NAGOYA UNIVERSITY Research RCNP Yamagata University

"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

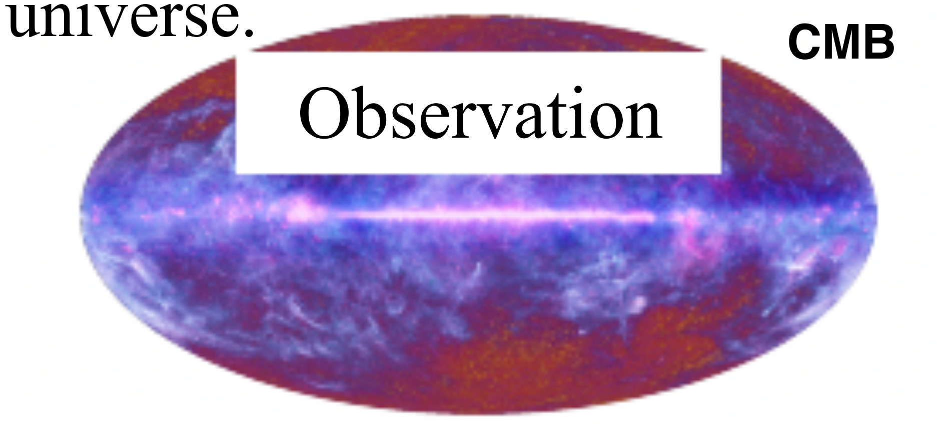
and **NOPTREX Collaboration**

Why is there far more matter than antimatter?

Standard theory cannot explain the matter-dominated universe.
There must be CP-violation somewhere .

Sakharov conditions

- Baryon number violation
- Departure from thermal equilibrium
- C, **CP Violation**



Photon number density

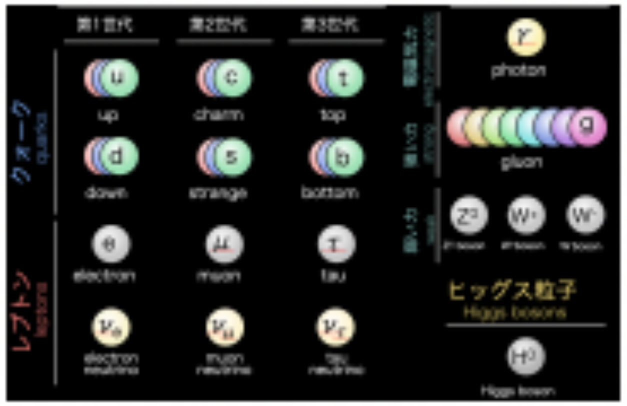
$$n_b/n_\gamma = 0.61 \pm 0.02 \times 10^{-9}$$

Baryon number density

One solution :
"existence of unknown CP-violation"

We Search for Unknown CP-violation
through the T-violation search
Using compound nuclear resonance.

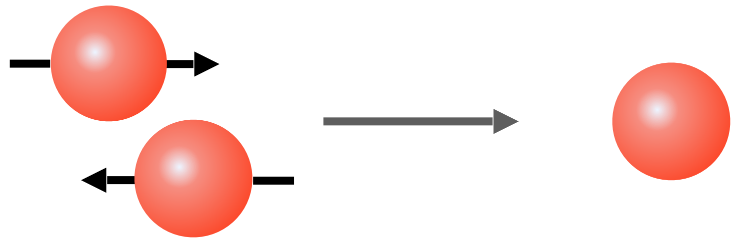
Standard Model



$$n_b/n_\gamma = 10^{-18}$$

P-violation measurements

P-P scattering



Polarized Proton
(15 MeV)

Proton

Helicity dependence of cross section

$$= -(1.7 \pm 0.8) \times 10^{-7}$$

In nucleon-nucleon scattering, P-violation is $\simeq 10^{-7}$

Using Nuclear resonance

In compound nuclear resonance,
the amplification is $\sim 10^{6}$,
compare with P-P scattering.

Compound nuclear reaction with a Neutron

Polarized Neutron
(0.74 eV)

^{139}La

Helicity dependence of cross section at ^{139}La nuclear

$$= -(0.97 \pm 0.03) \times 10^{-1}$$

In Compound nuclear resonance, P-violation is $\simeq 10^{-1}$

Forward scattering amplitude in the Compound nuclear resonance

$$f = \overbrace{A'}^{\substack{\text{Spin Independent}\\ \text{P-even, T-even}}} + \underbrace{B'}_{\substack{\text{Spin Dependent}\\ \text{P-even, T-even}}}\,\hat{\sigma}\cdot\hat{I} + \overbrace{C'}^{\substack{\text{P-violation}\\ \text{P-odd, T-even}}}\,\hat{\sigma}\cdot\hat{k} + \underbrace{D'}_{\substack{\text{T-violation}\\ \text{P-odd, T-odd}}}\,\hat{\sigma}\cdot(\hat{I}\times\hat{k})$$

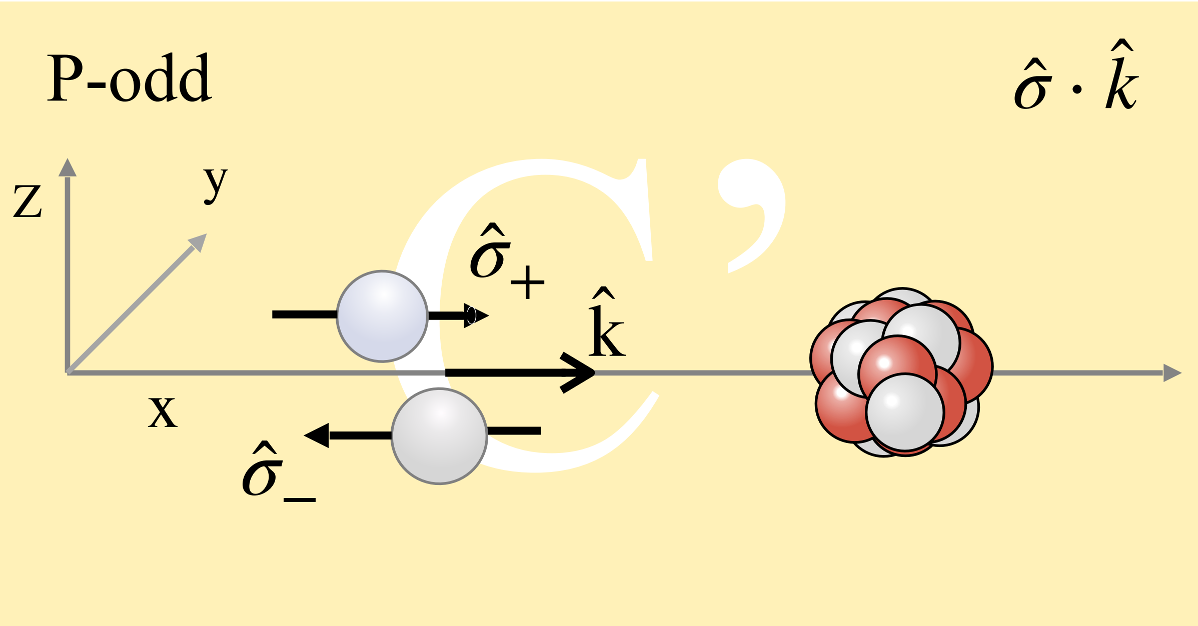
Forward scattering amplitude in the Compound nuclear resonance

P-violation $\longrightarrow$ **Discover T-violation**

$$f = \overbrace{A'}^{\substack{\text{Spin Independent}\\ \text{P-even, T-even}}} + \underbrace{B'}_{\substack{\text{Spin Dependent}\\ \text{P-even, T-even}}}\, \hat{\sigma}\cdot\hat{I} + \overbrace{C'}^{\substack{\text{P-violation}\\ \text{P-odd, T-even}}}\, \hat{\sigma}\cdot\hat{k} + \underbrace{D'}_{\substack{\text{T-violation}\\ \text{P-odd, T-odd}}}\, \hat{\sigma}\cdot(\hat{I}\times\hat{k})$$

Measure :

Difference in P-odd cross section between Up and Down spin. (neutron spins)



Helicity dependence of cross section at ^{139}La nuclear

$$= -(0.97 \pm 0.03)\times 10^{-1}$$

In Compound nuclear resonance, P-violation is $\simeq 10^{-1}$

Forward scattering amplitude in the Compound nuclear resonance

Spin Independent
P-even, T-even

P-violation
P-odd, T-even

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

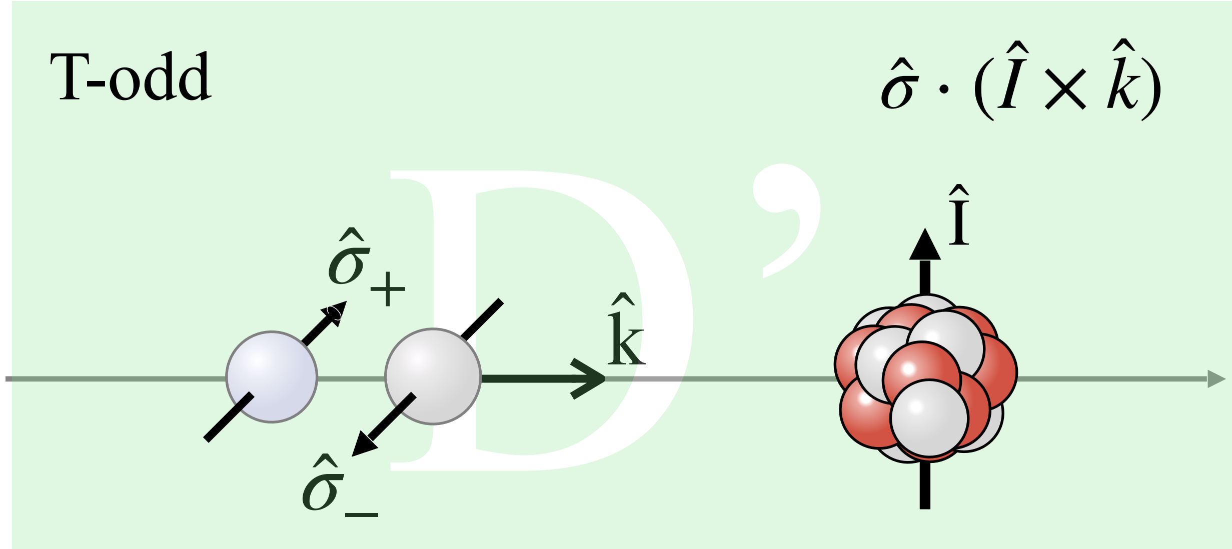
Spin Dependent
P-even, T-even

T-violation
P-odd, T-odd

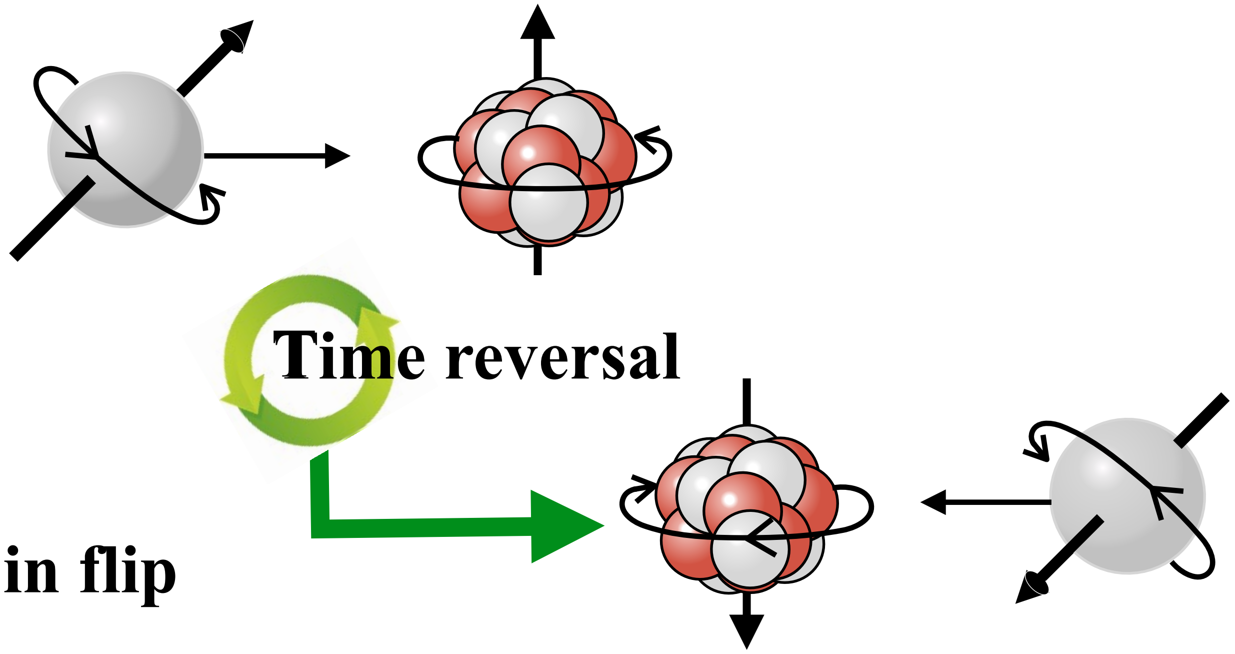
Discover T-violation

Measure :

