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T-violation in neutron scattering

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The fundamental symmetry violation can be studied by using nuclear reactions with polarized neutron beam and target nuclei. The large enhancement of the parity violation was observed in the neutron capture reactions for some nuclei. It is predicted that time reversal symmetry violation is also enhanced with the same mechanism. Our recent results of ^{139}La(n,γ) reaction suggested that the enhancement is large enough to search T-violation with high sensitivity, which can reach to the sensitivity of neutron electric dipole moment and which has different systematics. We are performing the research and development for the T-violation search experiment at J-PARC, for example, details of nuclear reactions with candidate nuclei and that of experimental setup. We are also developing the polarization technique for both of neutron beam and target nuclei, so-called spin exchange optical pumping and dynamic nuclear polarization, respectively.

KEYWORDS: CP violation, Time reversal symmetry violation, resonance capture reaction, compound nuclei

1. Introduction

Today's matter universe requires CP-violation from new physics, which is related to asymmetry between matter and antimatter, larger than that from standard model of particle physics. One of the strongest constraints of large CP-violation in hadron sector comes from searches of the neutron static electric dipole moment (nEDM). Non-zero value of the permanent nEDM signals the violation of time-reversal (T) invariance directly. Although experimental searches have been pursued in the world, the nEDM has not yet been observed. The present upper limit is $|d_{\mathrm{n}}| < 1.8 \times 10^{-26} e{\cdot}\mathrm{cm}$ (90% C.L.), which close to the predictions for EDMs which arise from new physics beyond the standard model of particle physics (from supersymmetry, for example) [1]. This value was obtained by using confined ultra-cold neutrons (UCNs). It is internationally competition to develop the new type of neutron source for high-density UCNs, which enables us to search the neutron EDM of the order from 10^{-27} to 10^{-28} $e{\cdot}$cm. Although next-generation UCN sources are being developed intensively, it is valuable and very important to develop different methods to search the T-violation with the other methods with different systematic uncertainties and hopefully to improve the experimental sensitivity.

Now we are planning to search for the large T-violation by measuring nuclear resonance reactions with polarized neutrons and polarized nuclei as NOPTREX. In the reactions the enhancement of the symmetry violation is predicted to give the possibility of search for T-violation with high sensitivity.

2. T-violation in resonance capture reaction

The large enhancement of parity (P) violation of the weak interaction contained in the nuclear interaction was discovered in the 1980's [2–4] and later explored in detail in the 2000's [5]. The asymmetry of the capture cross section in a several nuclei with respect to the helicity of incident neutrons was enhanced by at most 10^6 times larger than that of proton-proton scattering cross section (Fig.

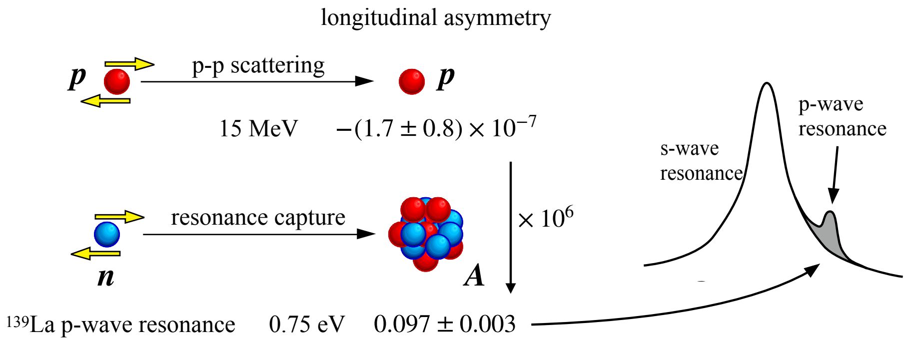

Fig. 1. Enhancement of parity (P) violation around p-wave resonance.

1). The enhancement is explained as the result of the combination of the terms for kinematical enhancement of the asymmetry visibility and the terms for statistical mechanism of the parity-violating effect in multistep processes in the compound nuclear states [6, 7]. This means the entrance channel interference between neighboring s-wave (orbital angular momentum $l = 0$) and p-wave ($l = 1$) amplitudes.

