^{3}He nuclear polarization for neutron spin analysis

Yasuhiro Masuda[1], Koichiro Asahi[2], Masashi Doi[2], Kenji Sakai[1,*], Hiromi Sato[2]
and
Z. Zhi Jian[1]

1 National Laboratory for High Energy Physics, 1-1 Oho Tsukuba-shi, 305 Japan
2 Tokyo Institute of Technology, Megro-ku Tokyo, 152 Japan
* On leave from Tohoku University

I Introduction

The spin is a very useful probe for the space-time symmetry violation in fundamental interactions. A recent topics in this field is about large enhancement (10^6) of the parity (P) violation in the neutron-nucleus interaction in the incident neutron-energy region of eV, where the large neutron-helicity dependence is found in the cross section.[1,2,3,4] The large enhancement is also expected in the symmetry-violation effect under time reversal (T). A T-odd triple-correlation term between the neutron spin, nuclear spin and neutron momentum, which changes in sign under T, is measured in the T-violation test. The neutron spin is also used as a probe in condensed matter science. For example, the magnetic moment of the neutron and the neutron magnetic Bragg-scattering have been widely used for the study of the magnetism in condensed matter. In these studies, the neutron-spin polarization plays a decisive role. ^{3}He nuclear polarization has potentially most preferable properties as a neutron-spin polarizer and analyzer. The reason is the followings.

The ^{3}He nucleus has a large capture cross-section for the neutron, for example, the value of the cross section is more than ~1000 b below the neutron energy, $E_n = 1$ eV. The capture process is induced by a resonance reaction of ^{3}He(n, p)t. The resonance energy and the width are $E_0 = -518$ keV and $\Gamma = 1153$ keV, respectively.[5] The spin of the resonance state is zero. The neutron spin and the ^{3}He nuclear spin are both 1/2, therefore, neutrons whose spins couple with ^{3}He nuclear spins antiparallel are absorbed by ^{3}He nuclei. The scattering cross-section of the ^{3}He nucleus is negligible compared with the absorption cross-section. These properties are quite suitable as a neutron-spin filter. If the ^{3}He polarization is 100% and the filter thickness is much larger than the neutron mean-free-path, neutrons whose spins are parallel to the ^{3}He polarization transmit through the filter without attenuation, on the other hand neurons whose spins are antiparallel are absorbed completely. As a result, the transmittance of the polarized ^{3}He filter becomes 50% and the polarization of the transmitted neutrons achieves 100%. This is a prominent feature of the polarized ^{3}He filter as a neutron-spin polarizer. The polarized proton filter was unique method to obtain polarized neutrons in the epithermal region so far.[6,7] However, the proton has large scattering cross-section for the neutron. Therefore, the transmittance of the polarized proton filter is rather small than the polarized ^{3}He filter. In addition to that, scattered neutrons may induce background in the neutron experiment. The ^{3}He filter can be also applied to the neutron-spin analyzer. Namely, the neutron spin is analyzed by the neutron transmittance of the polarized ^{3}He filter. A polarized ^{3}He neutron counter is more ambitious application. Since the neutron of antiparallel spin induces the emission of charged particles through the nuclear reaction ^{3}He(n, p)t , which produces an electric signal, the polarized ^{3}He counter senses only neutrons of antiparallel spin. It means a great gain of the analyzing power for the neutron spin.[8]

Although the ^{3}He nucleus has the prominent properties in the application to the neutron-spin polarizer and analyzer as mentioned above, the polarized ^{3}He filter has not been realized for neutron experiments. Here, we discuss development of ^{3}He nuclear polarization at KEK and application to the *P*- and *T*-violation experiments.