Difference in T-odd cross section between Up and Down spin.
(neutron spins)



Time reversal converting is only neutron spin flip



Forward scattering amplitude in the Compound nuclear resonance

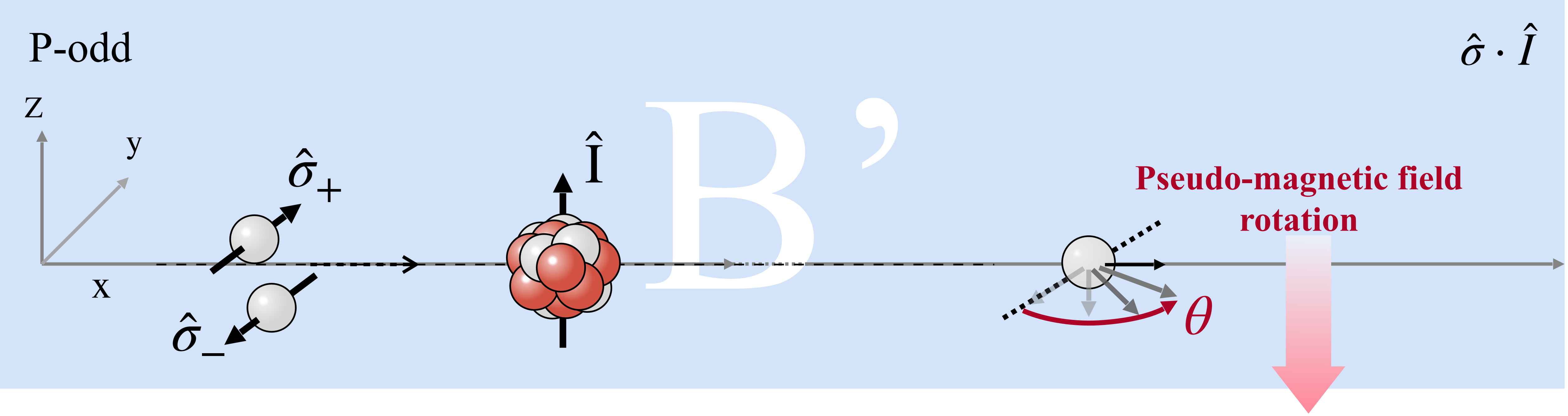
Spin Independent
P-even, T-even

P-violation
P-odd, T-even

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

Spin Dependent
P-even, T-even

T-violation
P-odd, T-odd

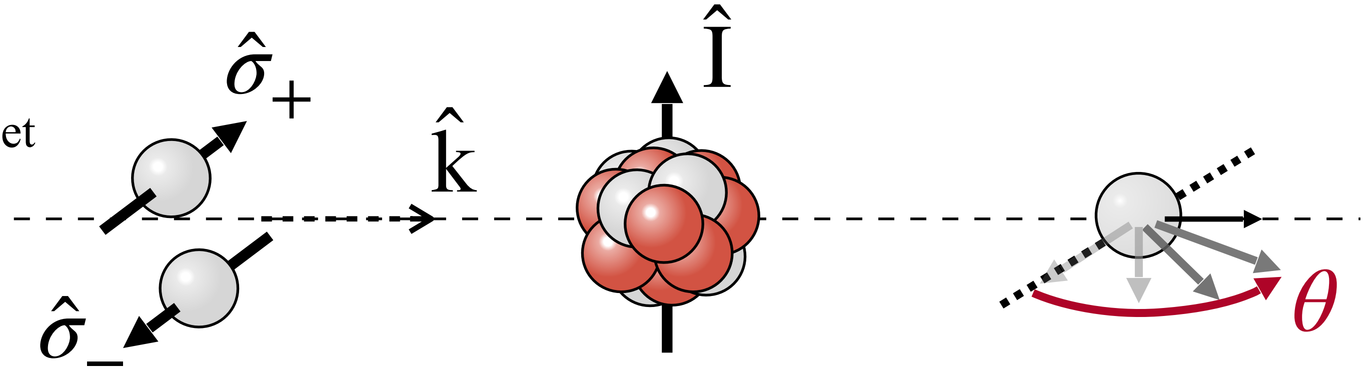


Largest systematics error of the T-violation search.

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

Pseudo-magnetic field effect
created by interaction with the nuclear potential of the target

⟶ Rotating neutron spin
(transmitted through the sample)



Polarized Neutron

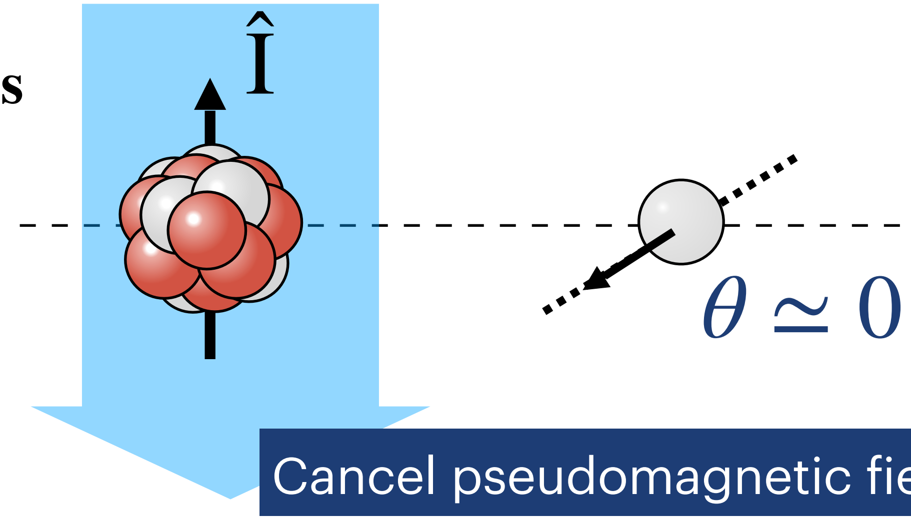
Polarized target

Pseudo-magnetic field rotation

Solutions

Cancellation of the pseudo magnetic field with the target nucleus

Magnitude of the external field
$\simeq$ Magnitude of the pseudo magnetic field at the $LaAlO_3$ crystal



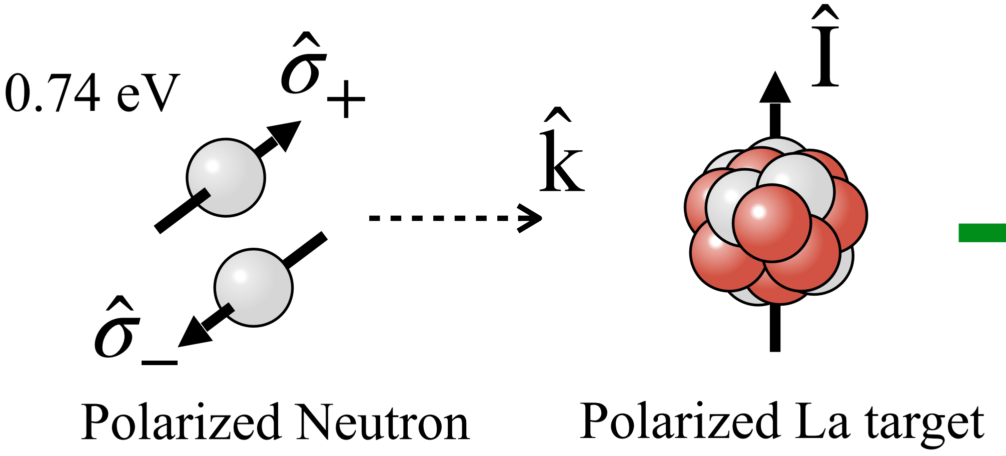
Cancel pseudomagnetic field

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

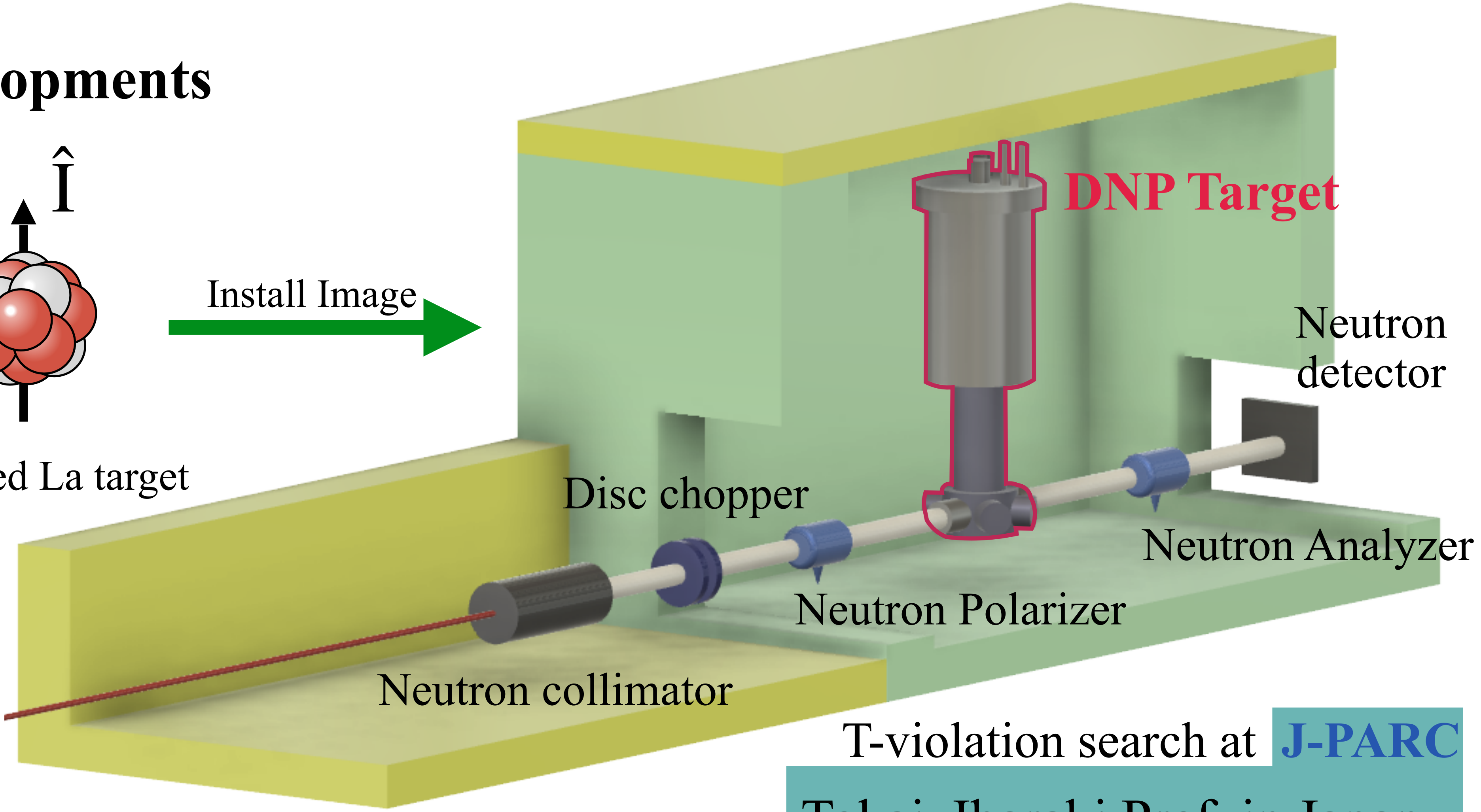
50% → 0.1 [T]

