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Abstract. New precise measurements of the neutron electric dipole moment (nEDM) are strongly motivated by the tight constraints they will place on new sources of CP violation. A number of experiments are commencing in the next few years that aim to reduce the experimental uncertainty on the nEDM by more than an order of magnitude. The experiments pursue a variety of complementary techniques. The TUCAN (TRIUMF Ultra-Cold Advanced Neutron) EDM experiment is one such experiment which combines a spallation-driven superthermal He-II source of ultracold neutrons with a room-temperature nEDM spectrometer.

1. Introduction, Theoretical Overview, and Experimental Technique

The neutron electric dipole moment (nEDM) is an experimental observable of considerable interest in fundamental physics. The observable violates time-reversal symmetry, and hence is regarded as a test of CP symmetry. To date, all experiments have demonstrated that the nEDM is zero. Improving the experimental precision of the measurements places tighter and tighter constraints on sources of CP violation within the standard model and beyond.

Measurements of the electric dipole moment of the neutron are complementary to those conducted in other nuclear, atomic, and molecular systems [1, 2, 3]. The experiments can be divided roughly into systems containing paramagnetic atoms, diamagnetic atoms, and bare nucleons. For the paramagnetic case, the most precise recent experiment used molecules of ThO [4] and can be interpreted as placing an upper bound on the electric dipole moment of the electron of $|d_e| < 1.1 \times 10^{-29}$ $e$cm at 90% confidence level. In the diamagnetic case, the most precise experiment has used ^{199}Hg [5] finding the atomic EDM to be $|d_{\mathrm{Hg}}| < 7.4 \times 10^{-30}$ $e$cm (95% C.L.). Using nuclear and atomic theory [6], this result implies a constraint on the nEDM of $|d_n| < 1.6 \times 10^{-26}$ $e$cm. The free neutron EDM is most tightly constrained by a measurement done using ultracold neutrons [7, 8] which determined $|d_n| < 3.0 \times 10^{-26}$ $e$cm.

Recent theoretical work addressing the physics impact of a new precise measurement of the nEDM has focused on three general (and overlapping) themes: (1) new sources of CP violation beyond the standard model [9, 10, 11, 12], (2) baryogenesis scenarios, especially new physics contributions to electroweak baryogenesis [13, 14, 15, 16, 17] and (3) the strong CP problem, which is in turn related to the existence of axions [18, 19]. There has also been new theoretical work on time-varying EDM's, which may be induced by axion-like particles [20].

The experimental technique used to determine the nEDM is to measure the neutron's spin-precession frequency ν when placed in parallel (+) and antiparallel dc (−) magnetic (B) and

Table 1. Ongoing and future nEDM experiments, a few of their principal features, and status. The three sections of the table are meant to indicate the different experimental techniques being employed. In the upper portion, ultracold neutron experiments done using room-temperature nEDM spectrometers are grouped together. The SNS experiment uses a polarized cold neutron beam to create ultracold neutrons and the EDM measurement is done entirely in He-II. The lower section of the table groups together two neutron beam experiments. The various experiments are discussed further in the text.

Experiment	Features	Status
PSI	spallation so-D_2, magnetic fields	analysis/upgrading
PanEDM (ILL/Munich)	reactor He-II, 1st MSR	commissioning
ILL/PNPI/Gatchina	dual cell, 2^{nd} best nEDM meast	upgrading source
LANL	spallation so-D_2 UCN source	2021-
TUCAN (Japan/Canada)	spallation He-II, MSR	upgrading, 2022-
SNS	fully cryogenic source/experiment	2022-
ILL/ESS n-beam	intense pulsed neutron beam	R&D, 2025-
J-PARC crystal	high E in crystal	R&D

electric fields (E)

$$h\nu_{\pm} = 2\mu_n B \pm 2d_n E \tag{1}$$

where μ_n is the neutron magnetic moment and d_n its EDM. Since the second term reverses sign with the relative direction of the applied fields, subtraction of the measured frequencies allows a direct measurement of d_n. Key experimental parameters in nEDM experiments are the number of neutrons sampled, the strength of the electric field that can be achieved, and the coherence time of the precessing neutron spins, which should all be maximized for the best sensitivity. The most precise measurement to date used ultracold neutrons (UCN). UCN are valuable experimentally because they can be stored in material traps.

2. Ongoing and Future Experiments

The current experimental situation and the recent theoretical work strongly motivate a new, more precise measurement of the nEDM. A number of groups are pursuing nEDM measurements worldwide (Table 1).