When the neutron total angular momentum $\boldsymbol{j} = \boldsymbol{l} + \boldsymbol{s}$, where $\boldsymbol{s}$ is neutron spin, can be considered as a good quantum number in the reaction, the partial component with $j = 1/2$ in p-wave can be interfered by s-wave component (Fig. 2). The longitudinal asymmetry of the capture cross section A_{L} can be written as

$$A_{\mathrm{L}} = -\frac{2W}{|E_{\mathrm{p}} - E_{\mathrm{s}}|}\sqrt{\frac{\Gamma_{\mathrm{n}}^{\mathrm{s}}}{\Gamma_{\mathrm{n}}^{\mathrm{p}}}}\sqrt{\frac{\Gamma_{\mathrm{n}}^{\mathrm{p},j=1/2}}{\Gamma_{\mathrm{n}}^{\mathrm{p}}}}, \tag{1}$$

where W is the average value of P-violating matrix element in the nucleon-nucleon interaction in nuclei, E_{s} and E_{p} are s- and p-wave resonance energies, $\Gamma_{\mathrm{n}}^{\mathrm{s}}$ and $\Gamma_{\mathrm{n}}^{\mathrm{p}}$ are neutron width for s- and p-wave resonance, and $\Gamma_{\mathrm{n}}^{\mathrm{p},j=1/2}$ is a partial width with $j = 1/2$ in the p-wave resonance, respectively. When we consider that the p-wave component consists of $j = 1/2$ and $j = 3/2$ components, the mixing parameters x, y, and mixing angle ϕ can be defined as

$$x = \sqrt{\frac{\Gamma_{\mathrm{n}}^{\mathrm{p},j=1/2}}{\Gamma_{\mathrm{n}}^{\mathrm{p}}}} = \cos\phi, \quad y = \sqrt{\frac{\Gamma_{\mathrm{n}}^{\mathrm{p},j=3/2}}{\Gamma_{\mathrm{n}}^{\mathrm{p}}}} = \sin\phi, \tag{2}$$

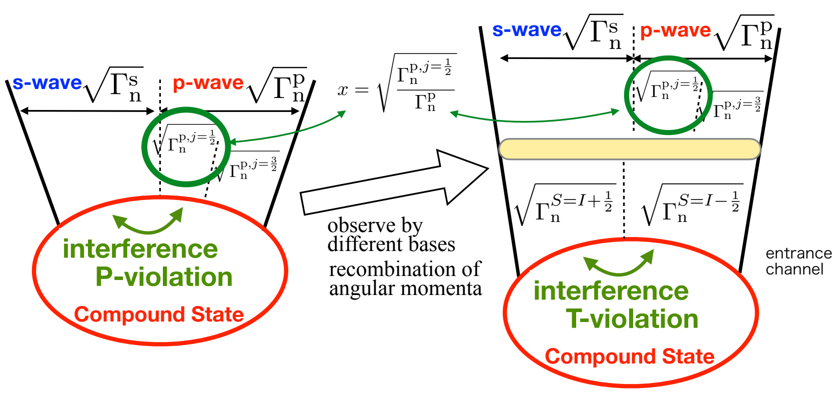

Fig. 2. Enhancement of time-reversal (T) violation in compound nuclei by recombination of angular momentum coupling [8]. The mixing parameter x determines the magnitude of the violation.

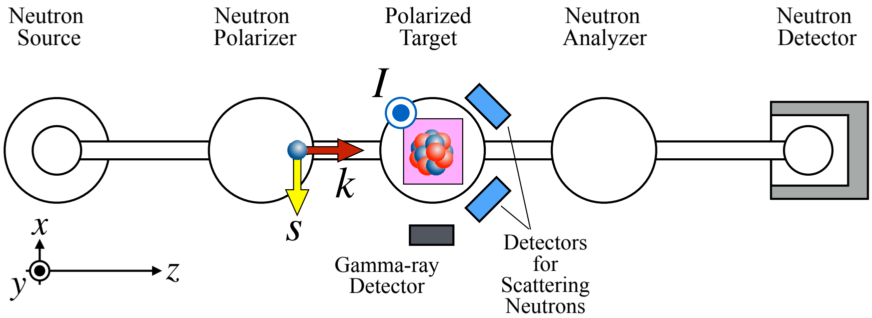

Fig. 3. Configuration for time reversal (T) violation measurement. Correlation term of $\hat{\boldsymbol{s}} \cdot (\hat{\boldsymbol{I}} \times \hat{\boldsymbol{k}})$ is searched by measuring the asymmetry of transmitted neutrons. The germanium γ ray detectors and neutron detectors should be placed around the target to monitor the capture and scattering reactions.