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

Setup image and Developments

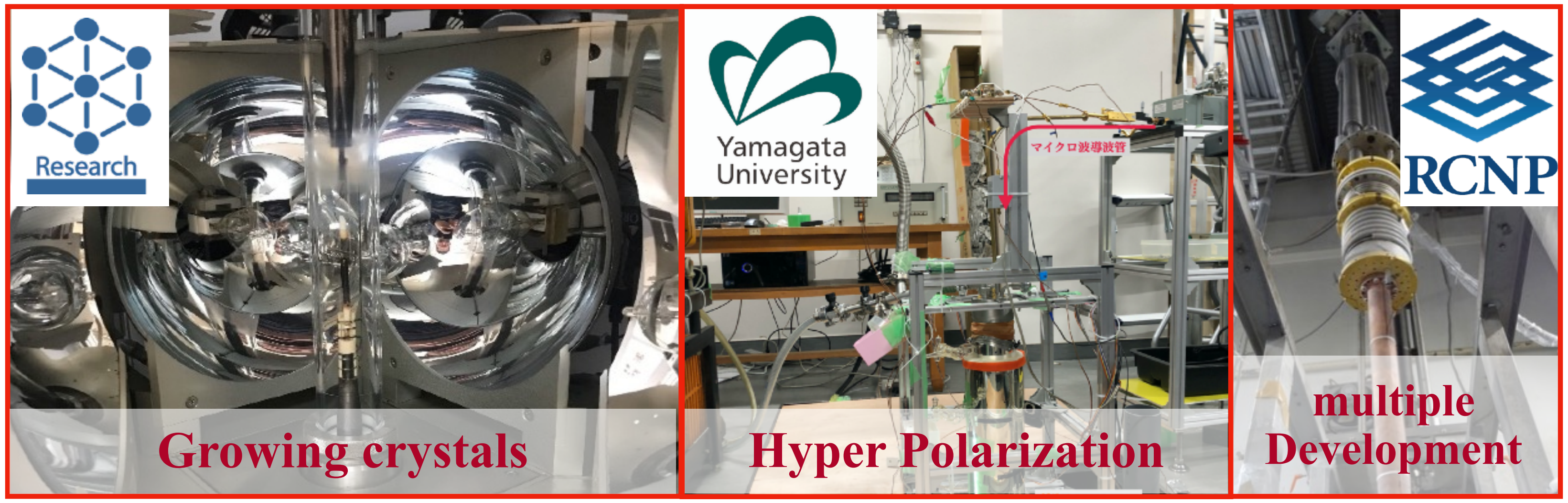


Install Image



Developments

DNP Target



Growing crystals

Hyper Polarization

multiple Development

T-violation search at **J-PARC**

Tokai, Ibaraki Pref. in Japan

Polarize Target

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

Attic number 57

^{139}La

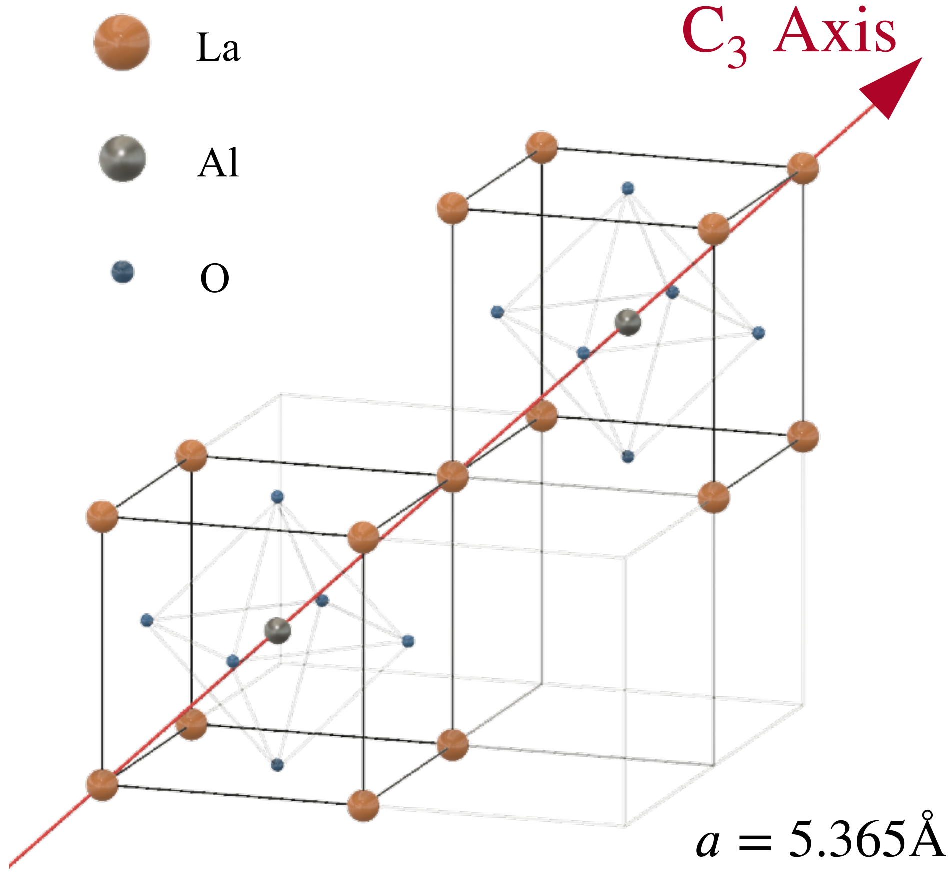
Spin $I = 7/2$

High Natural Abundance **99.91 %**

Merit

- Quadrupole interaction diagonalized on C_3 axis
- Achievement of the high polarization by the DNP
  (P. Hautle, M. Iinuma, 2000, NIM A)
- Increase of doping amount Nd
  → Higher efficient polarization transfer
  →Strong spin-lattice relaxation

$LaAlO_3$ crystal structure



Perovskite / Pseudo Cubic

$a = 5.365Å$
$c = 13.11Å$

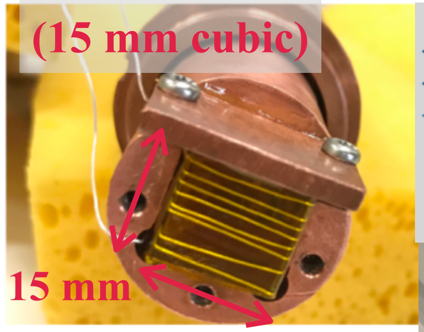
One of the plan

Condition of the polarized target → **0.1 K, 0.1 T**

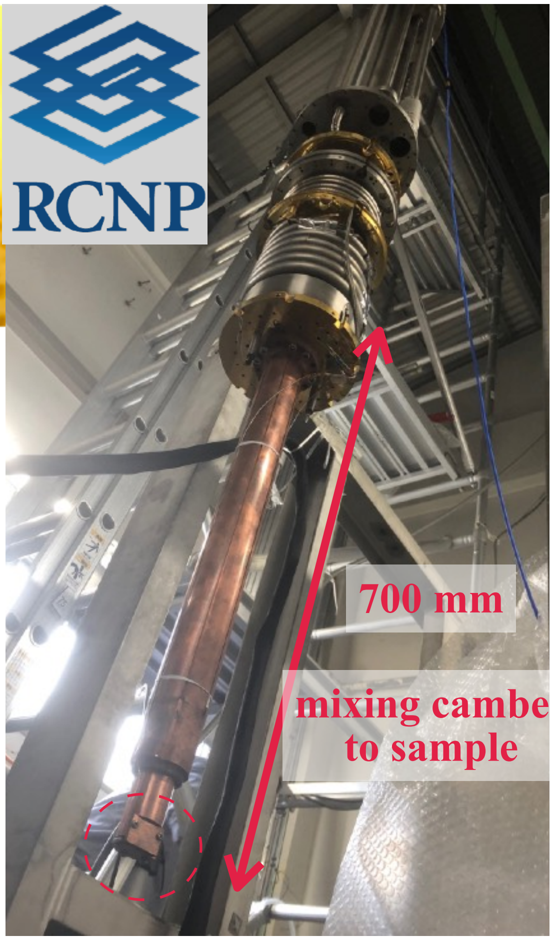
- Canceling the pseudo magnetic field
- Spin frozen for a long relaxation time.

Estimation of the Relaxation Time at 0.1 [T]

K.Ishizakietal., Nucl. Instr. and Meth. A 1020(2021)165845.



Nd conc. : 0.03 mol %



T1 measurement at the Al nuclei in the $LaAlO_3$ crystal

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)

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

La relaxation time $\cong$ Al relaxation time

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

Nd Conc. [mol %]	(Temp. , Mag. Field) ([K], [T])	—	—	Relaxation Time at 0.1 T, 0.1 K
0.03	(0.1 K, 0.1 T)	—	—	T1 > 60 min

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

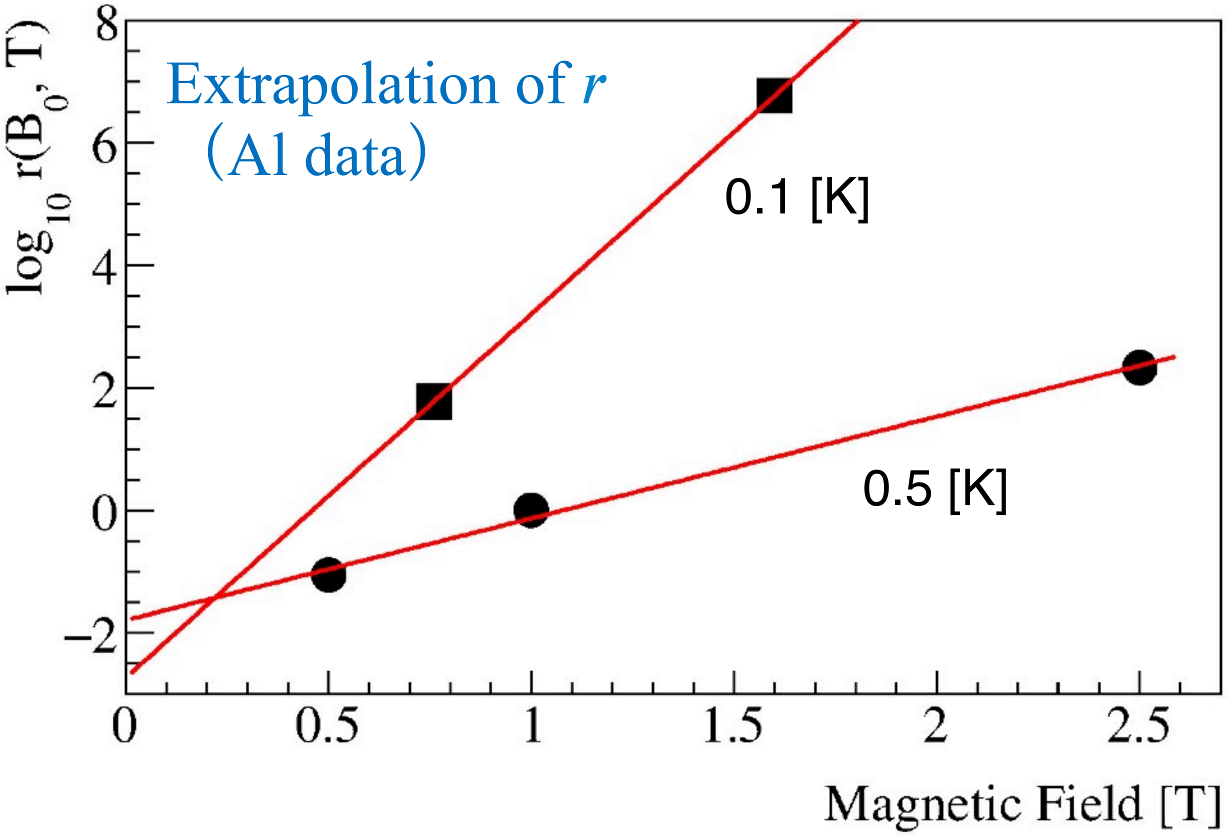
$$\frac{1}{T_{1n}} \propto \boxed{C^2} \frac{1}{H_0^2} \left(\frac{1}{T_{1SS}} \right) \left(1 - P_0^2 \right)$$

Nd concentration

La relaxation time $\cong$ Al relaxation time

Extrapolation of ratio of T_{1SS}

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



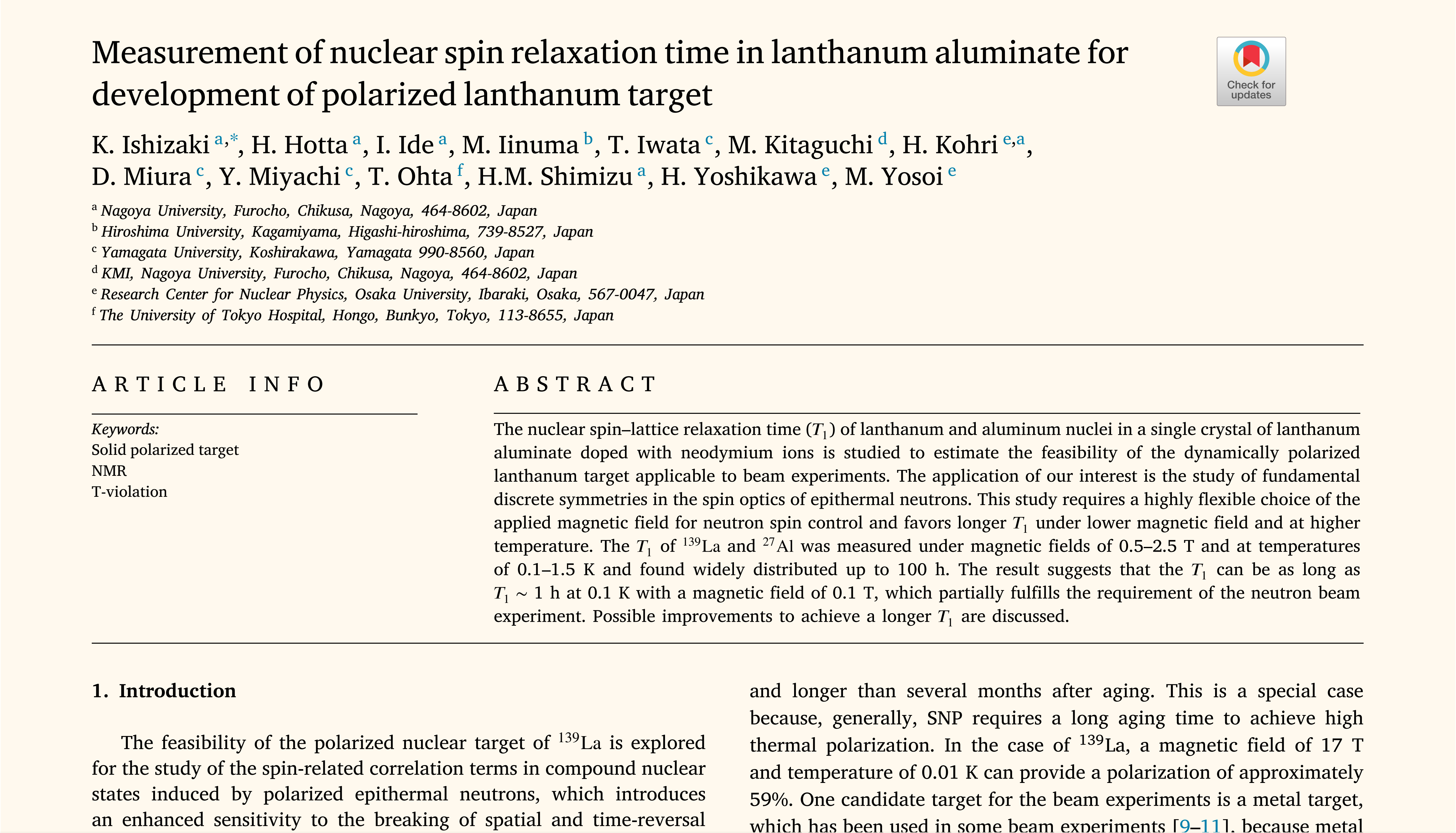
Estimation at 0.1T 0.1K

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

Necessity of the optimization of Nd concentration

Estimation of the Relaxation Time at 0.1 [T] in RCNP, Osaka University.

