Proc. Int. Symposium on Neutron Optics and Related Research Facilities, Kumatori, 1996
J. Phys. Soc. Jpn. **65** (1996) Suppl. A pp. 169-173

Test of Parity and Time Reversal Invariance with Low Energy Polarized Neutrons

Akira MASAIKE

Department of Physics, Kyoto University, Sakyo-ku, Kyoto 606-01, Japan

(Received 7 May 1996; accepted 12 July 1996)

Measurements of helicity asymmetries in slow neutron reactions on nuclei have been performed by transmission and capture γ-ray detection. Large enhancements of parity-violation effects have been observed on p-wave resonances of various medium and heavy nuclei. The weak matrix elements in hadron reactions have been deduced from these experimental results. Neutron spin precession near the p-wave resonance has been measured.
In recent years violation of time reversal invariance is being searched for in the neutron reactions in which large enhancements of the parity violation effects have been observed. The measurement of the term $\sigma_n\cdot(k_n \times I)$ in a neutron reaction using polarized neutrons and a polarized target is an example of the test of T-violation.
Polarizations of the neutron and lanthanum nucleus for these experiments are also presented.

KEYWORDS: Parity violation, Time reversal invariance, Low energy polarized neutron

§.1. Introduction

Parity non-conservation(PNC) in hadron-hadron reactions is of importance from the viewpoint of the weak interaction in hadronic processes. Such effects are very small in nucleon-nucleon (N-N) interactions, since the strong interaction is dominant in these systems. Exchanges of light pseudoscalars and vectors with vertexes of weak interactions are the main contributions to the parity violating processes. The ratio of PNC potential to parity conserving one is estimated to be about $G_F m_\pi^2 \approx 2 \times 10^{-7}$. The PNC helicity asymmetry in the total cross section for p-p scattering (A_L^{tot}) was measured to be -(0.15 ± 0.022) $\times 10^{-6}$ at 45 MeV. [1] Over the last decade experimental effort has been devoted to the measurement of large PNC asymmetries in nucleon-nucleus interactions where the PNC effects are enhanced due to the interference between the energy levels of the same spin and opposite parities close each other. Very large effects in the helicity asymmetries have been found in low energy neutron capture reactions at p-wave reactions at Dubna, KEK and recently at Los Alamos. The largest helicity asymmetry has been observed on the resonance at E_n=0.734 eV for the n+^{139}La reaction in the above institutions. From these results we could study the mechanism of the enhancement of the parity violation effect in neutron resonance absorptions. Furthermore, the weak matrix element of the hadronic process could be deduced from the experimental results.

On the other hand, the large spin rotation of transversely polarized neutrons near the p-wave resonance for the n-^{139}La reaction has been found at KEK and Gatchina.[2] The result is consistent with the interference model which explains the helicity asymmetries.

In the first half of this report we show the recent results of the measurement of parity violating effect in neutron capture reactions in the resonance region. In the second half of this report we explain the possibility to measure time reversal violation in the neutron resonance absorption using the large enhancement effect as in the case of parity violation. Polarizations of slow neutron and La nucleus for these experiments are also shown.

§.2. Measurement of Parity Violation in Neutron Capture Reactions at KEK

The measurements of spin dependent parameters related to the parity violating effect in neutron resonance absorptions on nuclei have been carried out by means of detection of emitted γ-rays at KEK. The γ-rays detection method is advantageous compared to the neutron transmission experiment, since it is insensitive to potential scattering which has no parity violating effect. In the resonance absorption of epithermal neutrons, s-wave contribution is dominant and small contribution of p-wave also exists.
Neutrons have been produced in a spallation source, where pulsed proton beams from a 500 MeV booster synchrotron at KEK have bombarded a uranium target. Neutrons are polarized with a polarized proton filter after moderation. The helicity asymmetries of capture γ-rays, which correspond to $A_{10}\sigma_n\cdot k_n$, have been measured on p-wave resonances for several target materials with medium mass numbers, where σ_n is the neutron spin vector and k_n is the neutron momentum vector. Non-zero A_{10}'s have been found at p-wave resonances for ^{139}La, ^{81}Br and ^{111}Cd targets as shown in Table 1.[3),4)]

