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✓ KEK p 93-185
SW 9412

KEK Preprint 93-185
January 1994
H/M

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National Laboratory for High Energy Physics, 1994

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T-violation in Neutron Spin Rotation

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Abstract

A new *T*-violation experiment concerning the neutron-nucleus interaction is proposed. In this experiment the neutron spin rotates around the nuclear spin by 180° from the forward to backward direction during propagation through the target. The rotation direction and incident neutron spin are reversed at a suitable period. The *T*-violation effect is found in the asymmetry of the transition probability of the neutron spin state with respect to the two kinds of reversals. The systematic error can be small compared with the *T*-violation limit bound by the neutron EDM measurement.

I. Introduction

T-violation in the neutron-induced reaction in the eV region is one of the recent topics concerning fundamental symmetry violations, since a large enhancement of the *P*-odd $\sigma \cdot k$ 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 k the neutron momentum. Several kinds of *T*-violation experiments have been proposed. Among them, a measurement of the *T*-odd and *P*-odd $\sigma \cdot (k \times I)$ correlation term, where I is the nuclear spin, is most interesting, since it has the following three advantages. Firstly, a large enhancement is expected. Secondly, the effect is free from final-state interactions, since the initial and final states are the same plane wave. 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, neutron-spin rotation around $k \times I$ during propagation through a polarized nuclear target was proposed.[5] However, fake effects due to the coupling of two different kinds of spin-correlation terms, $\sigma \cdot k$ and $\sigma \cdot I$, disable one from carrying out an accurate measurement.

Measuring the transmission asymmetry and polarization for the neutron spin in the $\mathbf{k} \times \mathbf{I}$ 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 $\boldsymbol{\sigma} \cdot (\mathbf{k} \times \mathbf{I})$ correlation term is a good candidate to obtain the T -violation effect without any 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 T -violation information beyond the present limit bound by the neutron EDM measurement.

Here, we discuss a new method, which breaks through the problem. The present method involves a double asymmetry in the transition probability of neutron spin states during propagation through a polarized nuclear target. During propagation, the neutron spin rotates by 180° around the nuclear spin from forward to backward and vice versa. The T -violation effect is found in the difference in the transition probability upon a reversal of the rotation as well as upon a reversal of the incident neutron spin. The present method is a combination of the T -odd transmission asymmetry and the spin-detailed balance. The size of the present T -violation effect is as large as the T -odd transmission asymmetry and polarization. There is no fake effect in the present asymmetry like that in the spin detailed balance. Furthermore, another systematic error which may be induced by a mis-alignment between the neutron spin and nuclear spin is canceled in the double asymmetry. As a result, a considerable improvement is expected in the T -violation limit.

II. Rotation asymmetry as a measure of the T -violation

The propagation of a polarized neutron through a polarized nuclear target is discussed in terms of the forward scattering amplitude ($f(0)$) and the density matrix.^[8] The general form of the scattering amplitude for the polarized nucleus can be described as

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

Here, $\boldsymbol{\sigma}$ is the Pauli spin operator.^[6] F_i ($i = 0,1,2,3$) are scattering amplitudes. After propagation through the target, the effect of the nuclear interaction is found in a phase shift (Δ) of the neutron wave,

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

Here, λ is the neutron wavelength, l the neutron propagation-length and N the target-nucleus-number density. The density matrices of the incident

neutron spin states, which are parallel and anti-parallel to the neutron momentum (z axis), are

$$\rho_{\pm} = 1/2 \cdot (1 \pm \sigma_z), \quad (3)$$

respectively. After propagation, the density matrices are modified in the presence of the phase shift as

$$\rho_f = F \rho_{\pm} F^{\dagger}, \quad (4)$$

where, F is

$$F = \exp(i\Delta). \quad (5)$$

The 180° neutron spin rotation is described in terms of the density matrices and projection operators ($P_{\pm}$) for parallel and anti-parallel spin states to the z -axis