where $x^2 + y^2 = 1$. Because the ratio between $\Gamma_n^{p,j=1/2}$ and Γ_n^p in the equation (1), which is now defined as the mixing parameter x, could not be measured directly by cross section measurements previously, the matrix element W was estimated by using statistical treatment with some experimental data for several nuclei. The kinematical enhancement of the P-violating has been proposed theoretically to be applicable to enhance the experimental sensitivity to search the time-reversal (T) violation effect in the p-wave resonances [8, 9]. When the channel spin $\boldsymbol{S} = \boldsymbol{s} + \boldsymbol{I}$, where $\boldsymbol{I}$ is target nuclear spin, is also considered as a good quantum number, we can discuss the experiment to search for T-violation in the resonance capture reaction with the enhancement (Fig. 2). The neutron-nucleus forward scattering amplitude of the reaction can be expanded as

$$f = A' + B'(\hat{\boldsymbol{s}} \cdot \hat{\boldsymbol{I}}) + C'(\hat{\boldsymbol{s}} \cdot \hat{\boldsymbol{k}}) + D'\hat{\boldsymbol{s}} \cdot (\hat{\boldsymbol{I}} \times \hat{\boldsymbol{k}}), \tag{3}$$

where k is neutron momentum, and the hat symbol represents the unit vector. A' is the spin independent (P-even, T-even) term. B' is the spin dependent (P-even, T-even) term, which is corresponding to neutron spin rotation through the polarized target called as 'pseudomagnetic effect'. C' is the P-violating (P-odd, T-even) term and D' is the T-violating (P-odd, T-odd) term. Because the neutron propagation through the target material can be described by the neutron optics, T-odd effects due to the final-state interaction is expected to be negligibly small in this experimental setup (Fig. 3). The existence of non-zero value of D' signals T-violation, which appears as the value of A'^*D' as the interference of A' and D' in the measured forward intensity f^*f. The T-violating cross section $\Delta\sigma_T$ can be written by using recombination of the angular momenta from $\boldsymbol{l}$ to $\boldsymbol{S}$ as

$$\Delta\sigma_T = \kappa(J)\frac{W_T}{W}\Delta\sigma_P, \tag{4}$$

where $\Delta\sigma_P$ are the P-violating cross section, which is provided from the interference between A' and C', and W_T denotes the T-violating matrix elements. The enhancement factor $\kappa(J)$ from the recombination of the angular momenta is represented with the mixing angle ϕ as

$$\kappa(J) = (-1)^{J+I+\frac{3}{2}}\sqrt{2(2S+1)} \times \left(\begin{Bmatrix} 1 & \frac{1}{2} & \frac{1}{2} \\ I & J & S \end{Bmatrix} + \sqrt{2} \begin{Bmatrix} 1 & \frac{1}{2} & \frac{3}{2} \\ I & J & S \end{Bmatrix} \tan\phi \right). \tag{5}$$

Recently the value of ϕ was studied for ^{139}La and the magnitude of $\kappa(J)$ is found at the order of unity. More details about the experimental studies is presented in section 3.