The experiments pursue a broad variety of different experimental techniques. Most of the near term experiments pursue a similar technique to the previous best experiment, which used ultracold neutrons (UCN) stored in a room-temperature nEDM spectrometer. These experiments are grouped together in the upper portion of Table 1. These experiments are motivated by access to new superthermal sources of UCN. Progress on UCN sources can drastically increase the statistical precision of the experiment, which is generally the chief limiting factor.

The next major result in this field will come from an experiment conducted at Paul-Scherrer Institut (PSI, Villigen, Switzerland). Using an improved version of the former ILL apparatus coupled to a spallation-driven solid ortho-deuterium UCN source, the experiment completed running in late 2017. Analysis of the data is underway, and is expected to result in a new world record statistical uncertainty of $\delta d_n \sim 10^{-26}$ $e$cm [21, 22].

The UCN groups (including PSI) aim at achieving a significant improvement in the statistical uncertainty to the $\delta d_n \sim 10^{-27}$ $e$cm level with experiments beginning soon. The PSI group is upgrading their experimental apparatus with a new spectrometer called n2EDM, with the goal of achieving this sensitivity in 500 days. The experiment is presently being constructed.

One improvement considered by most experiments is the use of two measurement cells (double chamber) to contain the UCN, with a central high-voltage electrode separating them. This technique was pioneered by the Petersburg Nuclear Physics Institute (PNPI) group working at ILL, who obtained a competitive nEDM measurement [23]. The PNPI group plans to use the same apparatus with an improved UCN source either at ILL or in the future at a reactor in Gatchina [24].

The PanEDM collaboration is likely to be the first nEDM experiment to use a magnetically shielded room (MSR). The experiment is undergoing commissioning at ILL using the SUN-2 source [25]. In the future it will use an upgraded UCN source at ILL called SuperSUN.

A room-temperature nEDM spectrometer is being developed at Los Alamos National Laboratory (LANL), to use a recently upgraded spallation-driven solid ortho-deuterium UCN source. The source has already been demonstrated to deliver the required densities to a test experiment [26] and a new EDM spectrometer is now being constructed [27].

The TUCAN EDM experiment will be discussed in more detail in Section 3. The experiment features a spallation-driven He-II source of UCN coupled to a room temperature nEDM experiment.

The SNS EDM experiment will use a fully cryogenic experiment with UCN being produced and interrogated within He-II. The He-II will also serve as an insulator thereby allowing a large E field to be obtained. The experiment will also use of a small amount of polarized ^{3}He within the He-II as both a comagnetometer and sensor for the neutron spins via the strongly spin-dependent neutron capture cross-section. The experiment aims for first data taking in 2023 [28]. It is anticipated that the new techniques developed could lead to the breakthrough to the next order of magnitude in precision beyond that achievable in room-temperature nEDM experiments.

Finally, Table 1 lists two experiments which will use beams of cold neutrons to measure the nEDM.

An experiment conducted at ILL and in the future at the European Spallation Source (ESS) will use the traditional method employed in most experiments prior to UCN-based EDM measurements. In this method, cold neutron beams are passed through a long set of parallel plates producing a high electric field. Since many more neutrons can be sensed, and a higher electric field produced, this technique can be competitive with the UCN experiments. A disadvantage of the technique is that systematic shifts in the neutron spin-precession frequency arising due to $\vec{v} \times \vec{E}$ do not average to zero as for the UCN experiments, giving rise to a false EDM signal. These can be mitigated using pulsed neutron beams. A prototype apparatus has produced first results recently [29]. First nEDM experiments are planned for ILL with the full apparatus being developed for ESS [30].

An experiment conducted at JPARC aims to use diffraction of neutrons passing through a single crystal to determine the nEDM. The advantage is that the crystal can be selected to have a very large internal electric field, thereby enhancing the sensitivity to the nEDM. The experiment has produced initial results on diffraction techniques [31]. The precision will be improved by developing different crystals and an nEDM experiment in the future [32].

3. The TUCAN EDM Experiment

The TUCAN (TRIUMF Ultra-Cold Advanced Neutron) EDM experiment aims to measure the nEDM to a statistical precision of $d_n = 1 \times 10^{-27}$ $e$cm in 400 days. A layout of the planned experiment is presented in Fig. 1.