$$P_{\pm} = (1 \pm \sigma_z)/2. \quad (6)$$

The transitions from positive to negative and from negative to positive state (R_{+-} and R_{-+}) are described as follows:

$$\begin{aligned} R_{+-} &= \text{Tr} (F \rho_+ F^{\dagger} P_-) \\ &= \exp(-2\text{Im}(\phi_0)) (\sin b/b)^2 \\ &\quad \{ |\phi_1|^2 + |\phi_2|^2 + 2 (\text{Im}(\phi_1) \cdot \text{Re}(\phi_2) - \text{Re}(\phi_1) \cdot \text{Im}(\phi_2)) \}, \end{aligned} \quad (7)$$

and

$$\begin{aligned} R_{-+} &= \text{Tr} (F \rho_- F^{\dagger} P_+) \\ &= \exp(-2\text{Im}(\phi_0)) (\sin b/b)^2 \\ &\quad \{ |\phi_1|^2 + |\phi_2|^2 - 2 (\text{Im}(\phi_1) \cdot \text{Re}(\phi_2) - \text{Re}(\phi_1) \cdot \text{Im}(\phi_2)) \}, \end{aligned} \quad (8)$$

respectively. Here,

$$b = \sqrt{|\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2}, \quad (9)$$

and ϕ_i are spin-dependent phase shifts, which can be represented by

$$\phi_i = \lambda N F_i \quad (i = 0, 1, 2, 3). \quad (10)$$

In the eq. (9), $|\phi_1|^2$ is dominant,

$$b^2 = |\phi_1|^2 (1 + \delta_\phi). \quad (11)$$

In the p-wave resonance of ^{139}La ,

$$\text{Re}(\phi_1) \gg \text{Im}(\phi_1). \quad (12)$$

The dominant term in R_{+-} and R_{-+} is $|\text{Re}\phi_1|^2$. According to the theoretical prediction^[9] and a recent experiment concerning parity-violating neutron-spin rotation,^[10]

$$\text{Im}(\phi_3) \gg \text{Re}(\phi_3). \quad (13)$$

As a result,

$$R_{+-} = \exp(-2\text{Im}(\phi_0)) (\sin b)^2 (1 - \delta_\phi) \{1 - 2\text{Im}(\phi_2)/\text{Re}(\phi_1)\}, \quad (14)$$

and

$$R_{-+} = \exp(-2\text{Im}(\phi_0)) (\sin b)^2 (1 - \delta_\phi) \{1 + 2\text{Im}(\phi_2)/\text{Re}(\phi_1)\}. \quad (15)$$

Since the neutron spin rotates around the nuclear polarization (x axis) by 180° from forward to backward and vice versa, the neutron spin is in $+y$ ($\mathbf{k} \times \mathbf{I}$) region and $-y$ region during the propagation through the target, respectively. The imaginary part of the phase shift (ϕ_2), which is the T -odd term, is found in the neutron wave after propagation. The sign of the T -odd term is changed upon reversal of the incident neutron spin. From this point of view, the present method is similar to the T -odd transmission asymmetry. The asymmetry of the transition probabilities (R_{+-} and R_{-+}) is

$$\begin{aligned} A_s &= (R_{+-} - R_{-+}) / (R_{+-} + R_{-+}) \\ &= -2\text{Im}(\phi_2)/\text{Re}(\phi_1). \end{aligned} \quad (16)$$

