Progresses of the TUCAN collaboration toward a neutron electric dipole moment measurement with a new high-intensity ultra-cold neutron source

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As part of the international TRIUMF Ultra-Cold Advanced Neutron (TUCAN) collaboration, the RCNP UCN group engages in development of a high-intensity ultracold neutron (UCN) source for a new measurement of the neutron electric dipole moment (nEDM). UCNs refer to neutrons with kinetic energies of $\lesssim 300\,\mathrm{neV}$, which can be stored in a cell made of appropriate material. This enables long observation times, making them a suitable tool for measurements of the neutron's fundamental properties including the EDM. A finite EDM, if found, would violate time-reversal symmetry, thus giving an important input on the understanding of the Charge Parity violation in the universe. The experimental limit on the nEDM will also give a crucial test of theories beyond the Standard Model such as the supersymmetry theories. The current best upper limit on the nEDM is reported to be $1.8 \times 10^{-26}\,e \cdot \mathrm{cm}$ (90% C.L.)[1], being limited by the statistical uncertainty. The TUCAN collaboration aims at a new nEDM measurement with a sensitivity on the order of $10^{-27}\,e \cdot \mathrm{cm}$ by use of its high-intensity UCN source. We have demonstrated the principle of UCN production by a prototype UCN source which was developed at RCNP and recently installed on a dedicated beamline of the TRIUMF 520 MeV cyclotron. Currently, development work is performed to build an upgraded UCN source and an apparatus for an nEDM measurement.

This report summarizes recent results published in Refs. [2, 3, 4] and ongoing research activities which the RCNP members are involved in.

1 The first UCN production at TRIUMF

The UCN production scheme of TUCAN was earlier developed at RCNP [5], which is a combination of accelerator-driven neutron spallation and super-thermal UCN conversion with superfluid helium (He-II). High-energy neutrons produced by spallation reactions are slowed down to a meV energy range by cold-neutron moderators such as heavy water or liquid deuterium and reach the He-II convertor. There they lose their energies by inelastic scattering of phonons excited in He-II and become UCNs. The prototype UCN source using this method was developed at RCNP and was operated with proton beams from the RCNP ring cyclotron at 400 MeV energy and $1\,\mu\mathrm{A}$ beam current.

To accommodate the UCN source, a new dedicated beamline, BL1U, for neutron fundamental physics was built in the TRIUMF Meson Hall. Beamline components such as beam optics and diagnostic elements, and a spallation target were developed [3]. These included a fast-switching kicker magnet, which extracts a fraction of the proton beam to BL1U and enables beam sharing with other experiments in the facility [4].

In 2016, the prototype UCN source was transported from RCNP to TRIUMF and was installed above the spallation target on BL1U. After commissioning the beamline and the UCN source, we succeeded in the first production of UCNs at TRIUMF during the 2017 beam time [2]. Typical detector counts acquired in this run are shown in Fig. 1 (a). After beam irradiation on the target for 60 s, UCNs stored in the production volume were extracted toward a downstream detector via about 6 m long UCN guides. Shown in Fig. 1 (b) is the scaling of the UCN production rate against the beam current. At currents below $1\,\mu\mathrm{A}$, the UCN yield is proportional to the currents. However for currents higher than $1\,\mu\mathrm{A}$, the temperature of the He-II convertor increased above the nominal 0.9 K, and the yield dropped from the linear scaling. This is due to an increase of the up-scattering rate of UCNs with phonons in the convertor, which scales as $\propto T^7$ with the convertor temperature T. Thus the prototype source is limited by the cooling power of the cryostat. A typical UCN yield achieved under nominal beam parameters of 483 MeV and $1\,\mu\mathrm{A}$ and irradiation time of 60 s was 47 500 UCNs/cycle.