II Principle of ^{3}He nuclear polarization

For the ^{3}He nuclear polarization, a spin-exchanging hyperfine-interaction during atomic collision between polarized alkali atom and ^{3}He atom is used.[9,10] The rubidium atomic-spin is polarized by an optical pumping. Namely, the rubidium atom is polarized upon the absorption of circularly polarized D1-resonant-light as it is shown in Fig. 1. The 5S1/2 state excites to the 5P1/2 state upon the absorption of the D1 light, where the magnetic quantum-state of m = -1/2 transits to the 1/2 state. The 5P1/2 state deexcites to the 5S1/2 state emitting unpolarized D1-light. If another polarized rubidium-atom absorbs the unpolarized resonant light, the atom depolarizes. A small amount of nitrogen gas is added to quench the unpolarized light. The 5P1/2 state deexcites during collision with a nitrogen molecule without emitting the resonant light. During the collision, the magnetic substates of the 5P1/2 state mixed with each other, therefore, the populations of the magnetic substates are equalized. Each magnetic substate of 5P1/2 decays into the magnetic substate of the 5S1/2 without changing the magnetic quantum number. As a result, a half of the photon spin is transferred to the 5S1/2 state. The spin-transfer rate from the photon to the rubidium atom is determined by the photon-absorption cross-section and incident laser intensity. However, the polarization of rubidium atom, P_{Rb} is limited by spin destruction during Rb-Rb and Rb-^{3}He-^{3}He atomic collisions. The spin-destruction rate, Γ_{sd} is Γ_{sd}~1 ms^{-1}. The incident laser power is applied to overcome the spin-destruction rate.

The rubidium atomic polarization is transferred to the ^{3}He nuclear spin by a

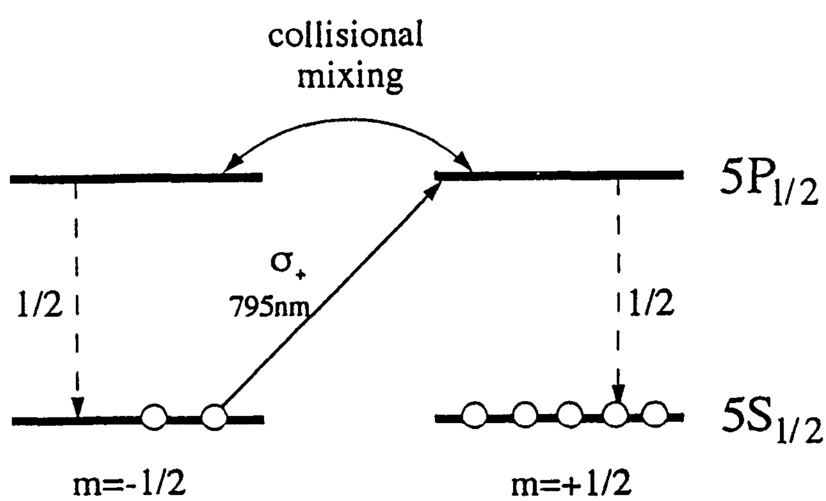

Fig. 1 Optical pumping of rubidium atom

hyperfine interaction during a Rb-^{3}He atomic collision. The spin-exchange rate from the rubidium atom to the ^{3}He nuclear spin is $\Gamma_{se} = 9.4 \times 10^{-2}$ h^{-1} for a rubidium atomic-number-density of 4 x 10^{14}/cc.[10] The evolution of the ^{3}He polarization, P_{He} is predicted by a rate equation. The solution is

$$P_{He} = [\, P_{Rb}\Gamma_{se}/(\Gamma_{se} + \Gamma)\,]\, [\, 1 - exp(-(\Gamma_{se} + \Gamma)t)\,]. \tag{1}$$

The value of P_{He} is directly proportional to the value of P_{Rb}, since the ^{3}He polarization is also depolarized upon collision with an unpolarized rubidium-atom and the optical pumping rate for the rubidium atom is very fast compared with the spin-exchange rate, Γ_{se}. Γ is the relaxation rate of the ^{3}He nuclear polarization.