Eq. (16) is essentially the same as the spin-detailed balance. If the value of λlN is

$$\lambda lN = 2.4 \times 10^{14} \text{ cm}^{-1}, \quad (17)$$

the value of A_s is

$$A_s = 1.4 \times 10^{-2} \eta P_I. \quad (18)$$

Here, η is

$$\eta = \text{Im}(\phi_2)/\text{Im}(\phi_3). \quad (19)$$

The sign of the T -odd term is also changed upon a rotation reversal. The asymmetry of the transition probability with respect to the rotation reversal, which is referred to as rotation asymmetry, is

$$\begin{aligned} A_r(+) &= (R_{+-} (+180^\circ) - R_{+-} (-180^\circ)) / (R_{+-} (+180^\circ) + R_{+-} (-180^\circ)) \\ &= -2 \text{Im}(\phi_2)/|\text{Re}\phi_1|, \end{aligned} \quad (20)$$

when the incident spin is in the $+z$ direction. When the incident spin is in the $-z$ direction,

$$\begin{aligned} A_r(-) &= (R_{-+} (+180^\circ) - R_{-+} (-180^\circ)) / (R_{-+} (+180^\circ) + R_{-+} (-180^\circ)) \\ &= +2 \text{Im}(\phi_2)/|\text{Re}\phi_1|. \end{aligned} \quad (21)$$

III Experimental scheme and systematic error

The experimental scheme is shown in Fig. 1. The neutron beam is polarized by either a polarized ^3He filter or a polarized proton filter. A neutron enters into a target section through a flipper section. After propagation through the target, the neutron spin is analyzed by a ^3He neutron polarimeter.^[11] The neutron spin is manipulated as follows.

After transmission through the polarizer, the neutron spin rotates following an adiabatic passage upstream of the flipper. The magnetic field direction is along the y -axis at the flipper and reversed at a suitable period. The neutron spin is reversed with a reversal of the field direction. After the flipping magnet, the neutron spin enters into a 90° coil through a superconducting sheet. In the superconductor the magnetic field is zero due to the Meissner effect. The neutron sees a sudden decrease in the magnetic field to zero upon passing through the surface of the superconductor. The magnetic field penetration-depth of niobium is $\lambda(0) = 440 \text{ \AA}$ at $T = 0 \text{ K}$. The neutron time of flight for the penetration depth is $3.7 \times 10^{-12} \text{ sec}$ at a neutron energy of $E_n = 0.734 \text{ eV}$. 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 $2.9 \times 10^3 \text{ Hz/G}$. As a result, the neutron spin enters into the 90° coil without any change in its direction. In the 90° coil, the magnetic field direction is along the x -axis. The neutron spin rotates from the y - to z - direction before entering into the polarized nuclear target. In the target section, a static magnetic field (H_0) is applied in order to hold the nuclear polarization. In addition to the magnetic field, the neutron sees a field called a "pseudomagnetic field (H^*)" due to the F_1 term during transmission through the target. Therefore, the neutron-spin

rotates in the sum of these fields ($H_0 + H^*$). The neutron-spin-rotation is controlled by adjusting the magnetic field (H_0) so that neutron-spin-rotation angle is either 180° or -180° during transmission. After transmission, the neutron spin rotates from the z - to y - direction in the second 90° coil and is then analyzed by a polarized ^3He neutron polarimeter.

In the neutron-spin manipulation, detection of the neutron-spin-rotation angle is very important. We have developed a rotation phase detector by using the Meisner effect.^[12] The neutron-spin-rotation phase is converted to a projection angle on the magnetic field. The projection component of the neutron spin is measured by the ^3He neutron polarimeter. In this method, an accuracy of $\delta\theta < 1^\circ$ has been found to be possible. 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. Neutrons of $E_n = 0.734$ eV rotate ~ 10 turns upon passage through a 1 kG magnetic field for a 4-cm length. A 1° -rotation adjustment means a field adjustment of $\delta H_0/H_0 = 3 \times 10^{-4}$.

