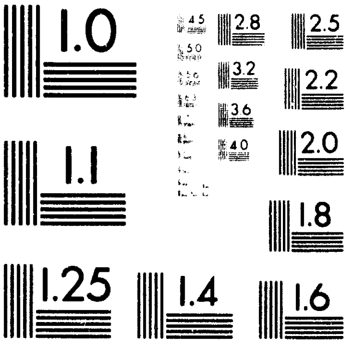
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Author(s): Yasushiro Masuda

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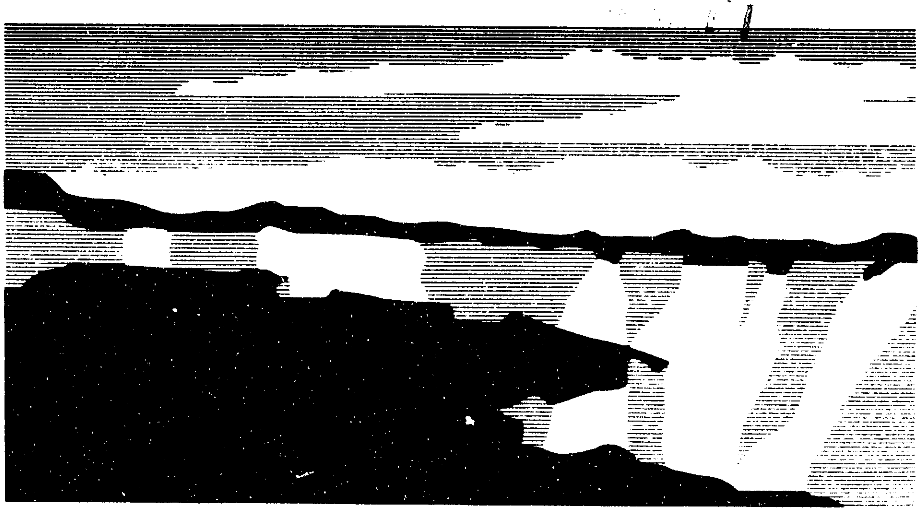

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T violating Neutron Spin Rotation Asymmetry

Yasuhiro Masuda

National Laboratory for High Energy Physics
1-1 Oho, Tsukuba-shi, Ibaraki-ken, 305 Japan

Abstract

A new experiment on T-violation is proposed, where a spin-rotating-neutron transmission through a polarized nuclear target is measuered. The method to control the neutron spin is discussed for the new T-violation experiment. The present method has possibility to provide us more accurate T-violation information than the neutron EDM measurement.

I. Introduction

T-violation on the neutron-induced reaction in eV region is one of the recent topics on the fundamental-symmetry-violation, since large enhancement of a P-odd $\sigma \cdot \boldsymbol{k}$ correlation term has been found in the p-wave resonance of the neutron-radiative-capture reaction.[1, 2, 3, 4] σ is the neutron spin and $\boldsymbol{k}$ the neutron momentum. Many kinds of T-violation experiments have been proposed. Among them, the measurement of a T-odd and P-odd $\sigma \cdot (\boldsymbol{k} \times \boldsymbol{I})$ correlation term, where $\boldsymbol{I}$ is the nuclear spin, is the most interesting experiment, since it has the following three advantages. Firstly, the large enhancement is also expected. Secondly, the effect is free from final state interactions, since the comparison of completely time-reversed processes is possible. Thirdly, the ratio of the T-odd to P-odd effect is insensitive to the nuclear wave-function uncertainty. As a result, the measurement can be compared with other elementary-particle experiments, for example the neutron electric-dipole-moment (EDM) measurement. Therefore, many experimental methods have been proposed to measure the T-odd and P-odd term.

