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# Lanthanum nuclear polarization for T-violation experiment

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Abstract Nuclear polarization for the measurement of a triple correlation between the neutron spin, the neutron momentum and the nuclear spin in the neutron-nucleus interaction is discussed. Productions of polarized neutron and polarized lanthanum target are presented. Also, feasibility of polarized $^3$He nuclei as a polarized neutron detector is discussed.

## Introduction

Nuclear polarization has been used for tests of fundamental symmetry violations, P violation and T violation. In the experiments, psuedoscaler terms under space/time reversal are measured. In the P-violation experiment, a $\sigma \cdot \mathbf{k}$ term is measured, where $\sigma$ is a particle spin and $\mathbf{k}$ is a particle momentum. In the nucleon-nucleon interaction, P-violation effect is very small. An asymmetry in the cross section with respect to the helicity is about $10^{-7}$ for the proton-proton scattering. Concerning T violation, only CP violation is observed in the $K^0$ decay. If we assume the CPT theorem, T invariance is violated in the $K^0$ decay. No other T-violation process is found yet. In the nucleus, the symmetry violations are occasionally enhanced. For example, P-violating asymmetries in $\mathbf{I} \cdot \mathbf{k}_\gamma$ terms of $\gamma$-ray angular distribution from polarized nuclei are enhanced to $10^{-2}$–$10^{-4}$. Circular polarizations of $\gamma$-rays from unpolarized nuclei, namely $\sigma_\gamma \cdot \mathbf{k}_\gamma$ terms are enhanced to $10^{-3}$–$10^{-4}$. Here, $\mathbf{I}$ is the nuclear spin, $\mathbf{k}_\gamma$ is the photon momentum and $\sigma_\gamma$ is the photon spin. Recently, far more enhancement has been found in the neutron-nucleus interaction. The largest observed effect is for a p-wave resonance of $^{139}$La at the neutron energy of $E_n = 0.734$ eV. An asymmetry in the neutron helicity, namely the $\sigma_n \cdot \mathbf{k}_n$ term is about 10 %[1,2,3,4], where $\sigma_n$ is the neutron spin and $\mathbf{k}_n$ is the neutron momentum.

Many theoreticians expect such large enhancement also in T-violation effects as in the P-violation effect[5,6,7,8]. It is proposed to measure a triple correlation term, $\mathbf{I} \cdot \sigma_n \times \mathbf{k}_n$ in the neutron transmission for the T-violation test. In the T-violation experiment, transmission of polarized neutrons through a polarized target is measured as it is schematically shown in Fig. 1. The two processes in Fig. 1 transform to each other under time reversal and two rotations around the nuclear polarization axis and the beam axis. The second process is realized by inversion of the neutron polarization in the first process. The T-odd asymmetry which is defined as,

$$A_T = (T(+)-T(-))/(T(+)+T(-)) \qquad (1),$$

is considered to be free from final state interactions, since initial and final states as well as motion directions are reversed in the two processes in Fig. 1. Here, T(+) and T(-) are neutron transmission for the first and second processes, respectively. The effect of final state interactions is serious problem in the measurements of T-odd angular correlations in $\gamma$-decay and $\beta$-decay, since initial and final states can not be interchanged in the decay processes.