The facility at TRIUMF (Vancouver, Canada) presently operates with a prototype UCN source that was developed in Japan. First results from its operation at TRIUMF have been

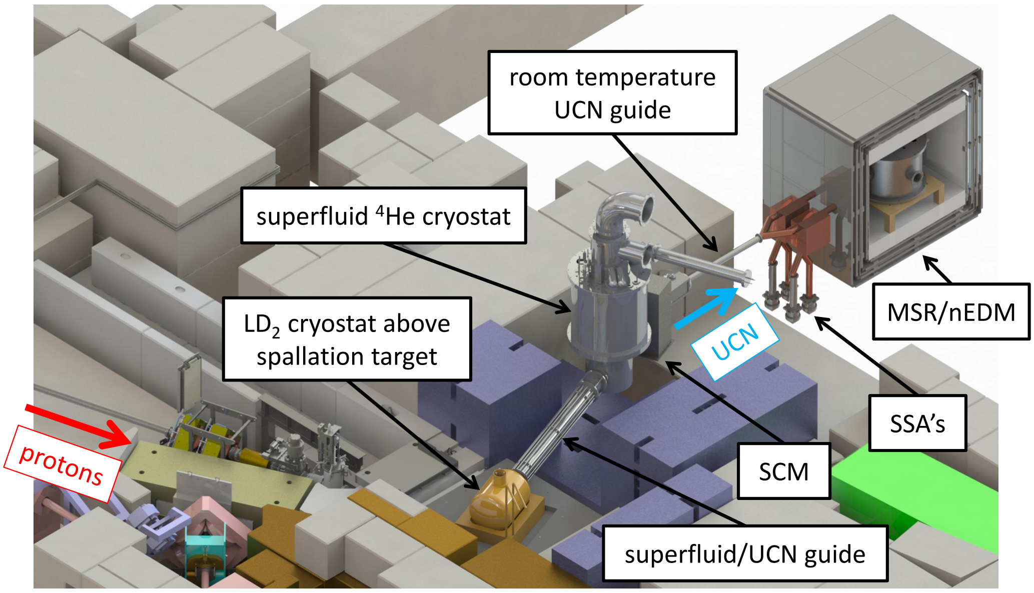

Figure 1. Conceptual design of the TUCAN EDM experiment. The major portion of the biological shielding is not shown. Protons strike a tungsten spallation target. Neutrons are moderated in the LD_2 cryostat and become UCN in a bottle containing He-II, which is cooled by a cryostat. UCN pass through guides and the superconducting magnet (SCM) to reach the nEDM experiment located within a magnetically shielded room (MSR). Simultaneous spin analyzers (SSA's) detect the UCN at the end of each nEDM experimental cycle. For scale, the innermost layer of the MSR is a 1.8 m side-length cube.

reported which enable characterization of the UCN source [33]. The results are used to benchmark simulations for the ongoing UCN source upgrade.

The UCN source upgrade will substantially increase the UCN output compared to the present vertical source. Since the neutron optical potential of the He-II is 18 neV, the source will use near-horizontal extraction. The cold moderator for the source will be upgraded from D_2O to LD_2 with considerably smaller uncertainty in the behavior of the cold neutrons (no scattering kernel exists for D_2O). The beam power will be increased from 1 μA to 40 μA necessitating a refrigerator upgrade from 300 mW to 10 W at the operating temperature near 1 K. The increased heat flux also necessitates a new large-area heat exchanger that is compatible with UCN. The He-II production volume itself will also be enlarged from 8 L to 33 L. The UCN source is completing technical design, and fabrication of parts of the source has begun.

The nEDM spectrometer developed at TRIUMF possesses a few features that are unique relative to the previous generation of nEDM experiments. It will feature a magnetically shielded room, a self-shielded main precession field coil, and dual measurement cells housed within a non-metallic vacuum chamber. The major subsystems of the spectrometer have been developed and the experiment is entering the design and construction phase.

4. Conclusions

Precise measurements of the nEDM carry a strong physics interest because they place a tight constraint on CP violation. The nEDM offers a particularly important constraint when new physics couples to quarks or gluons, and its sensitivity is similar to the Hg-199 EDM in this respect.

The experimental situation is highly competitive with a large number of experiments planned to commence in the near future that are pursuing a variety of new techniques. The next generation of nEDM experiments aim to reduce the uncertainty by an order of magnitude, to the 10^{-27} $e$cm level. For room-temperature experiments, this improvement is expected to come from an increase in the number of UCN delivered from superthermal UCN sources of either solid ortho-deuterium, or He-II. Experiments also are developing innovative techniques which could surpass this generation.

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