

Current status of NOPTREX experiment at J-PARC

Takuya Okudaira

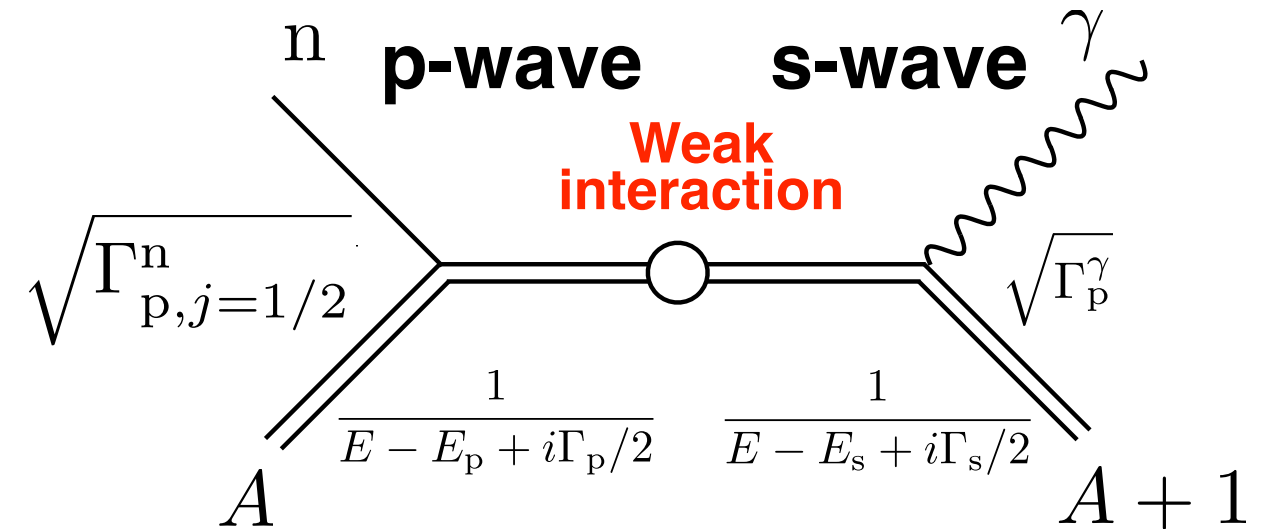
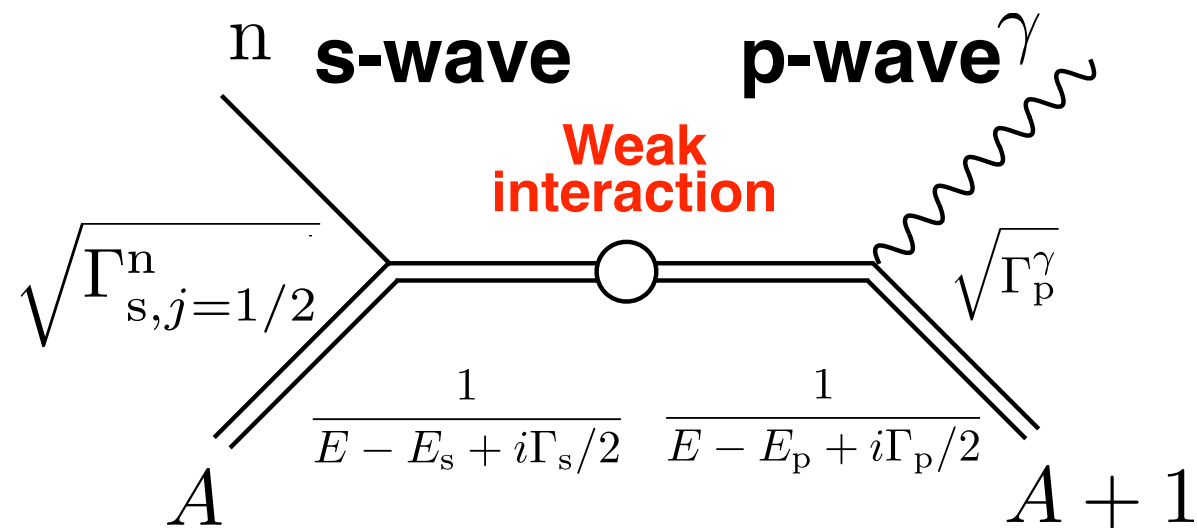
ϕ lab, Nagoya Univ.

for NOPTREX collaboration



Enhancement of parity violation

This enhancement is caused by the mixing of $j=1/2$ component of s-wave and $j=1/2$ component of p-wave → s-p mixing



Theoretically, the enhancement is written as

$$\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{\Delta\sigma_P}{2\sigma} = - \frac{2W}{E_p - E_s} \sqrt{\frac{\Gamma_s^n}{\Gamma_p^n}} \sqrt{\frac{\Gamma_{p,j=1/2}^n}{\Gamma_p^n}}$$

Weak matrix element

Dynamic Enhancement Structural Enhancement Partial neutron width $j=1/2$ component : χ

$10^2 - 10^3$ $\sim 10^3$ Unmeasured

Enhancement of T-violation

T-violation in fundamental interaction

T violation
in a compound
nucleus

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

P violation
in a compound
nucleus

Conversion factor
from P-violation to T-violation

P-violation in fundamental interaction

V. P. Gudkov. *Phys. Rep.*, 212:77, 1992.

Enhanced P-violation $\Delta\sigma_P \rightarrow$ Enhanced T-violation $\Delta\sigma_T$

Large $\Delta\sigma_P$ and $\kappa(J)$ are better $\rightarrow$ Large T-violating cross section

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

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

partial neutron width of p-wave resonance

$\kappa(J)$ also depends on the partial neutron width

Conversion factor from P- to T-violation : $\kappa(J)$

$\kappa(J)$ can be written by the nuclear spin and partial neutron width

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

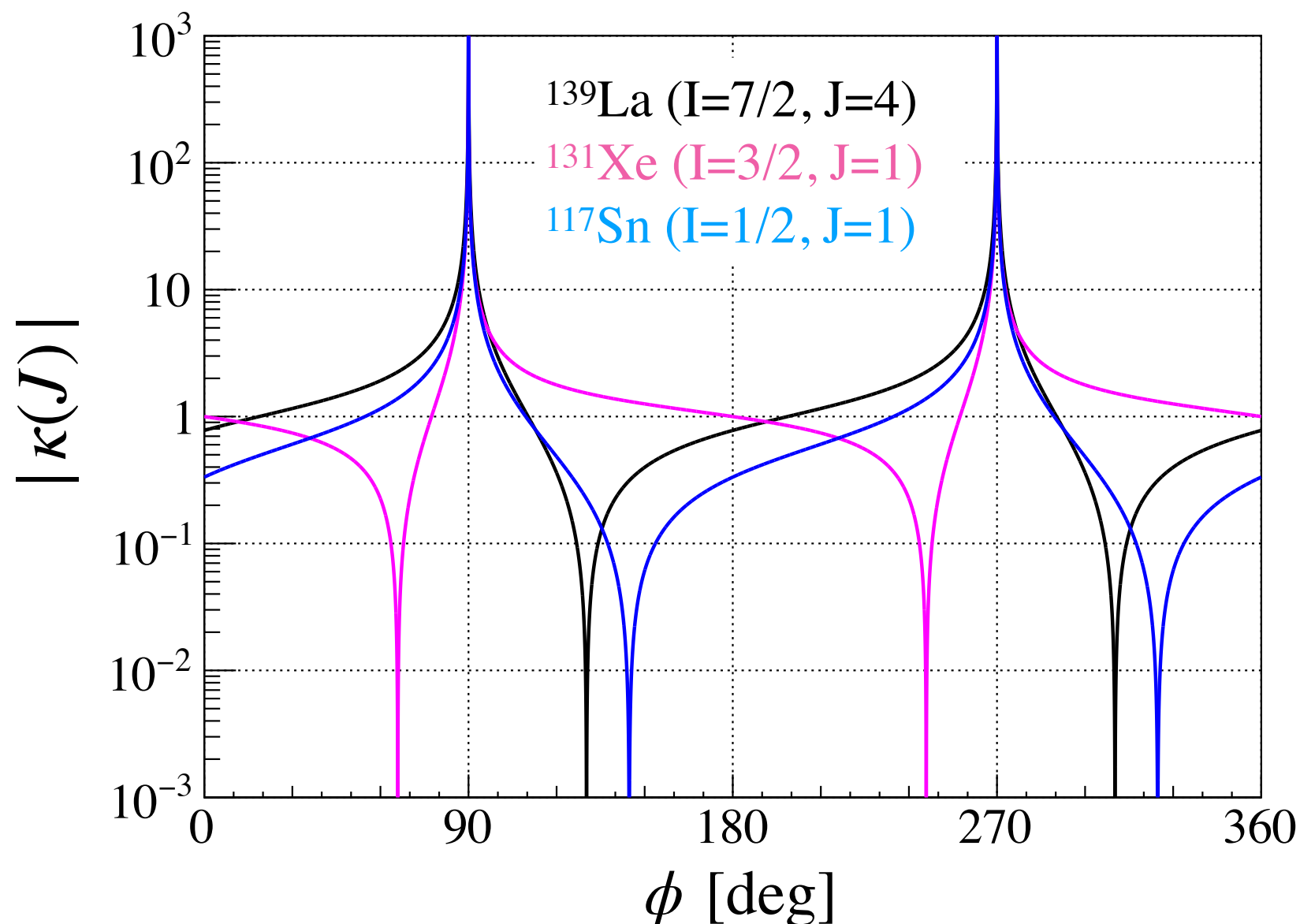
$$x^2 = \frac{\Gamma_{p,j=\frac{1}{2}}^n}{\Gamma_p^n}, \quad y^2 = \frac{\Gamma_{p,j=\frac{3}{2}}^n}{\Gamma_p^n}.$$

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

$$x = \cos \phi, \quad y = \sin \phi$$



j : total neutron spin
Mixing angle ϕ between
partial neutron with of
 $j=1/2$ and $j=3/2$



Determination of $\kappa(J)$
→ Measurement of ϕ
with (n, γ) reactions

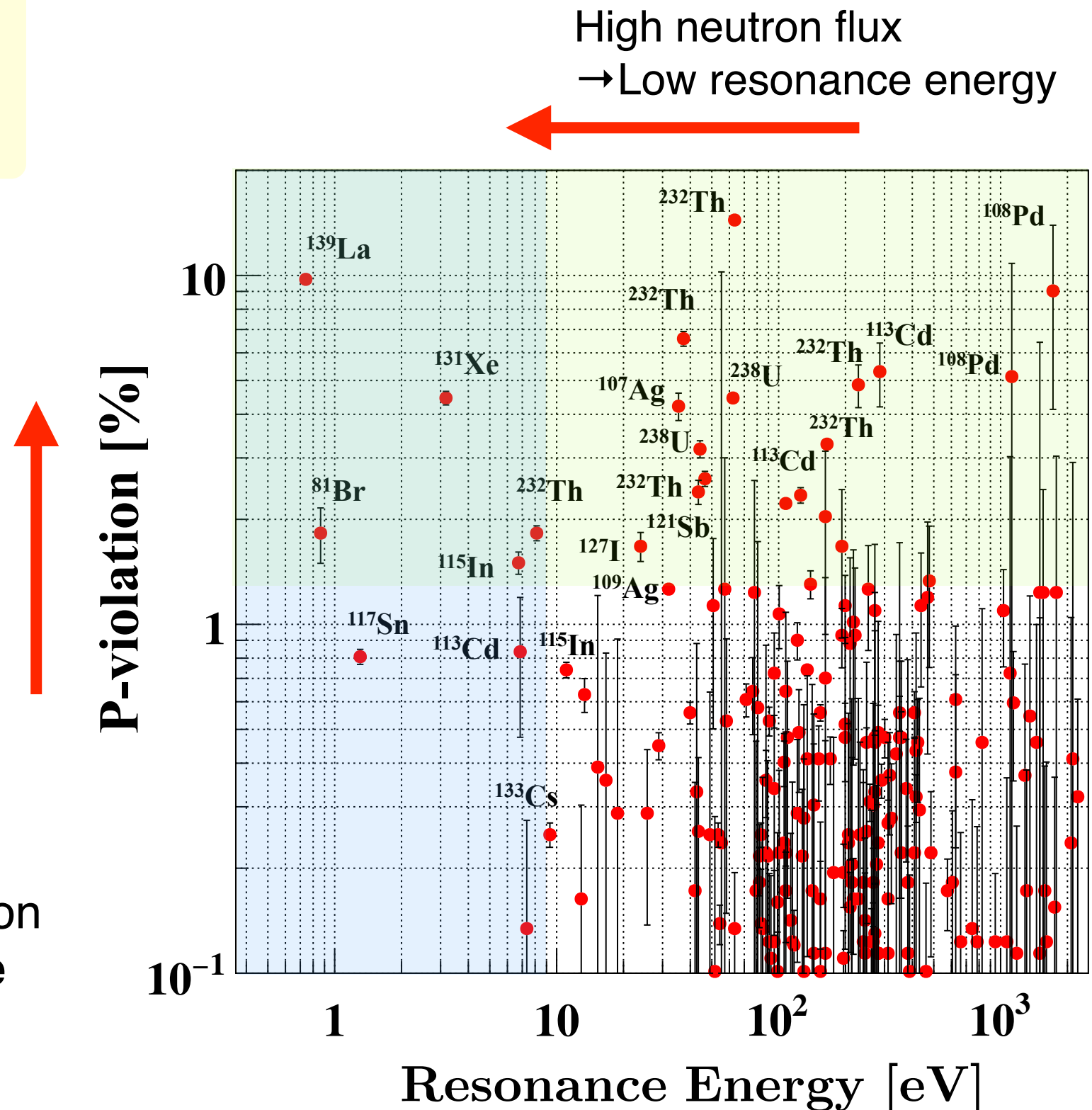
Candidate nuclei for T-violation search

The sensitivity of the T-violation search depends on the nucleus

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

Large T-violation
→ Large P-violation

- Large P-violation, $\kappa(J)$
- Low resonance energy
- Small nuclear spin
→ Large nuclear polarization
- Large natural abundance



Candidate nuclei for T-violation search

	¹³⁹ La	⁸¹ Br	¹¹⁷ Sn	¹³¹ Xe
Large P-violation	9.8%	2.4%	0.8%	4.8%
Low resonance energy	0.73eV	0.88eV	1.3eV	3.3eV
Small Nuclear spin	7/2	3/2	1/2	3/2
Large natural abundance	100%	50%	8%	21%
$ \kappa(J) $	?	?	?	?
Nuclear polarization	Dynamic Nuclear Polarization	–	–	Optical Pumping

Very good

Good

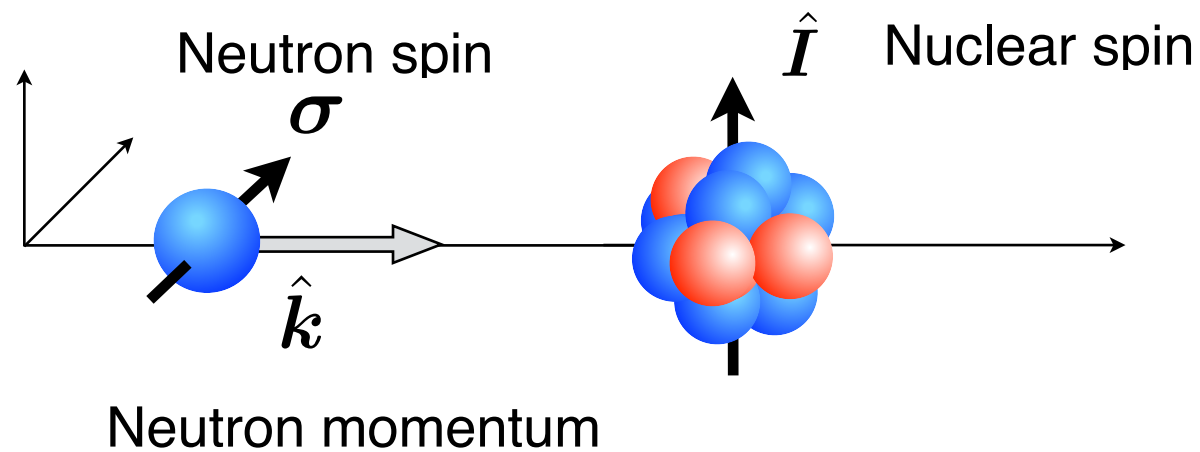
Acceptable

Bad

$\kappa(J)$ is unknown in all of nuclei.