T1 measurement at the Al nuclei in the $LaAlO_3$ crystal



Measurement of nuclear spin relaxation time in lanthanum aluminate for development of polarized lanthanum target

K. Ishizaki [a,*], H. Hotta [a], I. Ide [a], M. Iinuma [b], T. Iwata [c], M. Kitaguchi [d], H. Kohri [e,a], D. Miura [c], Y. Miyachi [c], T. Ohta [f], H.M. Shimizu [a], H. Yoshikawa [e], M. Yosoi [e]

[a] *Nagoya University, Furocho, Chikusa, Nagoya, 464-8602, Japan*
[b] *Hiroshima University, Kagamiyama, Higashi-hiroshima, 739-8527, Japan*
[c] *Yamagata University, Koshirakawa, Yamagata 990-8560, Japan*
[d] *KMI, Nagoya University, Furocho, Chikusa, Nagoya, 464-8602, Japan*
[e] *Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka, 567-0047, Japan*
[f] *The University of Tokyo Hospital, Hongo, Bunkyo, Tokyo, 113-8655, Japan*

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T-violation

ABSTRACT

The nuclear spin–lattice relaxation time (T_1) of lanthanum and aluminum nuclei in a single crystal of lanthanum aluminate doped with neodymium ions is studied to estimate the feasibility of the dynamically polarized lanthanum target applicable to beam experiments. The application of our interest is the study of fundamental discrete symmetries in the spin optics of epithermal neutrons. This study requires a highly flexible choice of the applied magnetic field for neutron spin control and favors longer T_1 under lower magnetic field and at higher temperature. The T_1 of ^{139}La and ^{27}Al was measured under magnetic fields of 0.5–2.5 T and at temperatures of 0.1–1.5 K and found widely distributed up to 100 h. The result suggests that the T_1 can be as long as $T_1 \sim 1$ h at 0.1 K with a magnetic field of 0.1 T, which partially fulfills the requirement of the neutron beam experiment. Possible improvements to achieve a longer T_1 are discussed.

1. Introduction

The feasibility of the polarized nuclear target of ^{139}La is explored for the study of the spin-related correlation terms in compound nuclear states induced by polarized epithermal neutrons, which introduces an enhanced sensitivity to the breaking of spatial and time-reversal

and longer than several months after aging. This is a special case because, generally, SNP requires a long aging time to achieve high thermal polarization. In the case of ^{139}La, a magnetic field of 17 T and temperature of 0.01 K can provide a polarization of approximately 59%. One candidate target for the beam experiments is a metal target, which has been used in some beam experiments [9–11], because metal

Summary of past experiments

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

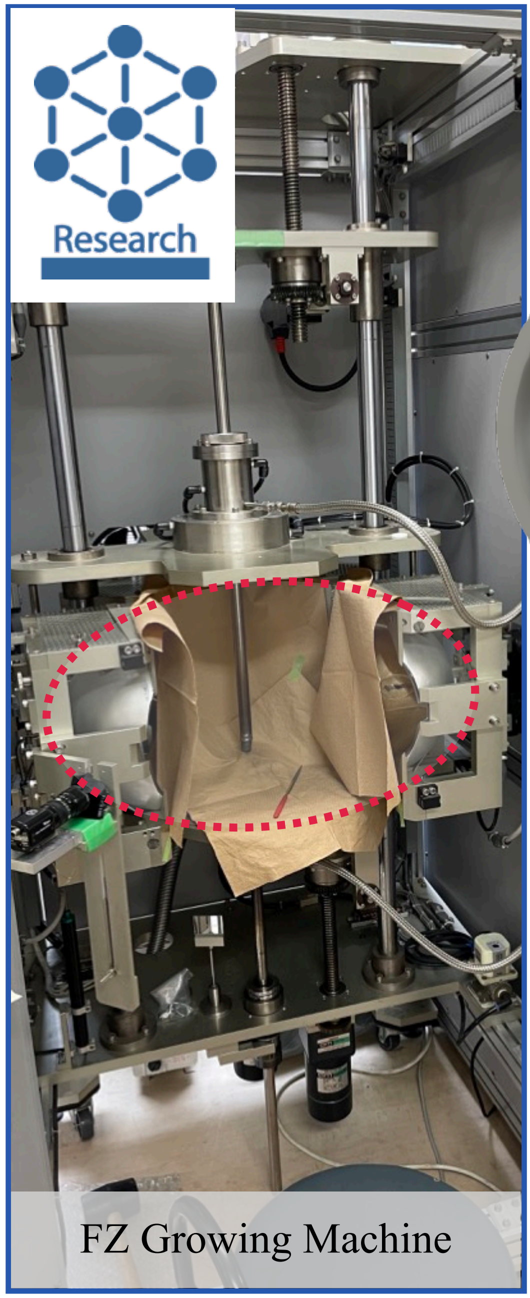
	Nd Conc. [mol %]	(Temp. , Mag. Field) ([K], [T])	Polarization [%]	Relaxation Time [min]	Relaxation Time at 0.1 T, 0.1 K
Don't Grow by Nagoya	**0.3**	(1.5 K, 2.3 T)	small	—	—
Crystal was Grown by Nagoya	**0.05**	(1.3 K, 2.3 T)	0.2%	15 min	
	0.03	(1.5 K, 2.3 T)	20%	82 min	T1 > 60 min
	0.003		—	—	—

- 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 %

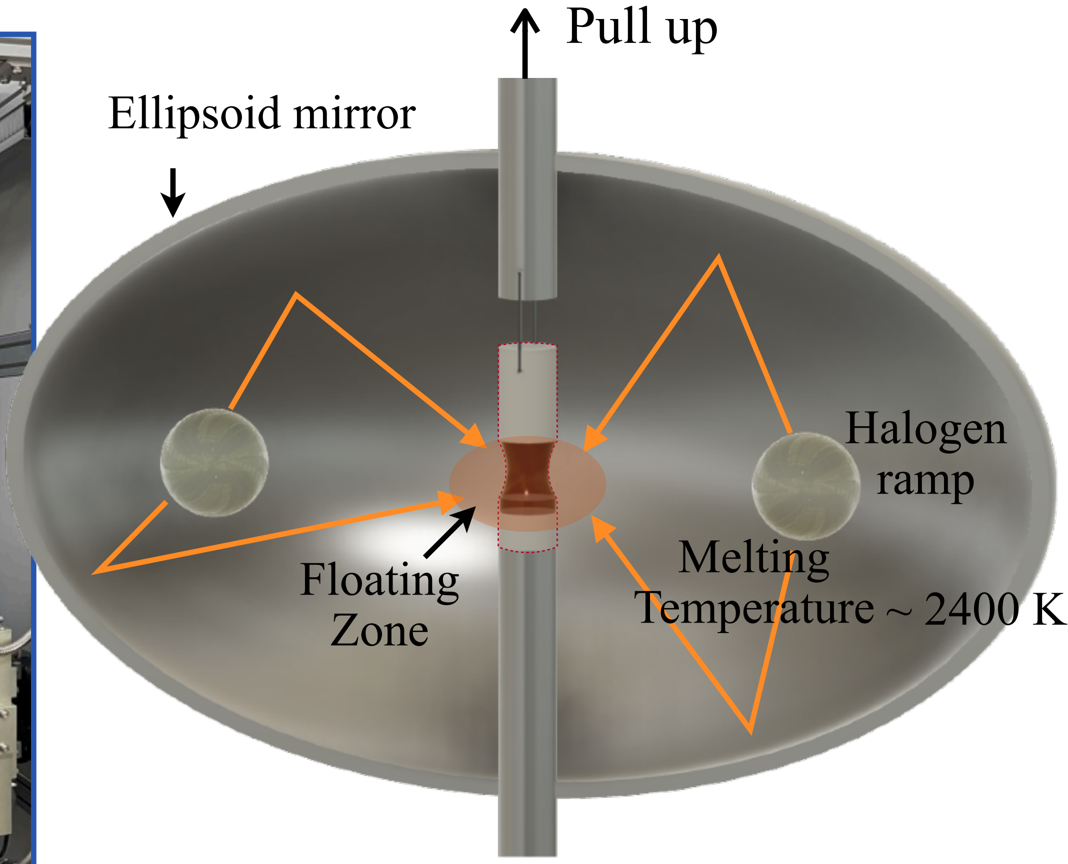
→ The appropriate amount of Nd concentration needs further study at lower Nd concentrations.

Required : Technique to control Nd concentration in the order of 0.001 mol %
→Growing crystals with different Nd concentrations

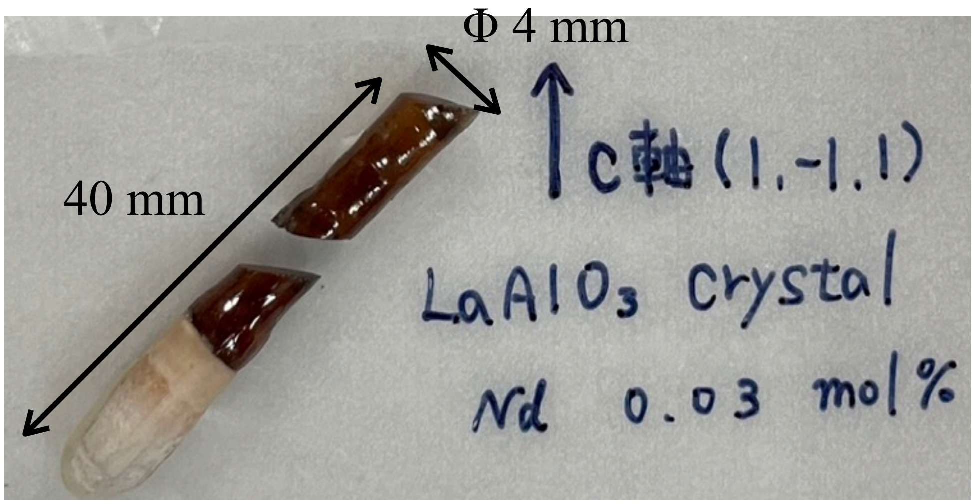
Growing $LaAlO_3$ Crystal (Doped Nd ion)
- Floating-Zone Method-



FZ Growing Machine



Grown crystals



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.

