Search for a Neutron Electric Dipole Moment at the SNS

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A new search for the neutrons Electric Dipole Moment (nEDM) is underway at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory. The goals, technical approach and status of this experiment are described.

I. EXECUTIVE SUMMARY

The discovery of a neutron EDM (Electric Dipole Moment) above the Standard Model background, which lies more than five orders of magnitude below the present limits, would be first evidence for a new type of time-reversal violation and CP violation (via the CPT theorem). Sakharov [1] explained a possible connection between such a violation and the empirical observation that matter, rather than anti-matter, dominates in our universe. Experiments have searched for the 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 goal of the SNS nEDM experiment is to achieve a sensitivity $< 5\times10^{-28}$ e-cm, which is two orders of magnitude below the existing limit. 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 ($\sim$ 30 mGauss) and electric ($\sim$ 75 kV/cm) fields. This experiment, based on Ref. [6], uses a novel polarized ^{3}He co-magnetometer and will detect the neutron precession via the spin-dependent neutron capture on ^{3}He. A high density of trapped ultra-cold neutrons is produced via phonon production in superfluid ^{4}He which can also support large electric fields.

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.

II. OVERVIEW OF THE SNS NEDM EXPERIMENT

The discovery of a neutron EDM (Electric Dipole Moment) above the Standard Model background, which lies more than five orders of magnitude below the present limits, would be first evidence for a new type of time-reversal violation and, hence, CP violation via the CPT theorem. Sakharov [1] explained the possible connection between such a violation and the empirical fact that matter, rather than anti-matter, exists in our universe. Experiments have searched for the 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 NSAC Fundamental Neutron Physics 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 NSAC report stated that "... a measurement with sensitivity at the anticipated reach of the US nEDM experiment ($\sim 4\times10^{-28}$ e-cm) would have a profound impact on nuclear physics, particle physics and cosmology even in the event of a negative result." The committee 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], for the neutron of 300×10^{-28} e·cm [4] as well as a recently announced order-of-magnitude improvement in the electron EDM from ThO[5]. In diamagnetic atomic systems (e.g.^{199}Hg), the EDM in primarily sensitive to hadronic effects so that the physics is complementary to that of the neutron EDM, however there are additional

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uncertainties due to the atomic theory of the electron screening and enhancement factors. The ^{199}Hg measurement, whose present limit is comparable to the neutron's in terms of basic physics reach, 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 could produce exciting results by 2020. Paramagnetic atomic systems and polar molecules (like ThO) are sensitive to the electron EDM which could have quite different origins compared to hadronic systems, although in some specific SuperSymmetric (SUSY) models they can be related. Measurements in both the leptonic and hadronic sector are crucial in identifying possible new sources of CP violation.

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

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
RCNP Osaka	Superfluid ^{4}He	Vacuum	Phase I	< 50
TRIUMF	Superfluid ^{4}He	Vacuum	Phase II	< 5
JPARC	Solid D_2	Vacuum	Under development	< 5

TABLE I: Summary of worldwide nEDM searches.

The goal of the SNS nEDM experiment is to achieve a sensitivity $< 5 \times 10^{-28}$ 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 ($\sim$ 30 mGauss) and electric ($\sim$ 75 kV/cm) fields. This experiment, based on Ref. [6], uses a novel polarized ^{3}He co-magnetometer and will detect the neutron precession via the spin-dependent neutron capture on ^{3}He. A high density of trapped ultra-cold neutrons is produced via phonon production in superfluid ^{4}He which can also support large electric fields.

The experiment has several characteristics that distinguish it from the others being planned. These characteristics typically reduce potential systematic effects, and/or allow us to better understand them. These characteristics include:

- directly loading the neutron trap with UCNs that are produced in $\sim$ 0.4 K liquid He via the phonon recoil process [7]
- 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. This works due to electron screening of the ^{3}He nucleus resulting in a negligible atomic EDM.
- using a sensitive 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 free precession 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 [6]
- 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