target nuclei	E_p(eV)	E_s(eV)	A_{10}	$\|xW\|$ (meV)
^{139}La	0.734 ± 0.005	-48.63	0.098 ± 0.003	1.7 ± 0.1
^{111}Cd	4.53 ± 0.03	-4	$-0.013 \pm^{0.007}_{0.004}$	$1.6 \pm^{0.9}_{0.5}$
^{81}Br	0.88 ± 0.01	101.10 ± 0.14	0.021 ± 0.001	2.6 ± 0.1

Table 1. The helicity asymmetries A_{10} of capture γ-ray yields measured in p-wave resonances for ^{139}La, ^{81}Br and ^{111}Cd targets. The $|x,W|$ as well as the energies of s- and p-wave resonances E_s, E_p are also shown.

The largest value of A_{10} was found to be 0.095 ± 0.003 on the p-wave resonance at E_n=0.734 eV for the ^{139}La target. The angular dependences of γ-rays for A_{10} with above three targets have also been measured and found to be independent of θ within experimental errors.

The enhancement of helicity asymmetries up to 10^6 can be explained in the frame work of s- and p-wave mixing in which the interference term becomes remarkably large due to long lifetimes of compound states, small difference in the resonance energies for s- and p-wave neutrons and large centrifugal potential barriers for p-wave neutrons.[5] In the case with only one p-wave resonance and one s-wave resonance the term A_{10} satisfies

$$A_{10} = \frac{2xW}{E_p - E_s}\sqrt{\frac{\Gamma_s^n}{\Gamma_p^n}} \tag{2.1}$$

where E_p and E_s are the resonance energies, $\Gamma^n{}_p$ and $\Gamma^n{}_s$ are the neutron widths of the p- and s-wave resonances, respectively. The W is the weak matrix element in the interference between the s- and p-wave resonance states and x is given as $x^2 = \Gamma^n{}_{p1/2} / \Gamma^n{}_p$, where $\Gamma^n{}_{p1/2}$ is the partial neutron width for j=1/2 p-wave neutrons. (The j is the total angular momentum of incident neutrons).

The exit channel interference effect has also been measured in the asymmetries of γ-ray yields for neutron capture reactions. The measurements of the terms $A_2\sigma_n\cdot(\boldsymbol{k}_n \times \boldsymbol{k}_\gamma)$ and $A_9\sigma_n\cdot\boldsymbol{k}_\gamma$ near the p-wave resonance of ^{139}La have been carried out, where $\boldsymbol{k}_\gamma$ is the momentum vector of emitted γ-rays. The parameters on the p-wave resonance of ^{139}La can be explained approximately by the following equations based on the s-p mixing model, assuming the spins of the resonance and the final state of the γ-transition are 4 [4),5)].

$$A_2 \approx \eta\sqrt{\frac{\Gamma_s^n}{\Gamma_p^n}}\sqrt{\frac{\Gamma_s^\gamma}{\Gamma_p^\gamma}}\frac{\Gamma_p(E_n - E_p)}{(E_n - E_s)^2 + (\Gamma_s/2)^2} \tag{2.2}$$
$$\cdot(-0.125x - 0.074y),$$

$$A_9 \approx \frac{-2W(E_n - E_p)}{(E_n - E_s)^2 + (\Gamma_s/2)^2}\frac{\Gamma_s^n}{\Gamma_p^n}\sqrt{\frac{\Gamma_s^\gamma}{\Gamma_p^\gamma}}(-0.125), \tag{2.3}$$