Successful preparation of some crystals with different Nd concentration

DNP Experiment at Yamagata Univ. (2022.03)

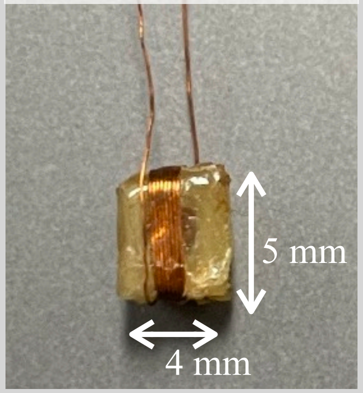
Sample Information

Nd^{3+} : $LaAlO_3$ Crystal

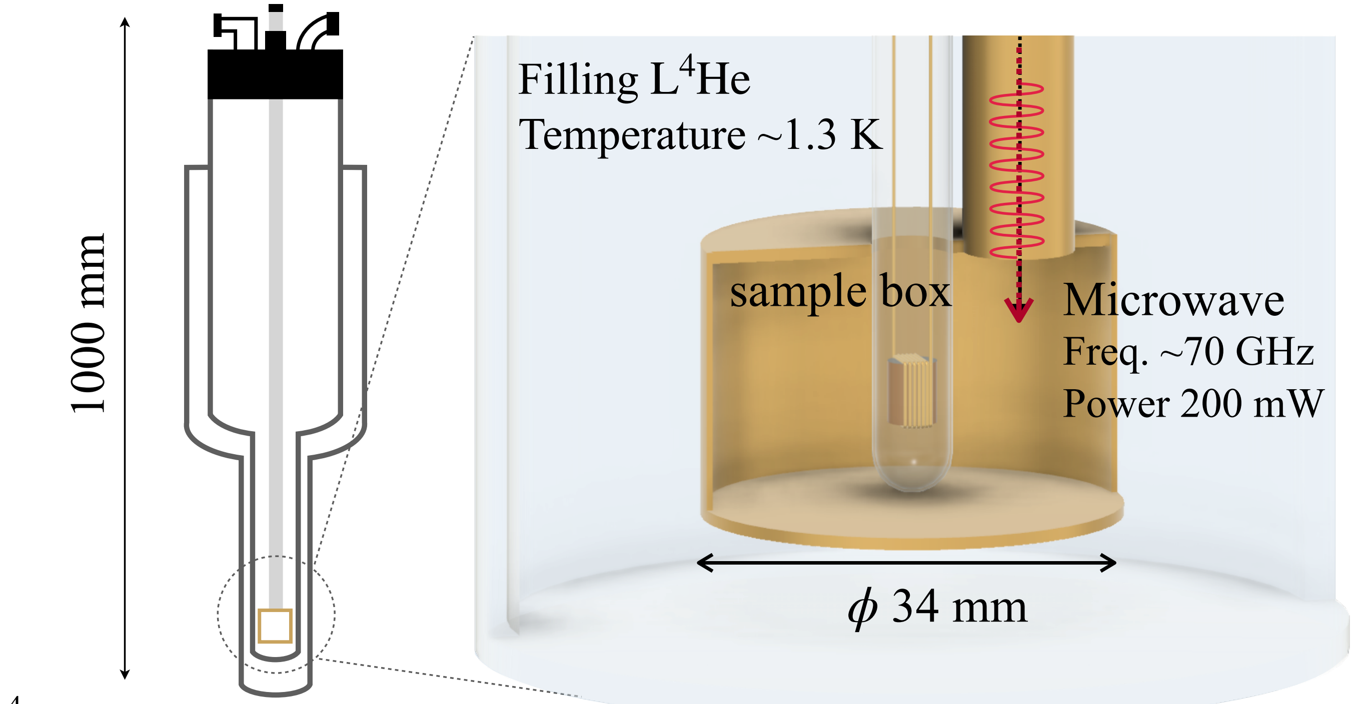
Nd^{3+} conc. : 0.01 mol %

Sample size : Cylinder (φ4 × 5 mm)

grown by Nagoya

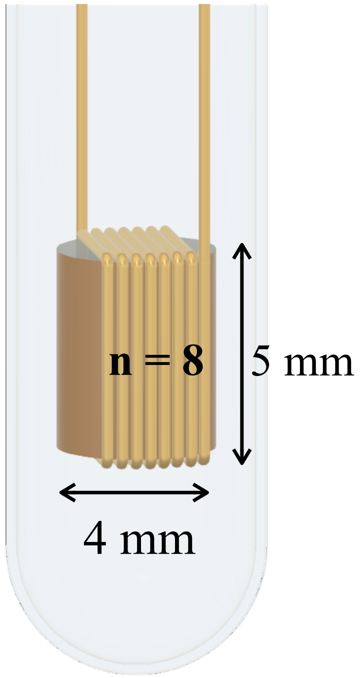


Detail of mount method

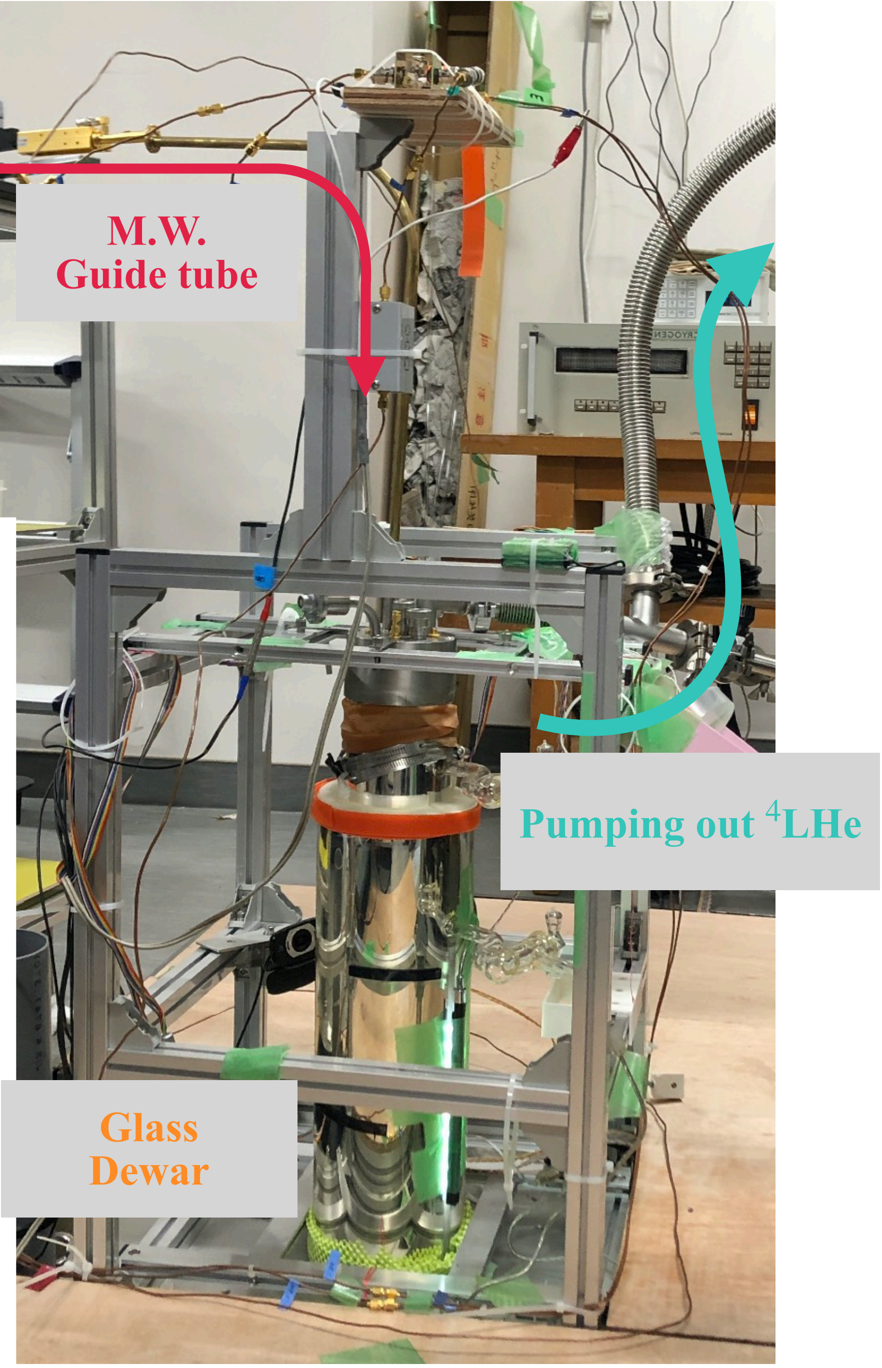


^4He pumping the refrigerator (glass Dewar)

Sample



Continuous running time ~5 [h]



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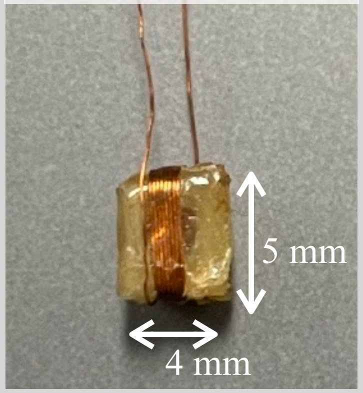

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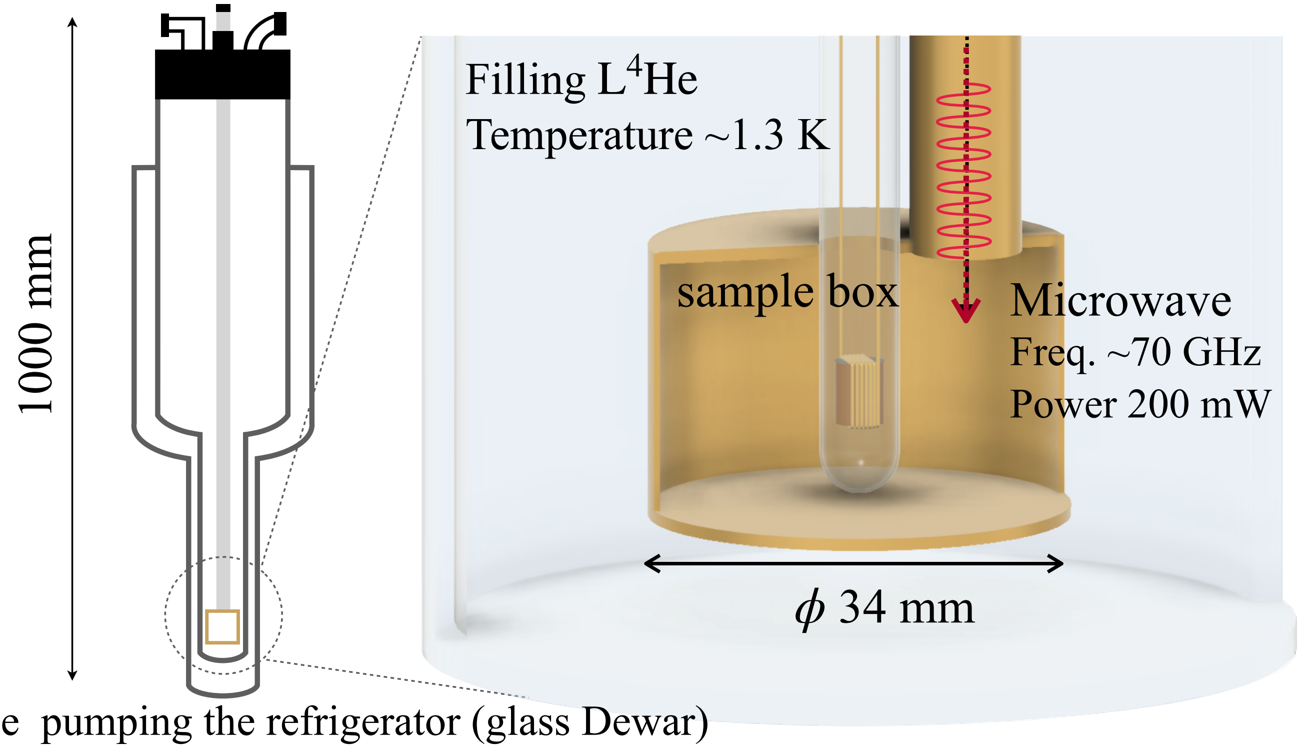


^{4}He pumping the refrigerator (glass Dewar)

Experiment Condition

Temperature : 1.33 K

Magnetic field : 2.336 T

NMR Frequency : 14.505 MHz

M. W. Frequency : 69.435 GHz

Measurement details

[1] **Polarization of ^{139}La nucleus**

Positive Polarization by DNP

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

[2] **Buildup Time of ^{139}La nucleus**

Estimates relaxation time from BuildupTime

[1] Polarization of ^{139}La nucleus

Positive Polarization by DNP

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

M.W. Freq. : 69.435 [GHz]

M.W. Irradiation Time : 2.5 [h]