The T-violating matrix element in the nuclear reaction is studied with statistical treatments on the basis of an effective field theory. The ratio between P-odd and T-odd matrix elements can be written at the leading order as

$$\frac{W_T}{W} \simeq (-0.47)\left(\frac{\bar{g}_\pi^{(0)}}{h_\pi^1} + (0.26)\frac{\bar{g}_\pi^{(1)}}{h_\pi^1}\right), \tag{6}$$

where $\bar{g}_\pi^{(0)}$ and $\bar{g}_\pi^{(1)}$ are isovector T-violating meson-nucleon coupling constants, h_π^1 is a P-violating meson exchange coupling constant. The value of $\bar{g}_\pi^{(0)}$ and $\bar{g}_\pi^{(1)}$ are limited experimentally by nEDM and ^{199}Hg-EDM searches [10] for the leading orders as

$$\bar{g}_\pi^{(0)} < 2.5 \times 10^{-10}, \quad \bar{g}_\pi^{(1)} < 0.5 \times 10^{-11}. \tag{7}$$

The value of h_π^1 is obtained from the measurement of P-violation in n + p → d + γ reactions [11] as

$$\bar{h}_\pi^1 = (3.04 \pm 1.23) \times 10^{-7}. \tag{8}$$

Then we find the upper limit of the ratio as

$$\frac{W_\mathrm{T}}{W} < 3.9 \times 10^{-4}. \tag{9}$$

There are several discussions on the details of the above treatment, such as whether the ratio should be larger or smaller. We notice that some theorist suggested a suppression factor of $A^{-1/3} \sim 5$, which corresponds to $W_\mathrm{T}/W < 0.8 \times 10^{-4}$ [12]. According to the recent result of $\kappa(J)$ and equations (9), we can determine the discovery potential with $\Delta\sigma_\mathrm{T} < 1.0 \times 10^{-4}$ barn. This experiment may be as sensitive or more sensitive than nEDM search for T-violation, and sensitive to another coupling in effective field theory.

3. Measurement of enhancement factor

The T-violation search experiment considered above requires several conditions for the candidates of the target nuclei, for example, ^{139}La, ^{131}Xe, ^{117}Sn, ^{115}In, and ^{81}Br. They have the p-wave resonance peak of neutron capture with the energy of the order of 1 eV, because the relatively-high intensity of incident neutron beam can be utilized at the accelerator-driven neutron source. The small nuclear spin is preferred and the nuclear polarization technique is required. Details of the nuclear polarization are not described in this article, however, several methods are being explored. The large P-violation should be observed because of the equation (4). The large value of $\kappa(J)$ is also desirable, however, the value of $\kappa(J)$ has rarely been investigated. In this section, our recent studies about $\kappa(J)$ of ^{139}La is presented.

The value of $\kappa(J)$ depends on the mixing angle ϕ as shown in equation (5). The mixing angle ϕ and the mixing parameter x or y, which means the fraction of partial amplitudes for p-wave neutrons with the total spin of $j = 1/2$, can be determined by measuring (n,γ) reaction. The differential cross section of (n,γ) reaction with unpolarized target can be expanded by using correlation terms between neutron spin $\boldsymbol{\sigma}_\mathrm{n}$, and γ ray helicity λ as

$$\begin{aligned}
\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \; & \frac{1}{2}\Big(a_0 + a_1\hat{\boldsymbol{k}}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma + a_2\boldsymbol{\sigma}_\mathrm{n}\cdot(\hat{\boldsymbol{k}}_\mathrm{n}\times\hat{\boldsymbol{k}}_\gamma) + a_3\Big((\hat{\boldsymbol{k}}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma)^2 - \frac{1}{3}\Big) + a_4(\hat{\boldsymbol{k}}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma)\Big(\boldsymbol{\sigma}_\mathrm{n}\cdot(\hat{\boldsymbol{k}}_\mathrm{n}\times\hat{\boldsymbol{k}}_\gamma)\Big) \\
& + a_5\lambda(\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma) + a_6\lambda(\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\mathrm{n}) + a_7\lambda\Big((\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_\gamma\cdot\hat{\boldsymbol{k}}_\mathrm{n}) - \frac{1}{3}\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\mathrm{n}\Big) \\
& + a_8\lambda\Big((\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\mathrm{n})(\hat{\boldsymbol{k}}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma) - \frac{1}{3}\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma\Big) + a_9\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma + a_{10}\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\mathrm{n} \\
& + a_{11}\Big((\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_\gamma\cdot\hat{\boldsymbol{k}}_\mathrm{n}) - \frac{1}{3}\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\mathrm{n}\Big) + a_{12}(\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\mathrm{n})\Big((\hat{\boldsymbol{k}}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma) - \frac{1}{3}\boldsymbol{\sigma}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma\Big) \\
& + a_{13}\lambda + a_{14}\lambda(\hat{\boldsymbol{k}}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma) + a_{15}\lambda\boldsymbol{\sigma}_\mathrm{n}\cdot(\hat{\boldsymbol{k}}_\mathrm{n}\times\hat{\boldsymbol{k}}_\gamma) + a_{16}\lambda\Big((\hat{\boldsymbol{k}}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma)^2 - \frac{1}{3}\Big) \\
& + a_{17}\lambda(\hat{\boldsymbol{k}}_\mathrm{n}\cdot\hat{\boldsymbol{k}}_\gamma)\Big(\boldsymbol{\sigma}_\mathrm{n}\cdot(\hat{\boldsymbol{k}}_\mathrm{n}\times\hat{\boldsymbol{k}}_\gamma)\Big)\Big),
\end{aligned} \tag{10}$$