where η is a phase factor and almost equal to ± 1 in low energy neutron capture reactions. The $\Gamma_s{}^\gamma$ and $\Gamma_p{}^\gamma$ are γ-ray widths for p- and s-waves, respectively. The E_n is the neutron energy. We define x and y as $\sqrt{\Gamma^n_{p1/2}/\Gamma^n_p}$ and $\sqrt{\Gamma^n_{p3/2}/\Gamma^n_p}$, respectively, where $\Gamma^n{}_p = \Gamma^n{}_{p1/2} + \Gamma^n{}_{p3/2}$. We have obtained A_9, A_2, $\sqrt{\Gamma_s^\gamma/\Gamma_p^\gamma}$, x and y for individual γ-ray transitions for the ^{139}La target.

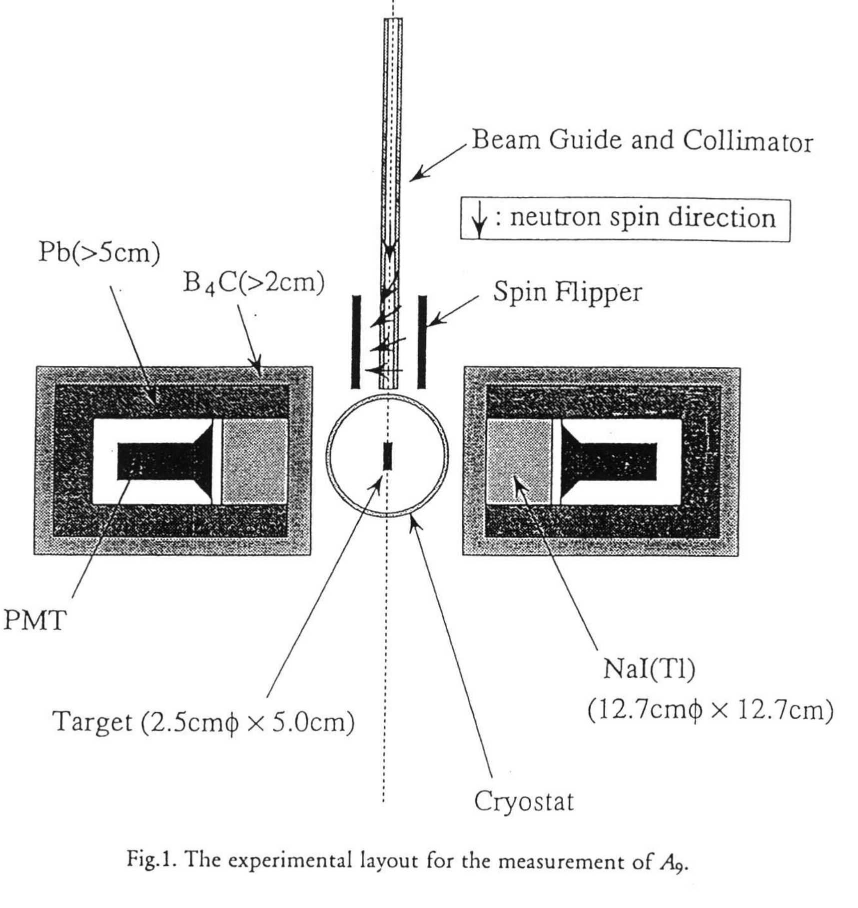

Fig.1. The experimental layout for the measurement of A_9.