If we assume that the uncertainty of the neutron-spin rotation is $\delta\theta$, the uncertainty of the phase of the neutron wave (δ) is

$$\delta = \delta\theta / 2. \quad (22)$$

Then, the real part of ϕ_1 is

$$\text{Re}(\phi_1) = \pi/2 + \delta. \quad (23)$$

In the measurement of A_s , the effect of the rotation uncertainty is canceled, if the common coefficient, $\exp(-2\text{Im}(\phi_0)) (\sin b)^2 (1 - \delta_\phi)$, is same under neutron-spin flipping. The values of $\exp(-2\text{Im}(\phi_0))$ and $(1 - \delta_\phi)$ are assumed to be constant. The value of $(\sin b)^2$ may change during neutron spin flipping, since it has a small polarization dependence,

$$b = \pi/2 + \delta + r_1/2 + \delta_\phi/2. \quad (24)$$

Here,

$$r_1 = (\text{Im}(\phi_1)/\text{Re}(\phi_1))^2 < 0.01 P_I^2 \quad (\text{for } \text{Re}(\phi_1) = \pi/2). \quad (25)$$

Here, P_I is the nuclear polarization. As a result,

$$\begin{aligned} (\sin b)^2 &= (\cos(\delta + r_1/2 + \delta_\phi))^2 \\ &= 1 - (\delta + r_1/2 + \delta_\phi)^2. \end{aligned} \quad (26)$$

If the change in δ upon neutron-spin flipping is 0.01° , the change in $(\sin b)^2$ is

$$\Delta((\sin b)^2) < 4 \times 10^{-6}. \quad (27)$$

This change corresponds to an error in the ratio η of

$$\delta\eta < 3 \times 10^{-4}, \quad (28)$$

for a nuclear polarization of 50%. If we assume a relaxation time of 10 h for nuclear polarization and a flipping period of 4 sec, the change in $(\sin b)^2$ is

$$\Delta((\sin b)^2) < 1 \times 10^{-6}. \quad (28)$$

In addition to the above-mentioned errors, a systematic error may be induced due to any mis-alignment between the neutron polarization and nuclear polarization. If the neutron-polarization direction slightly deviates by δ_n from 90° with respect to the nuclear polarization, a $\sin \delta_n$ component of the neutron polarization is held in the direction of the nuclear polarization during transmission through the target. This mis-alignment induces spin-dependent absorption which is proportional to $\sin \delta_n \text{Im}(\phi_1)$. Since the sign of δ_n is reversed upon neutron-spin flipping, the effect of the mis-alignment remains in the value of A_s . However, the absorption effect is small and independent of the neutron-spin-rotation direction. Therefore, the mis-alignment effect is canceled in the rotation asymmetry (A_r). As a result, the systematic errors are greatly reduced if we take a double asymmetry (A_d) of

$$A_d = (A_r(+) - A_r(-)) / (A_r(+) + A_r(-)). \quad (29)$$

We can expect a large T -violation effect in the T -odd transmission asymmetry and polarization. However, it is very difficult to reduce the fake effect in these measurements. Although the fake effect is canceled in the sum of the T -odd transmission asymmetry and polarization,^[7] the two measurements are independent of each other; therefore, the fake effect does not necessarily have the same value in the two measurements. In the spin-detailed balance there is no fake effect, since any difference in 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 any small difference between small spin-flip probabilities.^[15] Also, any mis-alignment between the neutron spin and the nuclear polarization induces a spurious effect. Based on this

point of view, the present method has great advantage. The value of A_s or A_r is as large as the T -odd transmission asymmetry and polarization. There is no fake effect as in the spin-detailed balance. The mis-alignment effect is also canceled. As a result, a comparison with the neutron EDM measurement is possible.

The present experimental accuracy of the neutron EDM corresponds to a η value of

$$\eta < 4 \times 10^{-3} \quad (\text{n EDM}), [8,16] \quad (30)$$

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

The author would like to thank Dr. V.P. Gudkov, Prof. K. Asahi and J.D. Bowman for their valuable discussions. He also expresses his thanks to his colleague concerning P -violation and T -violation experiments carried out at KEK for their indispensable collaboration. He also thanks Prof. H. Sugawara, Prof. N. Watanabe and Prof. K. Nakai for their warm encouragement.

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Fig. 1 Experimental scheme of the rotation asymmetry.

Fig. 1