Activities of the TUCAN collaboration in Japan 2020–2021

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The Japanese-Canadian TUCAN (TRIUMF Ultra-Cold Advanced Neutron) collaboration is building a new high-intensity ultracold neutron (UCN) source at TRIUMF with the aim of measuring the neutron electric dipole moment (nEDM) with unprecedented precision. As part of the collaboration, the RCNP UCN group is involved in developments of key components of the UCN source and the nEDM spectrometer. In the fiscal year 2020–2021, as situations due to the pandemic restricted international travel, we focused our efforts on research activities in Japan as summarized in this report.

1 Background

Measurements of the nEDM occupy an important place in today's particle physics, searching for violation of time-reversal symmetry and setting stringent constraints on the theories beyond the Standard Model. The current best upper limit on the nEDM obtained at PSI $1.8 \times 10^{-26} e\cdot\text{cm}$ (90% C.L.) [1] is limited by the statistical uncertainty. We aim at an order of magnitude improvement in precision by our new spallation-driven superthermal UCN source with superfluid helium (He-II). This UCN production scheme was successfully demonstrated by a prototype UCN source with proton beams of the TRIUMF's 520 MeV cyclotron [2]. The prototype source has been decommissioned by January 2021 and will be replaced by a new upgraded source which is currently being built by joint efforts of the Japanese and Canadian institutes. The new source is operated with a proton beam current of $40\,\mu\text{A}$, 40 times higher than the nominal value of the prototype source. Combined with other upgrades [3], the new source in its full operation capacity is expected to yield $\sim 1.5 \times 10^7$ UCN/s, 3 orders of magnitude higher than the nominal yield of the prototype. Figure 1 gives an overview of the new UCN source and the nEDM spectrometer. Among them, the focuses of the following sections are on the helium cryostat, the UCN guides, the UCN production volume and some of the nEDM spectrometer subsystems.

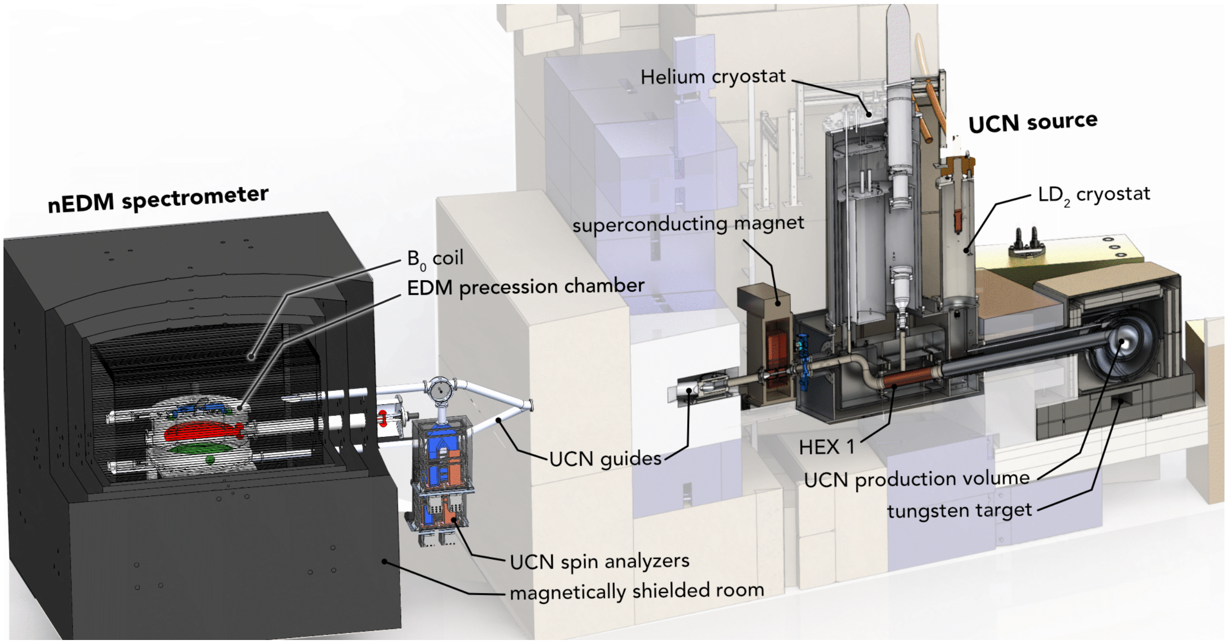

Figure 1: Overview of the UCN source and the nEDM spectrometer which are being developed by the TUCAN collaboration. Fast neutrons produced from the tungsten target are moderated to cold neutron energies and then converted to UCNs in the production volume filled with He-II. The UCNs are polarized by a 3.5 T magnetic field of the superconducting magnet and led into the nEDM spectrometer through the UCN guides.