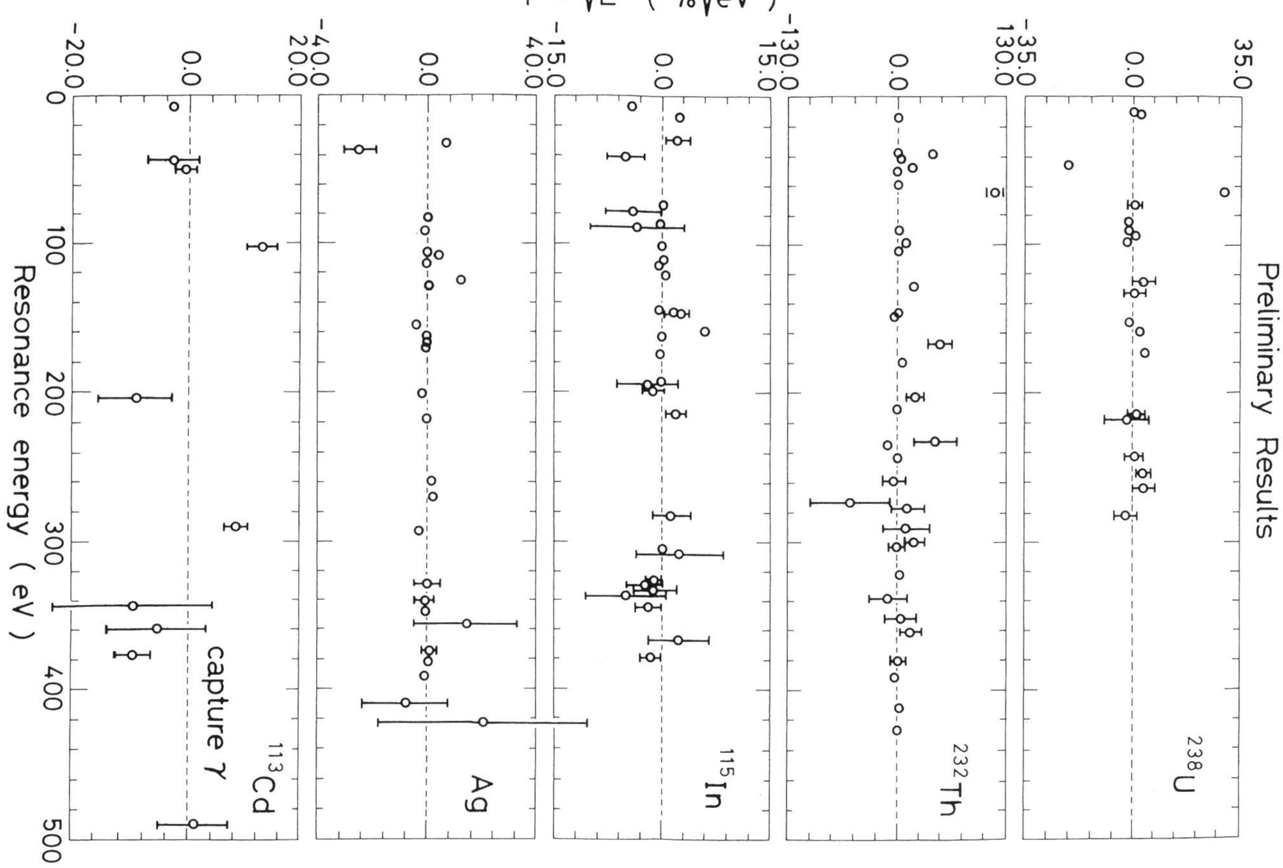

Fig.2. Preliminary results of parity violating helicity asymmetries P multiplied by √E at Los Alamos.

The A_2 and A_9 have dispersive E_n dependence near thep-wave resonance and they change the sign at the center of the resonance. In order to carry out the experiment, it is indispensable to observe individual γ-ray transitions separately. The measurements have been performed at KEK with a ^{139}La target and two γ-ray counters with 5"NaI(Tl) as shown in Fig.1.

Transversely polarized neutron beams have been used for A_9 and A_2 measurements.