The relaxation of the ^{3}He polarization is induced by Brownian motion in a inhomogenous magnetic field as well as collision with an unpolarized paramagnetic center on the wall of a ^{3}He container.[11,12] The ^{3}He container is placed in a magnetic field in order to hold the polarization. The direction of the field is defined as z axis. The ^{3}He nucleus sees a magnetic field rotation in its moving frame due to a change in the x or y component of the magnetic field because of its inhomogeneity. The ^{3}He spin rotates with the magnetic field rotation. In the frame where the magnetic field is in the z axis, the effect of the magnetic field rotation on the ^{3}He spin is described in terms of an effective field of $-\omega/\gamma$. ω is the angular frequency of the magnetic field rotation and γ is the gyromagnetic ratio of the ^{3}He spin. The direction of the effective field is in the xy plane. The effective field fluctuates under the Brownian motion. The fluctuating field has the Fourier component of ω_0 which is the Larmor frequency of the ^{3}He spin. The presence of the transverse RF field of a angular frequency, ω_0 induces a ^{3}He-spin flip process. Thus, the ^{3}He spin is depolarized by the Brownian motion in the inhomogeneous field.

III ^{3}He nuclear polarization at KEK

The apparatus for the ^{3}He polarization is shown in Fig. 2.[13] An alminosilicate-glass cell was filled with 3-atm ^{3}He gas, 100-torr nitrogen gas and a small amount of rubidium droplet. The size of the glass cell was 4 cm in length and 2.5 cm in diameter. The grass cell was placed in the center of a 40-G Helmholtz coil. The homogeneity of the magnetic field around the cell was designed to be lower than 10^{-3}, in order to suppress the inhomogeneous field relaxation. The temperature of the cell was controlled at 180°C, where the number density of the rubidium atom is 4×10^{14}/cc at thermal equilibrium. The ^{3}He cell was irradiated with circularly polarized light of 795 nm in wavelength, which corresponds to the wavelength of the D1 light . The circularly polarized light was supplied by a 4-W Ti-Sapphire laser system through a 1/4 λ plate. Linear polarization of the photon is transformed into circular polarization upon transmission through the $1/4\lambda$ plate. The evolution of the ^{3}He polarization was observed by a polarized neutron transmission. The method is also shown in Fig. 2.

Neutrons from the spallation source at KEK was polarized upon transmission through a polarized proton filter.[6] The neutron polarization is determined by the transmission enhancement, $\varepsilon = T/T_0$ as the following equation.