Result

measured DNP spectrum

couldn't measure TE spectrum

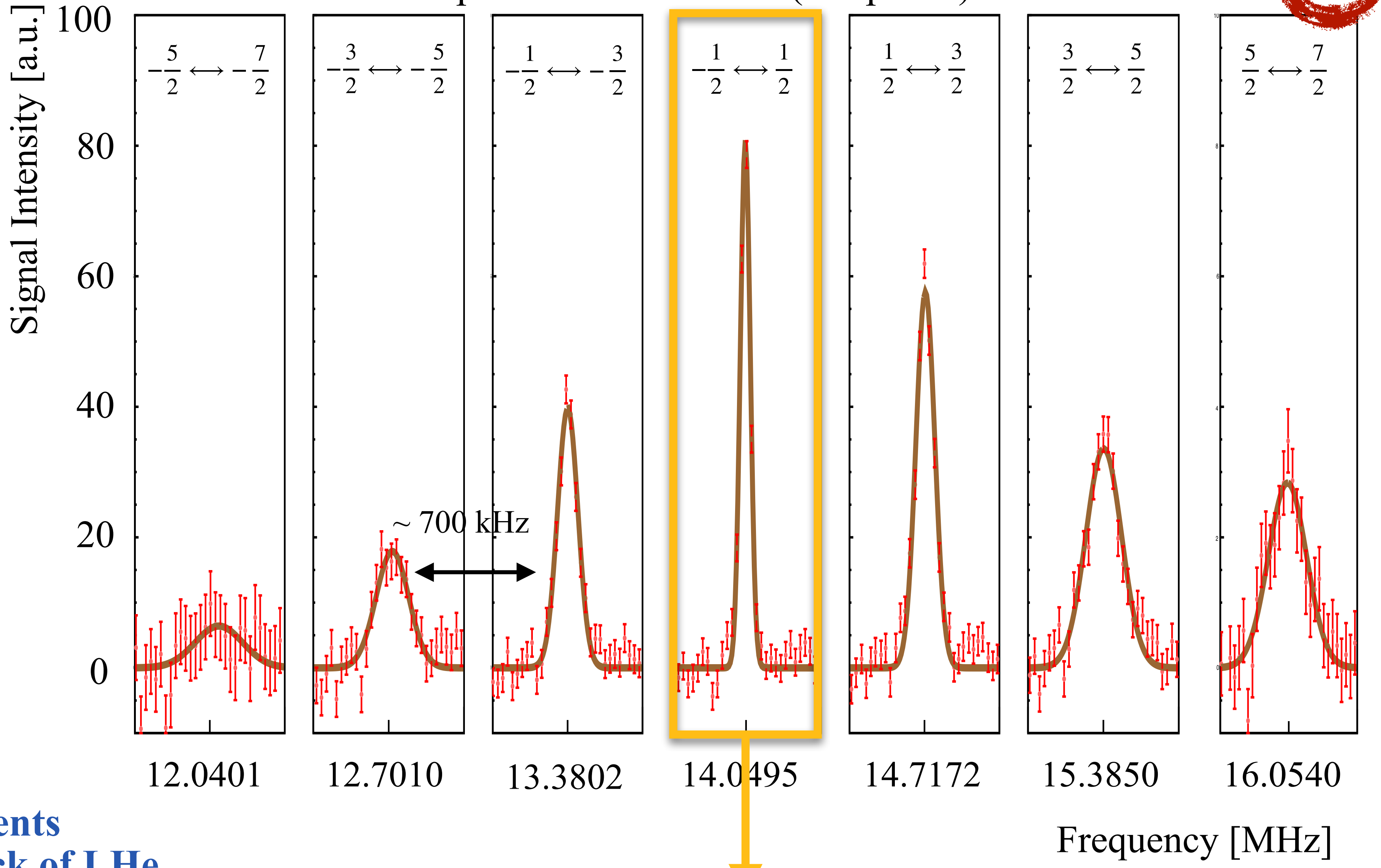
→ TE signal Intensity is Small.

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

Result

Polarization : 19.7 ± 2.6 [%]

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

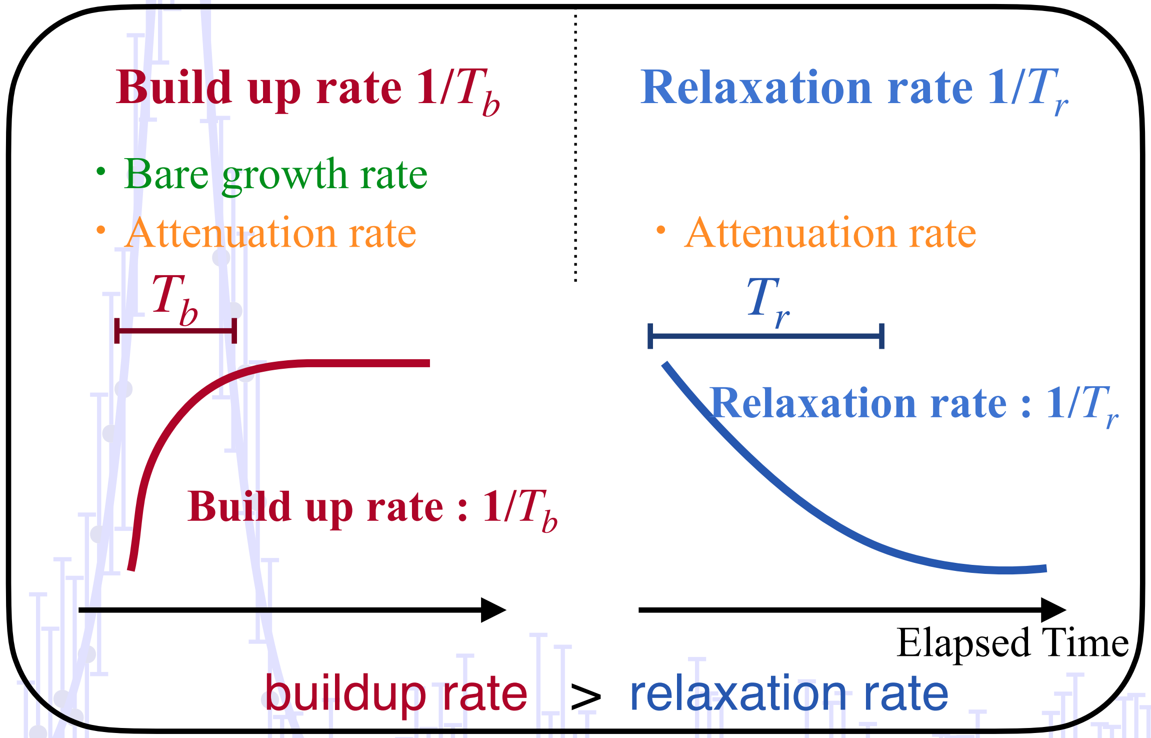


Monitors only the Center Peak growing by microwave (DNP)
→ Measure Build-up Time.

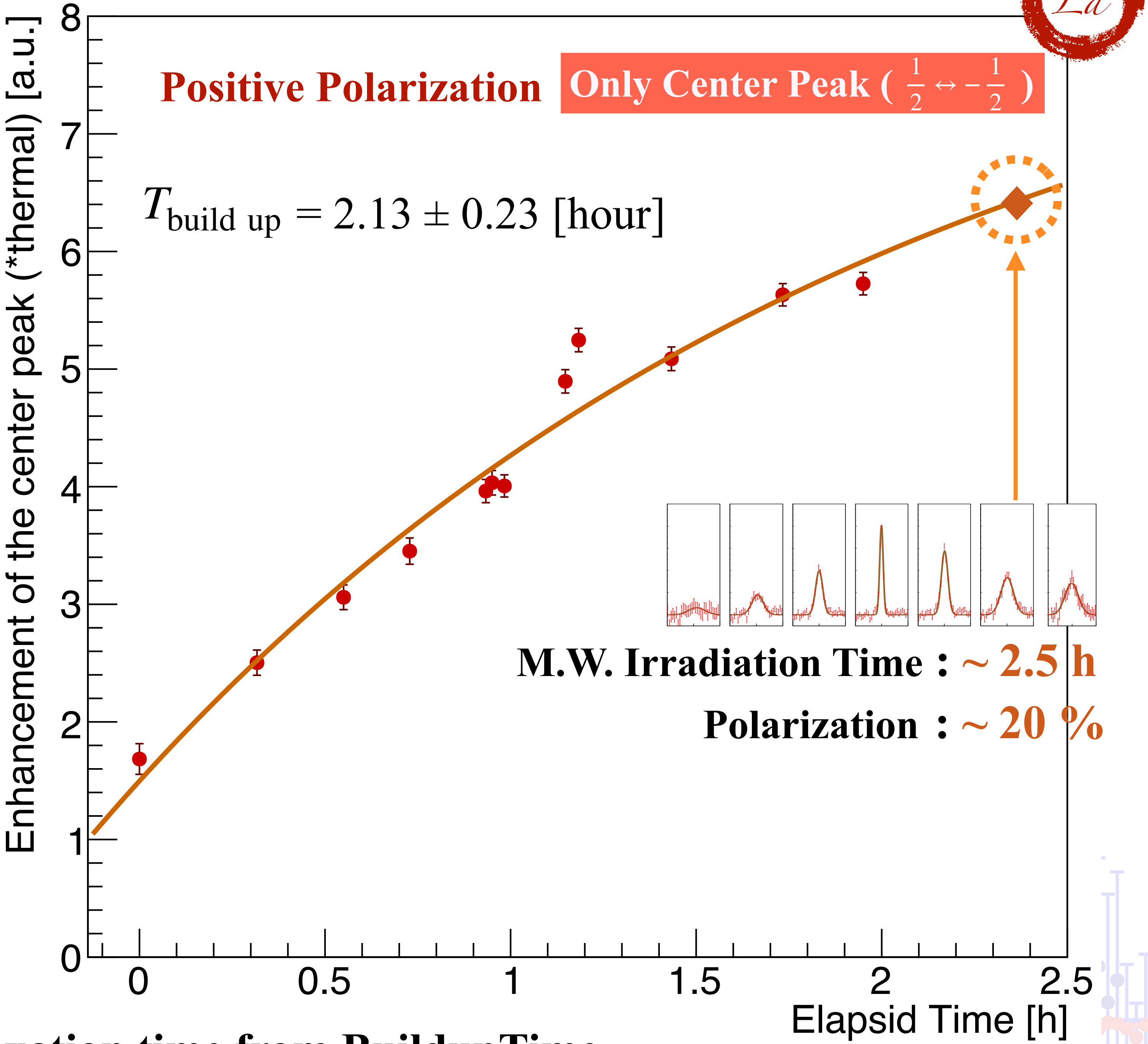
[2] Buildup Time of ^{139}La nucleus

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

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



buildup rate > relaxation rate

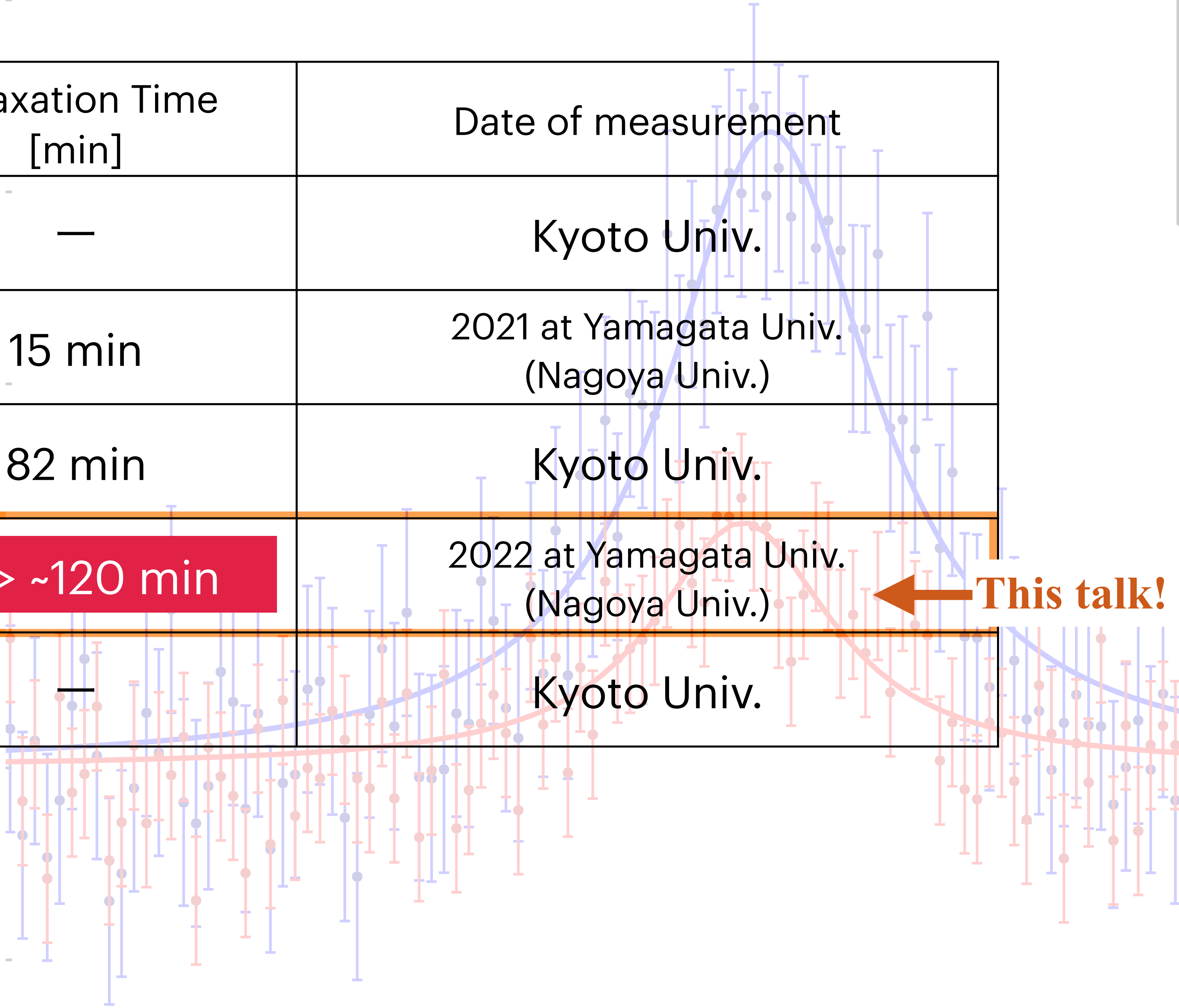


Estimates polarization relaxation time from BuildupTime

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

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
Don't made by Nagoya	**0.3**	small	—	Kyoto Univ.
Crystal made by Nagoya	**0.05**	0.2%	15 min	2021 at Yamagata Univ. (Nagoya Univ.)
	0.03	20%	82 min	Kyoto Univ.
	0.01	P > ~20%	T1 > ~120 min	2022 at Yamagata Univ. (Nagoya Univ.)
	0.003	—	—	Kyoto Univ.