Search for T-violation

→ Cross section measurement of polarized neutrons and polarized target



Cross section depending on spins
→ T-violation

Forward scattering amplitude

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

Ordinal cross
section

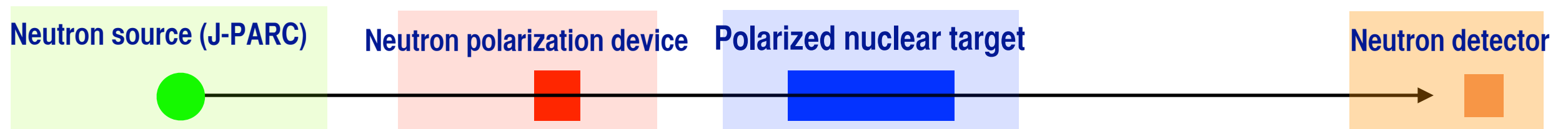
Spin
dependence

P-violation
↓
 $\mathbf{t} \rightarrow -\mathbf{t}$

T-violating cross
section

opposite sign

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



~1eV Neutrons, Neutron polarization device, Polarized target

Plan for T-violation search

Fundamental T-violation in nucleon interaction

1. Selection of target nuclei

→ Large P-violation, large $\kappa(J)$

1. Verification of s-p mixing

→ Angular correlation,
neutron transmission with polarized target

→ Study of nuclear reaction

2. Neutron polarization device

→ Depends on resonance energy

3. Polarized target

→ Depends on nuclear spin,
chemical properties

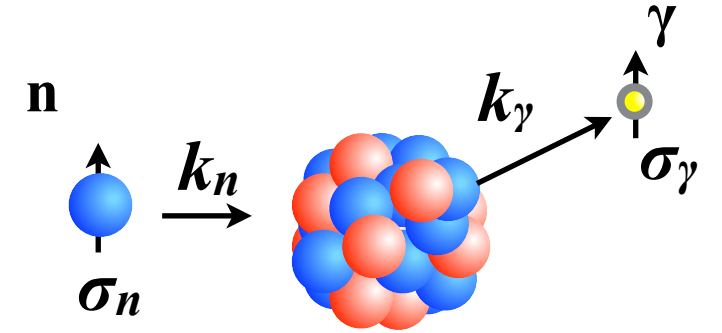
4. Neutron detector

→ High counting rate

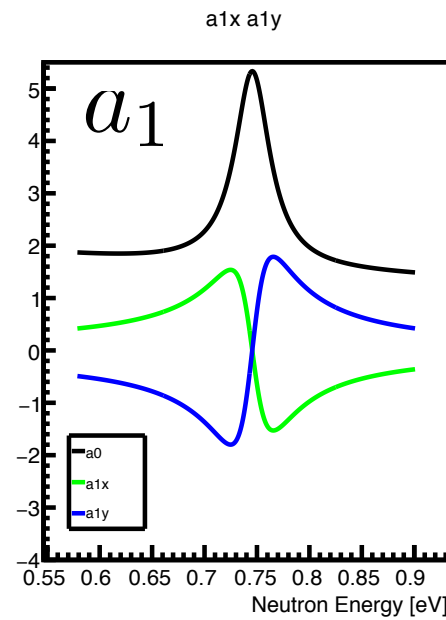
4. Measurement of T-violating cross section $\Delta\sigma_T$

Angular distribution of (n,γ) reactions

V. V. Flambaum et al, Nuclear Physics A, vol. 435, no. 2, pp. 352 – 380, 1985.



$$\frac{d\sigma_{n\gamma f}}{d\Omega_\gamma} = \frac{1}{2} \left(a_0 + a_1 \hat{k}_n \cdot \hat{k}_\gamma + a_2 \sigma_n \cdot (\hat{k}_n \times \hat{k}_\gamma) + a_3 \left((\hat{k}_n \cdot \hat{k}_\gamma)^2 - \frac{1}{3} \right) \right.$$



$$+ a_4 (\sigma_n \cdot (\hat{k}_n \times \hat{k}_\gamma)) + a_5 (\sigma_\gamma \cdot \hat{k}_\gamma) (\sigma_n \cdot \hat{k}_\gamma)$$

$$2\text{Re} (P(1/2, F) V_1 V_2^* \cos \phi + P(3/2, F) V_1 V_2^* \sin \phi)$$

$$+ a_{12} (\sigma_n \cdot \hat{k}_n) \quad V_1 \quad \text{s-wave} \quad \frac{1}{E - E_s + i\Gamma_s/2} \quad A \rightarrow A+1$$

$$V_2 \quad \text{p-wave} \quad \frac{1}{E - E_p + i\Gamma_p/2} \quad A \rightarrow A+1$$

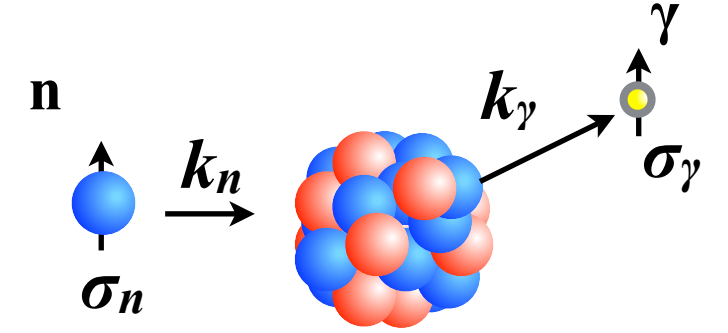
$$+ a_{13} \sigma_\gamma \cdot \hat{k}_\gamma \quad V_3 \quad \text{s-wave} \quad \text{Weak interaction} \quad \frac{1}{E - E_s + i\Gamma_s/2} \quad A \rightarrow A+1$$

$$V_4 \quad \text{p-wave} \quad \text{Weak interaction} \quad \frac{1}{E - E_p + i\Gamma_p/2} \quad A \rightarrow A+1$$

a term can be written by Φ parameter

Angular distribution of (n,γ) reactions

V. V. Flambaum et al, Nuclear Physics A, vol. 435, no. 2, pp. 352 – 380, 1985.



$$\begin{aligned}
 \frac{d\sigma_{n\gamma f}}{d\Omega_\gamma} = & \frac{1}{2} \left(a_0 + a_1 \hat{k}_n \cdot \hat{k}_\gamma + a_2 \sigma_n \cdot (\hat{k}_n \times \hat{k}_\gamma) + a_3 \left((\hat{k}_n \cdot \hat{k}_\gamma)^2 - \frac{1}{3} \right) \right. \\
 & + a_4 (\hat{k}_n \cdot \hat{k}_\gamma) (\sigma_n \cdot (\hat{k}_n \times \hat{k}_\gamma)) + a_5 (\sigma_\gamma \cdot \hat{k}_\gamma) (\sigma_n \cdot \hat{k}_\gamma) \\
 & + a_6 (\sigma_\gamma \cdot \hat{k}_\gamma) (\sigma_n \cdot \hat{k}_n) + a_7 (\sigma_\gamma \cdot \hat{k}_\gamma) \left((\sigma_n \cdot \hat{k}_\gamma) (\hat{k}_\gamma \cdot \hat{k}_n) - \frac{1}{3} \sigma_n \cdot \hat{k}_n \right) \\
 & + a_8 (\sigma_\gamma \cdot \hat{k}_\gamma) \left((\sigma_n \cdot \hat{k}_n) (\hat{k}_n \cdot \hat{k}_\gamma) - \frac{1}{3} \sigma_n \cdot \hat{k}_\gamma \right) \\
 & + a_9 \sigma_n \cdot \hat{k}_\gamma + a_{10} \sigma_n \cdot \hat{k}_n + a_{11} \left((\sigma_n \cdot \hat{k}_\gamma) (\hat{k}_\gamma \cdot \hat{k}_n) - \frac{1}{3} (\sigma_n \cdot \hat{k}_n) \right) \\
 & + a_{12} (\sigma_n \cdot \hat{k}_n) \left((\hat{k}_n \cdot \hat{k}_\gamma) - \frac{1}{3} (\sigma_n \cdot \hat{k}_\gamma) \right) \\
 & + a_{13} \sigma_\gamma \cdot \hat{k}_\gamma + a_{14} (\sigma_\gamma \cdot \hat{k}_\gamma) (\hat{k}_n \cdot \hat{k}_\gamma) \\
 & + a_{15} (\sigma_\gamma \cdot \hat{k}_\gamma) \sigma_n \cdot (\hat{k}_n \times \hat{k}_\gamma) + a_{16} (\sigma_\gamma \cdot \hat{k}_\gamma) \left((\hat{k}_n \cdot \hat{k}_\gamma)^2 - \frac{1}{3} \right) \\
 & \left. + a_{17} (\sigma_\gamma \cdot \hat{k}_\gamma) (\hat{k}_n \cdot \hat{k}_\gamma) (\sigma_n \cdot (\hat{k}_n \times \hat{k}_\gamma)) \right),
 \end{aligned}$$

Unpolarized neutron:
2017~

Polarized neutrons :
2019~
(with ³He spin filter)

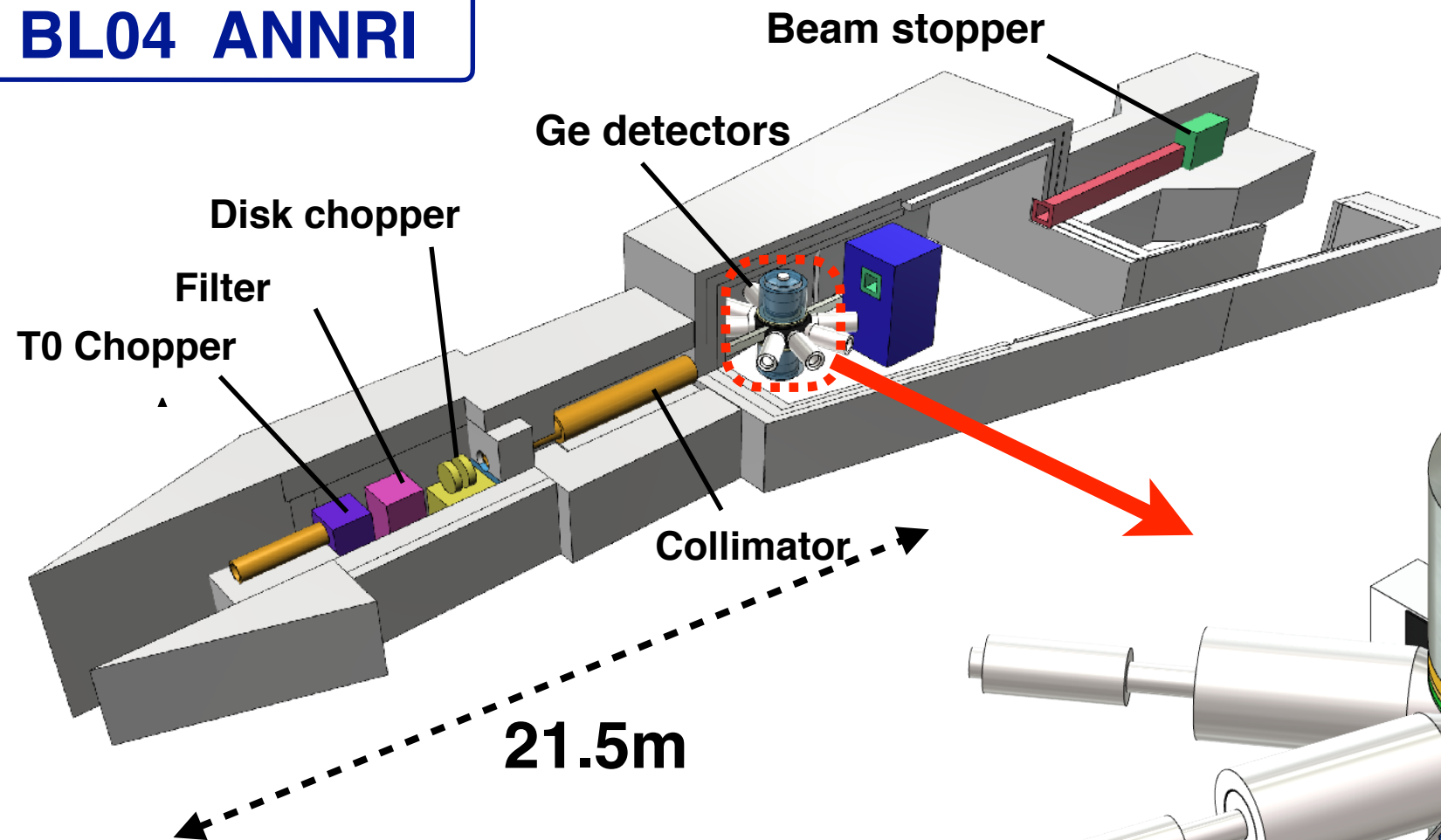
γ-ray polarization :
2021~
(with γ-ray polarimeter)

a term can be written by Φ parameter

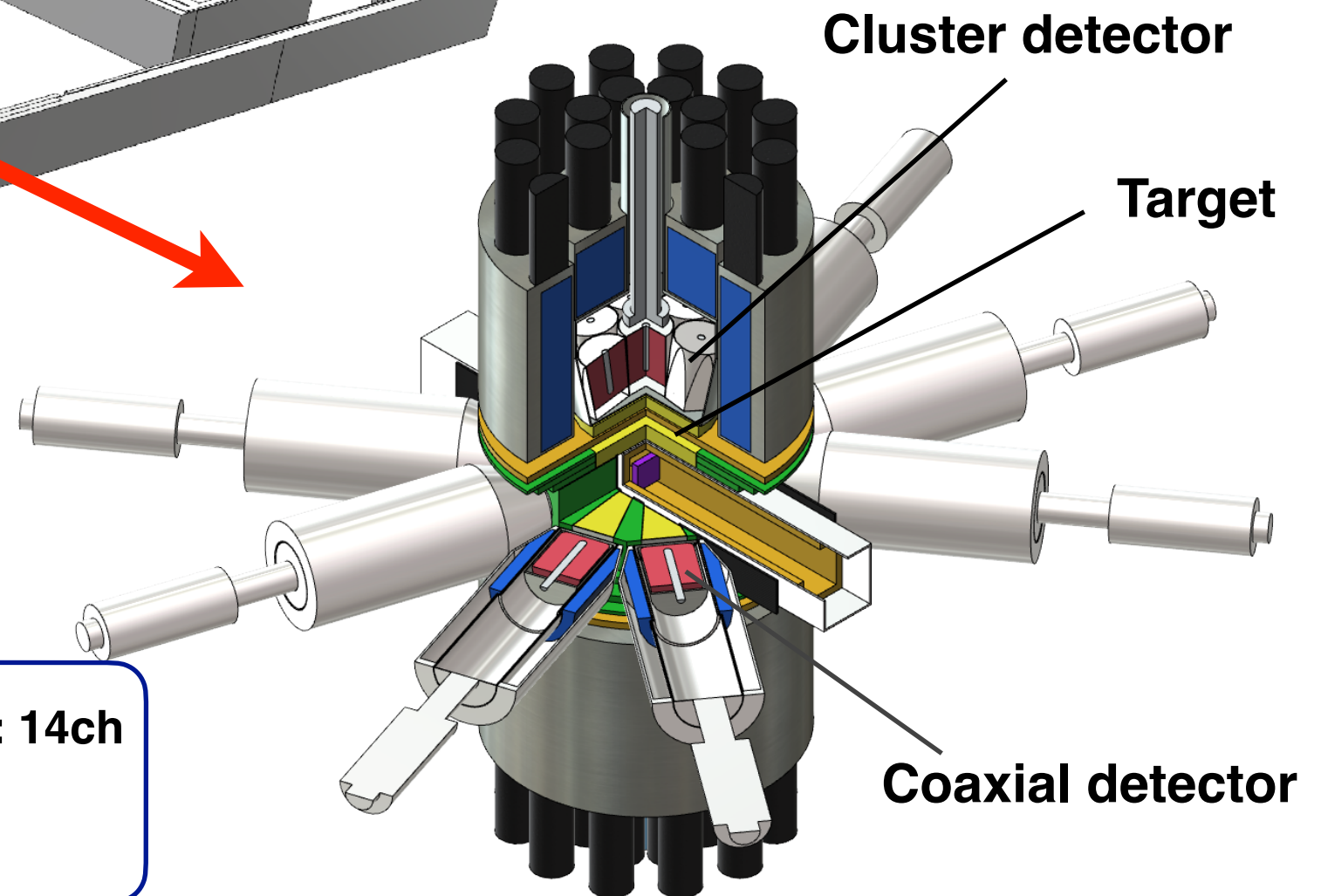
Angular distribution of (n, γ) reactions