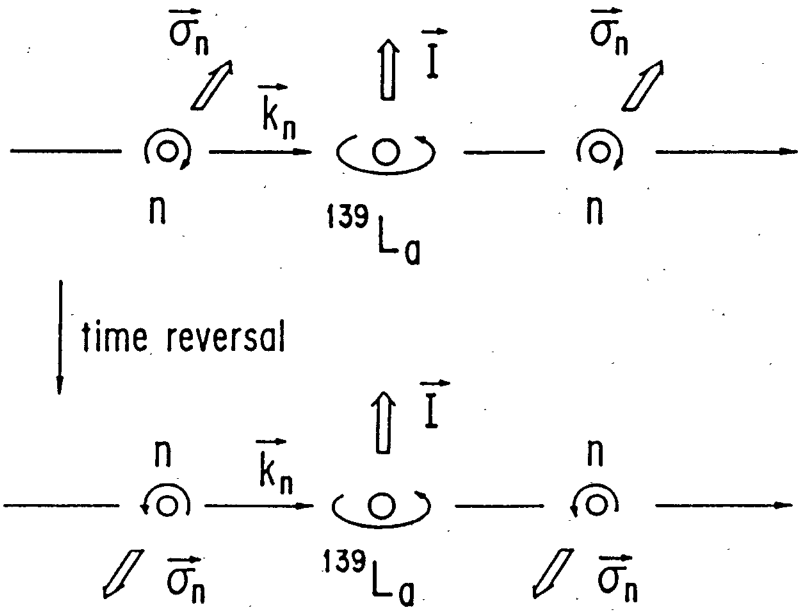

Fig. 1 T-violation test on the polarized neutron transmission through a polarized nuclear target.

Nuclear polarization for T-violation experiment

For the T-violation experiment, we need polarized neutron beam, polarized nuclear target and polarized neutron detector. We have already a neutron polarizer, namely the polarized proton filter[9]. Protons in organic material in a liquid $^4$He container are polarized by means of the dynamic nuclear polarization. The liquid $^4$He is cooled by 0.5 K liquid $^3$He from outside through a heat exchanger in order to avoid neutron absorption by $^3$He nuclei. The proton polarization is 80%. Neutrons from the spallation neutron source are polarized upon passing through the filter. The neutron polarization in eV region is more than 70% for a 1-cm thick filter.

The second problem is to polarize lanthanum nuclei. For this purpose we also used the dynamic nuclear polarization in a $LaF_3$ single crystal. We replaced about 0.1% of lanthanum atoms with neodymium atoms. The space group of the $LaF_3$ crystal is P3c1, but the crystal shows hexagonal symmetry by the twinning. Therefore, there are six magnetically inequivalent lanthanum sites into which a paramagnetic ion may substitute[10]. The orbital angular momentum of the paramagnetic electron of the neodymium atom is quenched in the crystal, but the Zeeman energy of the paramagnetic electron is affected by the orbital angular momentum through the spin-orbit interaction. Therefore, the g-factor of the paramagnetic electron changes from the free electron g-factor, $g_e = 2$. The g-factor is generally expressed by a tensor. The g-tensor is same for the six sites, because of the symmetry property of the crystal. The only difference is in orientation of the principal axes of the g-tensor. We measured the paramagnetic resonance of this crystal as a function of crystal orientation. A typical result is shown in Fig. 2. In this figure, the crystal is rotated around the crystal a* axis, which is set to be perpendicular to the magnetic field $H_0$. The rotation angle $\theta$ is defined by the angle between the crystal c axis and the magnetic field $H_0$. The present result is consistent with the result of Baker and Rubins[11]. The g-factors for the six sites should coincide with each other at $\theta = 0^\circ$. The experimental results did not coincide, since the a* axis slightly deviated from the vertical axis to the magnetic field. For the dynamic polarization, we set the crystal orientation angle at $\theta = 45^\circ$. The signal of the electron spin resonance ( ESR ) is shown in Fig. 3 in this orientation. Here, the temperature of the crystal was 0.5 K and the microwave frequency was 69.5 GHz. In the measurement of the ESR, a carbon resister was used as a bolometer of the microwave radiation in the microwave cavity where the crystal placed. The dynamic polarization was carried out at the magnetic field of 19.6 kG. The microwave frequency was shifted from the center of the ESR. The shift in the frequency corresponded to the nuclear Zeeman energy. The microwave power of about a few tens mW was switched on and a nuclear polarization build-up was observed. The result is shown in Fig. 4. In the figure, nuclear magnetic resonance ( NMR ) signal amplitude for fluorine nuclei is plotted against time in minute. The polarization of lanthanum nuclei can be estimated from the polarization of fluorine nuclei by means of the spin temperature theory. The present NMR detector is not calibrated for the signal amplitude. We could not obtain the value of the polarization. However, the effect of the dynamic polarization is clear as

