Search for a Neutron Electric Dipole Moment at the SNS

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The discovery of a neutron EDM (Electric Dipole Moment) above the Standard Model background, which lies about five orders of magnitude below the present limits, would be the first evidence for a new type of time-reversal violation (and, hence, CP violation via the CPT theorem). Sakharov [1] explained the connection between such a violation and the empirical fact that matter exists in our universe. Experiments have searched for a neutron EDM for over six decades, during which time the sensitivity has improved by nearly eight orders of magnitude. Failure to observe a non-zero EDM has severely constrained many different versions of beyond-Standard-Model physics, including minimal supersymmetry (e.g. MSSM).

The 2011 Fundamental Neutron Physics NSAC (Kumar) report [2] reiterated the scientific motivation for EDM searches, saying they remain as compelling as ever. This search will challenge theories for physics beyond the Standard Model (SM) and the weak baryogenesis hypothesis regarding the baryon asymmetry of the universe. The known CP-violation in the SM remains insufficient by many orders of magnitude to explain the latter, leaving a window of discovery for non-SM CP-violation, and making the search for new sources of CP-violation essential. The Kumar report stated that a measurement of the neutron EDM with sensitivity at the ultimate reach of the nEDM@SNS experiment would have a profound impact on nuclear physics, particle physics and cosmology, even in the event of a negative result, and deemed this to be the initiative with the highest scientific priority in US neutron science [2]. In their words, "A non-zero EDM would constitute a truly revolutionary discovery."

Since the last long range plan, the most important EDM results have been the new limit for ^{199}Hg of 0.3×10^{-28} e·cm [3] and for the neutron of 300×10^{-28} e·cm [4]. In atomic systems, the physics is complementary to that of the neutron EDM, however there are additional uncertainties due to the atomic theory of the electron screening and enhancement factors. The ^{199}Hg measurement will be pursued with a goal of another factor of ten improvement in precision in the next five years, and an additional factor of five after 2020. In order to take advantage of octupole enhancements, promising experiments on ^{225}Ra and ^{223}Rn are underway that should produce exciting results after 2020.

Meanwhile for the neutron, nine experiments worldwide have begun, at least one of which should produce an improvement by a factor of five by 2020. These experiments and their estimated reach are summarized in Table 1. The number of worldwide efforts to measure the neutron EDM illustrates the excitement in the scientific community to determine this important quantity.

The goal of the nEDM@SNS experiment is to achieve a sensitivity $< 3 \times 10^{-28}$ e-cm. A conceptual design of the experiment is shown in Fig. 1. A value (or limit) for the neutron EDM will be extracted from the difference between neutron spin precession frequencies for parallel and anti-parallel magnetic (~ 30 mGauss) and electric (~ 70 kV/cm) fields. This experiment, based on Ref. [5], uses a novel polarized ^{3}He co-magnetometer and will detect the neutron precession via the spin-dependent neutron capture on ^{3}He. The capture signal is observed via scintillation light produced from the ionization in liquid helium of the energetic proton and triton produced in the reaction. Since the EDM of ^{3}He is strongly suppressed by electron screening in the atom it can be used as a sensitive magnetic field monitor. High densities of trapped ultra-cold neutrons are produced via phonon production in superfluid ^{4}He which can also support large electric fields.

Table 1: Summary of worldwide nEDM searches.

Experiment	**UCN Source**	**Cell**	**Measurement Technique**	$\sigma_{\mathbf{d}}$ **(10^{-28} e·cm)**
CryoEDM (ILL)	Superfluid ^{4}He	^{4}He	Ramsey technique for ω External SQUID magnetometers	Phase 1 ≈ 50 Phase 2 < 5
PNPI (ILL)	ILL turbine PNPI/Solid D_2	Vacuum	Ramsey technique for ω $\vec{E} = 0$ cell for magnetometer	Phase 1 < 100 Phase 2 < 10
Crystal (ILL)	Cold neutrons	Solid	Crystal Diffraction	< 100
PSI EDM	Solid D_2	Vacuum	Ramsey technique for ω External Cs and $^3\vec{\mathrm{He}}$ magnetometers Possible Hg or Xe comagnetometer	Phase 1 ≈ 50 Phase 2 < 5
Munich FRMII	Solid D_2	Vacuum	Under construction Similar to PSI EDM	< 5
nEDM (SNS)	Superfluid ^{4}He	^{4}He	^{3}He capture for ω ^{3}He comagnetometer SQUIDS & Dressed spins	< 5
TRIUMF	Superfluid ^{4}He	Vacuum	Phase I RCNP	< 10
JPARC	Solid D_2	Vacuum	Under development	< 5
Crystal (NIST)	Cold neutrons	Solid	Under development	≈ 5?

Several unique features of the nEDM@SNS experiment include:

- loading the neutron trap with UCNs that are produced in 0.45 K liquid He via the phonon recoil process [6]
- using superfluid ^{4}He as a working medium for the very high electric field
- using a dilute mixture of polarized ^{3}He in superfluid ^{4}He as a co-magnetometer because the ^{3}He has a negligible EDM
- using a direct SQUID measurement of the precession frequency of the ^{3}He magnetic dipoles
- using a superconducting shield to isolate the measurement region from external magnetic field fluctuations
- determining the difference in the neutron and ^{3}He precession frequencies from the spin-dependent absorption cross section and the subsequent variations in light intensity from scintillations in the ^{4}He
- allowing two techniques for measuring the EDM, either the direct method with SQUIDs or a dressed-spin method that uses a high-frequency magnetic field to modify the effective magnetic moments of the two polarized species [7]
- providing a comparison measurement of changes in the precession frequency of the two species under E and/or B field reversal in two measurement cells
- using the temperature dependence of the geometric phase for the ^{3}He to measure this important systematic [8, 9].