At first, the measurement of a neutron-spin rotation around $\boldsymbol{k} \times \boldsymbol{I}$ (y axis) was proposed.[5] However, fake effects by a coupling of two different kinds of spin-correlation terms, $\sigma \cdot \boldsymbol{k}$ and $\sigma \cdot \boldsymbol{I}$ terms disable us to carry out an accurate measurement. The measurement of transmission asymmetry and polarization for the neutron spin in the y axis was also proposed.[6] According to the polarization-asymmetry theorem, fake effects are canceled out in the sum of the polarization and asymmetry.[7] A detailed balance in spin-flip processes induced by the $\sigma \cdot (\boldsymbol{k} \times \boldsymbol{I})$ correlation term is a good candidate to obtain the T-violation effect without fake effects, since the two processes which are time-reversed processes for each other, are compared in its measurement.[6] In these measurements, however, it is still very difficult to obtain the information about T-violation beyond the present limit of the neutron EDM.

Here, we discuss a new method, which enable us to obtain the T-violation information beyond the limit of the neutron EDM. The new method is a neutron-transmission measurement, where the neutron spin is rotating during the propagation through a polarized nuclear target. The incident neutron-spin direction is longitudinal and is flipped in a suitable period. The T-odd effect is found in a transmission difference for the neutron-spin flipped states. For 180° rotation, fake effects are canceled in the transmission difference. Furthermore, systematic errors due to a mis-adjustment of the rotation etc. are canceled by reversing the rotation direction and the nuclear polarization. For the 180° rotation, the neutron spin is in the positive or negative direction of y. Therefore, the present T-odd effect is as large as the T-odd transmission asymmetry and polarization.

During the experiment, the neutron-spin control has a crucial role. The method of measuring the neutron-spin direction was developed for the neutron-spin control. The limit of the accuracy for the present method, which is based on the experimental result, is also discussed.

II. Rotation asymmetry as a measure of the triple correlation term

The neutron transmission through a nuclear target is discussed in terms of the forward scattering amplitude $f(0)$. The general form of the polarized neutron scattering amplitude for the polarized nucleus is described in terms of a spin operator as the following.[6]

$$f(0) = F_0 + F_1 \sigma_x + F_2 \sigma_y + F_3 \sigma_z$$
$$F_0 + F_1 \sigma \cdot \hat{\boldsymbol{I}} + F_2 \sigma \cdot (\hat{\boldsymbol{k}} \times \hat{\boldsymbol{I}}) + F_3 \sigma \cdot \hat{\boldsymbol{k}}. \quad (1)$$

After the transmission through the target, the effect of the nuclear interaction is found in a phase shift Δ.

$$\Delta = \lambda l N f(0). \quad (2)$$

λ is the neutron wave-length, l the neutron propagation-length and N the target-nucleus-number density. The neutron transmission can be discussed in terms of the following operator F, which is a function of the phase shift.

$$F = \exp(i\Delta). \tag{3}$$

The density matrices of the neutron-spin states which are parallel and anti-parallel to z axis are

$$\rho_\pm = 1/2 \cdot (1 \pm \sigma_z), \tag{4}$$

respectively. After transmission, the density matrices are modified by the presence of the phase shift as

$$\rho_f = F\,\rho_\pm\,F^\dagger. \tag{5}$$

The transmission probabilities are calculated by using the density matrix of the final state as

$$\begin{aligned} T_\pm &= \mathrm{Tr}\,(\rho_f) \\ &= \exp\{-2\mathrm{Im}(\phi_0)\} \cdot [1 \pm \{-\sin 2b\,/\,b \cdot \mathrm{Im}(\phi_3) + \\ &\quad 2 \cdot (\sin b\,/\,b)^2 \cdot (\mathrm{Im}(\phi_1) \cdot \mathrm{Re}(\phi_2) - \mathrm{Re}(\phi_1) \cdot \mathrm{Im}(\phi_2))\}]. \end{aligned} \tag{6}$$

Here,

$$\phi_i = \lambda l N F_i, \qquad (i = 0,\ 1,\ 2,\ 3) \tag{7}$$

$$b = \sqrt{|\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2}\ . \tag{8}$$