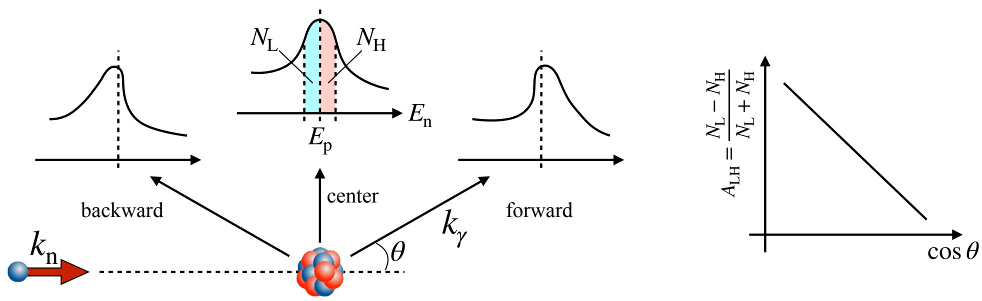

Fig. 4. (n,γ) measurement to extract a_1 term. The shape asymmetry $A_{\rm LH}$ is defined and compared with the theoretical calculation [14].

where $\hat{\boldsymbol{k}}_{\rm n}$ and $\hat{\boldsymbol{k}}_\gamma$ are unit vectors of neutron and γ ray momenta, respectively. According to the statistical treatments in the compound nuclei with mixing of s- and p-wave components, all the coefficients $a_1, \cdots, a_{17}$ can be described by using the resonance energies and the widths of s- and p-wave resonances, the total angular momentum and the spin of incident neutron, the spin of the initial and final states of the nuclei, and the mixing parameter ϕ [13]. Comparing the calculation with equation (10) and the measurements of the correlation terms for the compound states with well-known spin, the value of x can be extracted.

The measurement of the correlation terms of (n,γ) reaction of the candidate nuclei has been performing at the beamline BL04 ANNRI in Materials and Life Science Experimental Facility (MLF) in J-PARC. The 22 germanium detectors were arranged surrounding the nuclear target to measure the angular distribution of γ rays. The detectors also enabled us to separate the γ ray peaks due to the high energy-resolution. According to the intense pulsed neutrons, the resonance parameters can be measured with high precession simultaneously by analyzing time-of-flight of the neutron. Neutron polarizer with ^{3}He gas cell, which is so-called '^{3}He spin filter', can be installed into the upstream of the beamline to measure the correlation terms with neutron spin.

We measured ^{139}La(n,γ) reaction with unpolarized and polarized neutrons to measure a_1 and a_2 terms around p-wave resonance around the neutron energy with 0.75 eV. The coefficient a_1 makes the angular distribution of the shape of resonance peak according to the neutron energy (Fig. 4). The range of ϕ which was consistent with the resonance shape on each detectors was limited to [14]

$$\text{from } a_1 \quad \phi = \ (99.2^{+6.3}_{-5.3})^\circ, \ (161.9^{+5.3}_{-6.3})^\circ. \tag{11}$$

The coefficient a_2 with neutron polarization makes the dependence of the γ ray intensity on the neutron-spin direction. The measurement with vertical-polarized neutrons were performed to limit the range of ϕ [15]. Although the details about a_2 are under discussion, we find that ϕ about 160° is the most likely value to explain the experimental results. Finally in the case of the p-wave resonance of lanthanum at 0.75 eV, we find

$$\kappa(J) \simeq 0.99. \tag{12}$$

These results suggest that the enhancement of the time-reversal symmetry violation is 10^6 as large as that of the P-violation.