$$P_n = (1 - (T_0/T)^2)^{1/2} \,. \tag{2}$$

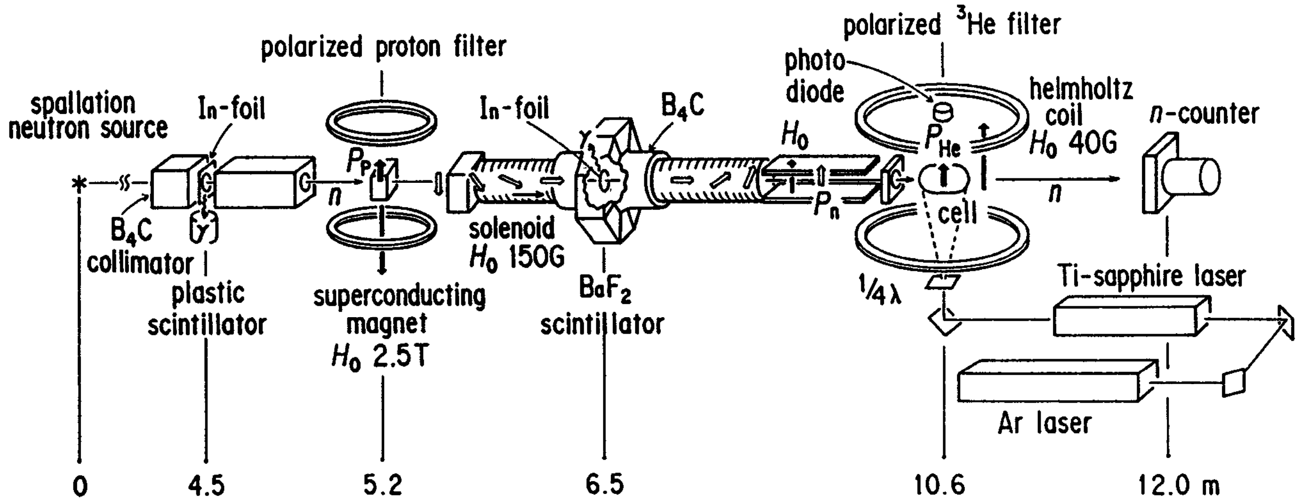

Fig. 2 Experimental set-up of ^{3}He nuclear polarization

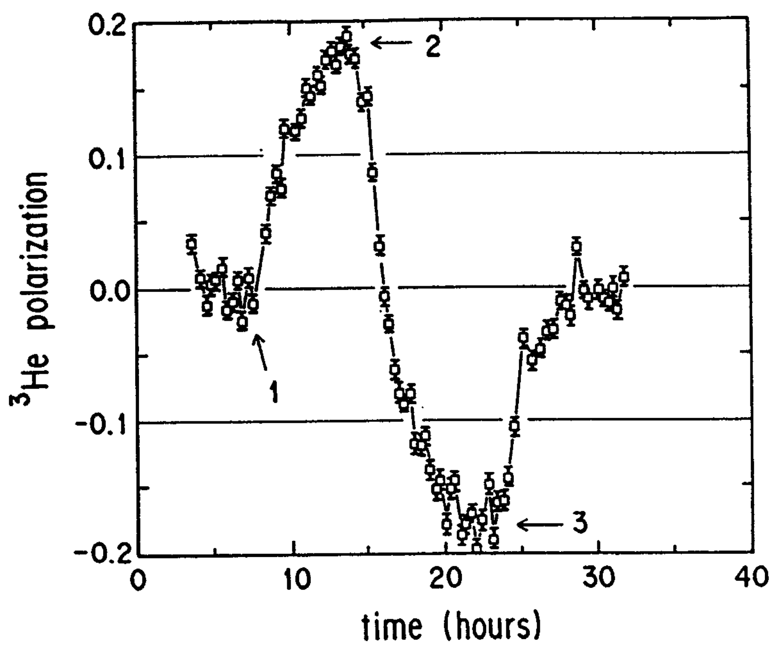

Fig. 3 ^{3}He nuclear polarization

T_0 and T are neutron transmissions in unpolarized and polarized states, respectively. The neutron transmissions were obtained by counting capture γ-rays from the two indium foil which were placed in up-stream and down-stream of the polarized proton filter. The neutron polarization was guided to the ^{3}He filter from the polarized proton filter by using an adiabatic passage. Transmitted neutrons through the ^{3}He filter were measured by a ^{10}B-loaded liquid scintillator placed downstream. A typical result is shown in Fig. 3. In the figure, the laser beam was switched on at point 1 and the polarization of ^{3}He started. Since the ^{3}He nuclear spin was polarized parallel to the incident neutron polarization, the neutron transmittance of the ^{3}He filter increased. At point 2, the circular polarization of the laser beam was reversed and ^{3}He nuclei were polarized antiparallel. Therefore, the neutron transmittance decreased. The value of the ^{3}He polarization is determined by the transmission enhancement,

$$\varepsilon = (1 + P_n)/2 \cdot exp(N\sigma t P_{He}) + (1 - P_n)/2 \cdot exp(-N\sigma t P_{He}). \qquad (3)$$