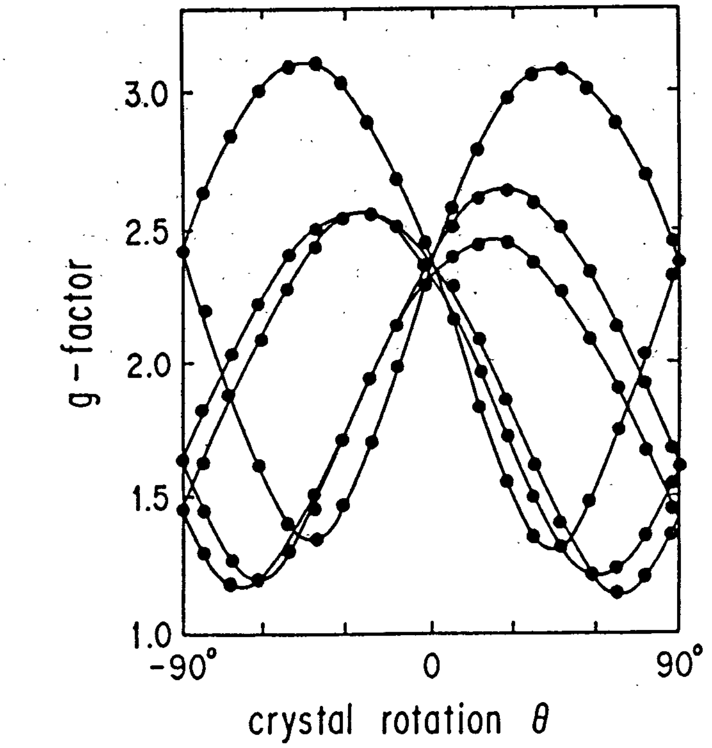

Fig. 2 g-factor of Nd in LaF3 as a function of the crystal orientation.

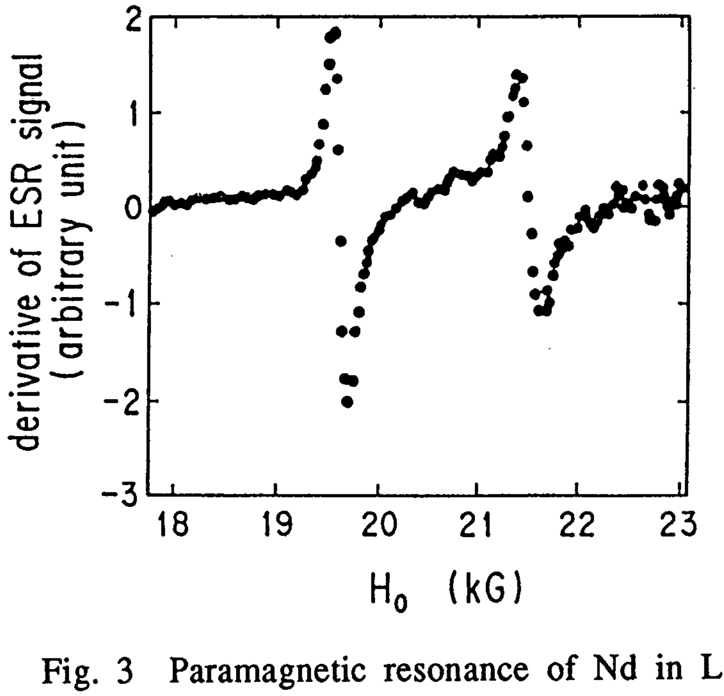

Fig. 3 Paramagnetic resonance of Nd in LaF3.

shown in Fig. 4. The NMR signal showed small relaxation after the microwave power was switched off. This is also shown in Fig. 4. The nuclear spin relaxation time was more than several days. The present polarization is small, but we can improve it by overlapping the g-factors for the six sites so that all the paramagnetic electrons contribute the dynamic polarization. It is possible by setting the crystal at $\theta = 0^o$ accurately, or by using some paramagnetic centers which show no anisotropy in the g-factor. We can also improve the nuclear polarization by using more strong magnetic field and a lower temperature cryostat, since the nuclear relaxation time become longer in these conditions.