Experimental data on the γ-ray transition of 5.1MeV show that

$$\sqrt{\Gamma_s^\gamma / \Gamma_p^\gamma} = 4.07 \pm 0.07, \quad A_2 = 0.011 \pm 0.115, \quad A_9 = 0.068 \pm 0.140. \tag{2.4}$$

From these results we have deduced the amount of the weak matrix element as: [6]

$$W = 3.3^{+6.4}_{-1.3} \text{ [meV]} \tag{2.5}$$

§.3. Determination of Weak Matrix Element from Data on Helicity Asymmetries for Neutron Transmission at Los Alamos

The TRIPLE collaborators from US, Japan, Russia, Canada and Netherlands have developed an apparatus to measure the helicity asymmetries of slow neutron induced reactions at LANSCE in Los Alamos. The longitudinal asymmetries on the targets, ^{238}U, ^{232}Th, ^{127}I, ^{115}In, and natural Ag and Xe were measured using transmission detectors made of ^{10}B-loaded liquid scintillator. In addition, the data on ^{113}Cd, and natural Pd and Sb were taken using both the neutron transmission detector and a capture γ-ray detector made of BaF_2. [7] Many new parity violating asymmetries have been observed on p-wave resonances in the energy region of 0.1 ~ 500 eV. The data are still under analysis. Preliminary helicity asymmetries from the data of 1993 are shown in Fig.2. The asymmetries were obtained by measuring the neutron transmission for all the target, except for ^{113}Cd. The data for ^{113}Cd were taken with γ-ray detectors made of BaF_2 scintillators.

In the case of the Los Alamos experiment there are many p-wave resonances interfered with several neighboring s-wave resonances. The parity violating asymmetry P_i for the ith p-wave resonance can be written as

$$P_i = \sum_j \left(\frac{2x_i V_{ij}}{E_{sj} - E_{pi}} \sqrt{\Gamma^n_{sj}/\Gamma^n_{pi}} \right), \qquad (3.1)$$

where

$$V_{ij} \equiv \langle \psi_{sj} | H_W | \psi_{pi} \rangle. \qquad (3.2)$$

According to the statistical model of the compound nucleus, the neutron decay widths and the weak matrix elements V_{ij}'s are Gaussian random variables with zero mean. If the spin of target nucleus is zero, parity violation takes place for the resonance with spin 1/2, then x_i=1. In this case the asymmetries are mean-zero with variance

$$< P_i^2 >= M^2 \left(\sum_j \frac{2}{E_{sj} - E_{pi}} \sqrt{\Gamma^n_{sj}/\Gamma^n_{pi}} \right)^2, \qquad (3.3)$$

where

$$M^2 = \langle V_{ij}^2 \rangle. \qquad (3.4)$$

In the cases of targets with spin non-zero we must treat x_i as a random variable with a probability density function, that is not Gaussian, since $\Gamma^n_{p1/2} + \Gamma^n_{p3/2}$ is fixed for each p-wave resonance. The values of M^2 are being calculated with measured asymmetries for the target nuclei by means of the likelihood analyses. [8] The results seem to indicate a smooth mass behavior of the weak matrix element.

§.4. Neutron Spin Precession near the p-wave Resonance

When the polarized neutron pass through matter, the weak interaction gives rise to precession of neutron spin around the neutron momentum. The amount of spin rotation is proportional to the real part of the difference between the forward scattering amplitudes for two opposite neutron helicities. The neutron spin rotation near the p-wave resonance is described as the formula,

$$\frac{d\phi}{dz} = \frac{4\pi n g}{k^2} \cdot \frac{xW(\Gamma^n_s \Gamma^n_p)^{1/2}}{\left[(E-E_s)^2 - \frac{1}{4}\Gamma_s^2\right] \cdot \left[(E-E_p)^2 + \frac{1}{4}\Gamma_p^2\right]} \cdot \left[(E-E_s)(E-E_p) - \frac{1}{4}\Gamma_s\Gamma_p\right] \qquad (4.1)$$

where n is the nuclear number density and g=(2J+1)/2(2I+1) is a statistical factor. The E is the incident neutron energy.

