Current Status for the search of time-reversal symmetry violation using compound nuclear reactions

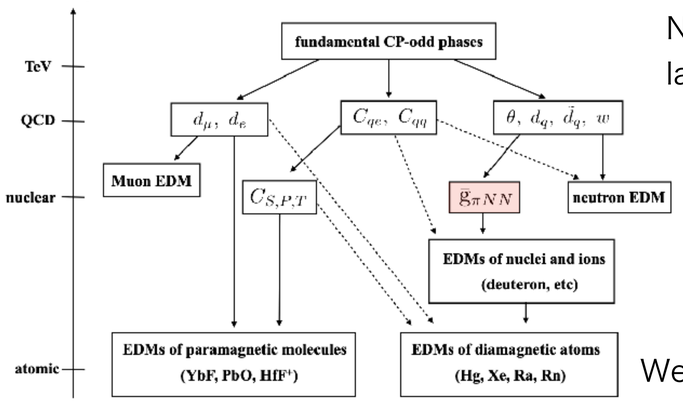
S. Endo[1,2], H. Fujioka[3], I. Ide[1], M. Iinuma[4], Y. Ito[1], K. Kameda[3], S. Kawamura[1], A. Kimura[2], M. Kitaguchi[1], T. Oku[2], T. Okudaira[1], K. Sakai[2], T. Shima[5], H. M. Shimizu[1], S. Takada[6], H. Yoshikawa[5], T. Yoshioka[7], NOPTREX collaboration

1) Nagoya University, 2) Japan Atomic Energy Agency, 3) Tokyo Institute of Technology, 4) Hiroshima University, 5) Osaka University, 6) Tohoku University, 7) Kyushu University

NOPTREX
Neutron Optical Parity and Time-Reversal EXperiment

Introduction

The existence of CP-violation(CPV) beyond the Standard Model is necessary to explain the matter-dominated universe.



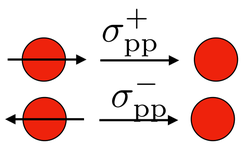
Neutron EDM measurement[1] gives the latest best limit for the CPV.

- It has been measured by various groups for more than 50 years.
- Measurement with different systematic uncertainty is significant.

We focus on the CPV in nuclear reactions.

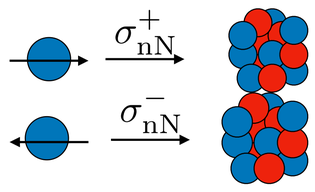
Enhancement of Parity-violation (PV) in compound nuclear reactions[2]

Polarized proton proton scattering



$$\frac{\sigma^+_{pp}-\sigma^-_{pp}}{\sigma^+_{pp}+\sigma^-_{pp}} \sim 10^{-7}$$

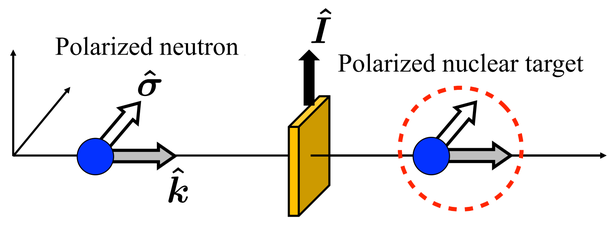
Polarized neutron nucleon scattering



$$\frac{\sigma^+_{nN}-\sigma^-_{nN}}{\sigma^+_{nN}+\sigma^-_{nN}} \sim 10^{-1}$$

This enhancement is understood to be the results of the mixing between s-wave and p-wave resonances (s-p mixing). It is suggested that the time-reversal violation (corresponding to CPV by the CPT theorem) is enhanced by the same principle[3].

Schematic of the T-violation search experiment



Forward-scattering amplitude

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

P-even T-even | P-odd T-even | P-odd T-odd

C term is P-violating cross-section mentioned above.

Measurement

(1) Search for candidate nuclei
(2) Fundamental study of enhancement mechanism
(3) Forward scattering amplitude (B and D terms)

Development

(4) Neutron Polarizer
(5) Polarized nuclear target
(6) Neutron detector

Strategy and current status of progress ("Done" is today's topic)

(1)	^{139}La Done; ^{117}Sn Done; ^{131}Xe, ^{81}Br, ^{115}In In progress
(2)	Correlation term of (n,γ) reaction[4]: ^{139}La, ^{117}Sn, ^{131}Xe — a_1 Done, Done, Done; a_2 Done, Done, Done; a_{13} Done; a_6 In progress → Theoretical Interpretation of T-violation
(3)	C term (Parity-violation) Done → ImB term (Pseudo-Magnetism in polarized target) Done → ReB term In progress → D term (T-violation)
(4)	Off-situ SEOP → In-situ SEOP
(5)	Crystal growth and quality study; DNP test with existing cryostat; Development of Cryostat and DNP system
(6)	R&D → Upgrade to 1GHz

[1] C. Abel et al., Phys Rev. Lett. 124, 081803 (2020), [2] G. E. Mitchell et al., Phys. Rep. 354, 157 (2001). [3] V. P. Gudkov, Phys. Rep. 212, 77 (1992).
[4] V. V. Flambaum and O. P. Sushkov, Nucl. Phys. A 435, 352 (1985).