The experiments to determine $\kappa(J)$ is ongoing at **ANNRI** (Accurate Neutron-Nucleus Reaction measurement Instrument) beam line in J-PARC

BL04 ANNRI



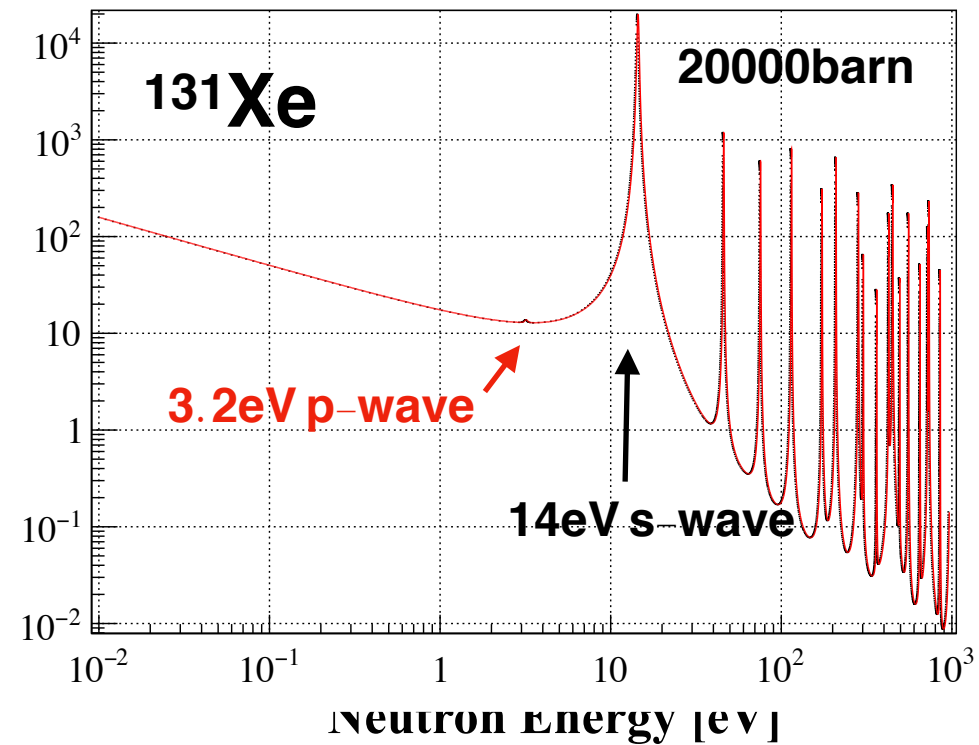
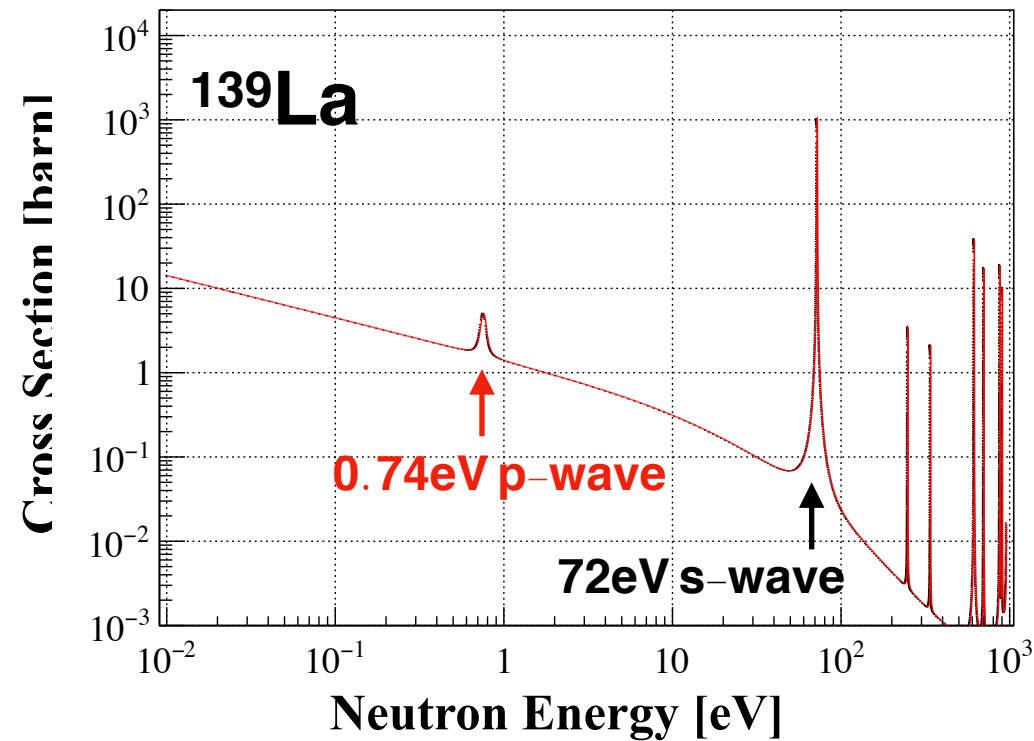
BL04 Ge Detectors



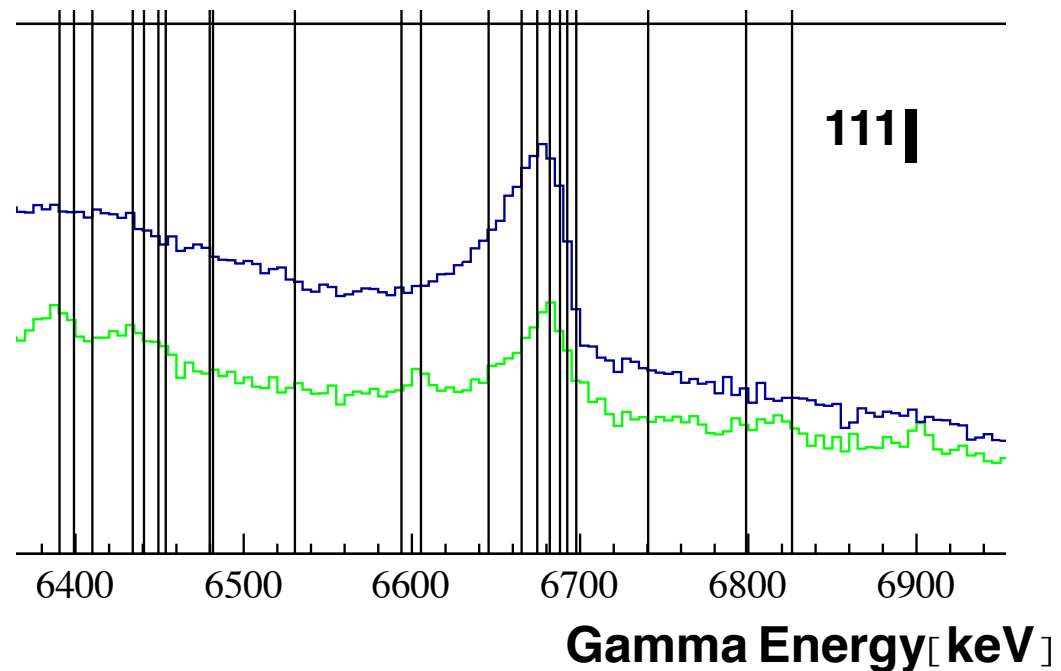
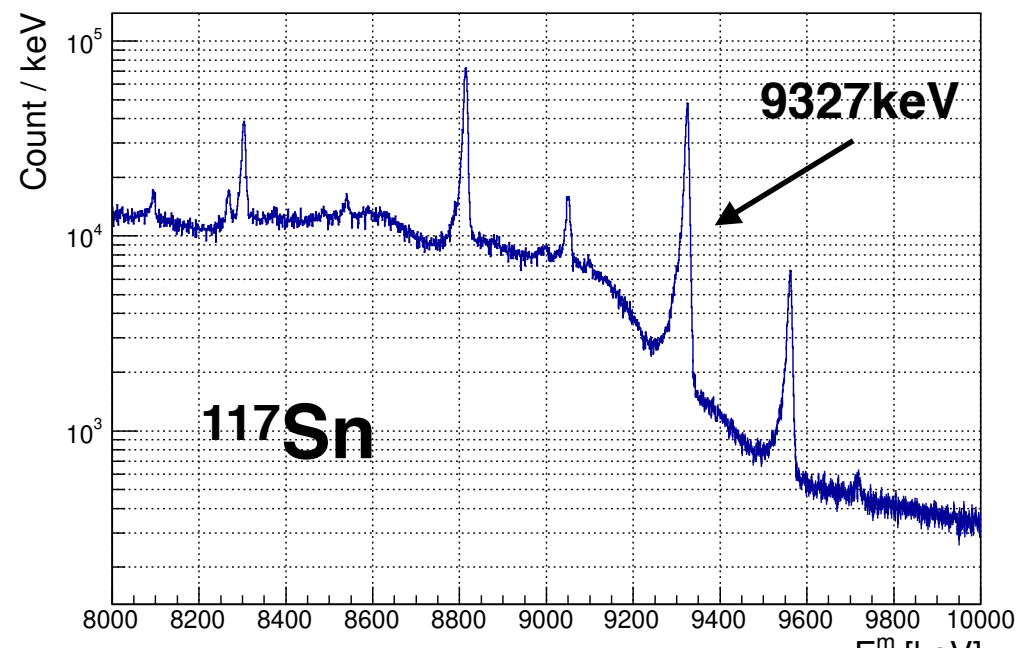
2 Cluster Detector (up • down) 7ch x2 : 14ch
8 Coaxial Detector (side) 8ch
Total 22ch

Nuclides that are easy to measure (n, γ) reactions

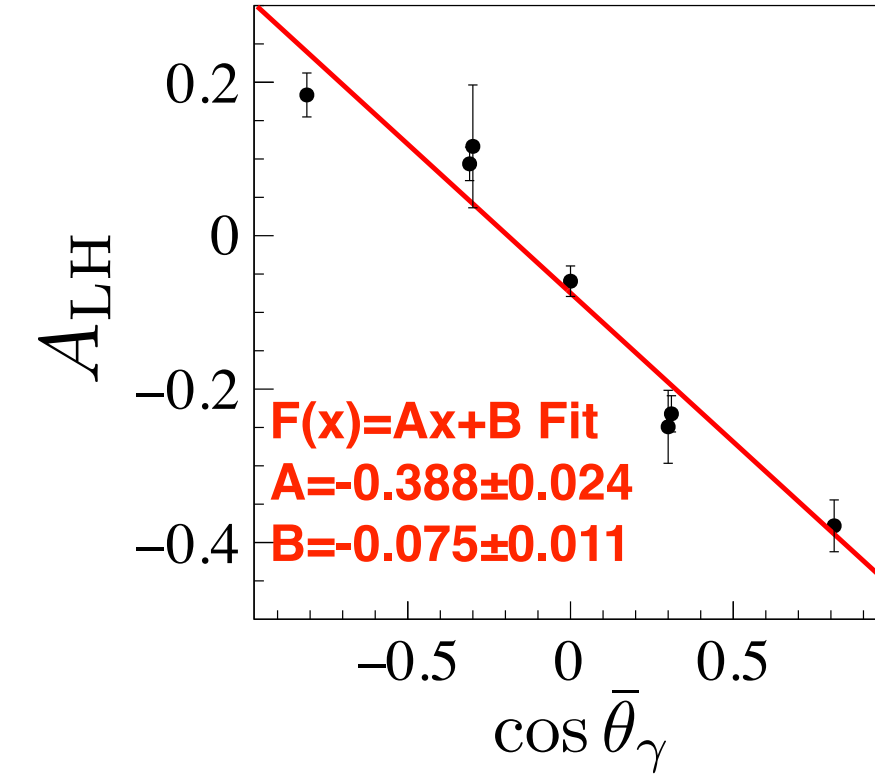
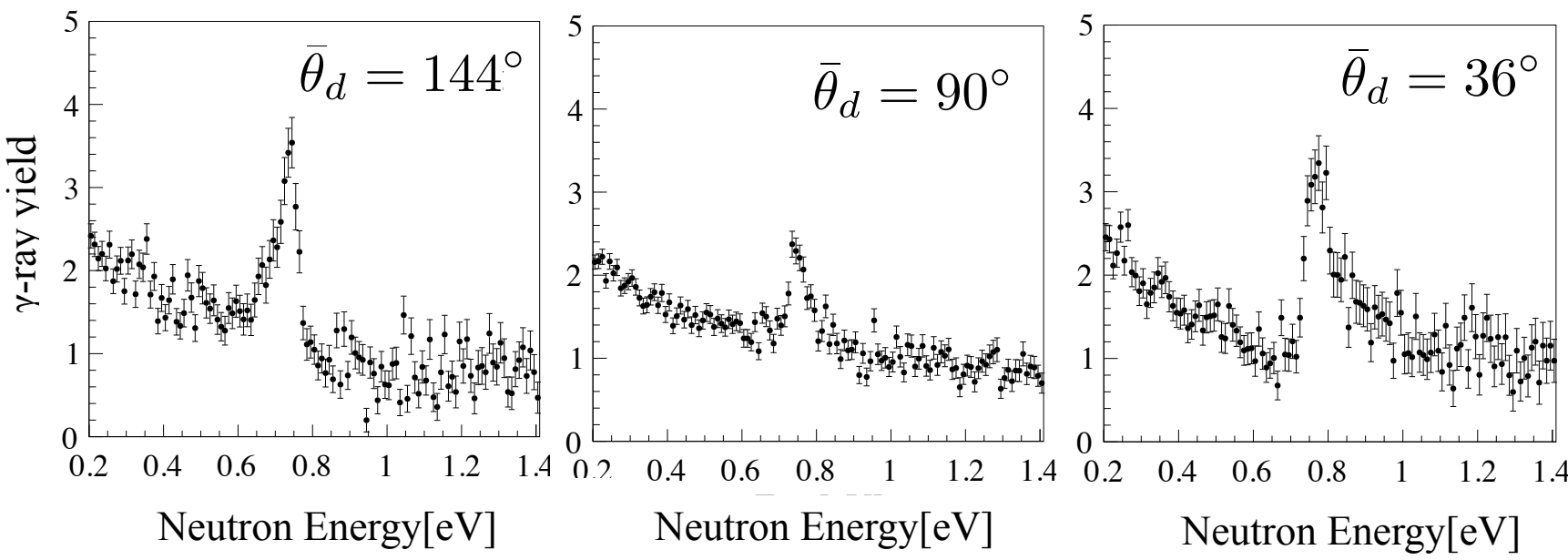
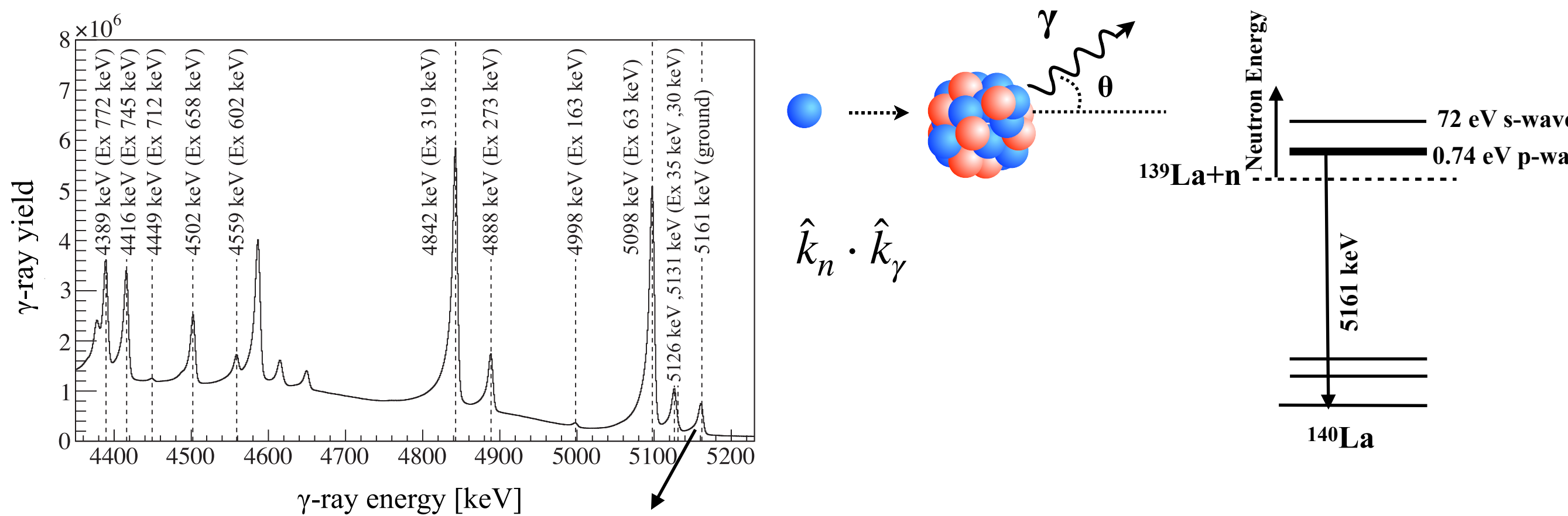
- p-wave with low energy and away from s-wave