T_+ and T_- are the neutron transmittances for positive and negative incident neutron-spin states, respectively. In the p-wave resonance of ^{139}La,

$$\mathrm{Re}(\phi_1) \gg \mathrm{Im}(\phi_1). \tag{9}$$

According to the theoretical prediction,[8]

$$\mathrm{Im}(\phi_3) \gg \mathrm{Re}(\phi_3). \tag{10}$$

The flipping ratio for the neutron transmission which is defined as

$$R = (T_+ - T_-)/(T_+ + T_-),$$

is

$$R = -\{\sin 2b\,/\,b + 2 \cdot (\sin b\,/\,b)^2 \cdot \mathrm{Re}(\phi_1) \cdot \eta \cdot P_I\}\ \mathrm{Im}(\phi_3). \tag{11}$$

η is a ratio of the T-odd to P-odd term. P_I is a nuclear polarization. $\mathrm{Re}(\phi_1)$ induces a neutron-spin rotation around x axis. If the rotation angle is 180°, then the value of the phase shift b is

$$b = \pi/2 + \delta, \tag{12}$$

since the values of ϕ_2 and ϕ_3 are negligibly samall. δ is a small deviation from the phase angle $\pi/2$. In this case, the flipping ratio is

$$R_+ = 4/\pi \cdot (\delta - \eta \cdot P_I) \cdot \mathrm{Im}(\phi_3). \tag{13}$$

The same kind of transmission asymmetry was suggested previously.[9] However, the uncertainty of the neutron-spin rotation limits the experimental error. The uncertainty can be greatly reduced in the following way.

In the neutron-spin-rotation control, we adjust the magnetic field H_0 so that neutron-spin-rotation angle is 180° during the transmission through the target. In addition to the Larmor precession, the neutron spin rotates around the nuclear spin in the presence of the F_1 term. The neutron sees an field called "pseudomagnetic field H^*" in addition to the magnetic field. As a result, the neutron-spin rotates in the sum of these fields $H_0 + H^*$. By adjusting the magnetic field, 180° and -180° rotations are realized. The uncertainty of the phase angle δ has two component. One is due to the uncertainty of magnetic field setting. The other is due to the uncertainty of the pseudomagnetic field.

The flipping ratio for opposite spin rotation and reversed nuclear polarization is

$$R_- = -4/\pi \cdot (\delta + \eta \cdot P_I) \cdot \mathrm{Im}(\phi_3). \tag{14}$$

The nuclear polarization can be reversed by an adiabatic fast passage. In the sum $R_+ + R_-$, which is defined as a rotation asymmetry, the uncertainty of the pseudomagnetic field is canceled as it is shown in the following equation.

$$\begin{aligned} A_r &= R_+ + R_- \\ &= 4/\pi \cdot \{\delta_L - 2\eta \cdot P_I\} \cdot \mathrm{Im}(\phi_3), \end{aligned} \tag{15}$$

δ_L is the uncertainty of the field setting. Mis-alignment of the nuclear polarization in x direction may induce a spurious asymmetry. The spurious effect is canceled in the sum, since the effect changes in sign under reversal of the nuclear polarization. As a result, the systematic effects in the rotation asymmetry can be greatly reduced.

The value of the rotation asymmetry is as large as the T-odd transmission asymmetry and polarization. Although the fake effects in the T-odd transmission asymmetry and polarization are canceled in their sum,[7] the two measurements are independent of each other, therefore, the values of the fake effects are not necessary same in the two measurements. In the spin detailed balance, there is no fake effect, since a difference of spin-flip probabilities which are time reversed to each other is measured.[6] Cancellation of the Larmor and pseudomagnetic precessions makes the effect of the F_1 term on the spin flip small so that the effect of the F_2 term increases in the spin detailed balance. However, the accuracy is limited, because we should measure a small difference between small spin-flip probabilities.[10] In this point of view, the rotation asymmetry has a great advantage.