Correlation term measurement

(1) and (2) are achieved by measuring the correlation term of (n, γ) reactions.

Differential cross-section

$$\frac{d\sigma}{d\Omega} = \frac{1}{2}\Big\{a_0 + a_1\boldsymbol{k}_n\cdot\boldsymbol{k}_\gamma + a_2\boldsymbol{\sigma}_n\cdot(\boldsymbol{k}_n\times\boldsymbol{k}_\gamma) + a_3\left((\boldsymbol{k}_n\cdot\boldsymbol{k}_\gamma)^2-\frac{1}{3}\right)$$
$$+a_4(\boldsymbol{k}_n\cdot\boldsymbol{k}_\gamma)(\boldsymbol{\sigma}_n\cdot(\boldsymbol{k}_n\times\boldsymbol{k}_\gamma)) + a_5\lambda(\boldsymbol{\sigma}_n\cdot\boldsymbol{k}_\gamma) + a_6\lambda(\boldsymbol{\sigma}_n\cdot\boldsymbol{k}_n)$$
$$+a_7\lambda\left((\boldsymbol{\sigma}_n\cdot\boldsymbol{k}_\gamma)(\boldsymbol{k}_\gamma\cdot\boldsymbol{k}_n)-\frac{1}{3}(\boldsymbol{\sigma}_n\cdot\boldsymbol{k}_n)\right) + a_8\lambda\left((\boldsymbol{\sigma}_n\cdot\boldsymbol{k}_n)(\boldsymbol{k}_n\cdot\boldsymbol{k}_\gamma)-\frac{1}{3}(\boldsymbol{\sigma}_n\cdot\boldsymbol{k}_\gamma)\right)$$
$$+a_9\boldsymbol{\sigma}_n\cdot\boldsymbol{k}_\gamma + a_{10}\boldsymbol{\sigma}_n\cdot\boldsymbol{k}_n + a_{11}\left((\boldsymbol{\sigma}_n\cdot\boldsymbol{k}_\gamma)(\boldsymbol{k}_\gamma\cdot\boldsymbol{k}_n)-\frac{1}{3}(\boldsymbol{\sigma}_n\cdot\boldsymbol{k}_n)\right)$$
$$+a_{12}(\boldsymbol{\sigma}_n\cdot\boldsymbol{k}_n)\left((\boldsymbol{k}_n\cdot\boldsymbol{k}_\gamma)-\frac{1}{3}(\boldsymbol{\sigma}_n\cdot\boldsymbol{k}_\gamma)\right) + a_{13}\lambda + a_{14}\lambda(\boldsymbol{k}_n\cdot\boldsymbol{k}_\gamma)$$
$$+a_{15}\lambda\boldsymbol{\sigma}_n\cdot(\boldsymbol{k}_n\times\boldsymbol{k}_\gamma) + a_{16}\lambda\left((\boldsymbol{k}_n\cdot\boldsymbol{k}_\gamma)^2-\frac{1}{3}\right) + a_{17}\lambda(\boldsymbol{k}_n\cdot\boldsymbol{k}_\gamma)(\boldsymbol{k}_n\cdot(\boldsymbol{k}_n\times\boldsymbol{k}_\gamma))\Big\}$$

unit vector parallel to …
$\boldsymbol{k}_n$: incident neutron momentum
$\boldsymbol{k}_\gamma$: emitted γ-ray momentum
$\boldsymbol{\sigma}_n$: neutron spin