- Well-separated γ -rays emitted from the p-wave



Angular distribution of $^{139}\text{La}(n,\gamma)^{140}\text{La}$ reactions

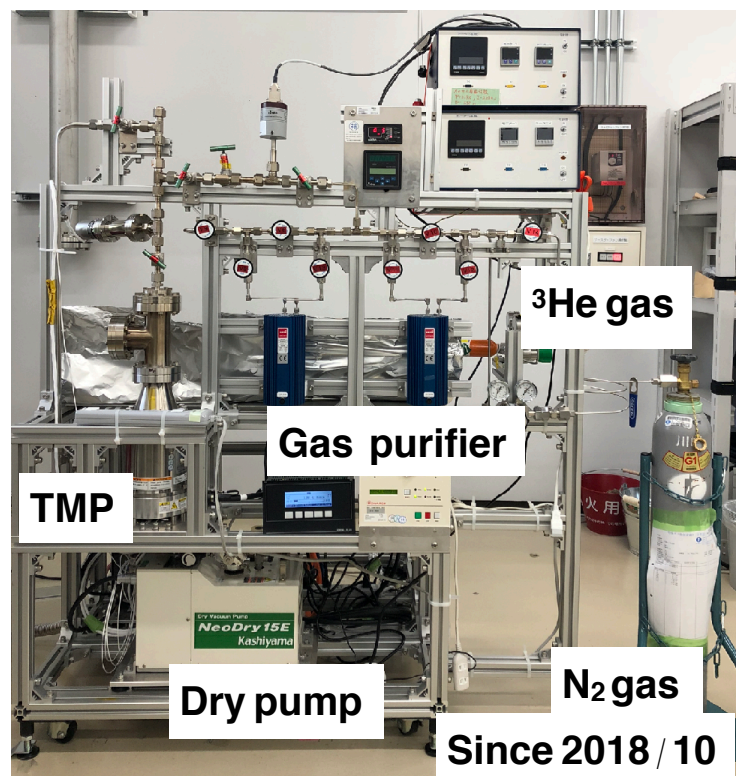


-0.388 ± 0.024 Experimental result
 $= 0.295 \cos \phi - 0.345 \sin \phi$ Theoretical calculation with s-p mixing

Development of ^3He Spin Filter at J-PARC

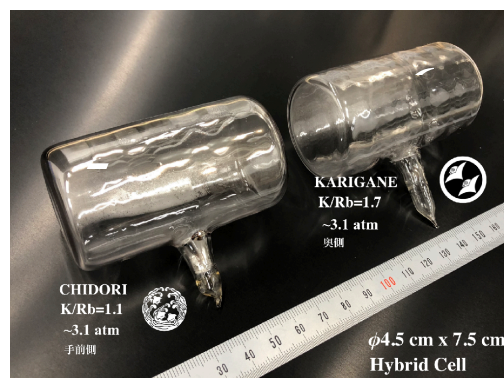
Fabrication of ^3He spin filter

Filling station for ^3He gas and alkali metal

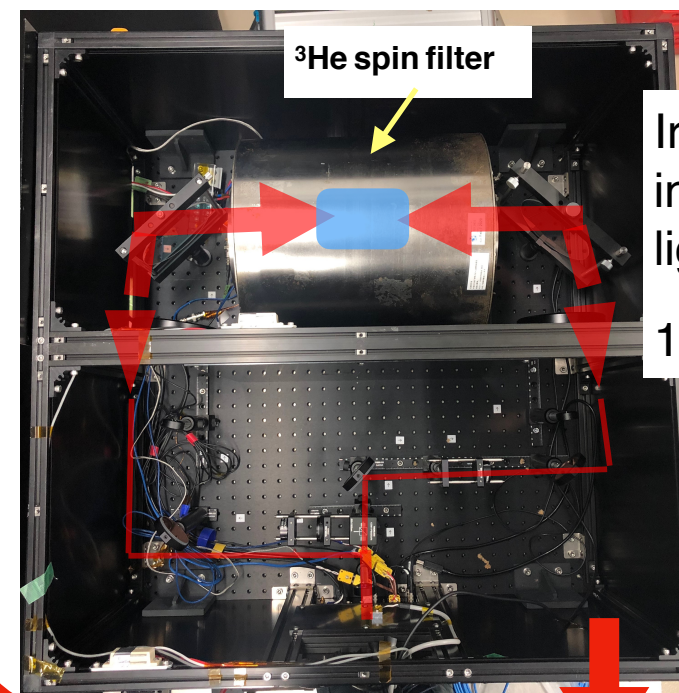


Ultimate pressure :
 3×10^{-8} Pa

^3He spin filter with long
relaxation time

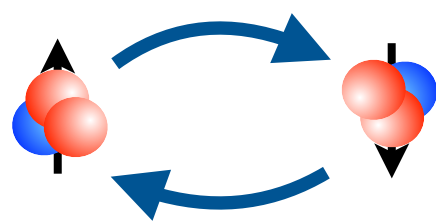


High power laser system



High ^3He polarization, long
relaxation time at neutron beamline

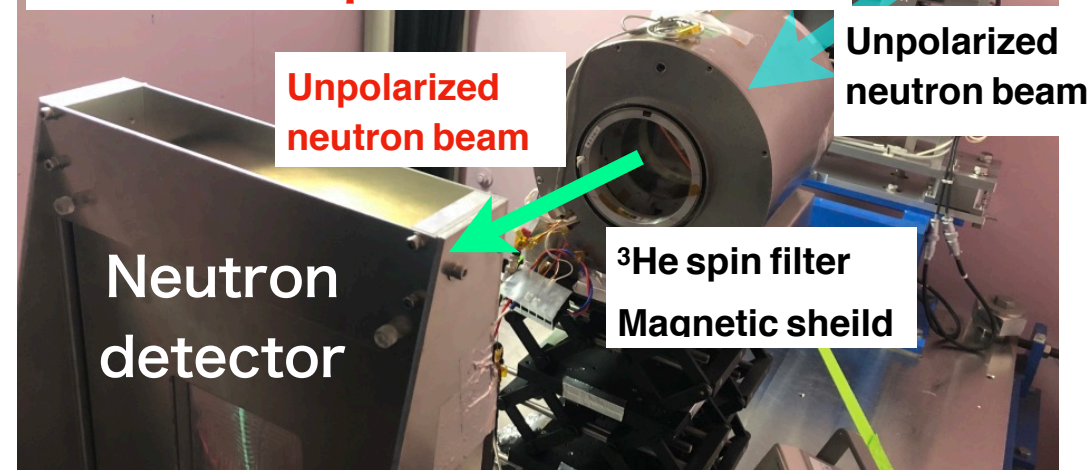
Spin flip system of ^3He



Low flip loss : 3×10^{-5} / 1 flip

^3He polarization 80%

→ Neutron polarization 40%

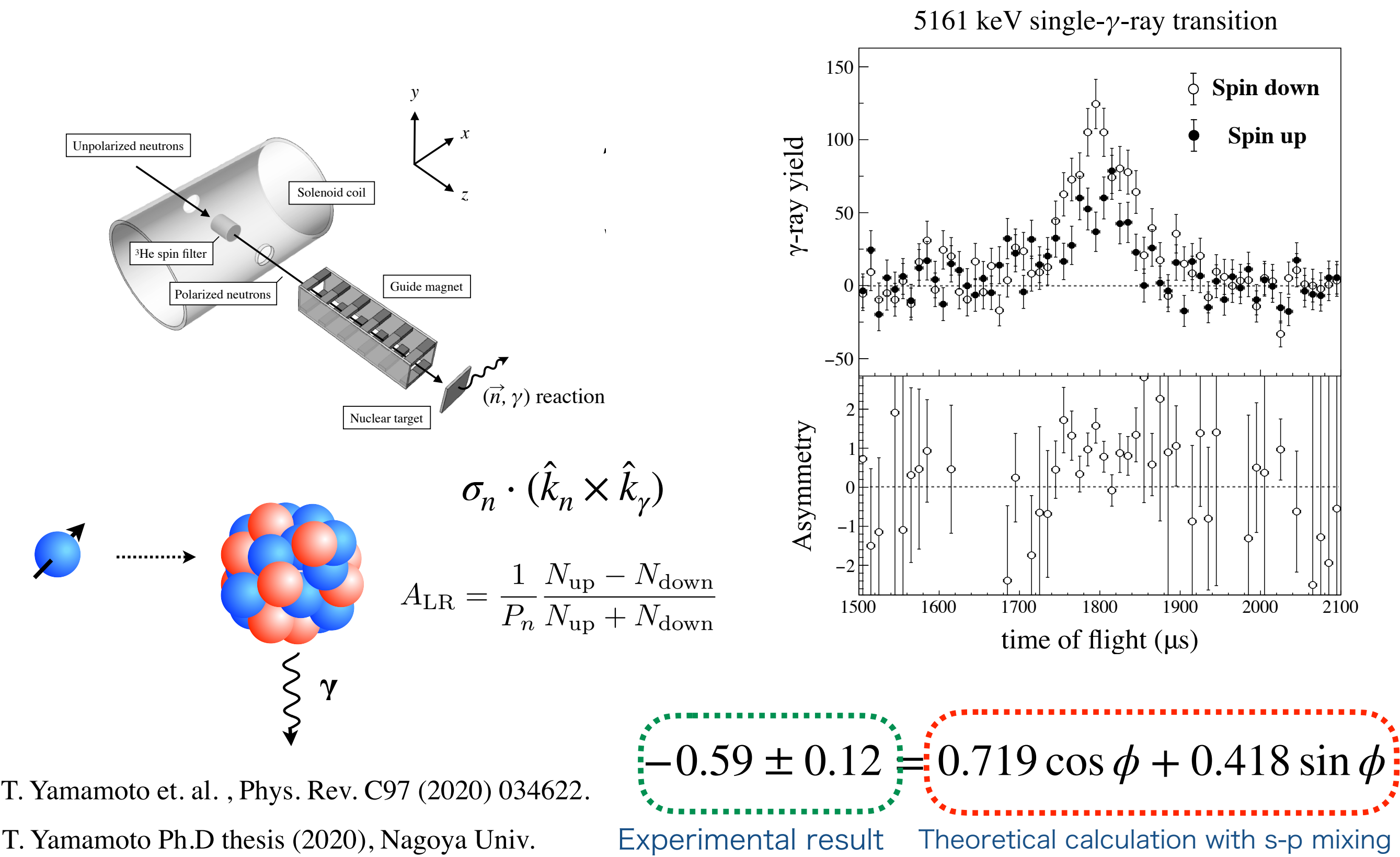


T. Okudaira *et. al.* , NIM A 977, 164301 (2020)

Used for industrial use and other purpose 14

Angular distribution with polarized neutrons

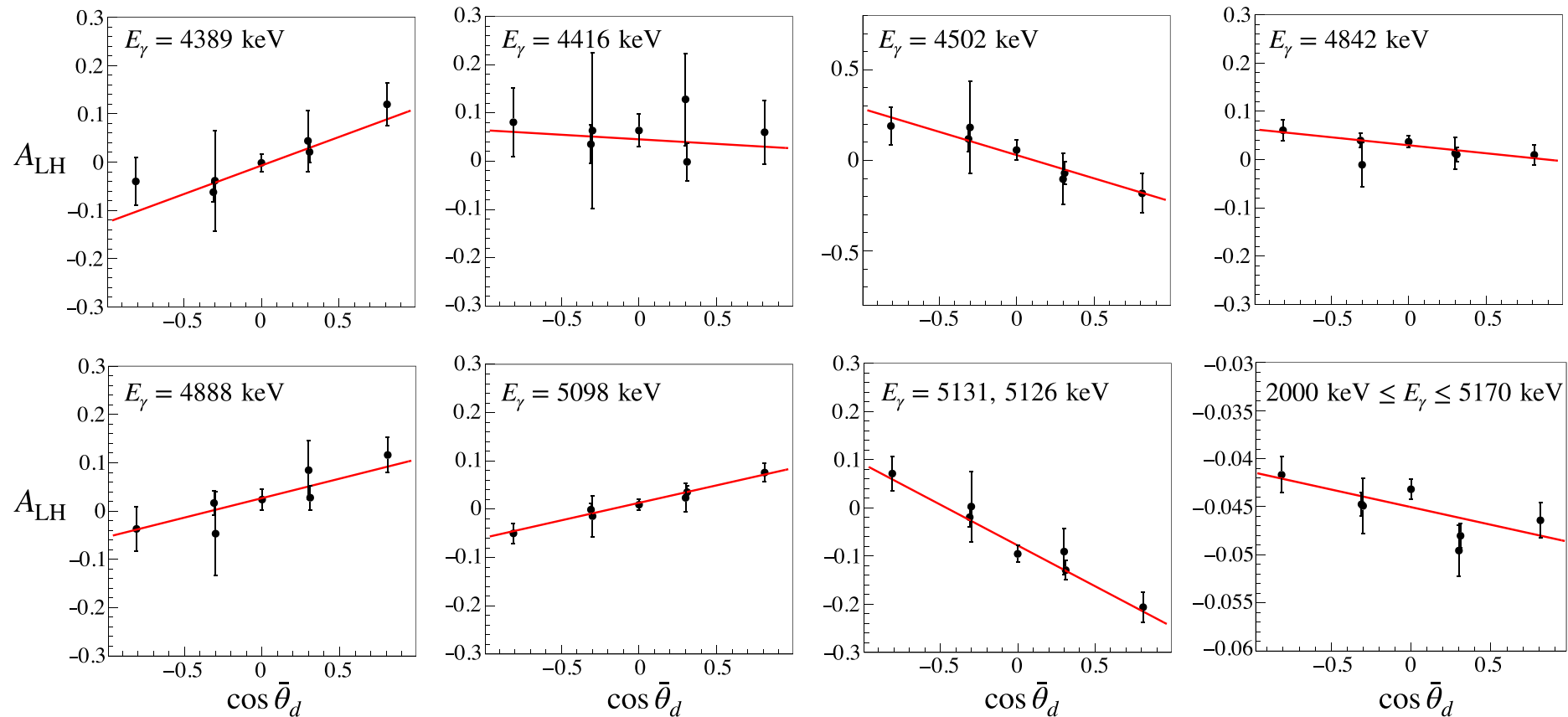
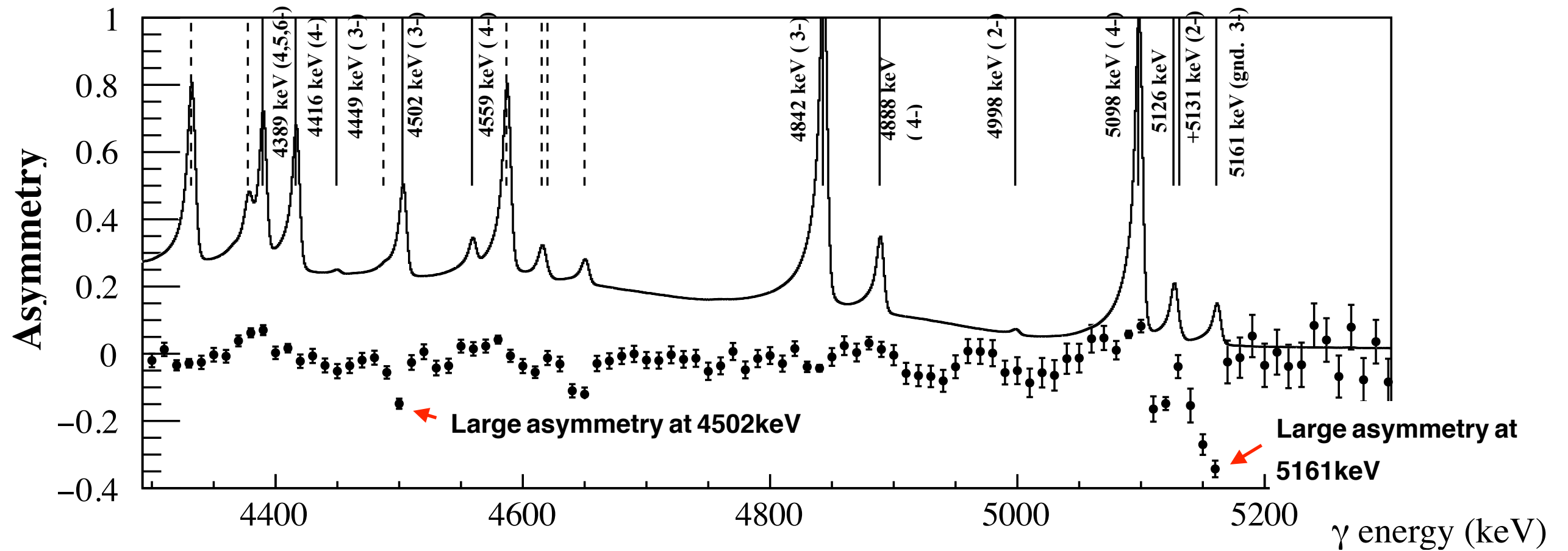
40% polarized neutron beam at 0.74eV was obtained with ³He spin filter