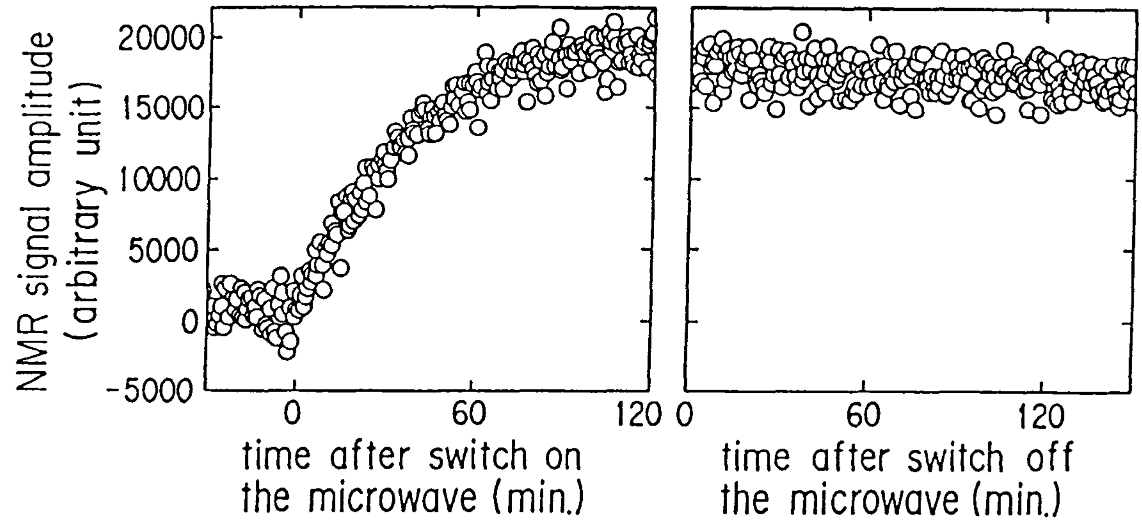

Fig. 4 Dynamic nuclear polarization of La(Nd)F3.

Lanthanum nuclei in a $La_2Mg_3(NO_3)_{12} \cdot 24H_2O$ ( LMN ) crystal can be of course polarized[12]. However, other nuclei have the large neutron scattering cross section and the concentration of lanthanum nuclei is very small. In this point of view, $LaF_3$ is quite suitable for the transmission measurement, since the concentration of lanthanum nuclei is large and the neutron scattering cross section of the fluorine nucleus is very small. In fact, we could observe clear parity violating transmission difference for this crystal. A typical example is shown in Fig. 5. The dip at $E_n = 0.734$ eV is due to the p-wave resonance of $^{139}La$. Other small dips are due to the nuclear Bragg scattering.

In the measurement of the T-violating transmission difference, we must control the neutron spin rotation. The neutron spin precesses around the magnetic field which is used for the polarization of the target nucleus spin. For example, the neutron spin precesses 60 turns during the passage through a 1-cm thick target in the magnetic field of 25 kG at $E_n = 0.734$ eV. The neutron spin also rotates around the nuclear polarization because