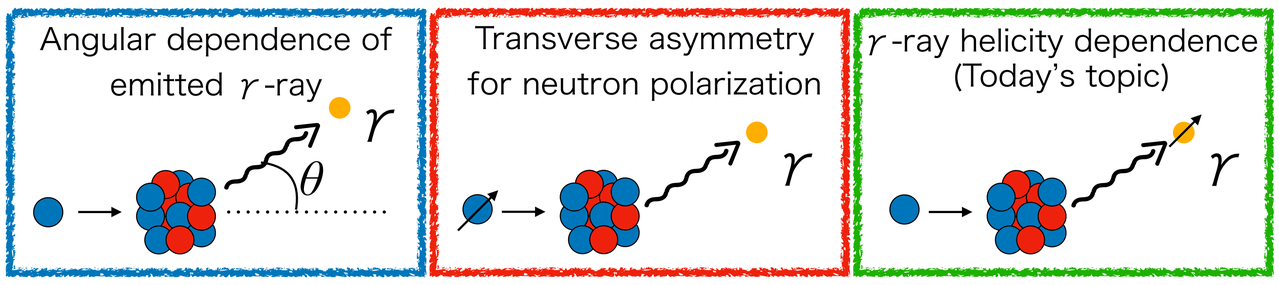
λ : γ-ray helicity

The coefficients a_1~a_{17} can be described using one unknown parameter, φ_p, and resonance parameters based on the s-p mixing model. The parameter is defined as:

$$x = \sqrt{\frac{\Gamma_{n,j=1/2}}{\Gamma_n}} = \cos\phi_p \quad y = \sqrt{\frac{\Gamma_{n,j=3/2}}{\Gamma_n}} = \sin\phi_p$$

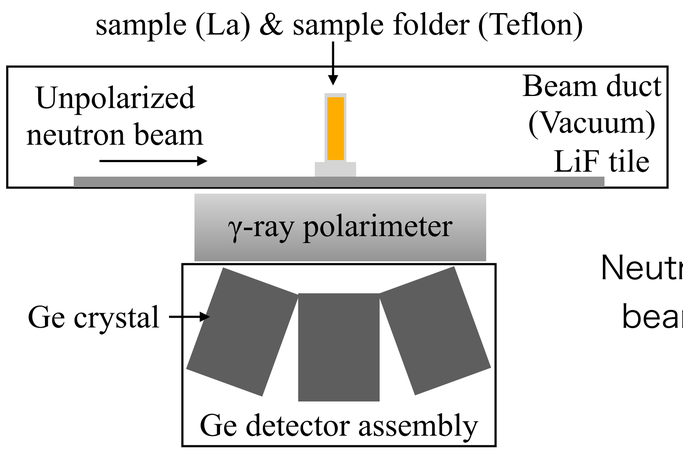
$\Gamma_{n,j=1/2}$: partial width for neutrons with total angular momentum j=1/2

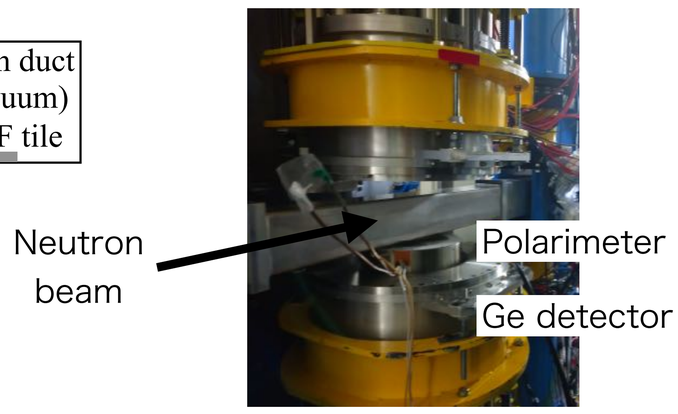
φ_p is significant to
- determine T-violation enhancement factor depending on φ_p
- verify the s-p mixing model by comparing the φ_p (or x and y) value



T. Okudaira et al. Phys. Rev. C 97, 034622 (2018) T. Yamamoto et al. Phys. Rev. C 101, 064624 (2020)

Experimental setup at J-PARC・MLF・BL04(ANNRI)





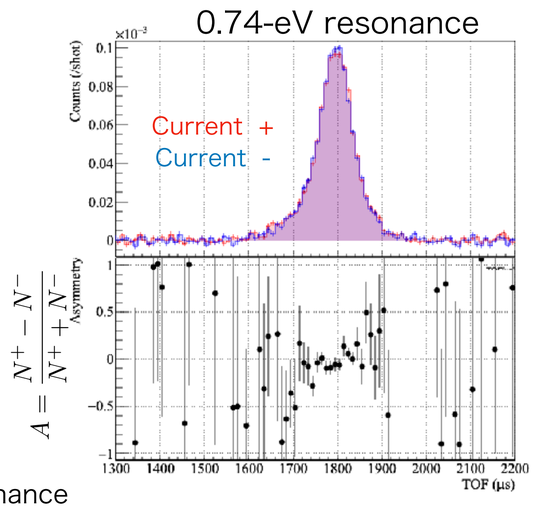
Results

The right figure shows the TOF spectra for current + and - of the polarimeter (top) and the asymmetry for the current + and - (bottom). If cross-section depends on the helicity, the non-zero asymmetry is observed.