Here, P_n is the neutron polarization, N the ^{3}He nuclear-number-density, σ the ^{3}He cross-section and t the thickness of the filter. The sign of P_{He} is assumed to be positive ,which is in the direction of the neutron polarization. The result of the calculation of the ^{3}He polarization is written on the vertical scale of Fig. 3. At present, the maximum ^{3}He polarization is about 50%. At point 3, the laser beam was switched off and ^{3}He-polarization relaxation was observed. The value of Γ is obtained by the time constant of the relaxation curve. The relaxation rate is also estimated by the polarization evolution. By using the value of 9.4 x 10^{-2} h^{-1} for Γ_{se} at a rubidium atomic-number-density of 4 x 10^{14}/cc, the value of the relaxation rate was obtained as $\Gamma = 7.4$ x 10^{-2} h^{-1} and the value of the rubidium polarization was obtained as $P_{Rb} = 0.66$. We can improve the ^{3}He polarization by decreasing the value of Γ and increasing the value of P_{Rb}. We are developing surface treatment of the glass wall by HF to remove the paramagnetic

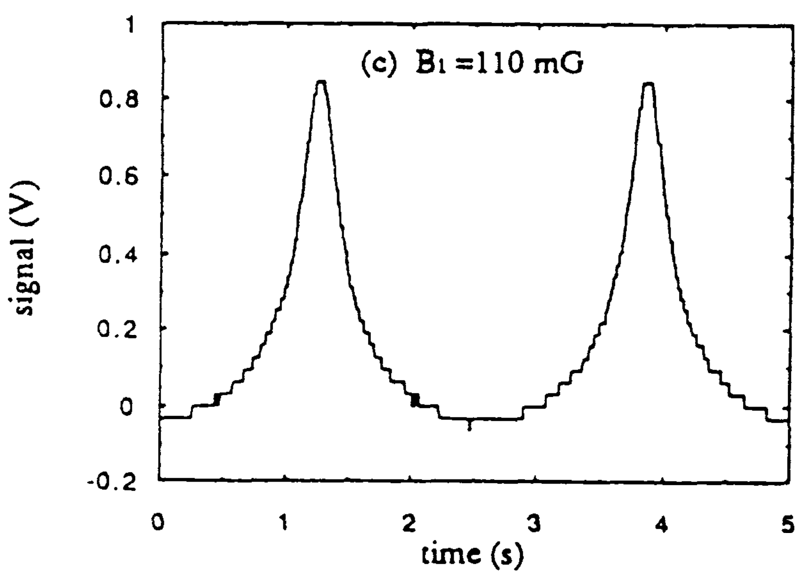

Fig. 4 ^{3}He NMR signal

impurity from the glass wall. To improve the rubidium polarization, we need more laser intensity in the glass cell.

We also used a NMR method to obtained the value of the ^{3}He polarization. In the 40-G Helmholtz coil, we mounted a drive coil, which applied the RF field ($H_1 \sin \omega t$) to the ^{3}He cell. The effective field in the rotating frame whose frequency is same as the RF field is $-\omega/\gamma$. The total magnetic field in the rotating frame is represented as[14]

$$\boldsymbol{H}_{\text{tot}} = (\boldsymbol{H}_0 - \omega/\gamma) + \boldsymbol{H}_1. \tag{4}$$

Here, $\boldsymbol{H}_0$ is the magnetic field of the Helmholtz coil. When the H_0 is swept across the resonant point, the effective field rotates from up to down or from down to up following the sweep of the magnetic field. If the sweep velocity satisfies the adiabatic condition, the ^{3}He spin follows the magnetic field rotation. The change of the ^{3}He spin direction was sensed by a pick-up coil. The magnetic induction signal at the pick-up coil was analyzed by a lock-in amplifier system. A typical result of the NMR measurement is shown in Fig. 4. The NMR signal amplitude was calibrated by the neutron-transmission measurement.

IV Neutron-spin rotation experiment

We have applied the polarized ^{3}He filter to the measurement of the neutron-spin rotation (NSR) during propagation through medium.[15] The NSR apparatus is shown in Fig. 5. The neutron-spin rotation-angle is converted to a projection angle on the magnetic field. In this conversion, we used a non-adiabatic passage of the neutron spin through a superconducting sheet, where the magnetic field is zero because of the Meissner effect.[16,17]

