論文の内容の要旨

Study of Optical System of the Ultra-Cold Neutron with High Intensity Pulsed-Beam at J-PARC for Discovery of Neutron Electric Dipole Moment
（中性子電気双極子能率の発見のための J-PARC における大強度パルスビームを用いた超冷中性子の光学系の研究）

片山 領

This thesis deals with the first basic study of the proposed experiment for searching the neutron electric dipole moment using ultracold neutrons produced by the J-PARC pulsed proton beams of the world's highest instantaneous luminosity.

The neutron electric dipole moment (EDM) is sensitive to new physics beyond the standard model (BSM). Currently, the best upper limit of neutron EDM, obtained at Institute Laue-Langevin (ILL), is 3×10^{-26} e $\cdot$ cm (90% CL). Many BSM models, such as supersymmetric models, predict 1 to 2 orders of magnitude larger EDM that can be detected by experimental techniques that can be developed today, which motivates a more precise measurement of neutron EDM. Today, the most precise neutron EDM measurement is possible by using low energy neutrons of 300 neV or less, which is referred to as Ultra Cold Neutron (UCN). The current neutron EDM experiment is mainly limited by the statistical precision. Therefore, a more intense UCN source is desired. Conventionally, the production method that neutrons emitted from a nuclear reactor are decelerated by reflection with a mirror has been used. In recent years, a new production method that cools fast neutrons to ultracold neutrons by inelastic scattering of quasiparticles in a substance has been developed and put into practice. This method is called the super-thermal method. Thanks to the super-thermal method, the statistical precision is expected to be improved. Accordingly, a lot of neutron EDM experiments adopting super-thermal method are being planned all over the world. In particular, there is significant progress at PSI in Switzerland and TRIUMF in Canada, and they announced that it has prospected to improve one or more order of magnitude from the ILL experiment. Both groups produce fast neutrons using an accelerator, and it is cooled by liquid helium or solid deuterium.

At Japan Accelerator Research Complex (J-PARC), an experimental facility located in Tokai, Japan, new neutron EDM experiment has been proposed which has the following quite unique characteristics:

1. To produce fast neutron beams by nuclear spallation reaction with J-PARC pulsed proton beam

with the world's highest instantaneous intensity.

2. To produce high intensity pulsed UCN beams by cooling via elastic scattering on heavy water and liquid deuterium and inelastic scattering on phonons in a solid deuterium converter.
3. To extract and transport the high-intensity pulsed UCN beams to the storage container for the neutron EDM experiment.
4. To refocus pulsed UCN to the shutter position in front of the storage container by decelerating high velocity component with the magnetic field interaction to avoid the UCN bunches diffused in the transportation.
5. To accumulate the refocused UCN in the storage container by the managing shutter opening/closing time to prevent back-flow.
6. To perform the EDM measurement when the UCN density is around the maximum.

This procedure was proposed in the 33rd proposal submitted to J-PARC. In this thesis, the experiment adopting the above procedure is called as the J-PARC P33 experiment. In addition, the above technique to refocus pulsed UCNs is called "rebunch", and the above method to take refocused UCNs into the container with preventing back-flow is referred to as "rebunch storage". Actually, the phase space density of UCNs in the solid deuterium converter produced by J-PARC LINAC pulsed proton beams is estimated to be ~ 4.1 UCN(cm)$^{-3}$(m/s)$^{-3}$, while the phase space density of UCNs for the ILL experiment is estimated to be ~ 0.084 UCN(cm)$^{-3}$(m/s)$^{-3}$ at its transport guide exit. When the generated UCNs are utilized efficiently by using transport with keeping the density, the statistical sensitivity of J-PARC P33 experiment should be expected to be drastically improved similarly to PSI and TRIUMF. However, despite the high experimental potential of the J-PARC P33 experiment, a reliable evaluation was yet to be performed so far.

This thesis describes the first basic study for the neutron EDM experiment based on P33 concept. For the J-PARC P33 experiment, there was a problem that the experimental capability was not evaluated because it was particularly difficult to understand effects of the reflection loss and the non-specular reflection on the statistical sensitivity. Therefore, in this study, first of all, the dependence of the statistical sensitivity on such reflection performances was tried to be quantitatively investigated by a full simulation that can deal with an experimental system and entire procedures based on J-PARC P33 concept. The simulation study assuming the J-PARC P33 was performed experiment as follows: (1) the J-PARC pulsed beams of 20 MW/pulse (400 MeV, 50 mA) of 0.5 Hz (2) the rebunch method (3) the UCN production in solid deuterium (sD_2) of 5,800 UCN/cm^3 (4) the UCN loss at reflection (5) the experiment setup based on the J-PARC P33 (6) the ortho-para ratio of sD_2 of 95:5 (7) the elastic cross section of sD_2 of 2.04 barn (8) the gradient magnetic field of the rebuncher of -3.2 T/m (9) the total experiment period of 3 years (10) the time assigned to EDM measurement of 18 hours/day. Neutron optical theory and micro-roughness model were used to represent the reflection loss and the non-specular reflection. Total reflection energy, V_F, and UCN loss probability coefficient, η, were used for controlling the reflection loss. In this study, the Fermi potential of the transport guide was chosen to be 210 neV, that of the container side was chosen to be 91 neV or 160 neV, and that of the top-bottom side was chosen to be 210 neV, respectively. he UCN loss probability coefficient of the storage container was chosen to vary from $8 \times 10^{-5} \sim 5 \times 10^{-4}$, and that of the transport guide was chosen to be 0. The RMS roughness of the transport guide was chosen to vary from 0 to 3 nm, and that of the other parts was chosen to be 0. As a result, it was shown that the statistical sensitivity was changed by 8 times according to the difference of reflection performances.

Full simulation study showed that the development of reflection materials is the key to improving the sensitivity. Hence, high efficient neutron mirrors, Nickel Molybdenum alloy (NiMo) and Diamond-Like Carbon (DLC), were developed. NiMo and DLC were fabricated using a quite unique film formation techniques such as binary vapor deposition method, Ionized Evaporation Method (IEM), Plasma Based Ion Implantation Deposition (PBIID) and Filtered Arc Ion Plating Deposition method (FAIPD). These reflectors were evaluated by surface analyses; the neutron reflectometry showed that V_F was 228 neV (NiMo), 243 neV (IEM), 264 neV (FAIPD), and 193 neV (PBIID); η was evaluated to be 3.6×10^{-4} (NiMo) and 3.4×10^{-4} (PBIID) by the UCN storage experiment, and b was evaluated to be 0.3 nm (IEM) and 0.49 nm (FAIPD) by AFM.

Finally, assuming the reflection performance obtained as above and the experimental setup used in the full simulation study, the statistical precision of J-PARC P33 experiment was estimated. In this study, the results actually obtained from the neutron reflectivity measurement and the UCN storage experiment were adopted as reflection performance. Assuming that IEM DLC or FAIPD DLC is used for the transport guide and NiMo and PBIID DLC are used for the storage container, the statistical precision of an averaged value of both cases was estimated to be $(1.6 \pm 0.2) \times 10^{-27}$ e·cm. Therefore, by combining it with the systematic error 2.5×10^{-27}e·cm, it is concluded that the experimental precision is $(\pm 1.6 \pm 0.2(\text{stat}) \pm 2.5(\text{syst})) \times 10^{-27}$ e·cm. This is the first comprehensive evaluation of the experimental capability based on J-PARC P33 concept including the reflection performance, which provides a reliable basis for future experiment design.