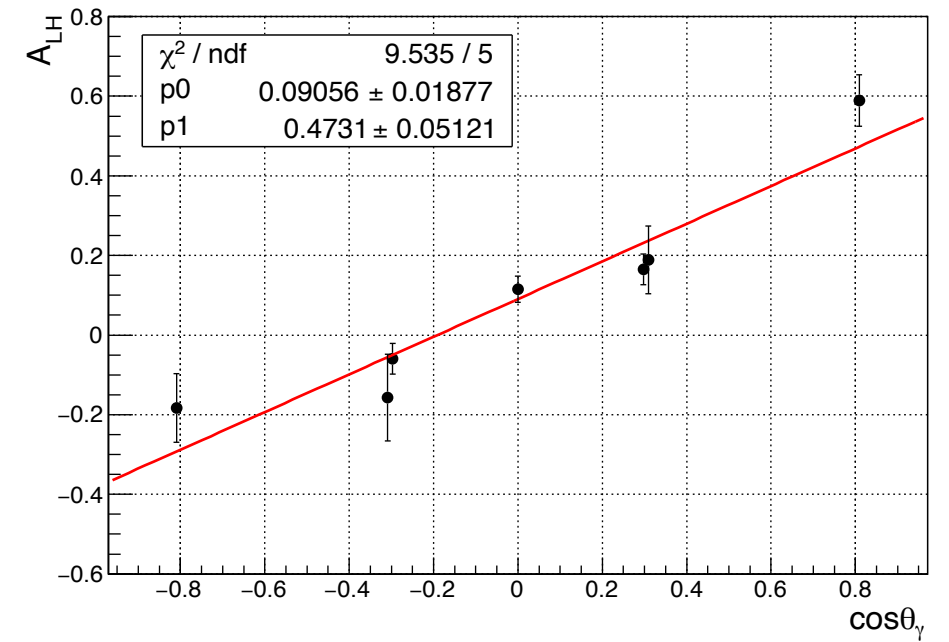
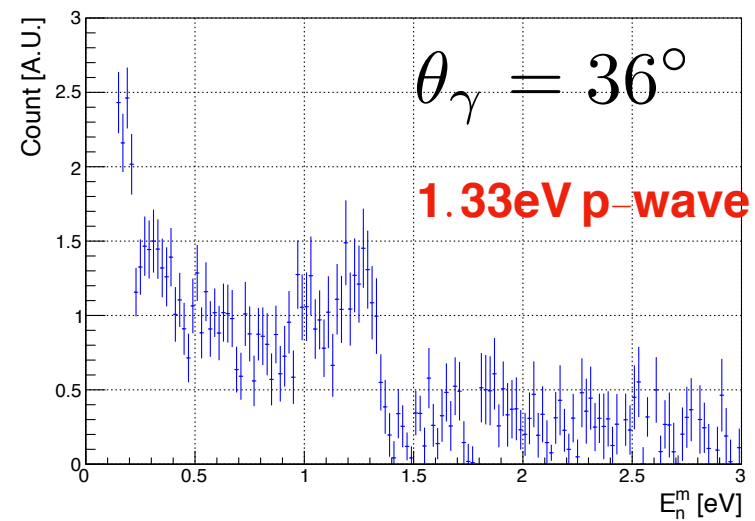
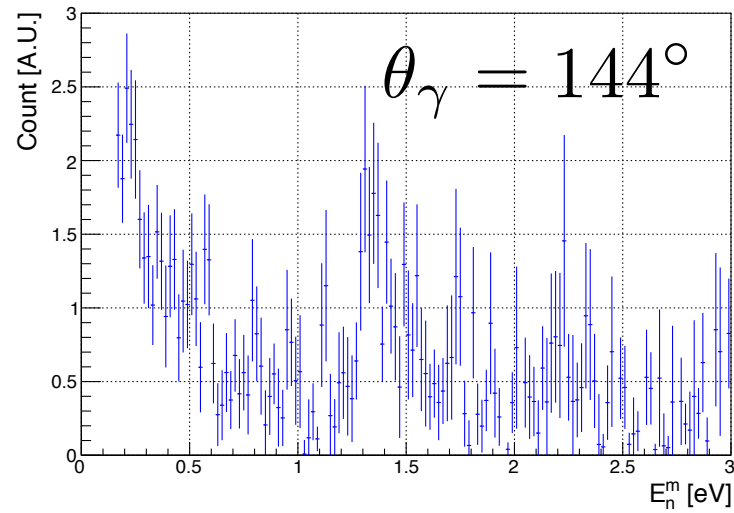
T. Yamamoto et. al. , Phys. Rev. C97 (2020) 034622.

T. Yamamoto Ph.D thesis (2020), Nagoya Univ.

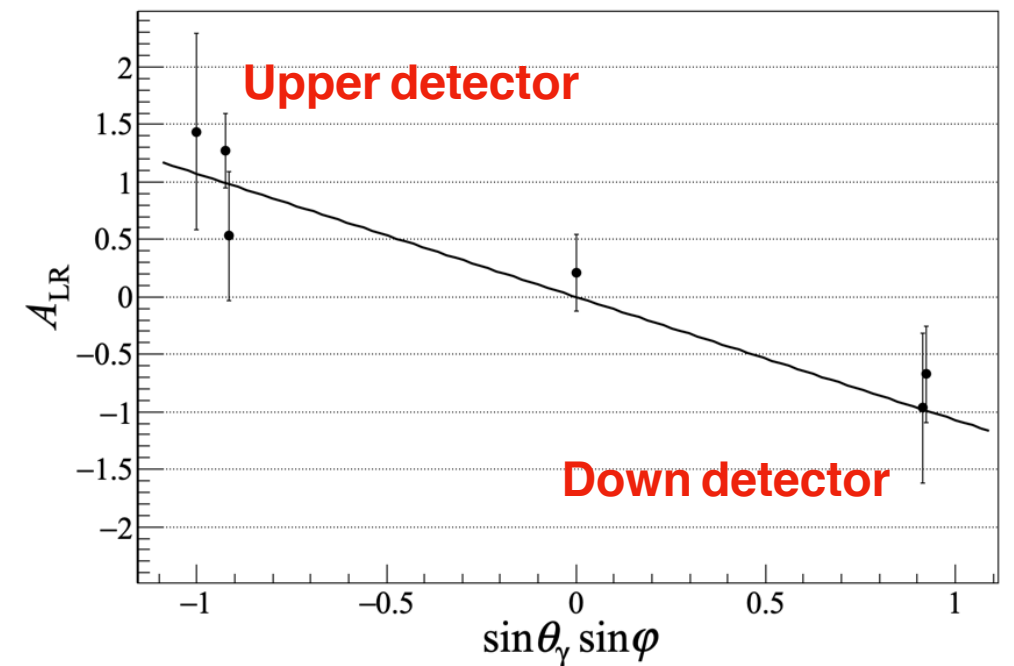
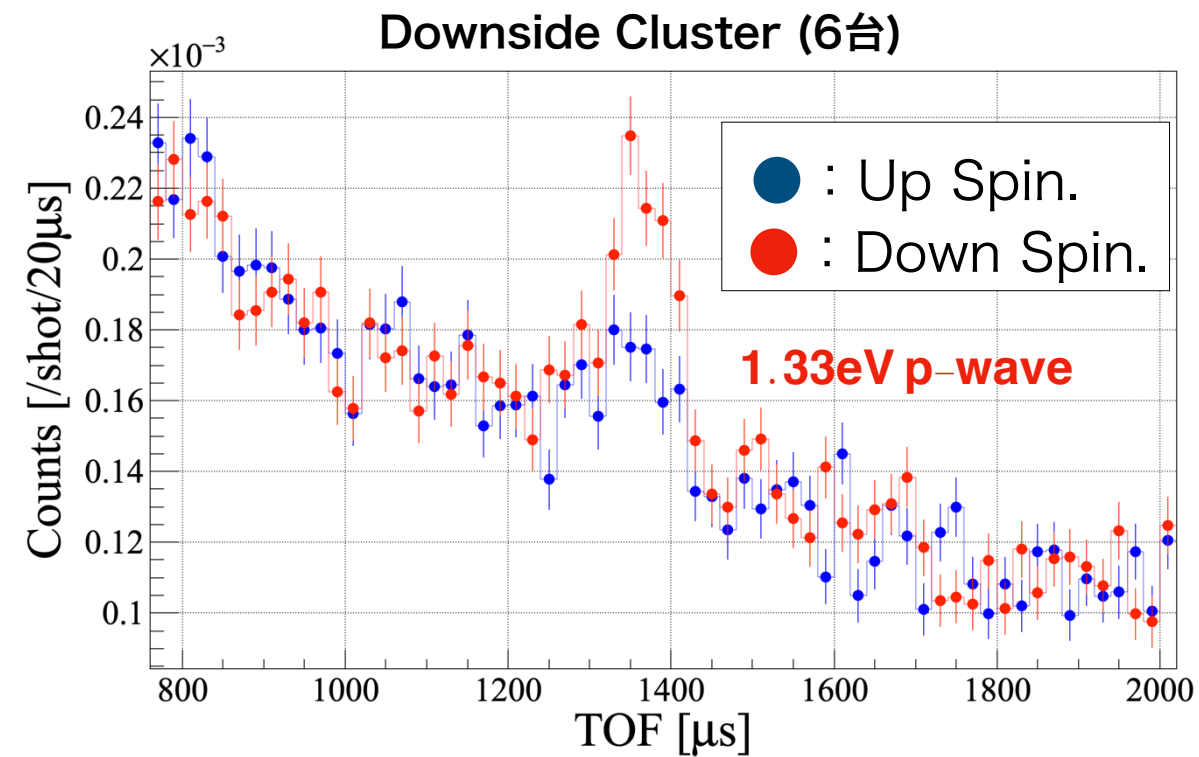
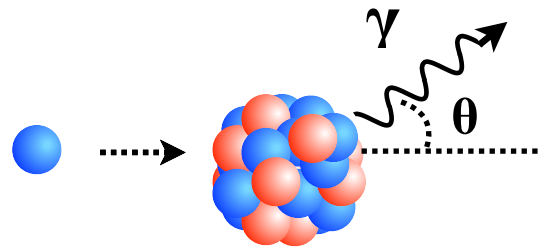
Angular distribution of $^{139}\text{La}(n,\gamma)^{140}\text{La}^*$



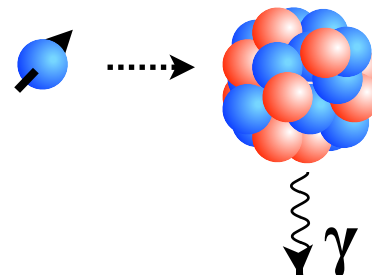
Angular distribution of $^{117}\text{Sn}(n,\gamma)^{118}\text{Sn}_{\text{gnd}}$



J. Koga et. al. , Phys. Rev. C97 (2021) 034622.



S. Endo et. al. , Phys. Rev. C97 (2022) 034622.



Nuclides measured at ANNRI

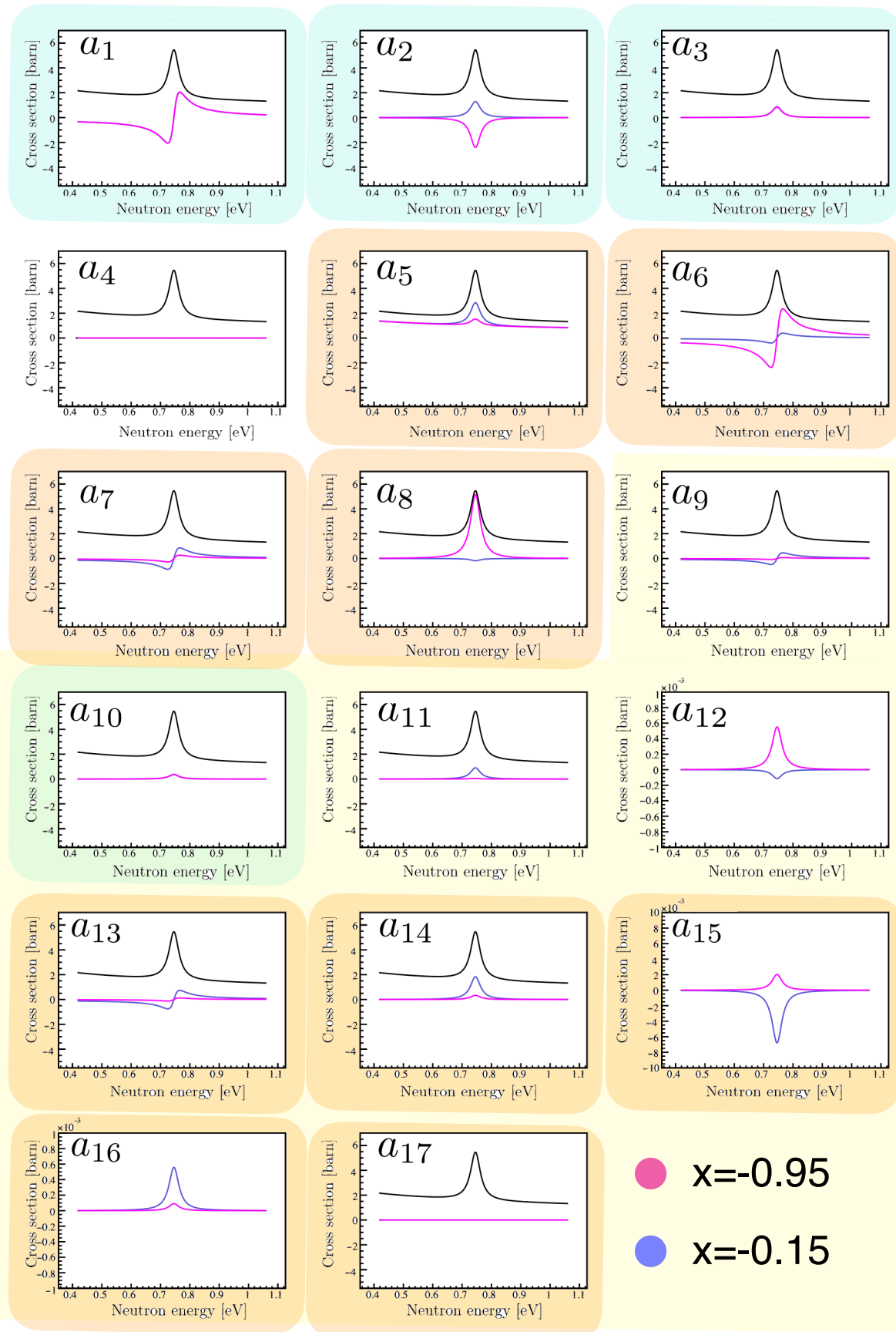
	En (eV)	P-violation (%)	A _{LH} (a ₁)	A _{LR} (a ₂)	A _{LH} (a ₃)
139La	0.74	9.8±0.2	-0.41±0.02 (ground) T.Okudaira, 2018 (Other 6 excited states) T.Okudaira 2020	0.73±0.14 (ground) T.Yamamoto, 2020	(0.29±0.04) (ground) T.Okudaira, 2018 N _L +N _H から計算
117Sn	1.33	0.79±0.04	0.47±0.05 (ground) J. Koga, 2021	1.1±0.2 (ground) S. Endo, 2022	-0.72 ± 0.40 (ground) J. Koga, 2021
81Br	0.88	2.1±0.1	-0.31±0.05 (291keV excited) H. Yosikawa, 2022	-0.31±0.05 Okuizumi 2023	-1.37±0.47 (291keV excited) H. Yosikawa, 2022
115In	6.85	-1.45±0.11	-0.17±0.13 (829keV, 813keV excited) S. Takada, 2022	-0.17±0.13	-1.1±1.2 (829keV, 813keV excited) S. Takada, 2022
131Xe	3.2	4.3±0.2	(0.15±0.04) (1803keV excited) T. Okudaira, 2022, P-waveのみ		
111Cd	4.53	-1.3	-0.063±0.043 (ground) Makise, 2020, Auton		
117I			Auton		