Recently, the rotation of neutron spin has been measured near the p-wave resonance of the reaction ^{139}La+n at E=0.734 eV at KEK and Gatchina. The results observed at Gatchina are shown in Fig. 3. [9] A theoretical prediction is also presented. $d\phi / dz$ at $E = E_p \pm \Gamma p/2$ has been found to be $\pm$(4.2 $\pm$ 0.5)$\cdot 10^{-3}$ rad/cm.

§.5. Test of Time Reversal Violation in Slow Neutron Resonance Absorption

The test of time-reversal (T) violation is in preparation at KEK using large enhancement which happens for parity violating effects in neutron resonance absorptions in nuclei. The measurement of the term $\sigma_n \cdot (\boldsymbol{k}_n \times \boldsymbol{I})$ is a simple example of the test of T-violation, where σ_n is the neutron spin, $\boldsymbol{k}_n$ is the neutron momentum, and $\boldsymbol{I}$ is the spin of the target nucleus. [10),11)]

The forward neutron scattering amplitude in neutron spin space is given as,

$$f = A' + B'\sigma_n \cdot \boldsymbol{I} + C'\sigma_n \cdot \boldsymbol{k}_n + D'\sigma_n \cdot (\boldsymbol{k}_n \times \boldsymbol{I}) \qquad (5.1)$$

The A' represents the main strong-interaction amplitude, B' the spin-dependent strong amplitude, C' the parity-violating term, and D' the T- and P- violating term. The incident neutron spin state (U_i) is related to the final state(U_f) after transmitted through a target as

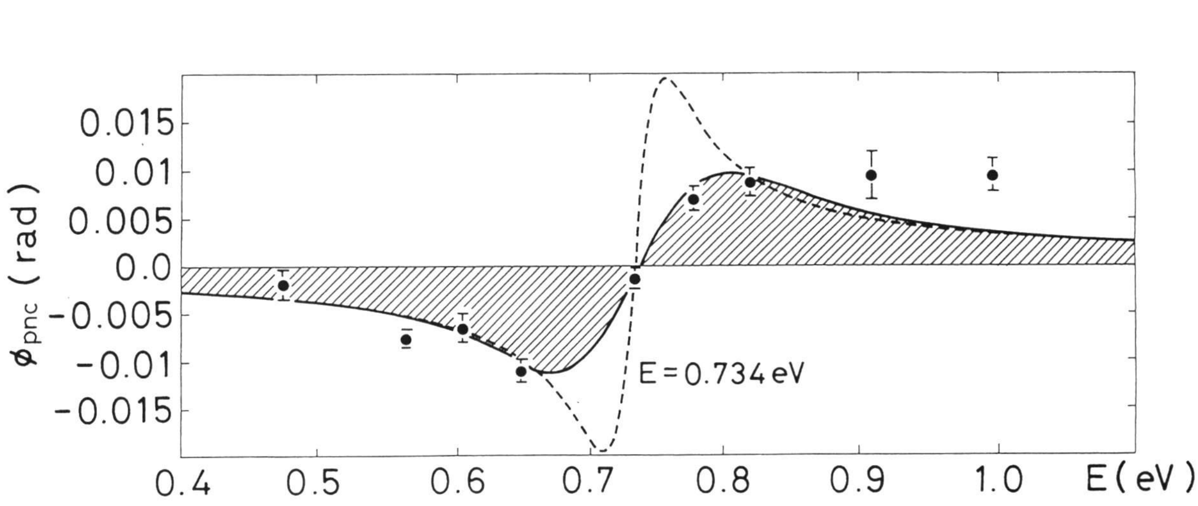

Fig.3. Experimental results of spin rotation of neutron near the p-wave resonance of ^{139}La at E=0.734 eV. The dashed line shows a theoretical prediction with ideal energy resolution and the solid line shows the one with real resolution.