III. Measurement of the neutron spin rotation

Here, we discuss the accuracy of the neutron-spin-rotation control, which is crucial in the measurement of the rotation asymmetry. We developed a new method to detect the neutron-spin-rotation angle. The method is shown in Fig. 1 and Fig. 2. The apparatus shown in Fig. 1 is a neutron polarimeter,[11] which measures the neutron polarization by using the polarization cross-section of the ^{3}He nucleus. The ^{3}He nucleus absorbs the neutron whose spin is antiparallel to the ^{3}He spin. We used this property as a neutron-spin analyzer. The neutron transmittance of a polarized ^{3}He filter is described in terms of neutron polarization P_n, filter thickness t, ^{3}He nucleus-number density N, neutron cross-section σ and ^{3}He polarization P_{He} as

$$T_\pm = (1 \pm P_n)/2 \cdot \exp\{-N\sigma t(1 - P_{He})\} \\ + (1 - (\pm P_n))/2 \cdot \exp\{-N\sigma t(1 + P_{He})\}. \qquad (16)$$

Positive and negative signs correspond to the neutron-polarization states parallel and antiparallel to the ^{3}He polarization, respectively. We can obtained the value of the neutron polarization by the measurement of a flipping ratio R for the ^{3}He transmittance. Following the eq. (16),

$$R = (T_+ - T_-)/(T_+ + T_-) \\ = P_n \cdot \tanh(N\sigma t P_{He}). \qquad (17)$$

The value of Nt can be obtained by a transmittance measurement for the unpolarized state of ^{3}He filter.

The neutron-spin-rotation angle was measured by using the conversion of the rotation angle to a projection angle on a magnetic field. We used a non-adiabatic passage through a superconducting sheet for this conversion, which is shown in Fig. 2.[12] The neutron sees a sudden

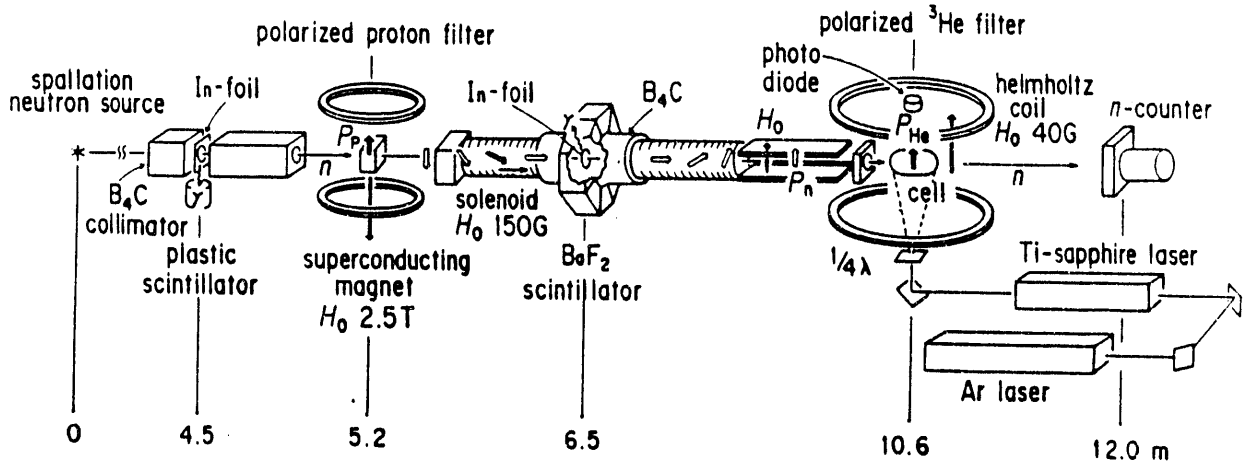

Fig. 1 Polarized ^{3}He neutron polarimeter.

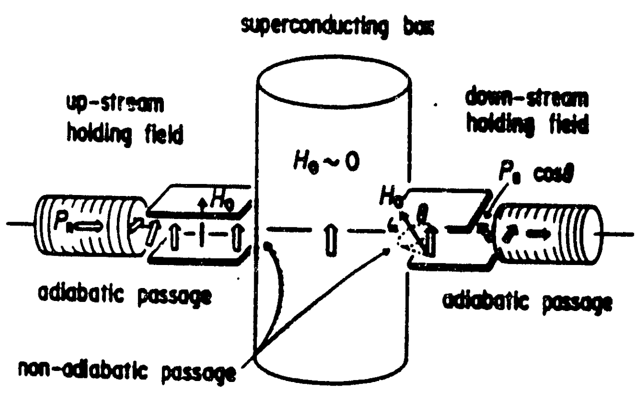

Fig. 2 Rotation angle detection.

