Progress report of the RCNP UCN group 2021–2022

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As part of the international TUCAN (TRIUMF Ultra-Cold Advanced Neutron) collaboration, we are developing an experiment to measure the neutron electric dipole moment with unprecedented precision with a new high-intensity ultracold neutron source. In this report, we report on our activities during the fiscal year 2021–2022 for developing the key components of the nEDM measurement.

1 Background

Measurement of the neutron electric dipole moment (nEDM) has a great significance in the context of searches of undiscovered sources of CP violation. The state-of-the-art nEDM measurements utilize ultracold neutrons (UCNs) stored in a material cell. In order to overcome a statistical limitation of the present experiment due to the numbers of UCNs, the TUCAN collaboration is developing a new high-intensity spallation-driven UCN source based on the super-thermal UCN production in superfluid helium [1, 2]. An order-of-magnitude improvement over the present best limit [3] is expected on the final stage of the experiment.

The RCNP UCN group has been involved in development of the new UCN source through commissioning of the helium cryostat which was built and tested in Japan and have been transported to TRIUMF. We have also conducted UCN experiments at J-PARC in the context of developing the key components of the UCN source and the nEDM spectrometer.

2 Development of the UCN source at TRIUMF

The new UCN source will produce UCNs via inelastic scattering of neutrons in super-fluid helium at $\sim$1 K. It is a complex consisting of multiple custom-made equipment including cryogenic vessels, high-performance helium and liquid deuterium cryostats. Among them, the helium cryostat was designed [4], built and tested [5] in Japan, and then transported to TRIUMF in 2021. Since November 2021, we have leak-tested the cryostat at a test bench setup at TRIUMF. The tests have been completed in March 2021 to confirm the cryostat to be leak-free. As the next step, it will be operated with liquid helium from fall 2022. We are currently preparing infrastructures for operating it with liquid helium.

3 Experiments with cold and ultracold neutron beams J-PARC

3.1 Characterization of UCN transmission through a guide tube

An UCN can be totally reflected at any incident angle on a material surface with high Fermi-pseudo potential, like a reflection of visible rays on a metal surface. The characteristic makes it possible to transport UCNs optically with a material guide tube coated by such materials and to handle them as a rarefied ideal gas. In the plan of the TUCAN nEDM experiment, UCN guide tubes are made by polished aluminum and stainless steel cylinders coated with nickel-phosphorus plating, and the UCN gas produced in the super-thermal source is transported to experimental bottles through the guide tubes with the total length of 12 m. The filling amount of UCN increases with the rise of the diffusion speed of UCNs, because, during their staying in the guides, UCN disappears with the probability of 10^{-3}–10^{-4} at every reflection due to the absorption or inelastic scattering by a nucleus. The diffusion speed decreases as increasing the number of random-walking UCNs, which are produced by off-specular scattering from the surface roughness of the guide. Therefore, it is essential to develop an UCN guide with an extremely smooth surface in order to increase the statistics of the EDM experiment. The transmittance of an UCN guide is evaluated in the comparison of UCN fluxes measured with and without the guide. In TRIUMF, such tests were carried out with UCN gas stored in a pre-storage chamber, and then the contribution of diffuse scatterings was estimated compared with a Monte Carlo simulation.

We have also carried out the transmittance measurement of UCN guides at J-PARC/MLF, as a cross-check against the TRIUMF tests, with a different method by using pulsed UCNs produced by the neutron Doppler-shifter [6]. In the experiment, UCNs were collimated with polyethylene tubes to the divergence less than ± 6 degrees and incident to an 1000-mm length guide at a specific angle, so that the number of reflections of UCNs was controlled. Then, the smoothness of the guide surface was evaluated by the comparison of the experiment and our Monte Carlo simulation about the dependence of transmittance on incident angles and the shapes of time-of-flight (TOF) spectra. We have carried out the first experiment in 2020 and concluded that the attenuation of the transmittance is approximately matched with the 10% contribution of the complete diffusion described by Lambert's cosine law. However, the result was considerably larger than the TRIUMF's result estimated to be the 3% contribution. Additionally, the shape of the TOF spectrum of UCN measured through the guide could not be reproduced with only the Lambert's law in the simulation. Meanwhile, the observation of a sample piece of the guide by using an atomic force microscope showed that the mean amplitude of the roughness is approximately the same order size as the de Broglie wavelength of the UCNs, which is too large to use in ordinary diffuse scattering models of neutron. In order to deal with the large roughness in the neutron optics, we have implemented a microfacet bidirectional reflectance distribution function model [7], which is established for a diffuse scattering model of visible rays, in our simulation. Furthermore, in March 2022, we have carried out again the transmittance measurement including additional angle conditions, and estimated the contribution of the complete diffusion, as a preliminary result, to be lower than 5%. At present, we are analyzing the results in detail by using the simulation.