$$U_f = \delta U_i = e^{i\varsigma} U_i (A + B\sigma_n \cdot \boldsymbol{I} + C\sigma_n \cdot \boldsymbol{k}_n + D\sigma_n \cdot (\boldsymbol{k}_n \times \boldsymbol{I}))U_i, \quad (5.2)$$

where $\zeta = 2\ \pi\rho d$, d is the thickness of the target and ρ is the density of target nuclei. A, B, C, and D are shown to be:

$$A = e^{i\varsigma A'} \cos b,$$

$$\begin{pmatrix} B \\ C \\ D \end{pmatrix} = e^{i\varsigma A'} \frac{\sin b}{b} i\varsigma \begin{pmatrix} B' \\ C' \\ D' \end{pmatrix}, \quad (5.3)$$

where b is given as

$$b = \varsigma\sqrt{B'^2 + C'^2 + D'^2} \quad (5.4)$$

One of the possible experiments is a measurement of the difference between the helicity flip ($+ \to -$) and that of ($- \to +$) during the transmission through a transversely polarized target. It is proportional to the imaginary part of interference between the B-and D-terms.

$$\text{Prob.}(+ \to -) - \text{Prob.}(- \to +) = 4\text{Im}BD^* \quad (5.5)$$

The difference between the probability of the spin non-flip ($+ \to +$) of vertically polarized neutrons during transmission in a target which is polarized perpendicular to the directions of the beam and the neutron spin and that of spin non-flip ($- \to -$) in the same target is also a T-odd parameter.

$$\text{Prob.}(+ \to +) - \text{Prob.}(- \to -) = 4\text{Re}AD^* \quad (5.6)$$

§.6. Polarization of Neutron Beam and La Target

In order to carry out the experiment of the test of T-violation, a new type of polarized proton filter for polarizing neutron beams and a polarized ^{139}La target have been constructed.

Neutrons become polarized after transmitting through a polarized proton filter.[12] Recently, a new method of polarization has been developed, in which protons in pentacence-doped naphthalene are polarized by means of laser excitation and dynamic polarization of a photo-excited triplet state of pentacene in room temperature or in liquid nitrogen temperature[13]. A pair of electrons in a pentacene molecule are diamagnetic on the ground state because these electrons are on a singlet state (S=0). Electrons are excited to a higher singlet state by means of the irradiation of a pulsed dye laser.The spin-orbit interaction causes transition from a singlet excited state to the lowest triplet state which is paramagnetic. When a magnetic field (~3 KG) is applied along the x-axis of pentacene, electrons on the triplet state are spontaneously aligned. The difference of the populations between two levels among three sublevels was transferred to the polarization of protons in pentacene and naphthalene by microwave irradiation during the lifetime of the triplet states. Electrons make transition to the ground state with relaxation time of 20 μsec. Protons on the ground state are kept polarized for very long time. The polarization of $\geq$ 20% has been achieved at liquid N_2 temperature and higher polarization is expected with fine tunings of several parameters of the ESR and the laser.

Recently, a Nd^{3+}:$LaAlO_3$ crystal has been proposed as a polarized ^{139}La target which is very important to the test of time reversal invariance. It was found that La nuclei in $LaAlO_3$ containing Nd^{3+} of 0.03 mol% can be polarized by means of the dynamic method. The microwaves of 70 GHz have been applied to the crystal in a magnetic field of 2.3T parallel to the C_3 axis of the crystal at the temperature of 1.5K. A pulse NMR technique has been used for observing signals of free induction decays with excitation frequencies in the range from 12MHz to 16MHz.[14] The polarization of ^{139}La nuclei has been more than 20%. The thermal contact between the nuclear spin system and the Nd^{3+} spin-spin interaction system plays an essential role in nuclear polarization. The polarization of ^{139}La nucleus in Nd^{3+}:$LaAlO_3$ is expected to increase at lower temperature.

A test of time reversal invariance will be carried out using a $LaAlO_3$ target, polarized neutron beams, and a neutron polarization analyzer.

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