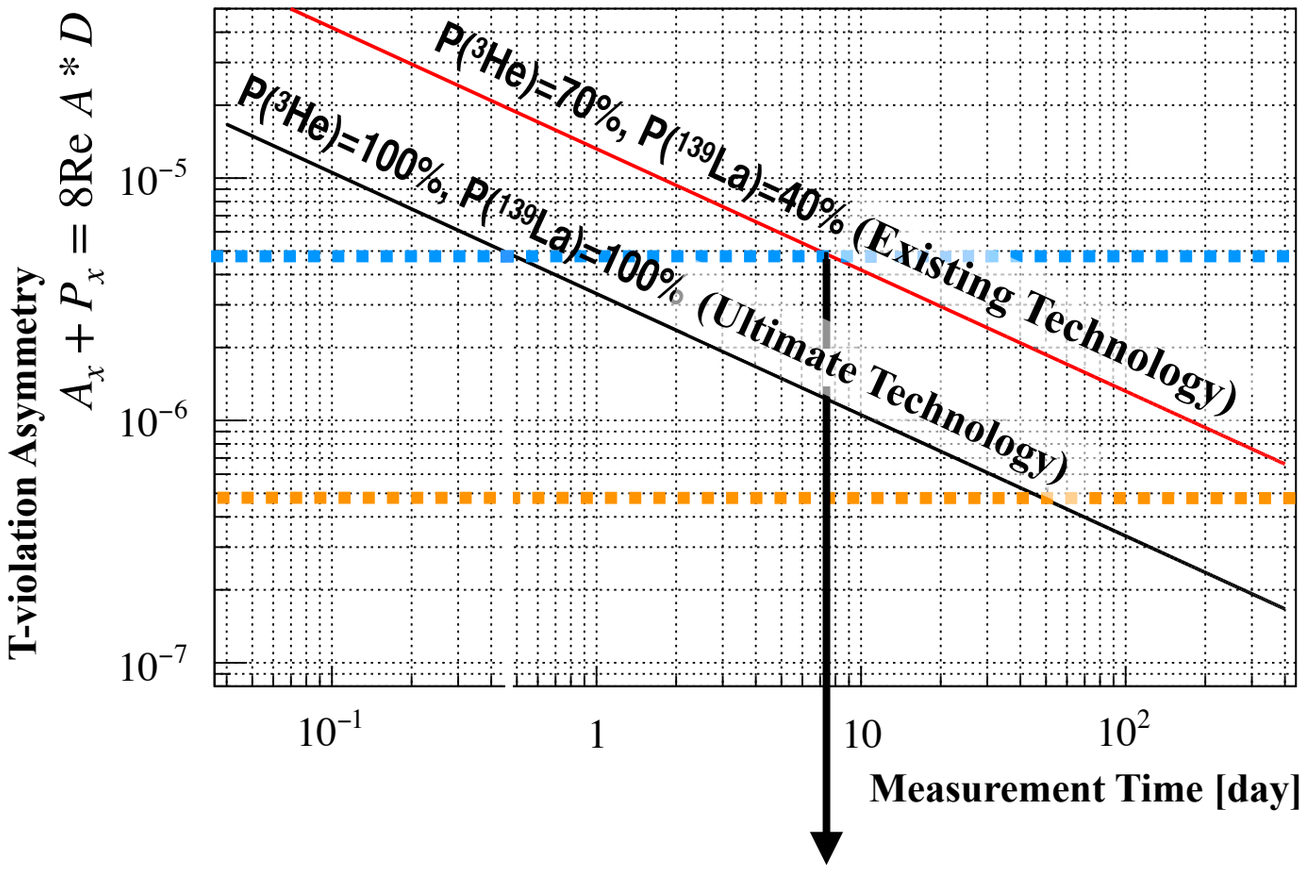
50% → 0.1 [T]

Future experimental design of T-violation search at **low field (0.1 T)**

Statistics required for T-violation search @ J-PARC

Polarization Condition:

Nuclear	Target	Size	B / T Low Field
^{139}La	$LaAlO_3$ crystal	$4 \times 4 \times \underset{\text{thickness}}{2.8}$ [cm]	$1 = \left(\frac{0.1\ [\mathrm{T}]}{100\ [\mathrm{mK}]} \right)$



Discovery potential
corresponding to nEDM ($d_n = 3.0 \times 10^{-26}$ [e cm])

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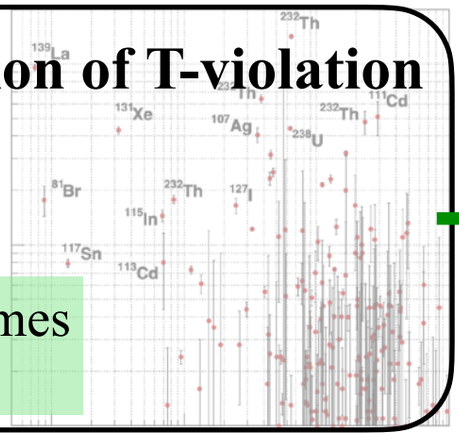
corresponding to nEDM ($d_n = 3.0 \times 10^{-27}$ [e cm])

Existing technology → Statistics required about **1 week**.
Nuclear Polarization ~ 40 % (pusedo magnetic field $\simeq 0.1$ [T])

Flow of planning for T-violation search

1. Selection of nuclides with large amplification of T-violation



T. Okudaira et al., Phys. Rev. C97 (2018) 034622.

J. Koga et al., Phys. Rev. C105 (2022) 054615.

→ In the case of ^{139}La, the amplification is 10^6 times compared to nucleon-nucleon scattering.

α. Validation of S-PMixing Model

T. Yamamoto et al, Phys. Rev. C 101, (2020)

T. Okudaira et al, Phys. Rev. C 105, (2021)

→ Verifying from a (n, γ) reaction

Developments

This Talk

2. Neutron Polarizer

T. Okudaira et al, NIM A 977, (2020).

→ ^{3}He Spin Filter
Neutron Polarization ~90 %

3. Nuclear Polarized target

K. Ishizaki et al, NIM A 1020, (2021).

→ Dynamic Nuclear Polarization
La Polarization > 20 % now

4. Neutron Detector

D. Schaperet al, NIM A 969, (2020).

→ U.S. NOPTREX Collaborator

T-violation Search

4. Install the developed device in the beamline, and search for T-violation in compound nuclei.

Summary

- Nd^{3+}:$LaAlO_3$ Crystal is a strong candidate for La polarization.
  Best Nd3+ concentration: 0.01 mol% Order

DNP Experiment @ Yamagata Univ. **Nd^{3+}:$LaAlO_3$ Crystal (Nd : 0.01 mol %)**
B = 2.335 T , T = 1.3 K

- Polarization (Nd3+ concentrations of 0.01 mol %) reached ~25 %.
- Buildup Time by DNP was measured as ~2 hours.
- Estimates polarization relaxation time from BuildupTime, longer than 2 hours.

Future Plan

- More accurate measurement of T1 at 0.01 mol %.
- The cooling system needs to be improved. → More than 10 hours
- Growing large crystals