This talk!

Summary

- T-violation search (NOPTREX) require highly polarized target crystals with long relaxation times.
- Nd^{3+}:$LaAlO_3$ Crystal is a strong candidate for La polarization.
  Best Nd^{3+} concentration: around 0.01 mol%

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 **~19.7 ± 2.6 %**.
- not saturated polarization
- Buildup Time by DNP was measured as ~2 hours.
- Estimated nuclear **relaxation time T1** from BuildupTime, **longer than 2 hours**.

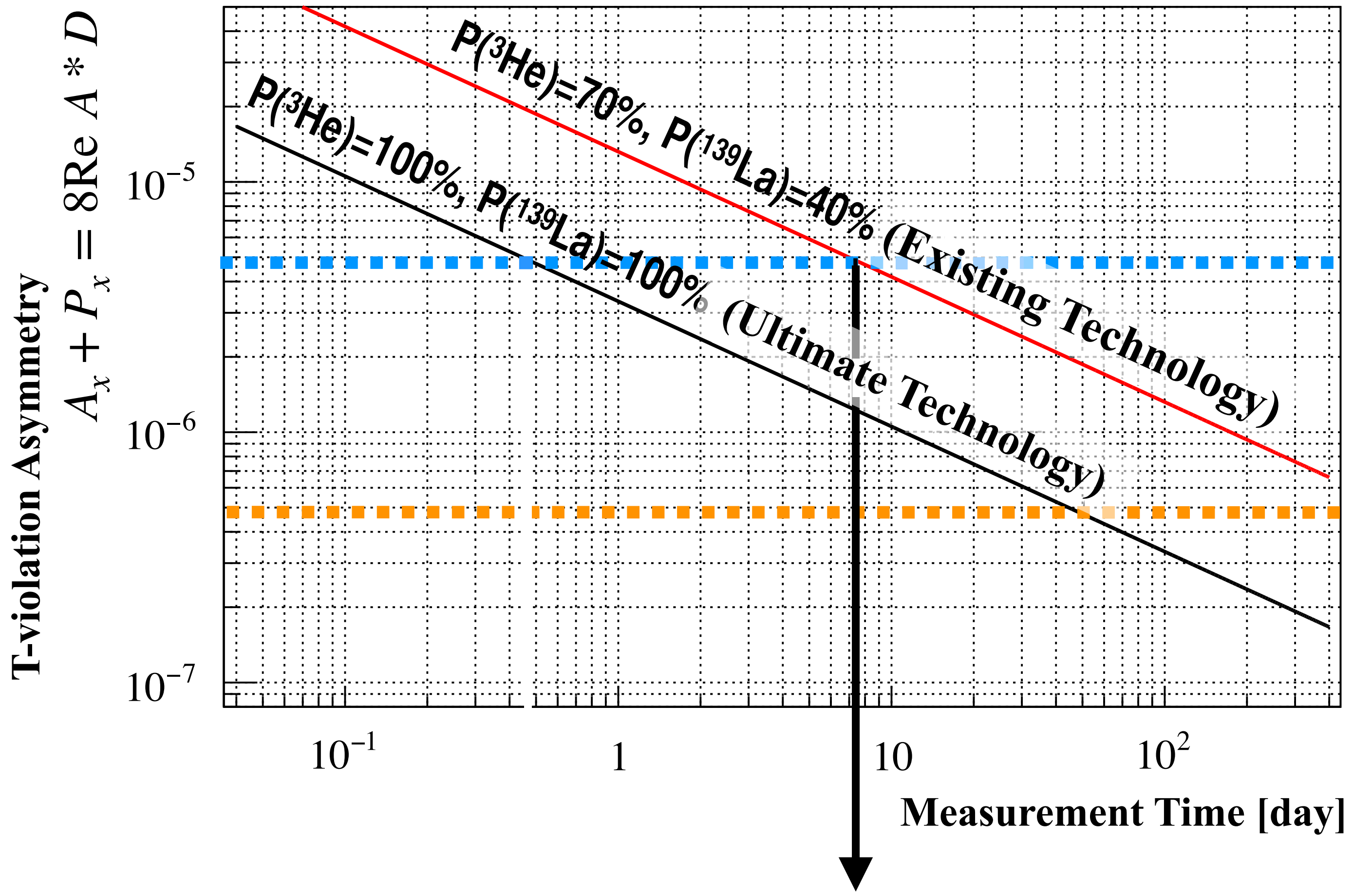
Future Plan

- More accurate measurement of T1 at 0.01 mol %.
- Need to more Study the effect T1 & Polarization by Nd concentration .
  - More dilute Nd conc. than 0.01 mol %
  - confirm that the grown crystals (Nd Conc. 0.03 mol %) are consistent with the previous experiments.
- Growing large crystals

Statistics required for T-violation search @ J-PARC

Polarization Condition:

Nuclear	Target	Size	B / T Low Field
^{139}La	LaAlO$_3$ crystal	$4\times 4\times \underline{2.8}$ [cm] thickness	$1 = \left(\dfrac{0.1\ [\mathrm{T}]}{100\ [\mathrm{mK}]}\right)$



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

Discovery potential
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 $\simeq 0.1\ [T]$)

[1] Polarization of ^{139}La nucleus

Convert for the calculation

Horizontal axis
→ converted to **Energy of the spin state**

Vertical axis
→ converted to **Population**

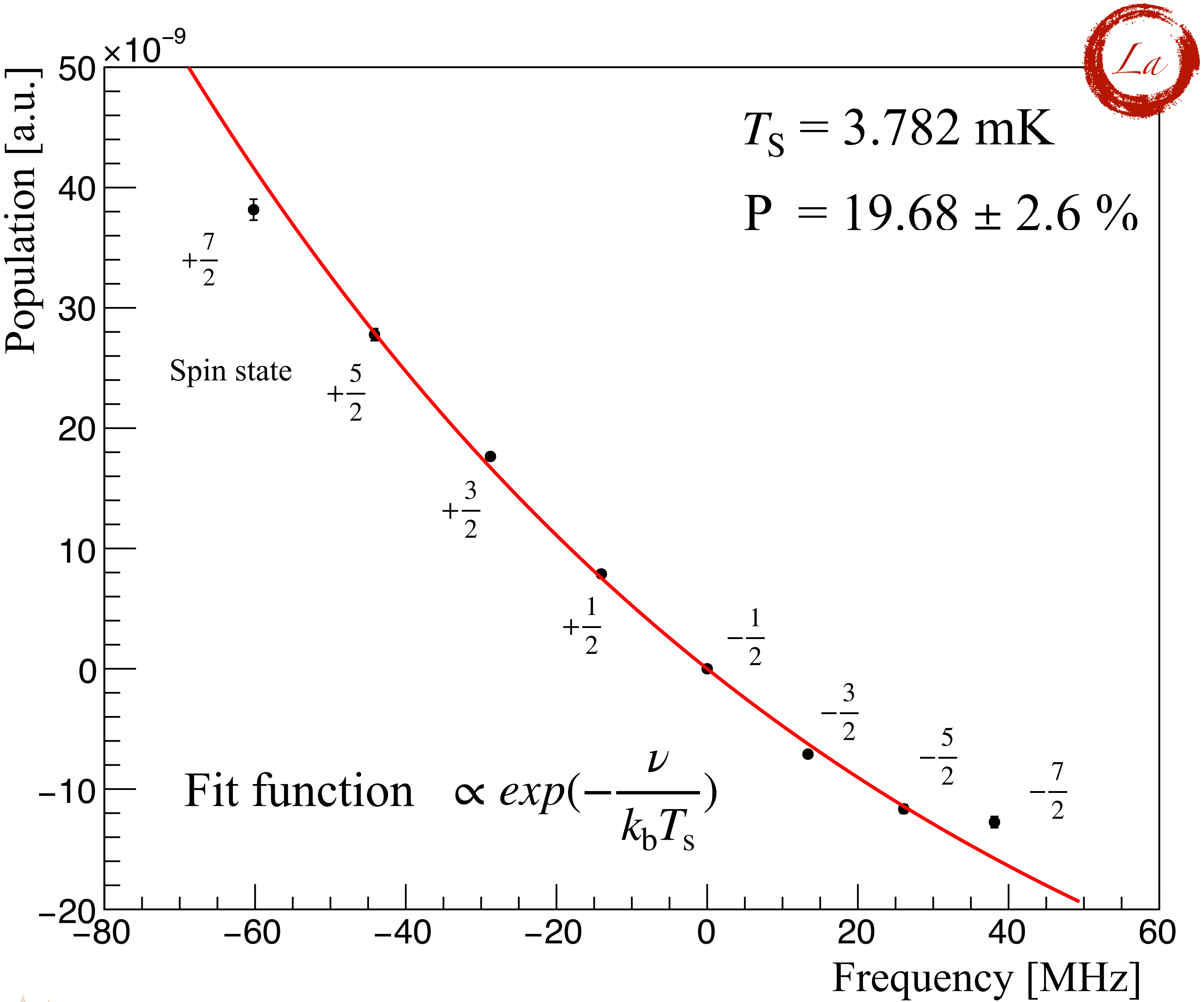
Assumption of following
Boltzmann distribution

$$\text{Fit function} \propto exp(-\frac{\nu}{k_b T_s})$$

Result

Spin Temperature : 3.782 mK

Polarization : 19.68 ± 2.6 [%]



Maximum Polarization ≥ ~19.6 [%]