3.2 Development of thin iron films for UCN polarization analysis

Another item under development is the UCN spin analyzer, whose main component is a thin iron film magnetized by a surrounding magnet. When a UCN traverses the film, it experiences a spin-dependent effective potential

$$V_{\mathrm{eff},\pm} = V_{\mathrm{F}} \pm |\vec{\mu}_n \cdot \vec{B}| \approx 209 \pm 60\ \mathrm{neV/T} \cdot B, \tag{1}$$

where $\mu_n \approx -60$ neV/T and $V_{\mathrm{F}} \approx 209$ neV represent the neutron magnetic moment and the Fermi potential of iron, respectively. Because of kinetic energies of UCNs being $\lesssim 300$ neV, $|\vec{B}| \approx 2$ T produced in a fully saturated iron film makes it a filter which selectively transmits the spin $-$ neutrons. Thin iron films used for this purpose are required to be saturated by a small ($\sim$10 mT) magnetic field, and have a saturation induction close to 2 T. In collaboration with Dr. M. Hino at the Institute for Integrated Radiation and Nuclear Science, Kyoto University (KURNS), we are investigating in-house production of iron films suited for this purpose. An ion beam sputtering facility [8] at KURNS is used to produce thin iron films on aluminum or silicon substrates (Fig. 1a). We produced films with the iron layer thicknesses of $\lesssim 100$ nm. For the substrates of the iron films, in addition to alumnium which has been used in previous works, we employed polished silicon discs. These choicses make the films to require much smaller magnetic fields to be saturated than a previous work [9], which has advantages of suppressing the stray fields from the system, and facilitating enlargement of the aperture.

We conducted characterized measurements of these thin iron films with cold and ultracold neutron beams of the J-PARC/MLF BL05. In July 2021, samples of silicon-substrate iron thin films were characterized by a cold-neutron reflectometry measurement on the low-divergenc branch of the BL05 [10]. A cold neutron beam polarized by a magnetic super-mirror was incident on a 20×30 mm^2 iron film sample placed in a magnetic field of a dipole magnet. The measurement was performed for samples with iron layer thicknesses of 30, 50 and 90 nm in a magnetic field of 0–8 mT. Fig. 1b shows the resullts of the 90-nm thickness sample in a 8 mT magnetic field. By fitting the measured profiled to a theoretical reflectivty convoluted with the wavelength-dependent polarization of the incident neutrons, the magnetic potential of Eq. (1) was extracted as $V_{\mathrm{eff}+} = 328(1)$ neV and $V_{\mathrm{eff},-} = 65(1)$ neV, for the + and $-$ spin states of neutrons, respectively [11]. This implies that the neutrons experienced potentials corresponding to iron saturated to ≈ 2 T by only a 1/8 of the applied field of what was used in the previous work [9], and opens up promising prospects for application of this type of films to UCN polarization.

In March 2022, we further tested iron thin films on silicon and aluminum substrates with pulsed UCNs provided by the Doppler-shifter-type UCN source at J-PARC/MLF BL05 [6]. A setup consisting of two sets of magnetized iron films and two spin flippers was built for this experiment. The inner diameter of the region where UCNs travel is 78 mm, which is about a half of the area planned in the actual polarizers used with the nEDM detector. The data acquired in this beamtime is currently being analyzed.

4 Summary and prospects

The helium cryostat was leak-tested and is being prepared for a cryogenic tests at TRIUMF which is expected to begin in fall 2022. We aim to complete installing the other UCN source components by winter 2023 to start full cryogenic tests in spring/summer 2023.

In parallel to the commissioning of the UCN source at TRIUMF, the experimental components are being developed using the cold and ultracold neutron beams at J-PARC/MLF as reported in this report. In addition, a beamtime is scheduled in June 2022 to measure UCN storage times of prototype nEDM measurement cells.

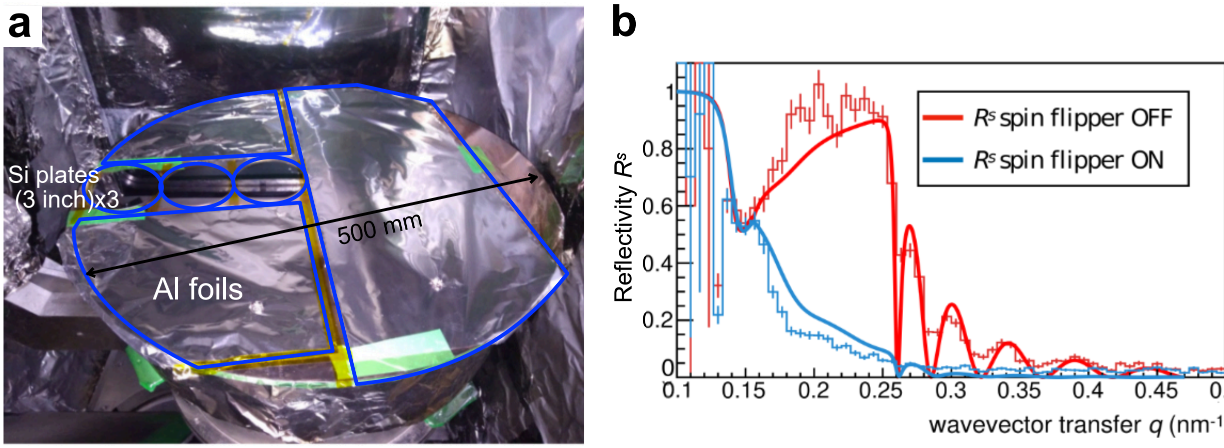

Figure 1: **a.** Photograph of the sample production by the KURNS IBS facility. An iron layer of 90 nm thickness was simultaneouly sputtered on silicon and an alumnium substrates. **b.** Results of the cold-neutron reflectometry measurment for the sample with the iron layer thickness of 90 nm. The sample reflectity R^s was obtained from the signals of a 2D detector by taking the ratio of the intensities of the incident and the reflected neutrons. By converting the TOF of the neutrons to their wavelengths, R^s was evaluated as a function of the wavevector transfer q. The different colors represent the states of a spin flipper which was placed between the polarizing super-mirror and the sample to manipulate the spin of the incident neutrons. The solid curves indicate the results of fit of the data to a theoretical reflectivity model on a single layer film. Reproduced from Ref. [11].

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