2 Developmental work during the fiscal year 2019–2020

2.1 Production and component tests of the new UCN source

The next-generation UCN source currently under development will overcome the limitation of the prototype source and enables UCN production with a full beam current of $40\,\mu\mathrm{A}$ [6, 7]. One of its major components is a high-performance helium cryostat. To keep the UCN up-scattering rate sufficiently low during the beam irradiation at $40\,\mu\mathrm{A}$, the He-II convertor in the production volume should be kept $\lesssim 1\,\mathrm{K}$ under a heat load of 10 W. Currently, a ^{3}He/^{4}He cryostat with a sufficient cooling power to satisfy this requirement is under

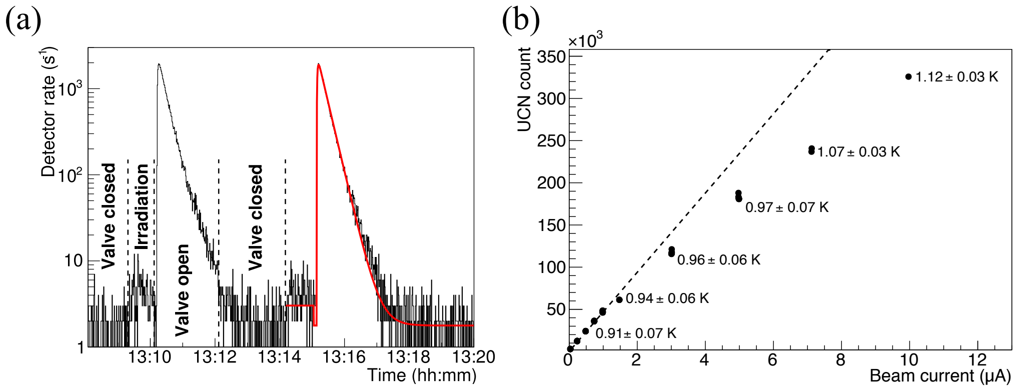

Figure 1: (a) Detector rate for two typical cycles in the 2017 beam time with a beam current of 1 μA. After the proton beam irradiation for 60 s, the valve was opened for 120 s, then the downstream valve was opened to detect UCNs stored in the irradiation volume. (b) The UCN counts extracted from the source after irradiating the spallation target for 60 s with different beam currents. The labels indicate the peak helium temperatures reached under each irradiation condition. Reproduced from Ref. [2].

construction [7]. During the fiscal year 2019, cryogenic tests of key cryostat components were performed at KEK, which included measurements of performances of the helium heat exchangers, and boiling curve measurements of helium on the surface of metal samples with different materials and structures. The results validated fluid mechanics simulations used for designing the heat exchangers, and gave important inputs for the design of components under development. Cooling tests of components were also performed to confirm their superfluid leak-tightness. The performance test of the heat exchanger between ^{3}He and He-II is planned from April 2020.

2.2 Beam time experiments at TRIUMF and J-PARC

The prototype UCN source at TRIUMF was operated during beam times in 2017, 2018 and 2019. The main purpose of the beam times was to test critical components of the new UCN source and the nEDM spectrometer by UCN storage experiments. Transmission rates and storage lifetimes of experimental components were measured by stored UCNs and the results were compared between different methods of coating and polishing. We also performed measurements of diffuse reflection on the surfaces of UCN guides. For this measurement, a neutron absorber is placed on the downstream end of a guide under test. Contribution of UCNs scattering backward was evaluated by a detector on the upstream side of the guide with different positions of the absorber.

Developmental work was also started at J-PARC to perform complementary tests to that of the TRIUMF beam time. In February 2020, the surface roughnesses of samples coated with NiP were measured by the use of a cold-neutron reflectometer at the J-PARC/MLF BL16. A Doppler-shifter-type UCN source on BL05 [8] has also been prepared to perform possible future tests to measure UCN transmission of experimental components.

2.3 Developmental work for magnetic field subsystems of the EDM apparatus

In parallel to the design and construction of the new UCN source, subsystems of the nEDM spectrometer are being developed. The principle of the nEDM measurement is to measure the Larmor precession frequency of stored UCNs with a strong electric field imposed. The environmental magnetic field in the accelerator facility should be well controlled to achieve extreme magnetic field stability required for nEDM measurements at the aimed sensitivity. In August 2019 and February 2020, we acquired three-dimensional magnetic field maps of the area. Based on these data, subsystems to compensate and shield ambient magnetic fields are being designed.

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