Control of systematic errors is essential for an experiment at the 10^{-28} e·cm level. The different teams have chosen different approaches, but the nEDM@SNS experiment has the most extensive program for estimating systematic errors. A list of techniques incorporated into the designs of the experimental approaches is shown in Table 2.

The experiment represents a major technical challenge and requires a team with broad technical knowledge and extensive experience. The collaboration, including researchers from twenty-one institutions with expertise in nuclear, atomic, and low-temperature physics, is continuing to address critical R&D developments in preparation for construction of a full experiment. Key issues being addressed include:

1. Maximum electric field strength for large-scale electrodes made of appropriate materials in superfluid helium below a temperature of 1 K.

2. Magnetic field uniformity for a large-scale magnetic coil and a Pb superconducting magnetic shield.

3. Development of coated measurement cells that preserve neutron and ^{3}He polarization along with neutron storage time.

4. Understanding of polarized ^{3}He injection and transport in the superfluid.

5. Estimation of the detected light signal from the scintillation in superfluid helium.

The experiment will be carried out on the Fundamental Neutron Physics Beamline (FNPB) at Oak Ridge National Laboratory's Spallation Neutron Source (SNS). Construction is likely to take at least five years, followed by hardware commissioning and data taking. Thus first results could be anticipated by the end of the decade.

Table 2: Comparison of capabilities for nEDM searches. Items marked with an * denote a systematics advantage.

Capability	**Cryo1**	**Cryo2**	**PSI2**	**PSI3**	**SNS**
$\Delta\omega$ via accumulated phase in n polarization	Y	Y	Y	Y	N
$\Delta\omega$ via light oscillation in ^{3}He capture	N	N	N	N	Y
*Comagnetometer	N	N	Y	Y	Y
*Superconducting B-shield	Y	Y	N	N	Y
*Dressed Spin Technique	N	N	N	N	Y
Horizontal B-field	Y	Y	N	N	Y
*Multiple EDM cells	N	Y	N	Y	Y
*Temperature Dependence of Geo-phase effect	N	N	N	N	Y

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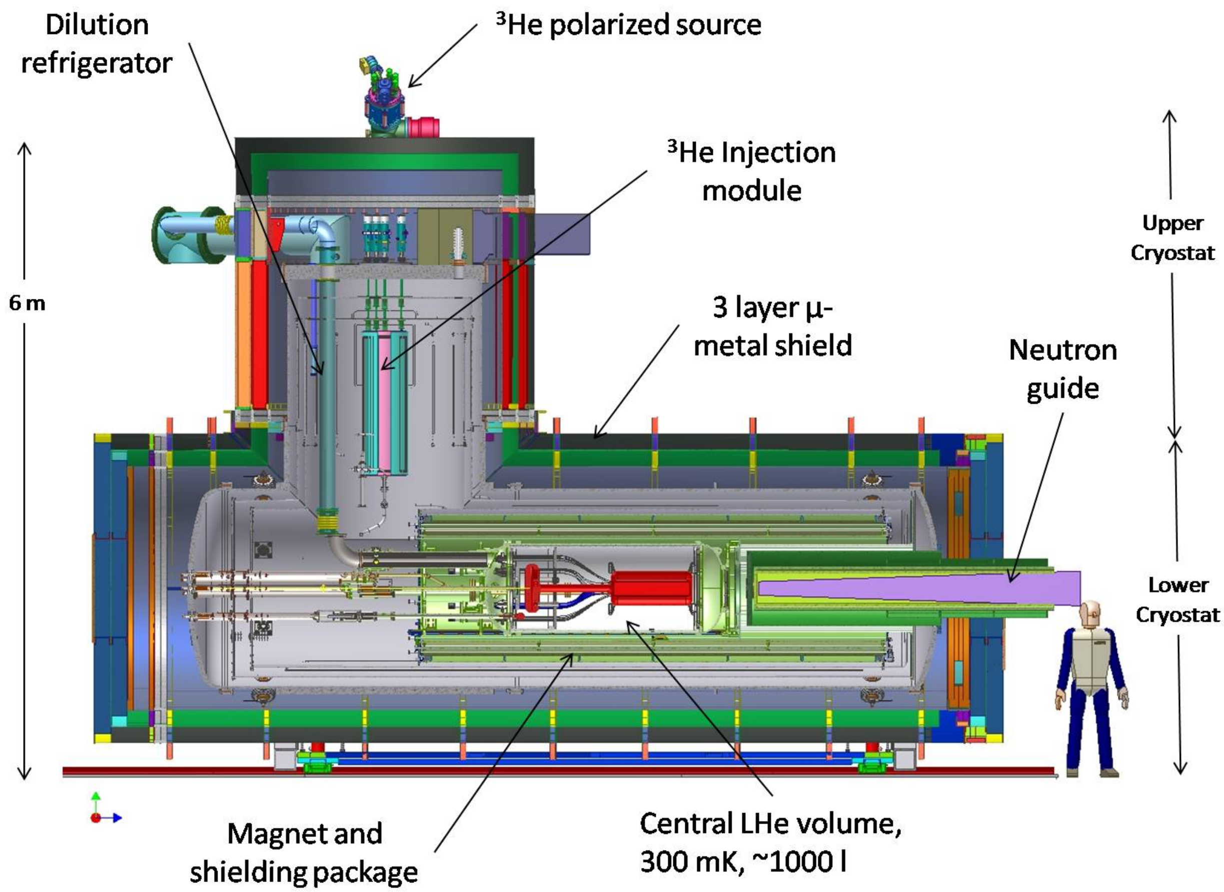

Figure 1: Schematic diagram of the nEDM@SNS apparatus.