The performance of the NSR apparatus was examined by the following method. The apparatus was placed at 8.6 m from the neutron source between the ^{3}He filter and the down-stream indium foil. Before the superconducting box, a dipole magnet was placed so that the neutron spin rotated from the longitudinal to transverse direction following an adiabatic passage. Since the magnetic field is zero in the superconducting sheet because of the Meissner effect, the neutron experiences a sudden change in the magnetic field at entering and going out of the superconducting sheet. Therefore, the neutron spin enters the box non-adiabatically, namely the neutron spin direction does not change. If there is no magnetic field inside the box, the neutron spin travels through the free space keeping it original direction. After propagation through the box, the neutron spin entered another transverse dipole field again non-adiabatically. If the direction of the down-stream magnetic field is rotated from the up-stream magnetic field by θ, the $\cos\theta$ component of the neutron polarization is held by the down-stream magnetic field. The $\cos\theta$ component of the neutron spin is guided to the ^{3}He filter by an adiabatic passage and analyzed by the transmission measurement. The transmittance of the ^{3}He filter was measured as a function of θ. During the experiment, the incident neutron spin was flipped by reversing the up-stream magnetic field every 4 sec. The change of the neutron transmission upon polarization reversal was observed. The flipping ratio, which is defined as

$$R = (T_+ - T_-)/(T_+ + T_-), \tag{5}$$

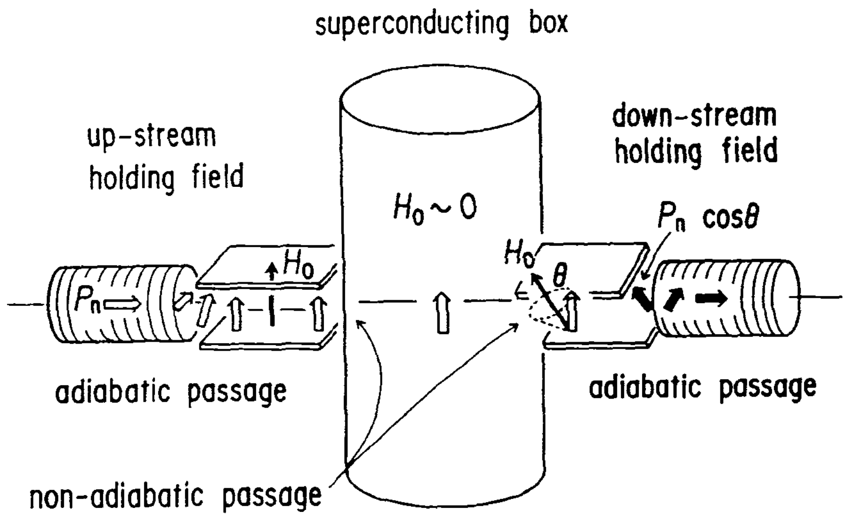

Fig. 5 Apparatus for neutron spin rotation measurement

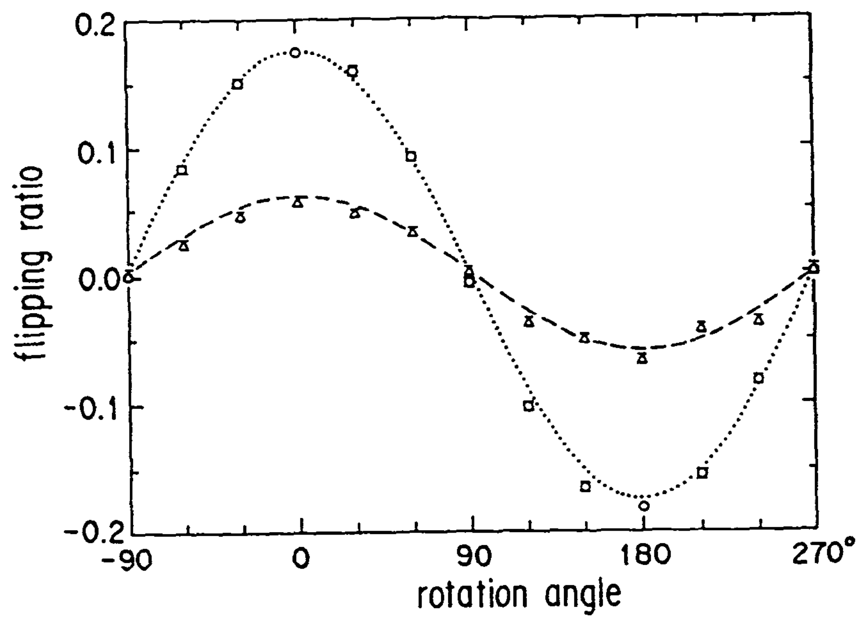

Fig. 6 Result of neutron spin rotation

was obtained. Here, T_+ and T_- are transmittances for flipper off and on states, respectively. If we use the equation (3), the flipping ratio is represented as

$$R = P_n \cos\theta \tanh(N\sigma t P_{He}). \tag{6}$$