We are now conducting the measurements for the other coefficients in the equation (10) with polarized neutrons and γ ray polarimeter, for example, a_9 and a_{13}. The studies with (n,γ) reactions of various nuclei are conducted by Nagoya University, Osaka University, Kyushu University, Tokyo Institute of Technology, J-PARC, and Indiana University.

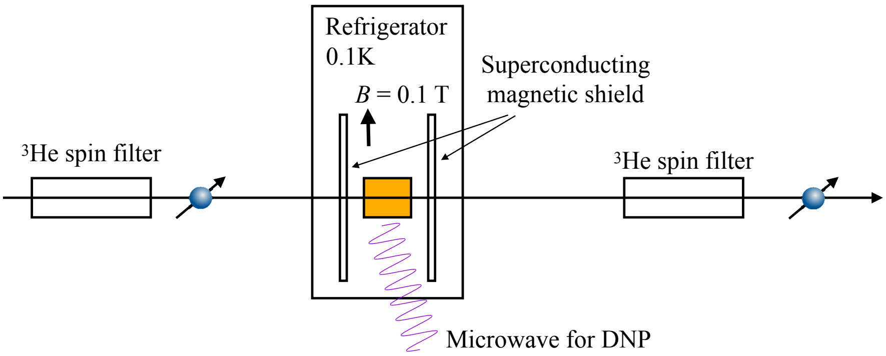

Fig. 5. Concept of setup around the polarized target. Neutron beam is polarized by ^{3}He spin filter. ^{139}La nuclei are polarized by DNP technique with low magnetic field and low temperature.

4. Development of neutron devices and polarized target

In order to search for T-violation by using the configuration described in section 2, the incident neutrons must be polarized. ^{3}He spin filter is a powerful device to provide polarized neutrons with low energy [16–18]. This uses the strongly spin-dependent absorption cross section of ^{3}He. Today K-Rb 'Hybrid SEOP' (Spin Exchange Optical Pumping) method can achieve the polarization of ^{3}He better than 0.8. We have established the fabrication of the ^{3}He spin filters and have already applied them to (n,γ) measurement at J-PARC [19]. In order to apply the ^{3}He spin filter to the experiments with the target nuclei which have p-wave resonance at the order of 1 eV, for example, 0.75 eV for ^{139}La, the large scale of ^{3}He gas cell is required. ^{3}He gas with the effective thickness of the order of 100 atm·cm is needed for a few eV resonance. Large cross section is also required to use the number of neutrons. We are continuing to develop ^{3}He spin filters for T-violation experiment.

Proton spin filter is the other candidate of the polarizer for relatively-high energy neutrons. This is required for the T-violation experiment with the candidate nuclei like ^{115}In. This uses strongly spin-dependent scattering cross section of proton. In order to polarize the proton, triplet-DNP (Dynamic Nuclear Polarization) method is now under development [20]. Electrons which are photo-excited to triplet state in pentacene molecule are polarized to 70 % , independently of the temperature and magnetic field. Protons can be polarized at relatively high temperature of 25-300 K and in a weak magnetic field of 0.3-0.7 T.

The polarization of target nuclei is also required for T-violation experiment. The dynamical nuclear polarization (DNP) technique is under development especially for lanthanum nuclei, which is a good candidate of the experiment. The lanthanum nuclei in $LaAl_2O_3$ crystal were successfully polarized by using DNP method [21]. We are continuing to research and develop the DNP for the lanthanum nuclei, for example, a large crystal with high quality and the optimization of spin relaxation with doping of spin source. Because the B' term in Eq. 3, which is much larger than C' and D', makes pseudomagnetic rotation of incident neutron spin through the polarized target, the spin-rotation of neutrons must be compensated and/or monitored. In principle, the magnetic field to keep nuclear polarization in DNP can be tuned to cancel the pseudomagnetic rotation due to B'. In the case of $LaAl_2O_3$ target, the magnetic field should be about 0.1 T, which is an order lower than that of normal DNP. The novel DNP technique with low magnetic field is now discussed. In addition, because the pseudomagnetic rotation depends on neutron velocity, information of the phase due to time-of-flight of pulsed neutrons can be used for correcting the effect from B' term.