2 Research activities in fiscal year 2020–2021

2.1 Commissioning of the helium cryostat at KEK

The highlight of achievements of this fiscal year is successful commissioning of the helium cryostat which will cool He-II in the UCN production volume. Because the He-II temperature strongly affects the UCN production rate [2], this is one of the most critical components of the new UCN source. In order to maintain the He-II temperature under the heat load due to the beam irradiation, cooling power of 10 W at 1 K is required. An efficient ^{3}He/^{4}He cryostat was developed to meet this requirement [4, 5].

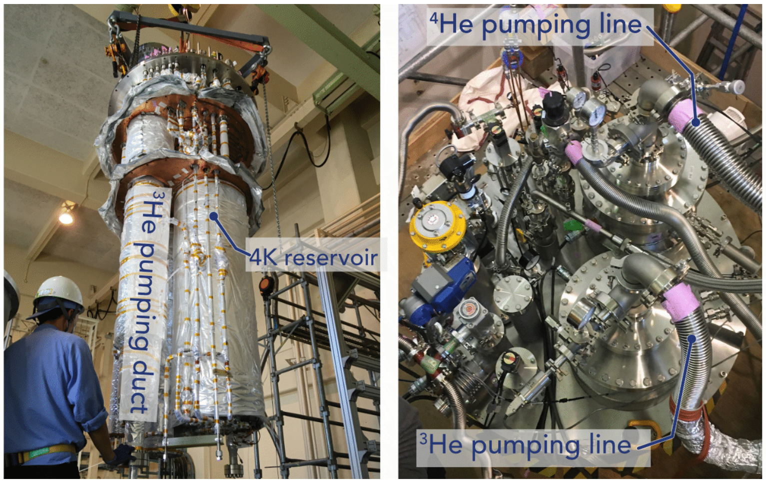

Figure 2: Photographs of the helium cryostat installed at KEK. (Left) The cryostat during the assembly of the heat shields. (Right) The top flange of the cryostat after being installed in a pit for tests. For more details of the design and the structure of the cryostat, see Ref. [4].

Its construction began in 2019 and the sub-components were individually tested as they were built [5]. In 2020, the full assembly of the cryostat was completed and installed at KEK for testing (Figure 2). The design of the cryostat allows replacement of the pool-boiling ^{3}He heat exchanger at the lowest temperature. This heat exchanger, called "HEX 1" as indicated in Figure 1, plays a crucial role to interface the $\sim$ 0.8 K ^{3}He bath of the cryostat with He-II in the UCN production region. Between August 2020 and March 2021, we performed in total four cool downs to obtain data to compare different models of HEX1, each time with a prototype HEX1 of different geometry or piping configuration. Through these tests, we also established operation procedures of the cryostat. A dedicated data-acquisition/control system was built for the tests in which the following functionalities were implemented:

- continuous recording of 60+ channels of temperature, pressure, differential pressure and flow sensors
- control of valves in the cryostat and on the return lines
- pressure regulations for automatic filling of liquid helium to the 4 K reservoir
- a routine of boiling curve measurements with a heater implemented in the prototype HEX1.

The testing campaign was completed in March 2021. The cryostat will be shipped to TRIUMF in summer 2021, there it will be commissioned as a part of the UCN source together with the other parts of the source.

2.2 Component tests by the J-PARC UCN source

UCNs can be totally reflected on the smooth surface of the materials with high Fermi-pseudo potential. Using this characteristic, they can be transported optically in polished guides coated with such materials and filled in the whole system consisting of the UCN production volume, guides, and experimental bottles, like a rarefied gas. The number of UCNs available for the nEDM measurement is proportional to the filling efficiency, which depends on the reflection loss per bounce and the number of reflections. Although the loss probability per bounce is smaller than 10^{-3}, the total amount of the loss cannot be negligible because an UCN reflects hundreds of times until reaching the precession chamber. On a realistic surface, an UCN is reflected diffusely due to a small surface roughness, so that the reflection number becomes larger than the case of only specular reflections. For example, if 10 percent of the UCNs are reflected isotopically (Lambert reflection model) at each reflection, the statistics of the nEDM measurement will be reduce to one third. Therefore the verification of the validity of reflection models and the estimation of characteristic parameters of a surface roughness are important for the performance evaluation of the UCN source and the estimation of the achievable statistical precision of the nEDM. These characteristics of an UCN guide can be evaluated with the measurement of the transmittance of UCN currents and the storage lifetime of UCN clouds.