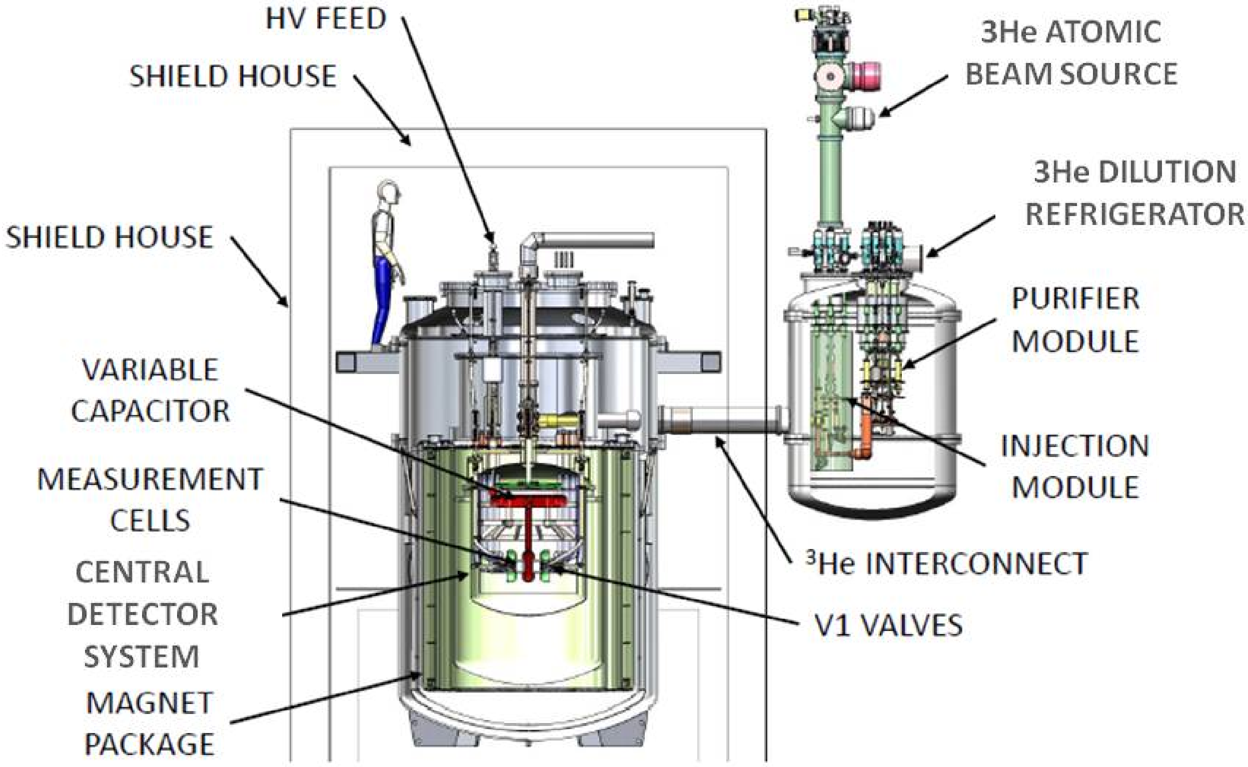

FIG. 1: Schematic diagram of the SNS nEDM apparatus. The neutron beam trajectory is into the page

- using the temperature dependence of the geometric phase for the ^{3}He to measure this important systematic [8–10].

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

Capability	**Cryo**	**FRM**	**PSI1**	**PSI2**	**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
Horizontal B-field	Y	N	N	N	Y
*Comagnetometer	N	Y	Y	Y	Y
*Superconducting B-shield	Y	N	N	N	Y
*Dressed Spin Technique	N	N	N	N	Y
*Multiple EDM cells	N	Y	N	Y	Y
*Temperature Dependence of Geometric phase effect	N	N	N	N	Y

TABLE II: Comparison of capabilities for nEDM searches. The last five items marked with an * denote a systematics advantage.

The experiment represents a major technical challenge and requires a team with broad technical knowledge and extensive experience. The collaboration (shown at the end of this document), including researchers from twenty institutions with expertise in nuclear, atomic, and low-temperature physics, has made significant progress in addressing important technical issues with a number of significant accomplishments. In December 2013 a joint NSF/DOE review of the experiment addressed the status of the experiment. At this review the funding agencies endorsed the collaboration's plan to begin a new phase of the experiment called Critical Component Demonstration (CCD) wherein the most technically challenging aspects of the experiment will be developed to a sufficient level of technical readiness to allow completion of the more conventional experimental components (such as neutron beam line, external magnetic shielding and local infrastructure). Key issues being addressed during the CCD phase include:

1. Maximum electric field strength for 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. Estimation of the detected light signal from the scintillation in superfluid helium.
4. Development of coated measurement cells that preserve neutron and ^{3}He polarization along with neutron storage time.
5. Understanding of polarized ^{3}He injection and transport in the superfluid.
6. Exploring the systematics of the dressed spin technique including polarized UCN and ^{3}He.

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