The technique for crystal growth and DNP are under development in Nagoya University, Tohoku University, Osaka University, Yamagata University and Hiroshima University. More detail about target polarization is discuss in the presentation by Prof. Iinuma in this conference.

Finally the development of neutron detector is briefly introduced here. We must measure the tiny asymmetry of transmitted neutrons in T-violation experiment. Neutron detectors which can count the neutron with the energy of 1 eV with the rate of the order from 10^8 to 10^9 cps/cm^2 are desirable. The first candidate is the current mode detector, which is a method of reading the current of PMT output signal. Incident neutrons are stopped at ^{10}B converter and emitted γ rays with 0.48 MeV are detected with surrounding NaI detectors. This detector is under development at Kentucky University and tested at J-PARC MLF BL10 and Los Alamos Neutron Science Center. We also tested the counting detector with liquid scintillators, which have faster decay-time than the glass scintillator, and the fast electric circuits.

5. Feasibility at J-PARC

To assess feasibility for a T-violation search in neutron resonance reactions at J-PARC, we consider a ^{3}He spin filter to polarize the incident neutrons and a $LaAl_2O_3$ single crystal as a nuclear target. We assume that the polarization of ^{3}He is 0.7 with SEOP and that of ^{139}La is 0.4 with DNP. The dimension of $LaAl_2O_3$ crystal, which is optimized based on the transmittance of neutron beam and the nuclear reaction volume requirements, is 4 cm × 4 cm of cross section and 2.8 cm thick. When the beamline at MLF in J-PARC is assumed, the asymmetry corresponding to T-violation, which is extracted as a combination of the analyzing power along x-axis A_x and polarization along x-axis P_x, can be achieved to the order of 10^{-5} by using about ten days (Fig. 6). Although there is the suppression factor mentioned in section 2, the required measurement time should be extended to about 200 days, which is realizable.

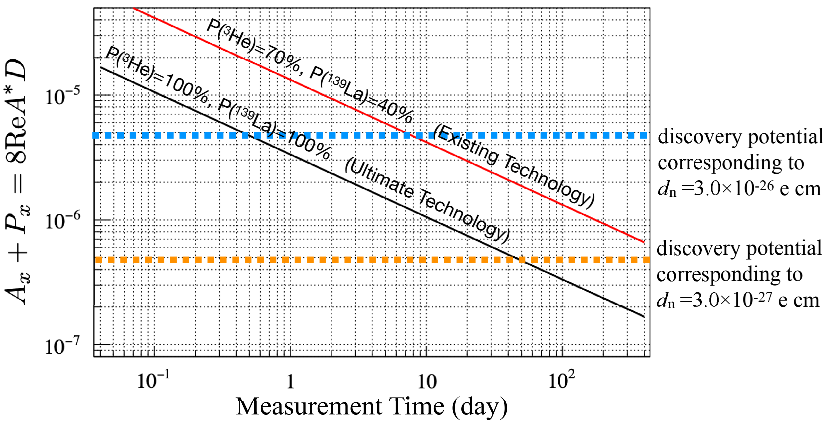

Fig. 6. Sensitivity of T-violation in nuclear reaction according to measurement time at J-PARC. $LaAl_2O_3$ crystal is assumed as a nuclear target.

6. Summary

The new type of T-violation search experiment is discussed. The enhancement of the violation of time-reversal symmetry is predicted in the neutron capture reaction for some nuclei. The enhancement factor for ^{139}La was estimated to be 10^6 by measuring angular distribution of γ rays from (n,γ) reactions at J-PARC. Polarization technique for both of incident neutron beam and target nuclei is under development. By using ^{3}He spin filter and DNP, which are achievable with today's technique, the discovery potential for T-violating asymmetry can be achieved with realizable beamtime. We are continuing research, development, and detail design of the experiment called as NOPTREX.

Acknowledgments

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