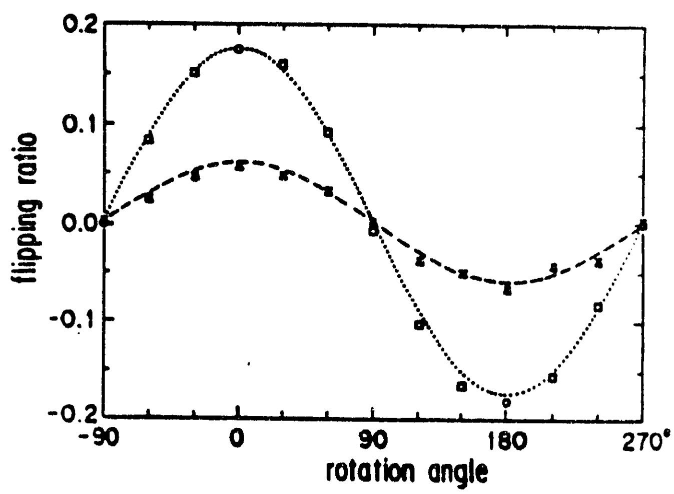

Fig. 3 Flipping ratio of the polarized ^{3}He transmittance as a function of θ.

decrease of the magnetic field to zero upon passing through the surface of the superconductor. The magnetic field penetration-depth of niobium is $\lambda(0)$ = 440 Å at T = 0 K. The neutron time of flight for the penetration depth is 3.7 x 10^{-12} sec at a neutron energy of E_n = 0.734 eV. The neutron spin does not follow this sudden change in the magnetic field, because the rate of the magnetic field change is very fast compared with the Larmor frequency which is 2.9 x 10^3 Hz/G. As a result the neutron spin enters into a zero magnetic field without change in its direction. At the exit of the superconducting box, the neutron spin goes out from the box and enters into a down-stream magnetic field also without change in its direction. If the neutron spin rotates from the magnetic field by θ at the exit of the superconducting box, the cosθ component of the neutron spin is held by the down-stream magnetic field and analyzed by the polarized ^{3}He filter. We measured the flipping ratio as a function of the rotation angle of the down-stream magnetic field. The result is shown in Fig. 3. A clear cosθ distribution is found in Fig. 3. The result shows that we can measure the neutron-spin rotation accurately inside the superconducting box. The accuracy of $\delta\theta = 1^o$ is possible.

In the T-violation experiment, the magnetic field is applied for holding the nuclear spin and for the cancellation with the pseudomagnetic field. If we use a LaF_3 or $LaAlO_3$ single crystal as a polarized nuclear target[13,14] and the nuclear polarization is 50%, the pseudomagnetic field is ~1 kG. Neurons of E_n = 0.734 eV rotate ~10 turns upon passage through a 1 kG magnetic field for a 4-cm length. The 1^o-rotation adjustment means a field adjustment of 3 x 10^{-4}. For the value of $\delta\theta = 1^o$, the experimental accuracy ot η in the ratios R_+ and R_- which is obtained by eq. (13) or (14) is

$$\delta\eta = 2 \times 10^{-2}. \qquad (18)$$

The uncertainty of the pseudomagnetic field is dominant in the value of $\delta\eta$. In the rotation asymmetry, the uncertainty of the pseudomagnetic field is canceled as shown in eq. (15). As a result, the systematic error is reduced down to the magnetic field uncertainty. If we assume the magnetic field uncertainty $\delta H_o/H_o < 1 \times 10^{-5}$, the error of η is

$$\delta\eta < 3 \times 10^{-4}. \qquad \text{(rotation asymmetry } A_r) \qquad (19)$$

The present experimental accuracy of the neuron EDM corresponds to the value of η as[8]

$$\eta < 4 \times 10^{-3}. \qquad \text{(n EDM)} \qquad (20)$$

Therefore, the rotation asymmetry has possibility to obtain more accurate information than the neutron EDM.

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