Since a_{13} term is expected to have an asymmetric energy dependence with respect to the resonance center, we derived the asymmetry A_{LH} defined as $A_{LH} = \frac{N_L - N_H}{N_L + N_H}$.

N_{LH} (N_H) is the integral value of left (right) side of resonance

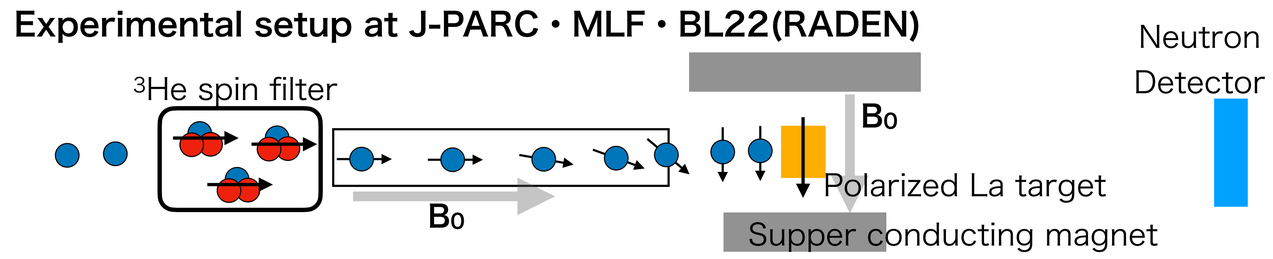
$\Delta A_{LH} = A^+_{LH} - A^-_{LH} = -0.0101 \pm 0.0088$ was obtained.



ImB term measurement

As a milestone toward the T-violation experiment, the ImB term was measured using static nuclear polarization method. Although the T-violation experiment requires a highly polarized nuclear target with DNP, the ImB term can be measured using an existing static nuclear polarization device.

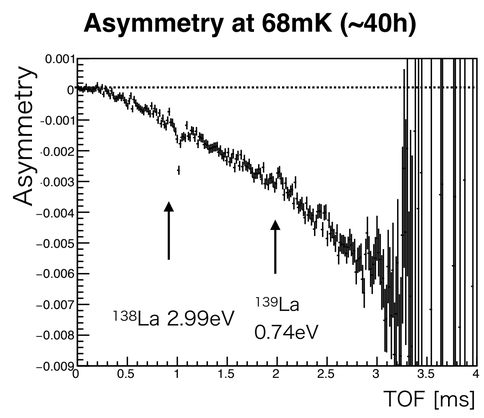
Experimental setup at J-PARC・MLF・BL22(RADEN)



Neutron polarization : 30~40% @0.74 eV Nuclear Polarization ~ 4.3% (6.8 T, 68 mK)

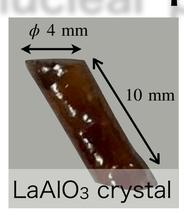
Results

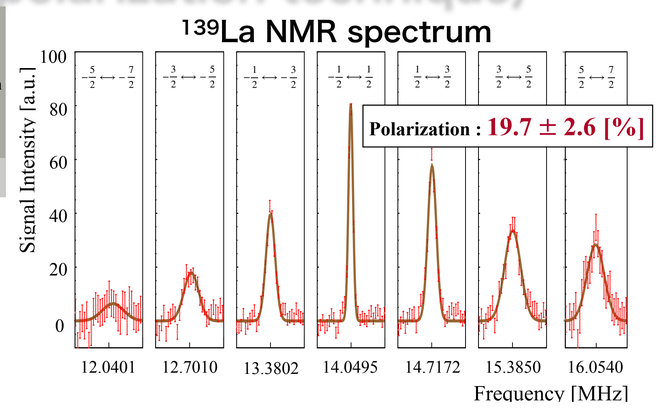
The right figure shows the asymmetry of the transmission for neutron spin up and down. For s-wave resonances, the total angular momentum of resonance can be determined directly from this measurement. For p-wave, φ_p can be determined. A detailed analysis is in progress and will be published soon.



Development (nuclear polarization technique)

On a polarization technique of La in Nd^{3+}:$LaAlO_3$ crystal, we have succeeded in growing $LaAlO_3$ crystals with different Nd concentrations. ^{139}La polarization enhanced up to ~20%. by Dynamic Nuclear Polarization (DNP) at mag. field 2.5 T, temp. 1.3 K.





Summary

We aim to search for time-reversal symmetry breaking using compound nuclear reactions. Measurements and development are being carried out in parallel.

- Correlation term : a_{13} term was done adding a_1 and a_2 terms.
- Forward-scattering amplitude : ImB term was done using polarized nucleus.
- Polarized nuclear target : La polarization of ~20% was achieved by Nd doping.