Only γ -ray spectrum : ^{109, 117}Ag, ¹³³Cs, ¹¹³Cd, ¹⁰³Rh

Published
Unpublished

Next plan of (n, γ) measurement

$^{139}\text{La}+n$ angular polarization for $F=4$



Measured

P-violating

γ -ray polarization

- P-violating term is small due to weak matrix element
- Measurement of γ -ray polarization is not easy due to low analyzing power of polarimeter

γ -ray polarization measurement

Magnetic Compton scattering

$$\sigma = 2\pi r_0^2 (\underbrace{\sigma_0}_{\text{Klein-Nishina term}} + \underbrace{SP\sigma_c \cos \alpha}_{\text{Magnetic term}})$$

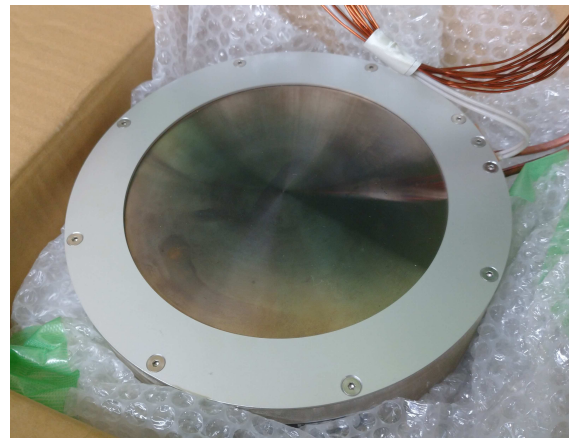
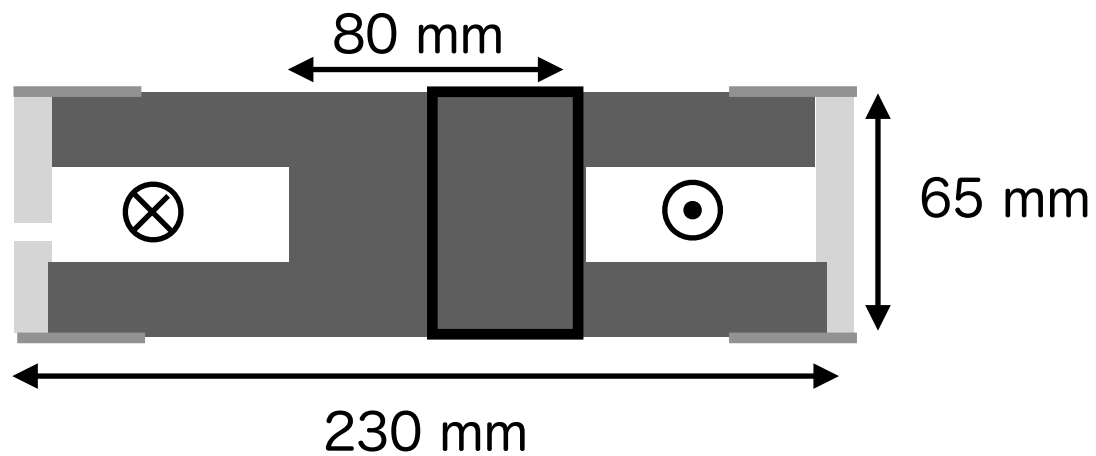
Klein-Nishina term

Magnetic term

S :Polarization of electrons

$P (= \lambda)$: γ -ray polarization

α :Angle between electron and γ -ray spins

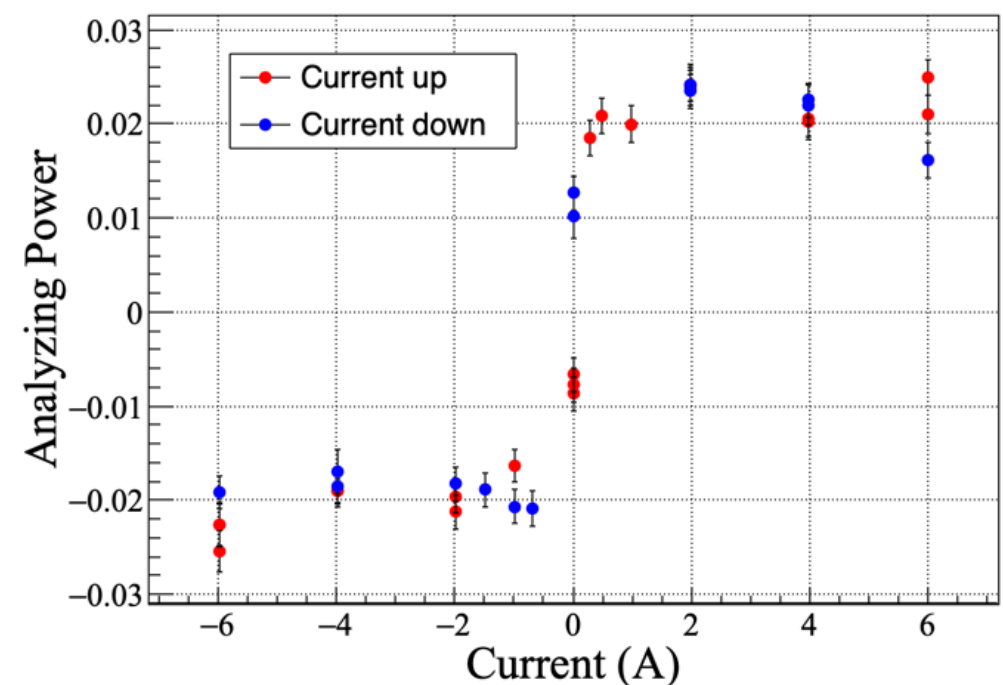


Test with polarized γ -ray beam at UVSOR

$$P_a = \frac{T^{\text{left pol}} - T^{\text{right pol}}}{T^{\text{left pol}} + T^{\text{right pol}}}$$

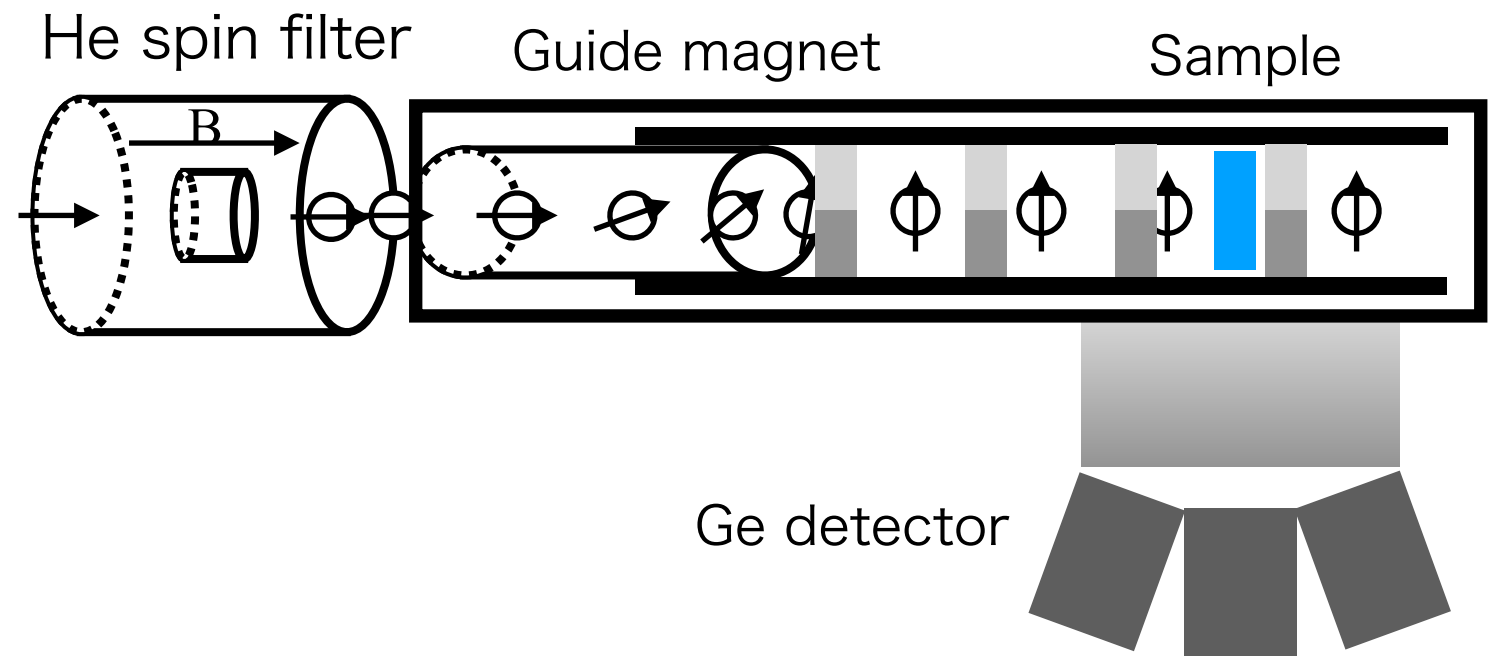
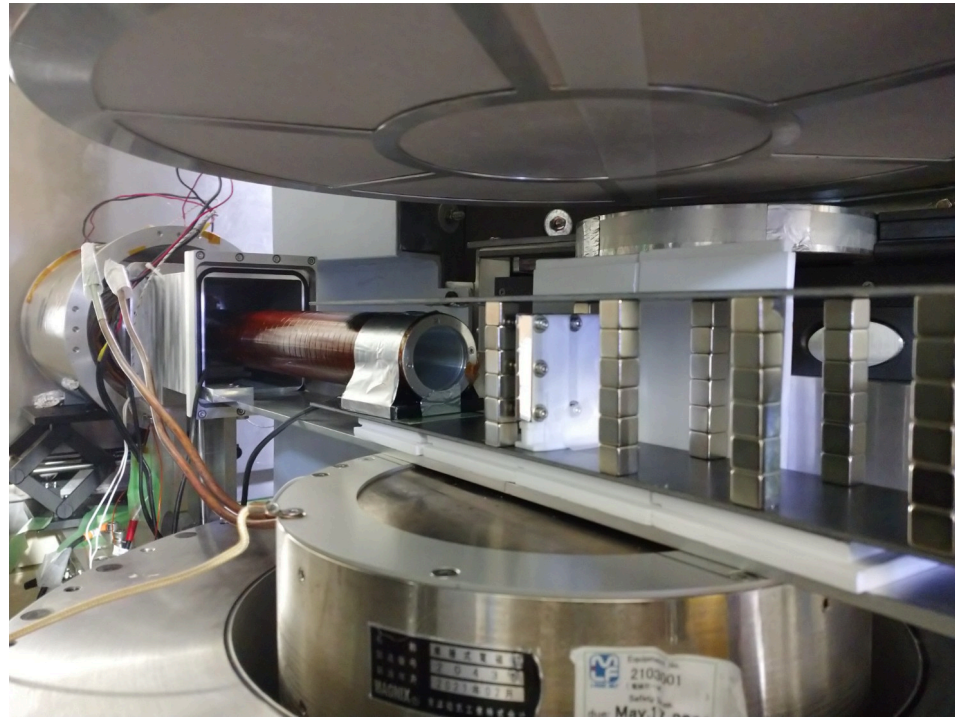
Analyzing Power