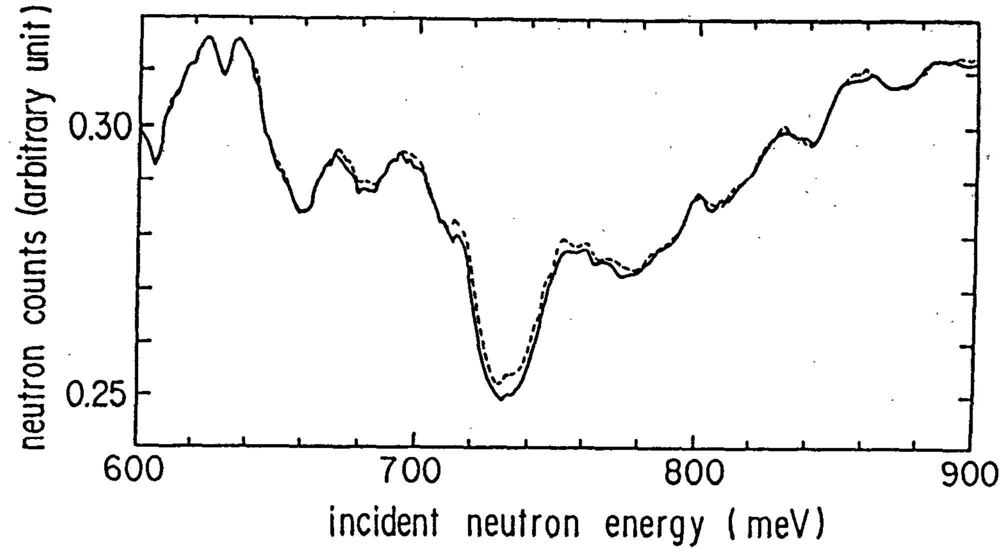

Fig. 5 P-violating transmission difference for a $LaF_3$ target. The solid and dotted lines are the results for positive and negative helicity states, respectively.

of the spin dependent neutron-nucleus interaction[13]. This rotation is called pseudomagnetic rotation. This phenomena was observed by the Saclay group[14]. The pseudomagnetic rotation is obtained by the following equations,

$$\omega = -\gamma_n H^* \quad (2),$$

$$H^* = 4\pi N_0 \mu_N{}^* P \quad (3),$$

$$\mu_N{}^*/\mu_B = I/\ g_n \cdot ((b_+ - b_-)/(I+1/2))/r_0 \quad (4).$$

Here, $\gamma_n$ is the gyromagnetic ratio of the neutron, $N_0$ the number of nuclei in the target, P the nuclear polarization, $g_n$ the neutron magnetic moment expressed in nuclear magneton, $r_0$ the classical electron radius and $\mu_B$ the Bohr magneton. $b_+$ and $b_-$ are neutron scattering amplitudes for parallel and antiparallel spin states between neutron and nuclear spins. The pseudomagnetic field H* corresponds to about 2 kG for the 100% polarized $LaF_3$ crystal. We can cancel out the two rotation in the target crystal, the Larmor precession and the pseudomagnetic rotation by adjusting the magnetic field strength. After the dynamic polarization, we can switch off the microwave power. The microwave heating disappear and the temperature in the crystal decrease. Therefore, we can reduce the magnetic field strength without a loss of the nuclear polarization so that the two rotation are cancelled out.

Finally, we need a polarized neutron detector. $^3He$ nuclei are quite suitable for the detection of polarized neutrons. The $^3He$ nucleus has the large resonance capture cross section for neutrons in the eV region. The resonance energy is $E_0$ = -518 keV and the width is $\Gamma$ = 1153 keV. The capture cross section is about 1000 b at $E_n$ = 0.7 eV. In the resonance, the neutron spin is antiparallel to the $^3$He spin. Therefore, polarized $^3$He nuclei are quite suitable to detect polarized neutrons. $^3$He nuclei are polarized by $^3$He-Rb optical pumping. The Princeton group polarized 3 x $10^{20}$ $^3$He nuclei up to 90% in order to polarize the neutron beam[15]. However, the number is short for this purpose. Recently, the TRIUMF group polarized the larger number of $^3$He nuclei up to 60_70% by using a powerful Ti-sapphire laser[16]. The polarized $^3$He nucleus number is 1.4 x $10^{21}$. The number is sufficient to detect polarized neutrons. The detection efficiency for 100% polarized neutrons is about 40% in the detection area of 4 cm$^2$.

In conclusion, the T-violation test on the p-wave resonance of $^{139}$La is quite promising. The upper limit of the T-violating transmission asymmetry is depend on the neutron counting statistics and the systematic error which comes from an uncertainty of the cancellation of the neutron spin rotation in the target. We estimated we can obtain the upper limit of less than $10^{-3}$. Of course, we need to improve the lanthanum nuclear polarization and to develop the $^3$He polarization for this purpose. We believe this is not out of the present technology.

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Q(J.B.Hayter): When you move to a new, 4T magnet? What microwave system do you plan to use? Will you choose a high g-factor sample orientation?

A(Y.Masuda): A new microwave oscillator will be used. Varian's klystron is one of candidates.