We have carried out the characteristic measurements of UCN guides in Japan in order to confirm the validity of previous results measured at TRIUMF and LANL. In June 2020, we have measured the transmittance of 1000-mm long UCN guides with the Doppler-shifter-type pulsed UCN source [6] at J-PARC/MLF BL05, as shown in figure 3 (a). The measured UCN attenuation is approximated by the 10% contribution of the Lambert reflection. Now we are researching more valid reflection models and estimating the roughness parameters by using a Monte Carlo simulation. Moreover, in February 2021 at J-PARC, we have carried out a UCN storage experiment with the guide and estimated the lifetime to be 62.6 ± 1.8 s. Figure 3 (b) shows the setup. These results are approximately consistent with previous results. We are currently preparing to measure the storage lifetime of the UCN production volume of the new UCN source (Figure 1) with the experimental setup at J-PARC in June 2021.

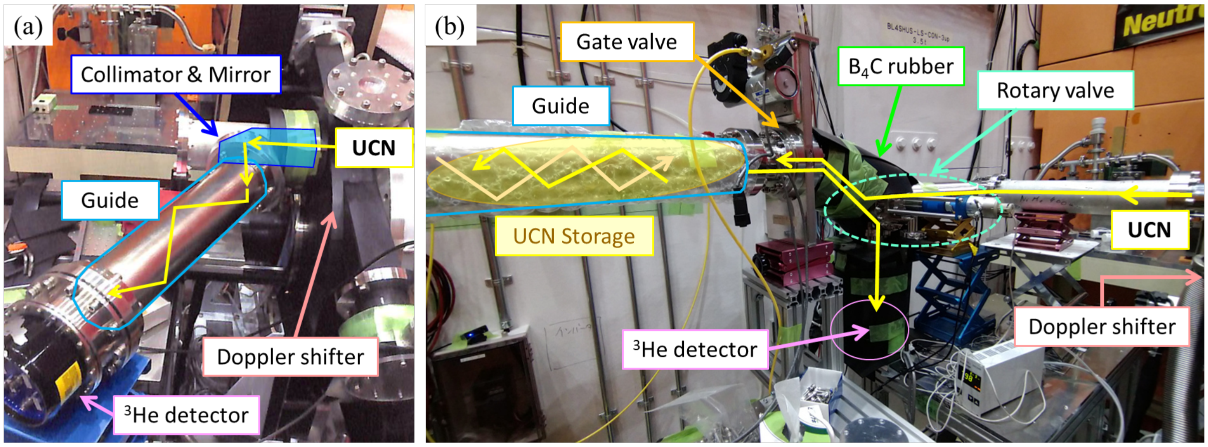

Figure 3: Photographs of the characteristic measurements of UCN guides at J-PARC/MLF. (a) The UCN transmittance measurement. This picture shows the measurement with a 500-mm length guide. (b) The UCN storage lifetime measurement.

2.3 Developmental works for nEDM spectrometer subsystems

In parallel to the new UCN source, the nEDM spectrometer is being developed. Among the subsystems composing the spectrometer, we are involved in development of a magnetically shielded room (MSR), a four-layer mu-metal shield which will realize an extremely stable ($< 10\,\mathrm{pT}$ at 0.01 Hz) magnetic field environment. A strong background magnetic field of up to $370\,\mu\mathrm{T}$ at the location of the MSR necessitates a set of compensation coils around the MSR to prevent saturation of the mu-metal sheets and guarantee the performance of the MSR. In 2020, we developed a baseline design of the compensation coil system based on detail three-dimensional magnetic field maps acquired in September 2019 and February 2020. In parallel, detailed design of the MSR has been led by collaborators of the University of Winnipeg and TRIUMF. We aim to install the MSR and the coil system by October 2022.

This fiscal year, we also launched a new project to develop magnetized iron foils which are a part of the spin analyzers to measure the UCN polarization at the end of each nEDM measurement cycle. The ion beam sputtering facility at Institute for Integrated Radiation and Nuclear Science, Kyoto University (KURNS) [7] was used to produce some test samples of thin iron foils spattered on aluminium foils and silicon plates. Their magnetic properties and performance as UCN polarizers will be evaluated by upcoming tests planned in 2021.

3 Summary and prospects

We have made steady progresses toward the completion of the new UCN source and the nEDM spectrometers. We foresee the first UCN production with the new UCN source from summer 2022 in earliest. The MSR will also be installed by October 2022, thereafter be followed by installation and testing of other nEDM spectrometer subsystems.

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