The result of the flipping ratio is shown in Fig. 6. A clear $\cos\theta$ distribution is found in the flipping ratio. The solid and broken lines are results of calculation for the incident neutron energy of 0.1 and 0.75 eV, respectively by using the values of P_n, P_{He} and $N\sigma t$. The experimental results are well explained by the calculation. The result proves that the conversion of the rotation angle into the projection angle by using the Meissner effect works very well and then the direction of neutron spin in the superconducting box can be detected precisely.

The NSR apparatus can be applied to measure the neutron-spin rotation by the P-violating neutron-nucleus interaction.[15] For this measurement, a target is placed in the superconducting box and the down-stream magnet is set at $\theta = 90^\circ$ in order to get higher detection sensitivity for the rotation. More important application of the NSR apparatus is for the T-violation experiment.[18] A new method to detect the T-violation effect is proposed quite recently, which has a possibility to overcome the present most stringent upper limit of the T-violation obtained by the neutron electric dipole moment measurement.[19] The experimental principle is shown in Fig. 7. In the experiment, the target nuclear spin is transversely (in x direction) polarized. Incident neutron spin is in z direction. The neutron spin rotates upon transmission through the polarized target by $+180^\circ$ or -180°. The T-violation effect is found in a transmission difference between the two opposite rotation states. The neutron-spin rotation is controlled by the following way. The neutron spin rotates around x axis by the magnetic field which is used for the polarization of the target spin (Larmor precession) and the spin dependent neutron-nucleus strong interaction (pseudomagnetic precession[20,21]). In the experiment, we will adjust the magnetic field strength so that $+180^\circ$ and -180° rotations are realized. For the rotation adjustment we will use the NSR apparatus. The apparatus for the polarization of the target nuclear spin is now under development.[22]

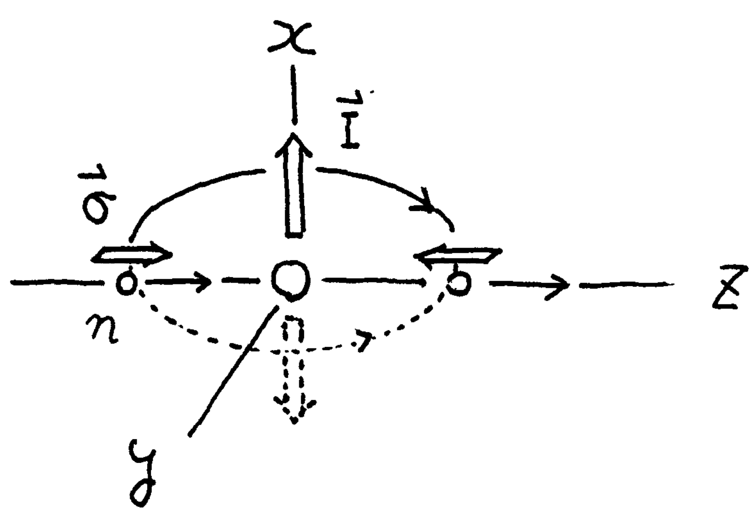

Fig. 7 Principle of spin rotation asymmetry

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