Calculation Method of the Polarization at ^{139}La

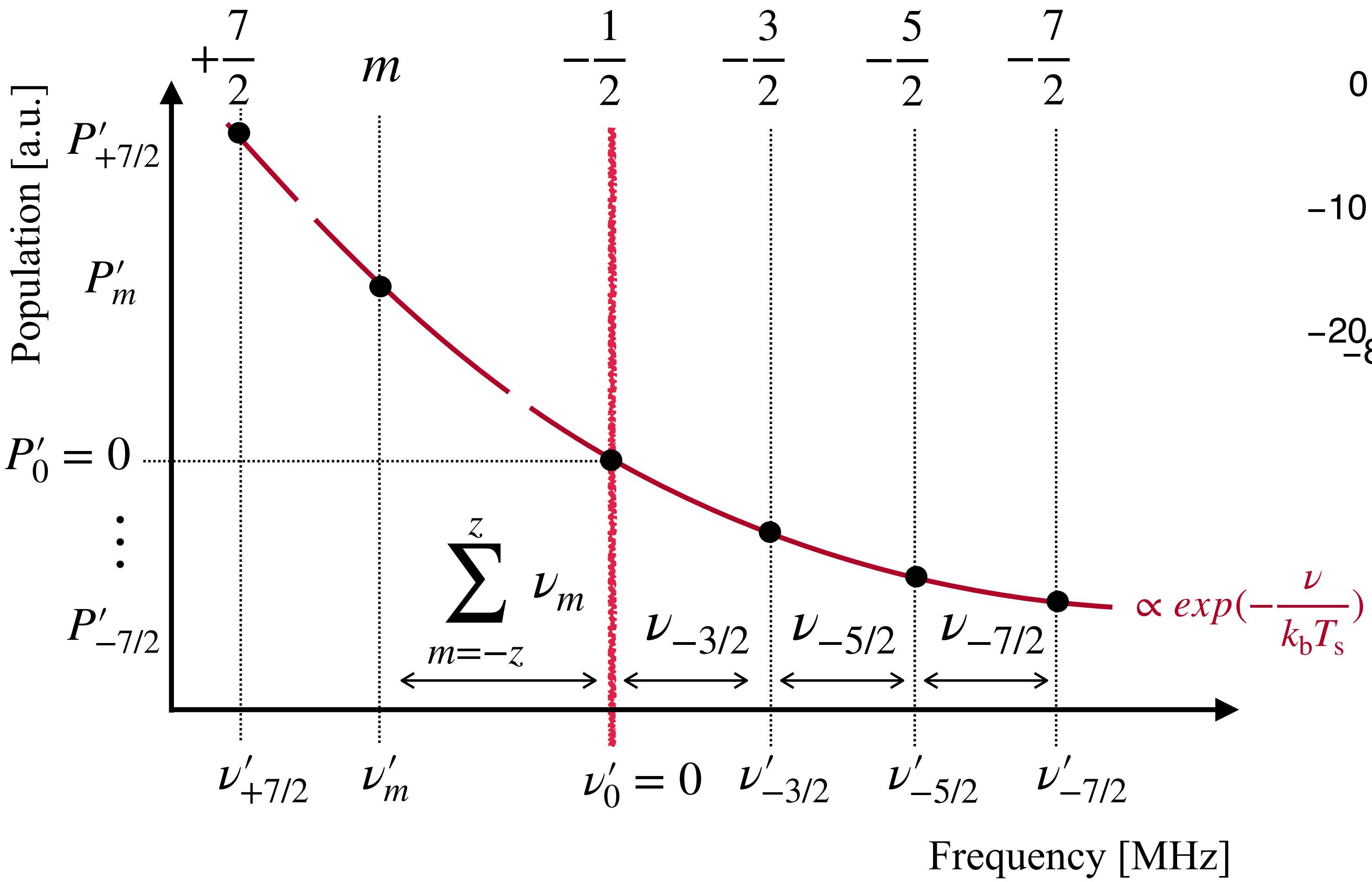
New frame graph

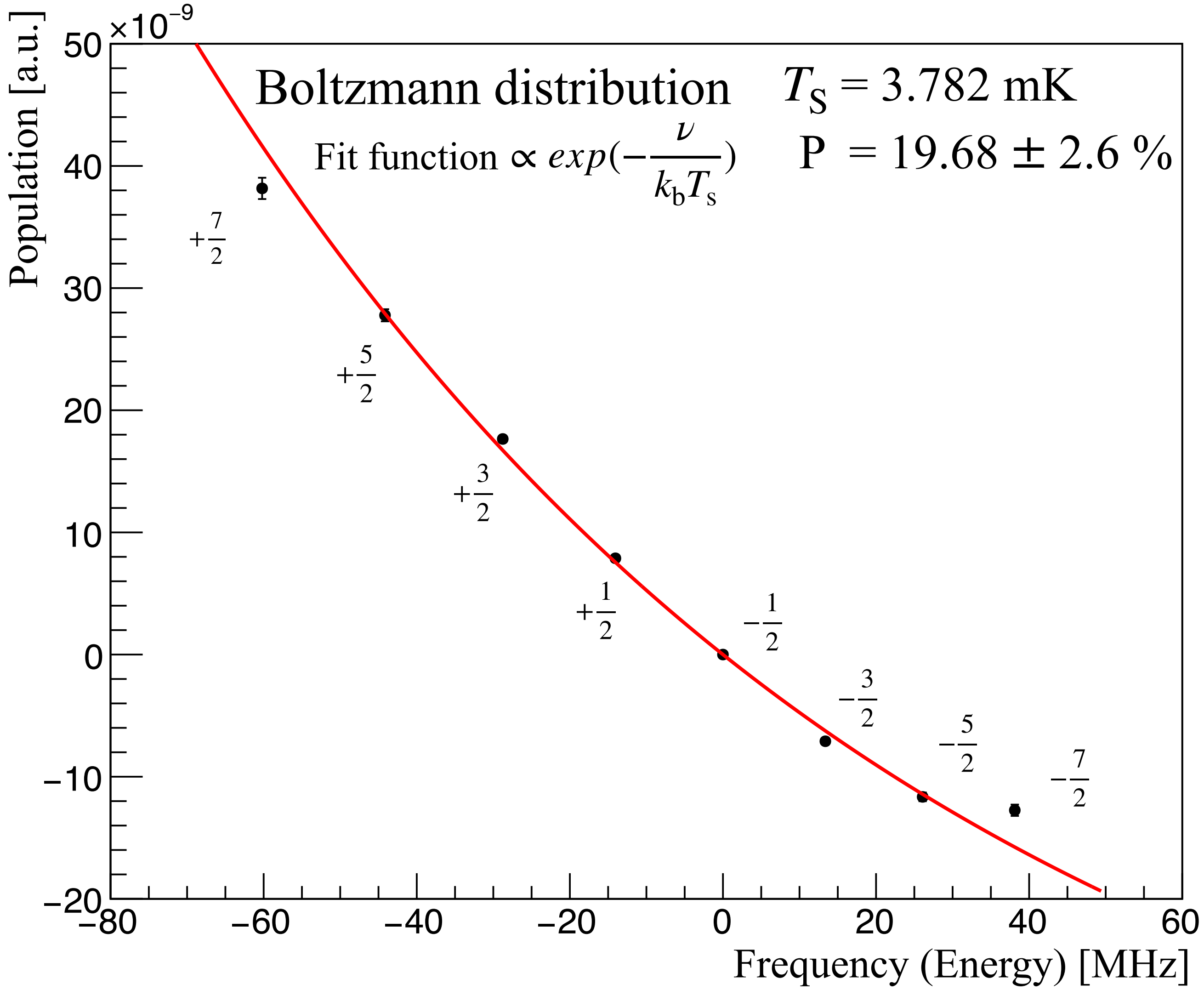
Energy Levels : $E_m \ (-I_z \leq m \leq +I_z)$

Frequency : $\nu(m) = \nu'(m) + \nu_0$

Population : $P(m) = P'(m) + P_0$

P_0, ν_0 is standard state





Result

Spin Temperature : 3.782 mK

Polarization : 19.68 ± 2.6 [%]

Calculation Method of the Polarization at ^{139}La

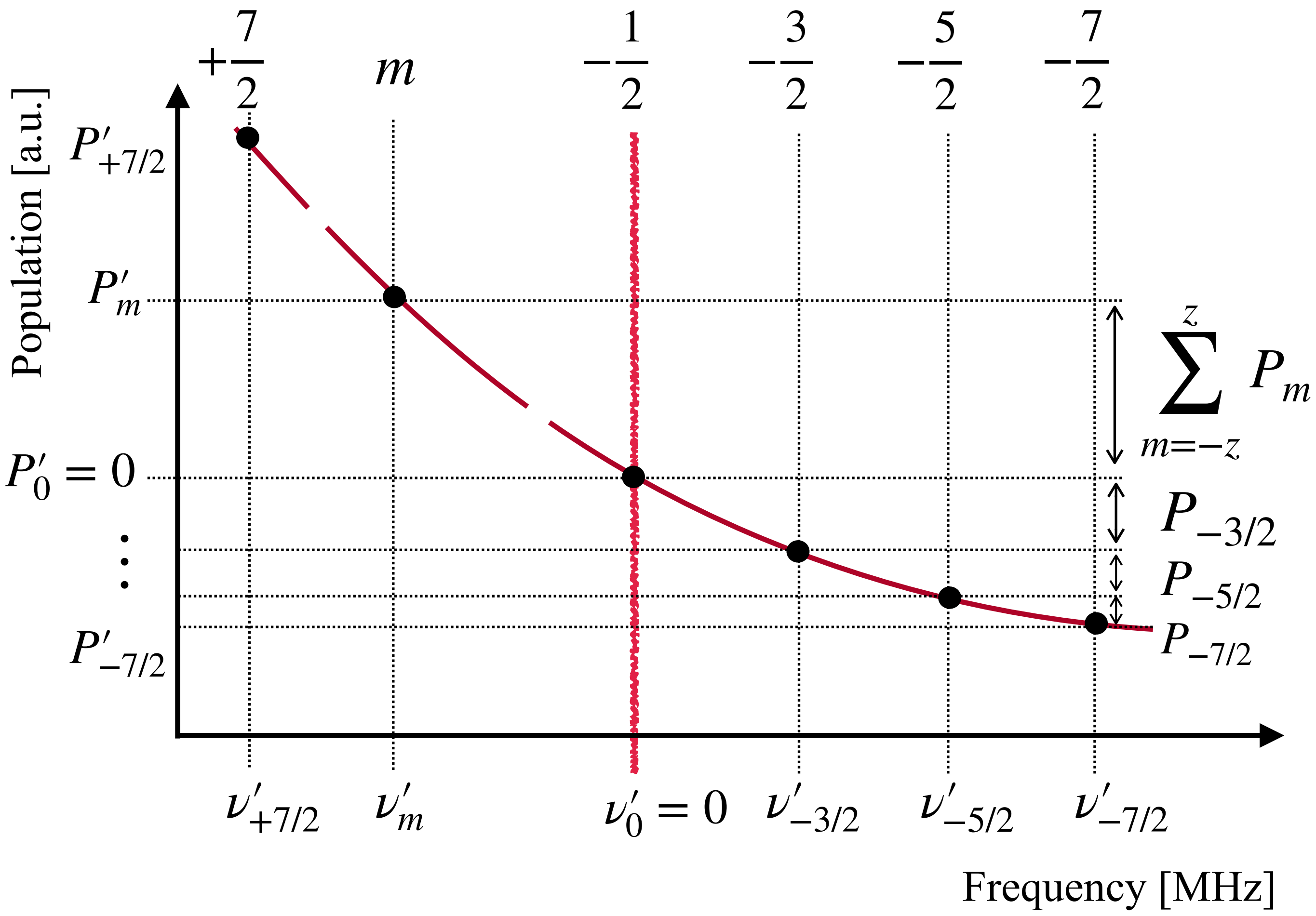
New frame graph

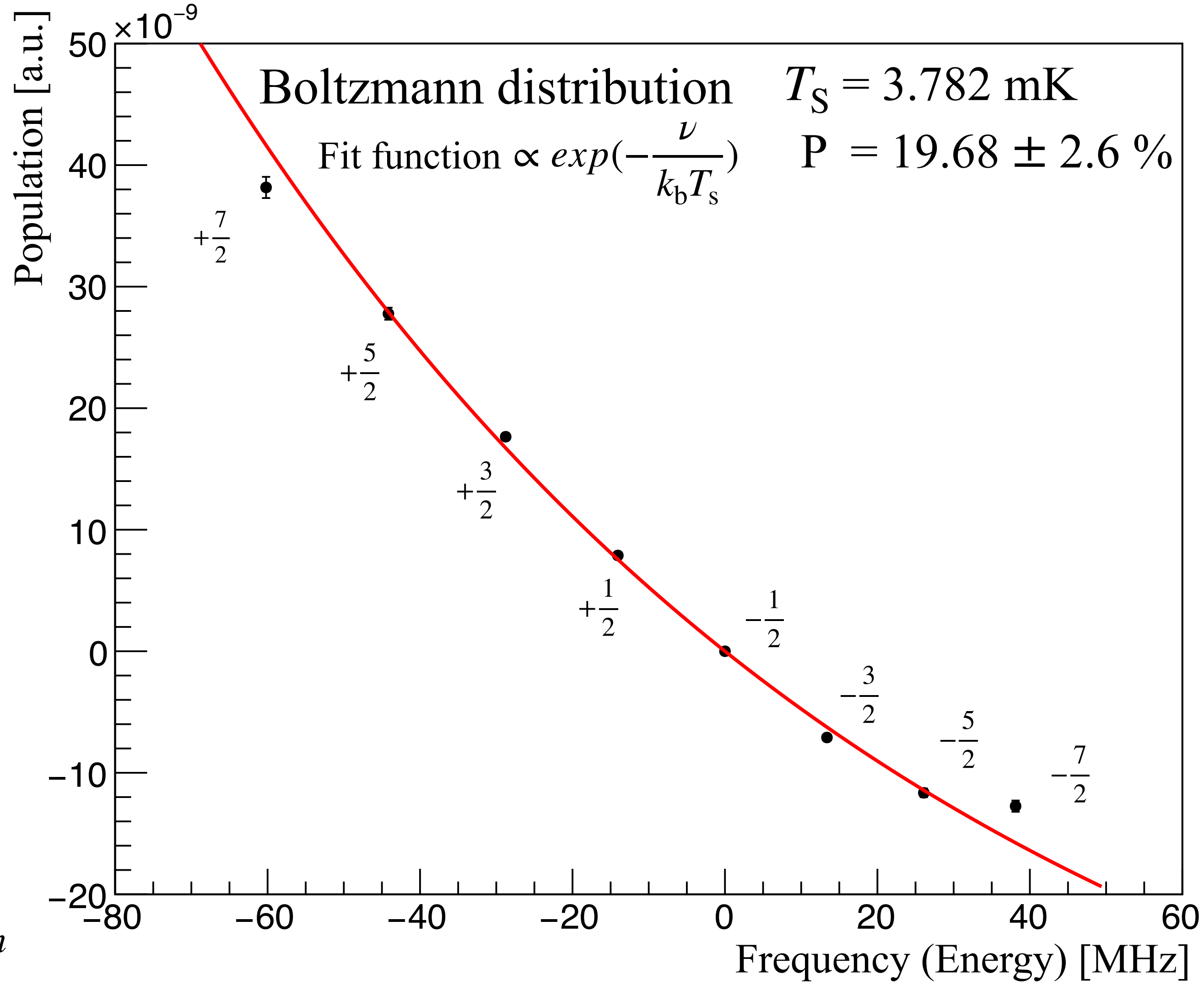
Energy Levels : $E_m \ (-I_z \leq m \leq +I_z)$

Frequency : $\nu(m) = \nu'(m) + \nu_0$

Population : $P(m) = P'(m) + P_0$

$P_0, \ \nu_0$ is standard state





Result

Spin Temperature : 3.782 mK

Polarization : 19.68 ± 2.6 [%]