$$P_a = 2.12 \pm 0.04\%$$



γ -ray polarization measurement with $^{32}\text{S}(n,\gamma)^{33}\text{Sn}$

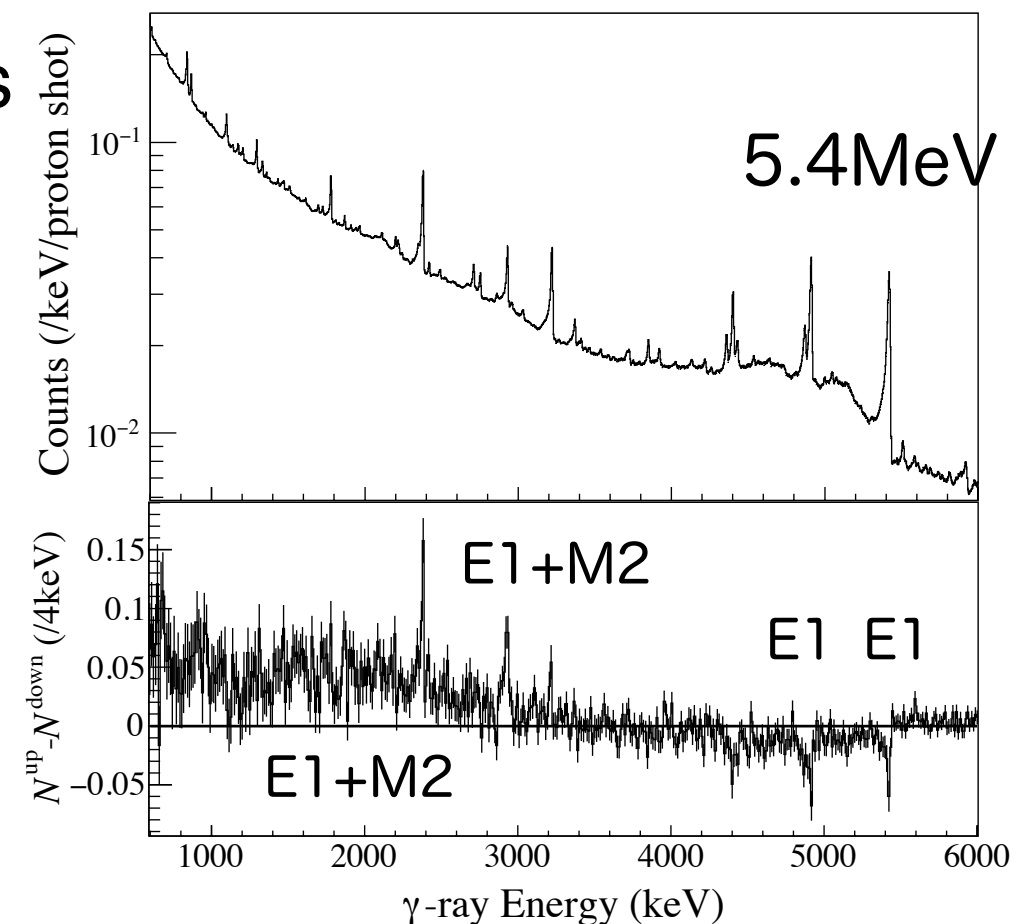
Test experiment at ANNRI beamline



γ -ray polarization for thermal polarized neutrons

γ -ray polarization depends on the transition type

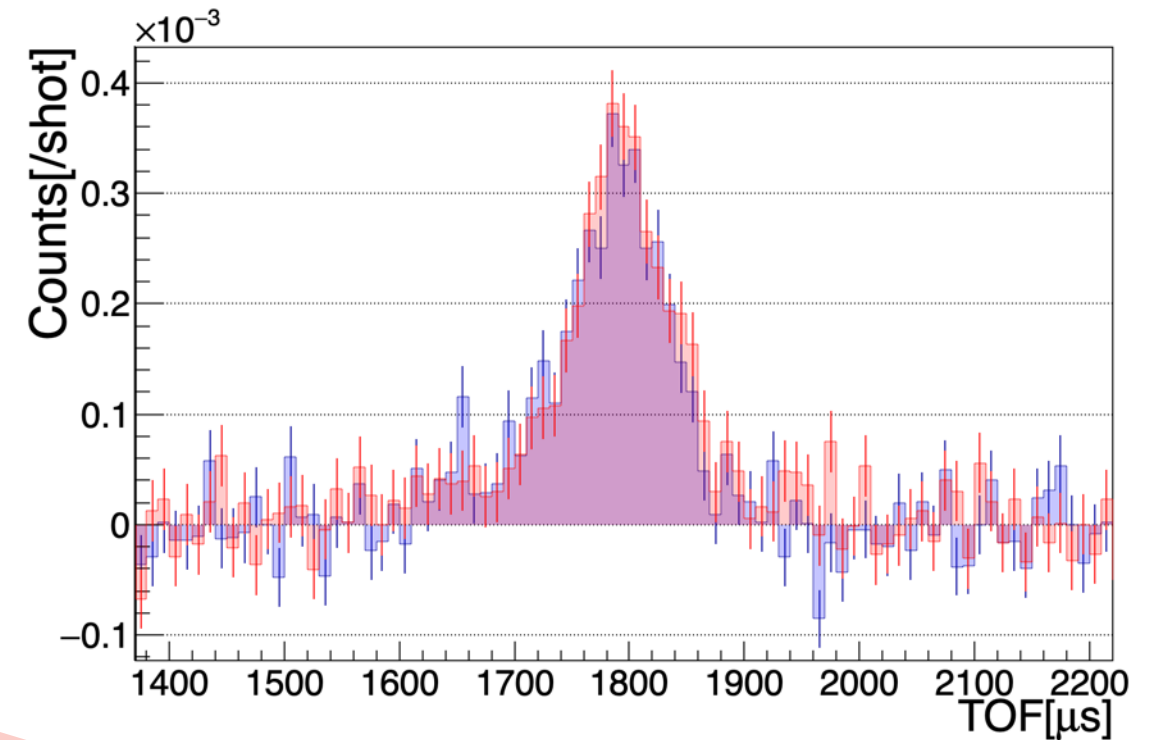
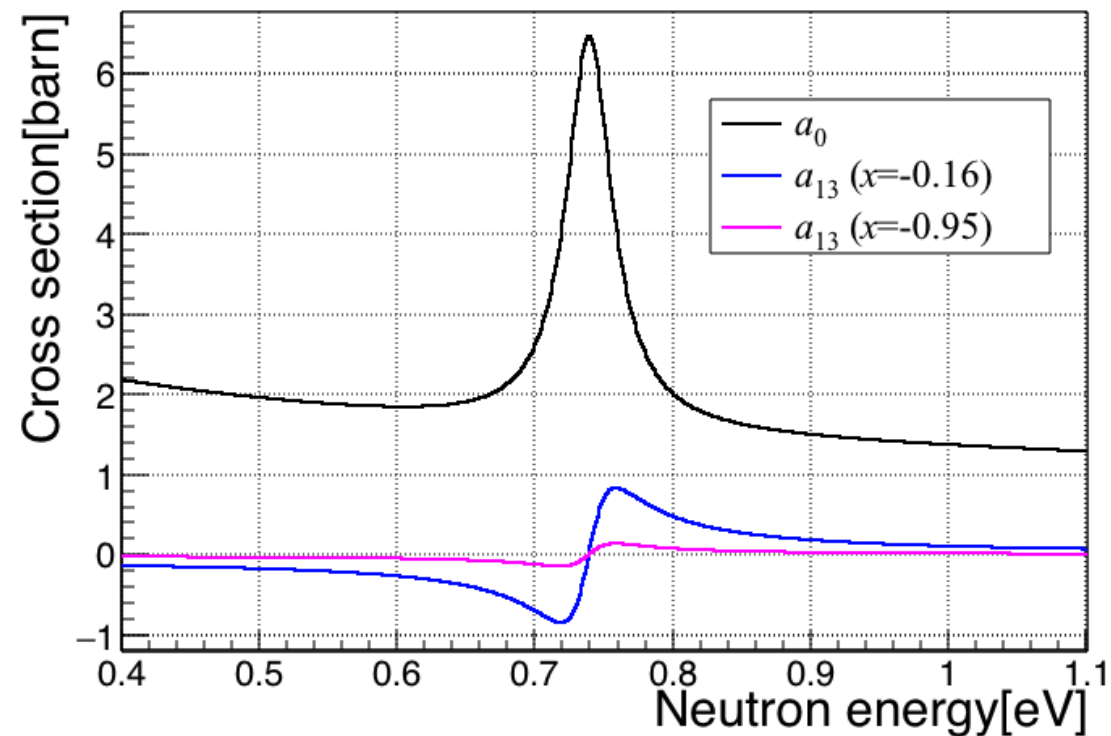
→ γ -ray multiplicity can be measured



γ -ray polarization measurement with $^{139}\text{La}(n,\gamma)^{140}\text{La}$

Parity violating γ -ray polarization with unpolarized neutrons

$$a_{13}\lambda$$



Preliminary

Plan for T-violation search

Fundamental T-violation in nucleon interaction



1. Selection of target nuclei with large enhancement of T-violation

→ First candidate : ^{139}La

T. Okudaira *et al.*, Phys. Rev. C. 97 034622 (2018) ^{139}La
T. Yamamoto *et al.* Phys. Rev. C. 101, 064624 (2020)
T. Okudaira *et al.*, Phys. Rev. C. 104, 014601(2021)

J. Koga *et al.*, Phys. Rev. C. **105**, 05461 (2022) ^{117}Sn
S. Endo *et al.*, Phys. Rev. C.106 064601 (2022)
T.Okudaira et al. arXiv:2212.10889 (2022) ^{131}Xe



2. Neutron polarization device

→ ^3He spin filter for $\sim 0.74\text{eV}$

80% ^3He polarization!!

T. Okudaira *et al.*, NIM A 977, 164301 (2020)

3. Polarized La target

→ Dynamic nuclear polarization

30% ^{139}La polarization!

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

4. Neutron detector

D. Schaper *et al.*, NIM A 969, 163961 (2020)

**U.S. NOPTREX
RCNP**

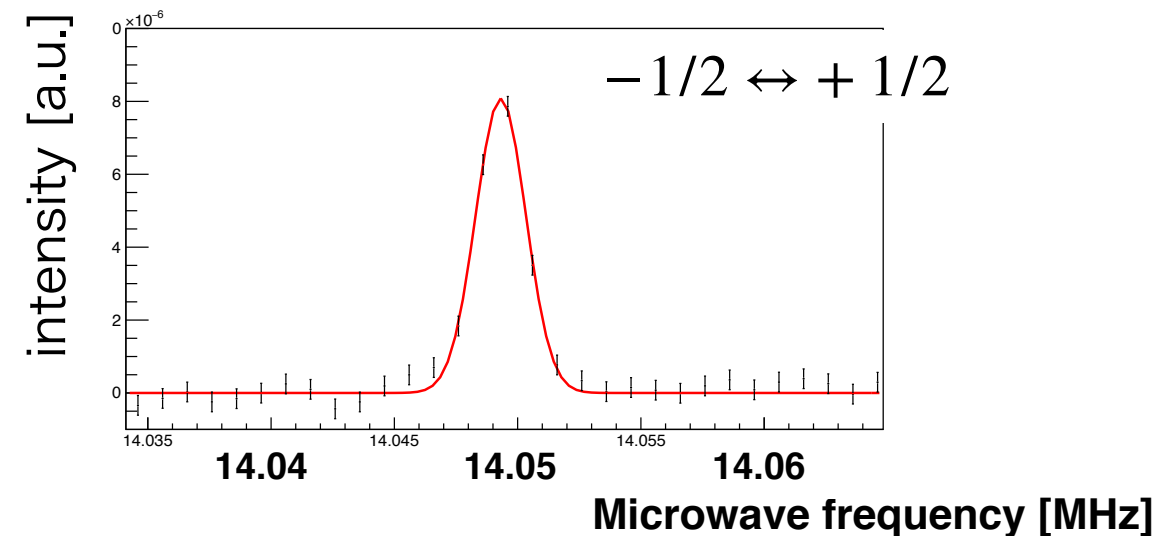
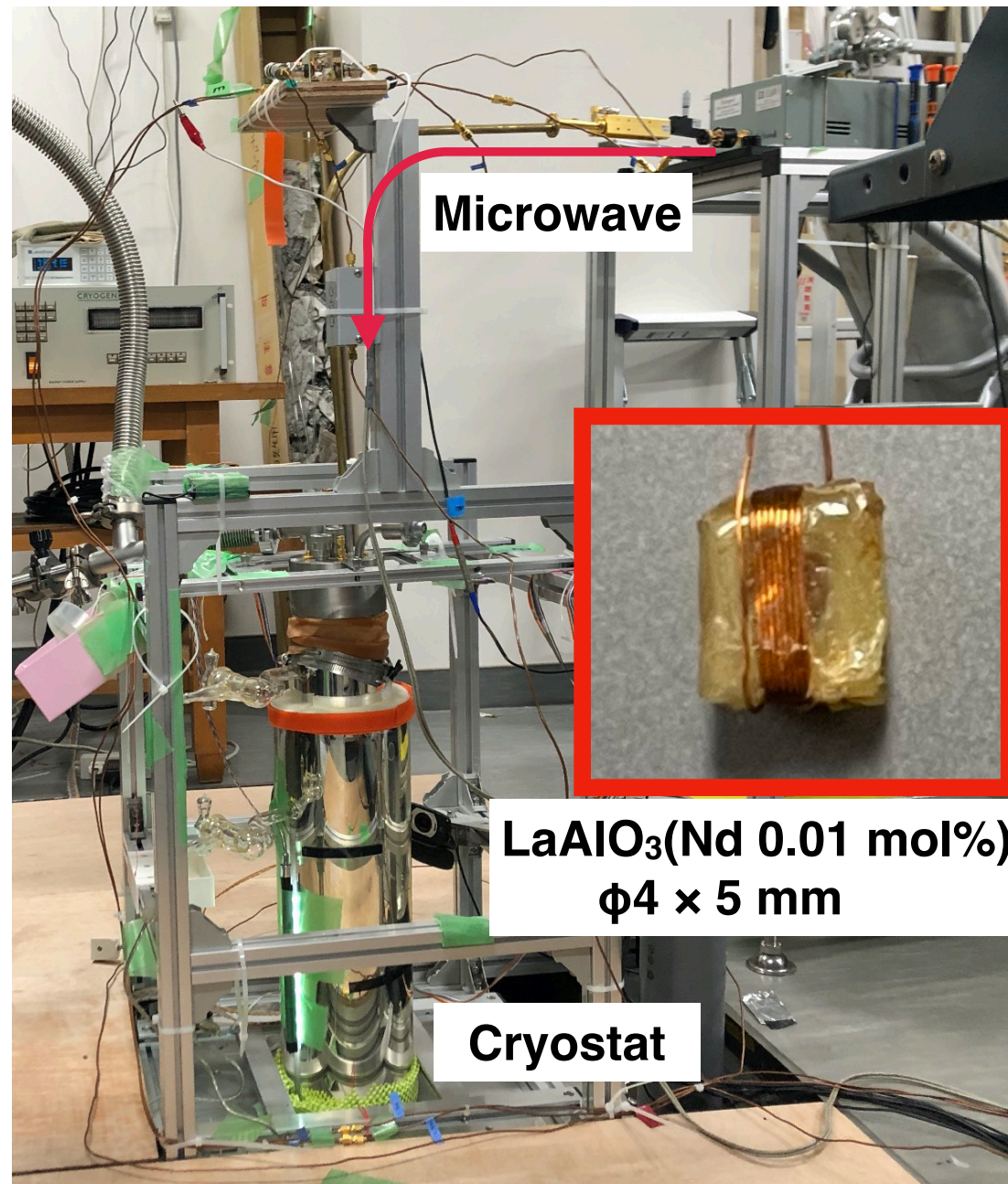
Key technique : Nuclear polarization

Development of polarized nuclear target

DNP experiment using LaAlO_3 crystal fabricated in Tohoku Univ.

Temperature ~ 1.5 K

Magnetic field ~ 2.3 T at Yamagata Univ.



Achievable ^{139}La polarization : $P(t \rightarrow \infty) \sim 31.9 \% !$

Time [min]

→ Higher La polarization with large LaAlO_3

Experiment using polarized La and neutrons

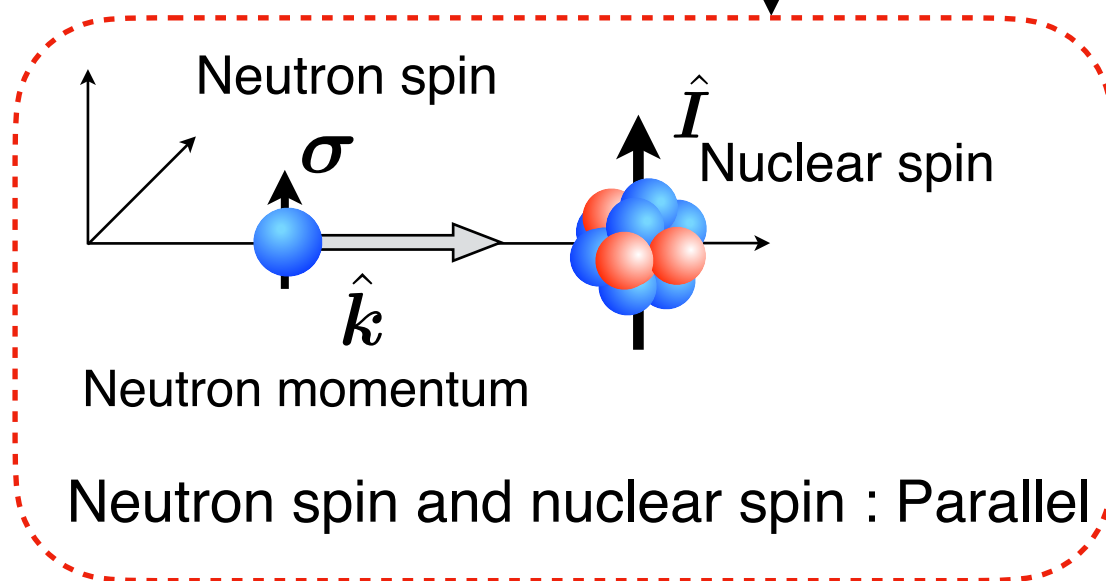
$$f = \underbrace{A'}_{\text{Normal cross section (Measured)}} + \underbrace{B'\sigma \cdot \hat{I}}_{\text{Spin dependence (Unmeasured)}} + \underbrace{C'\sigma \cdot \hat{k}}_{\text{P-violation (Measured)}} + \underbrace{D'\sigma \cdot (\hat{I} \times \hat{k})}_{\text{T-violation (Final goal)}}$$

Normal cross
section
(Measured)

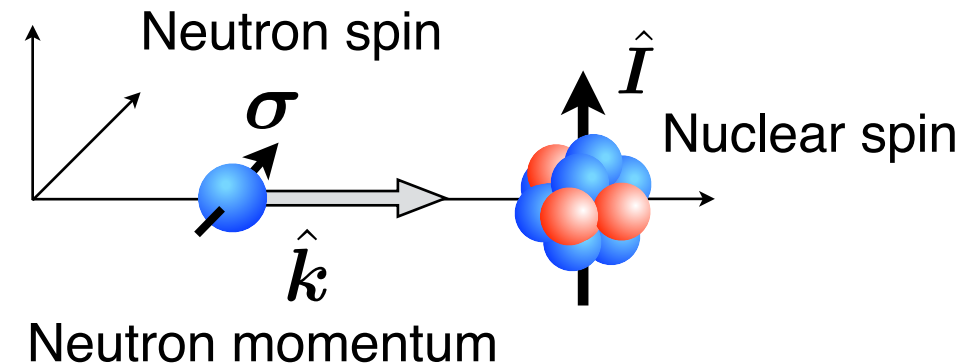
**Spin dependence
(Unmeasured)**

P-violation
(Measured)

**T-violation
(Final goal)**

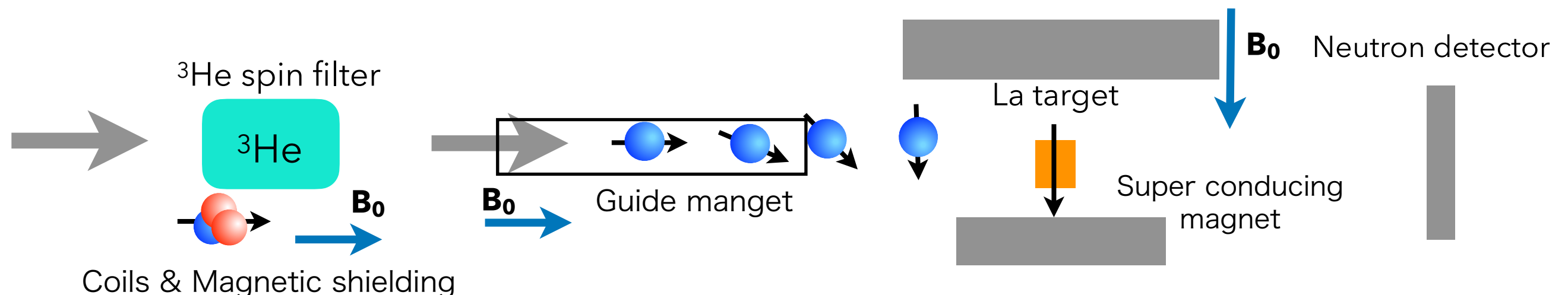


Systematic error in T-violation



Neutron spin and nuclear spin : Vertical
* With existing equipment, neutron spins rotate by applied magnetic fields

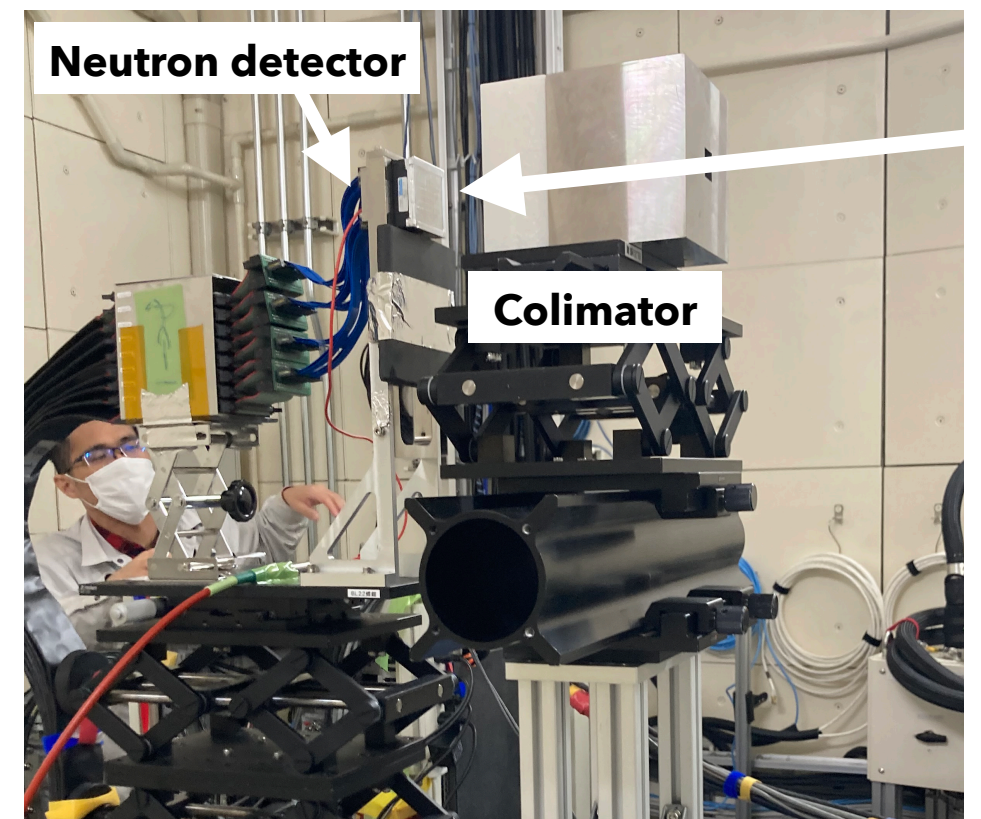
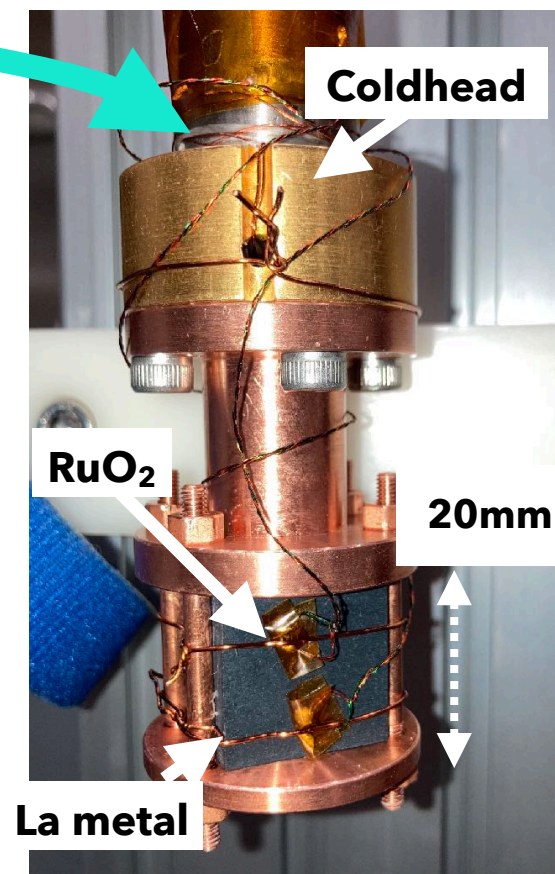
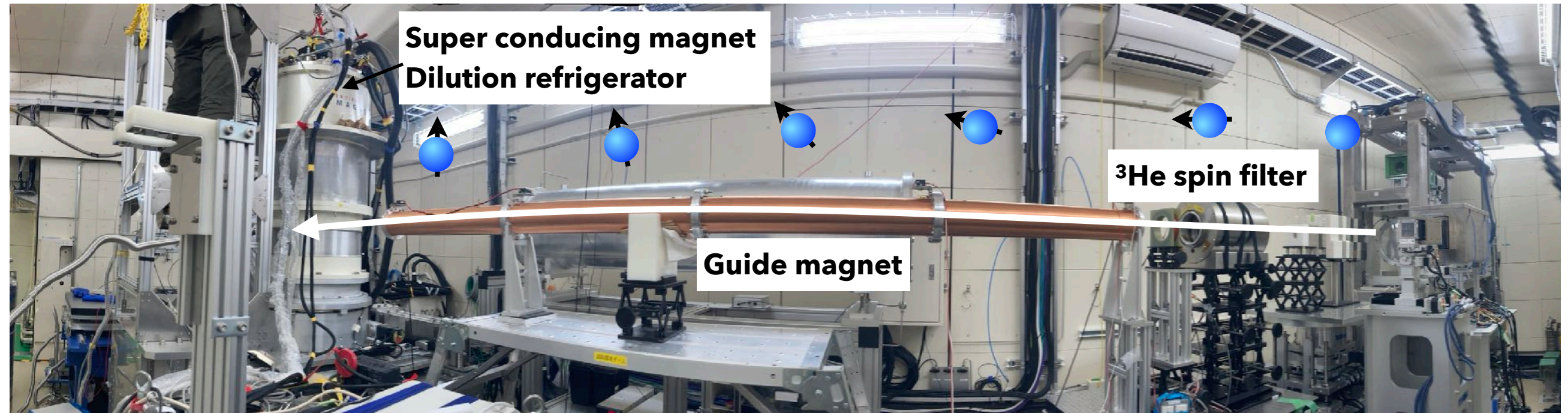
Spin dependent cross section measurement using static nuclear polarization



60mK dilution refrigerator, 7T super conducting magnet

68mK, 6.7T $\rightarrow$ ^{139}La polarization : 4.4%

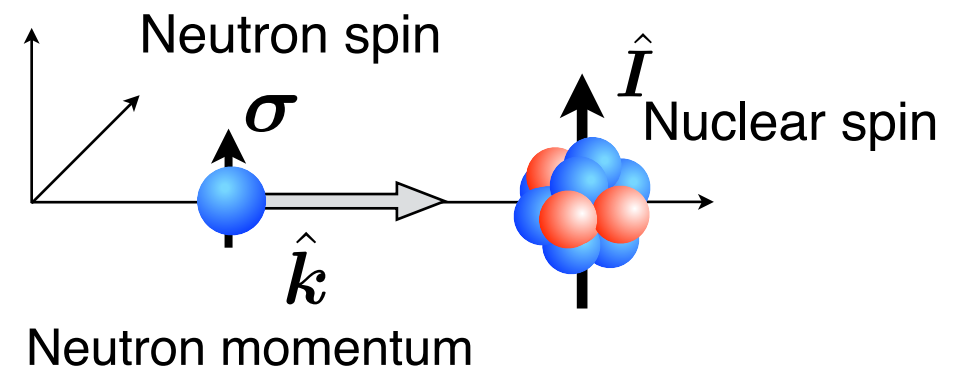
Experiment using polarized La and neutrons



Experiment using polarized La and neutrons

Asymmetry of transmitted neutrons
for parallel and anti-parallel spins

$$A_s = \frac{N_P - N_A}{N_P + N_A}$$



**Successfully measured spin-
dependent cross section!**

To be published...

Neutron counts/ μ s

^{138}La
2.99 eV s-wave

^{139}La
0.74 eV p-wave

p-wave resonance!



67mK
($P_{\text{La}}=4.4\%$)

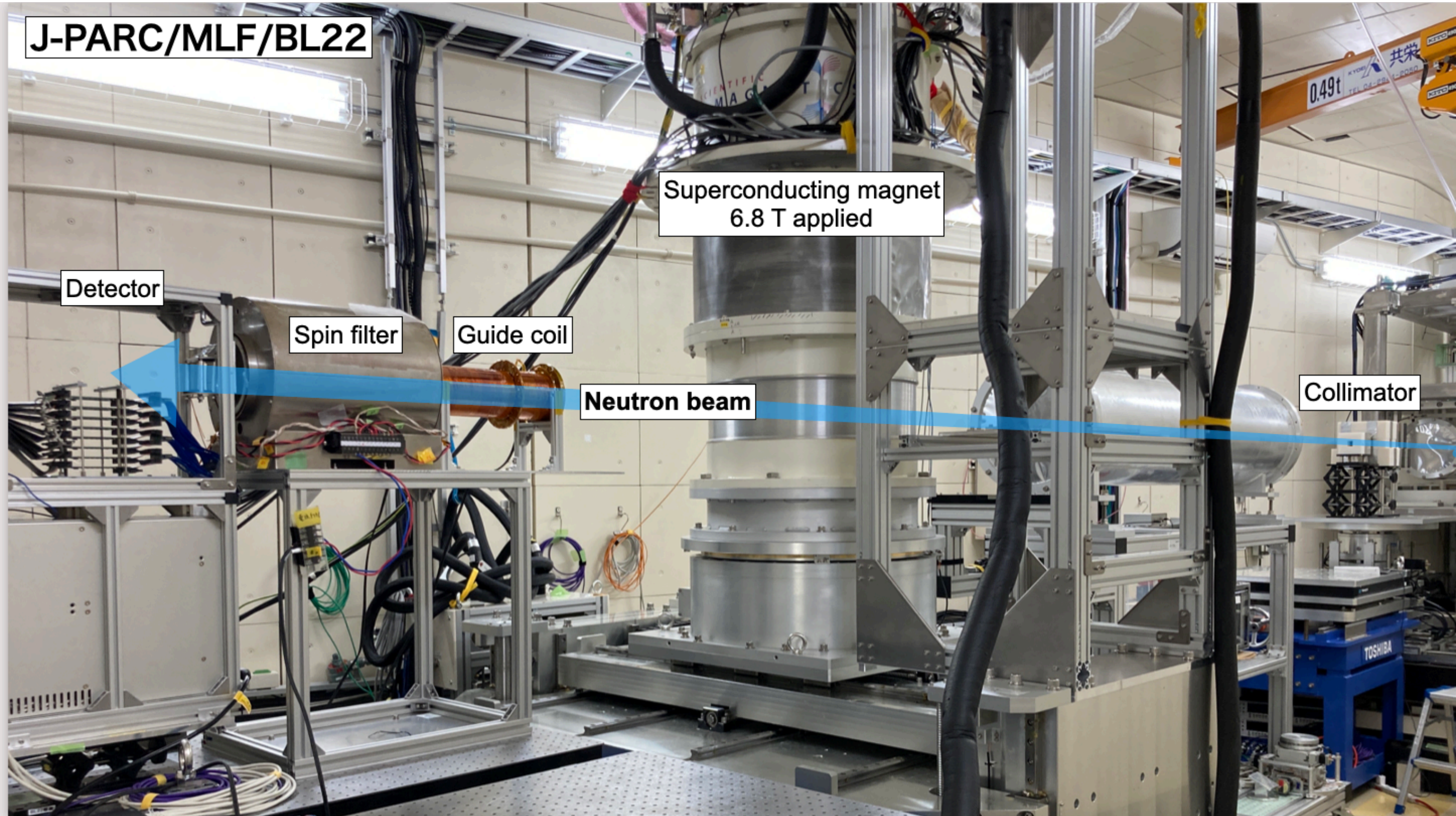
1 K ($P_{\text{La}}=0.3\%$)

Time of flight [ms]

Spin dependent asymmetry

Big Milestone for T-violation search!

Next experiment : polarization ability of polarized La target



Papers

1. Characterization of germanium detectors for the measurement of the angular distribution of prompt γ -rays at the ANNRI in the MLF of the J-PARC

Journal of Instrumentation 13 (2018) 2, S. Takada et al.

2. Angular Distribution of γ -rays from Neutron-Induced Compound States of ^{140}La

Phys. Rev. C 97 (2018) 034622, T. Okudaira et al.

3. Development and application of a ^3He Neutron Spin Filter at J-PARC

Nucl. Instrum. Methods Phys. Res., Sect. A, 977 (2020) 164301, T. Okudaira et al.

4. Transverse asymmetry of γ -rays from neutron-induced compound states of ^{140}La

Phys. Rev. C 101 (2020) 064624, T. Yamamoto et al.

5. Energy dependent angular distribution of individual γ -rays in the $^{139}\text{La}(n, \gamma)^{140}\text{La}^*$ reaction

Phys. Rev. C. 104 (2021) 014601, T. Okudaira et al.

6. **NIM A1020, 165845 (2021) Ishizaki et al.**

7. Angular distribution of γ rays from the p-wave resonance of ^{118}Sn ,

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

8. Measurement of the transverse asymmetry of γ rays in the $^{117}\text{Sn}(n, \gamma)^{118}\text{Sn}$ reaction

Phys. Rev. C.106 (2022) 064601, S. Endo et al.

9. Angular distribution of γ -rays from a neutron-induced p-wave resonance of ^{132}Xe

Phys. Rev. C 107, (2023) 054602, T. Okudaira et al.

PhD. thesis

1. 2018 Nagoya University. T. Okudaira

2. 2020 Nagoya University T. Yamamoto

3. 2020 Kyushu University J. Koga

4. 2022 Kyushu University S. Takada

Summary

- **T-violation search using enhancement mechanism in neutron induced compound nuclei**

- **Selection of candidate nuclei**

Angular correlations are measured with several nuclei

Undiscovered angular correlations were found and $\kappa(J)$ is determined by (n,γ) reactions

→ γ -ray polarization measurement

- **Experiment using polarized neutrons and polarized La**

→ γ -ray polarization measurement