LA-UR- 01-6216

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Submitted to: Workshop proceedings for "Fundamentals Neutron Physics at the Spallation Neutron Source", Oakridge National Laboratory, September 19 - 21, 2001

Los Alamos
NATIONAL LABORATORY

A Measurement of the Electric Dipole Moment of the Neutron

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Abstract

The construction of the Spallation Neutron Source offers a wonderful opportunity for an improved search for the electric dipole moment of the neutron. By combining the intensity of this new facility with the properties of superthermal production of ultra-cold neutrons, a sensitivity (90% confidence) of better than 10^{-28} e•cm should be achievable.

A non-zero value for the electric dipole moment (EDM) corresponds to an infinitesimal separation of positive and negative charges within the neutron along the spin axis. The current limit on the permanent EDM of the neutron is one of the most stringent in all of physics, $d_n < 6 \times 10^{-26}$ e•cm and represents 50 years of experimental effort [1]. Nevertheless, the motivation for improving this value has never been stronger. The interaction of the EDM with an external electric field produces a term in the Hamiltonian that violates time reversal (T) invariance [2]. The continuing reason for interest stems from the observation of a violation of T in the neutral kaon system. This T violation is usually attributed to the complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix of the standard model of electroweak interactions. The standard model predicts an immeasurably small value for the neutron EDM, $< 10^{-31}$ e•cm [3]. The gap between the standard model prediction and observation is territory for the discovery of new physics. However, the CKM phase may not be the entire story. If the observed baryon-antibaryon constitution of the universe is due to CP violation (equivalent to T violation assuming CPT conservation), the range of predicted values for the neutron EDM is $6 \times 10^{-28} < d_n < 2 \times 10^{-25}$ e•cm [4]. Many theories of physics beyond the standard model have been ruled out by their prediction of a sizable EDM for the neutron, and today, new classes of highly popular models, e.g. supersymmetry, predict values for the EDM that are also within these bounds [5]. The goal of this experiment is to span this range of the cosmological predictions and new extensions to the standard models [6].

The general technique for measuring the EDM of the neutron centers about the Hamiltonian for a particle with both electric and magnetic dipoles in the presence of strong electric and weak magnetic fields, $H = -(d_n \mathbf{I} \cdot \mathbf{E} + \mu_n \mathbf{I} \cdot \mathbf{B})/I$. A non-zero EDM would be manifest by a change in the Larmor precession frequency correlated with a change in the electric field direction.

Modern techniques for neutron EDM searches utilize the ability to store ultra-cold neutrons (UCN) for times comparable to the beta decay lifetime. The technique to be used in this measurement to improve the neutron EDM was proposed by R. Golub and S. K. Lamoreaux [7]. The figure of merit for EDM experiments varies as $E(N\tau)^{1/2}$, where E is the electric field strength, N is the number of neutrons in the system, and τ is the time the neutrons precess in the field. The figure of merit will be improved over expected results from an experiment currently acquiring data at the Institut Laue-Langevin (ILL) by a factor of 400 [8]. This improvement will result in a sensitivity (90% confidence) of better than 10^{-28} e•cm in about 10^7 live seconds of data taking.

The high density of UCN needed for this experiment will be obtained by using a superthermal ^{4}He source that will be located at the Spallation Neutron Source (SNS). The basic idea for such a source is to take advantage of the down scattering of 8.9-Å neutrons in a bath of superfluid ^{4}He sitting at about 0.5 K. Densities of 10^4 UCN/cc will be obtainable. This value is scaled from a recent UCN trapping measurement that is part of a neutron lifetime experiment [9], assuming a cold source flux of 2 x 10^{13} n/cm^2-s-sr and a 10-cm x 12-cm supermirror guide. The dielectric properties of superfluid He are favorable for the intended increase in electric field, and the cryogenic measurement cell is expected to lead to the anticipated increase in storage time.

The current ILL experiment includes a Hg co-magnetometer to deal with the large systematic error associate with time dependent changes in the magnetic field [8]. This feature is maintained by doping the superfluid with a small amount (10^{-10} atoms) of ^{3}He. ^{3}He is a light, diatomic atom that will not have an EDM. It has a magnetic moment that is within 10% of that of the neutron. Thus, it will precess with nearly the same frequency as the neutrons. The precession rate of the ^{3}He can be measured by detecting its magnetization with a superconducting quantum interference device (SQUID).

The ^{3}He-^{4}He mixture has the right properties to measure the precession rate of the neutrons. The neutron absorption cross section on ^{3}He is highly spin dependent. In the singlet state, it is roughly 10^4 b, while in the triplet state, it is less than 100 b. If the ^{3}He captures a neutron, it will produce a proton and a triton that will scintillate as they come to rest in the ^{4}He. The hard ultraviolet light can be detected in a photomultiplier tube if it is wavelength shifted into the blue. Light will only be observed when the spins are opposite, and its intensity will vary with time as $1\text{-}p_3p_n\cos(\gamma_n\text{-}\gamma_3)B_0t$, where p_3 and p_n are the polarizations of the ^{3}He and the neutron, $(\gamma_n - \gamma_3)$ is the difference of the magnetic moments, and B_0 is the applied field. It is quite plausible to construct a ^{3}He-quadrupole state selector that will give the required intensity of polarized ^{3}He. The neutrons are polarized by a polarizing beam-splitter [10] and further polarized by their absorption on ^{3}He if the spin is opposite to that of the ^{3}He.

Thus, the signal of a non-zero value for the EDM is a shift in frequency between the scintillation light and the magnetization of the ^{3}He as observed with the SQUID; the shift must be properly correlated with the value of the electric field.

A number of challenges have already been met in establishing this experimental technique. The signal-to-noise has been measured at 4 K for a SQUID and been shown to be satisfactory for detecting the ^{3}He precession; it gets better as the square root of the temperature. The ^3He atoms will occupy the same volume as the neutrons based on measurements of their distribution with neutron tomography. A new measurement of the diffusion coefficient for ^3He below 1 K shows that the ^3He will diffuse at about the same speed as the neutrons move at 0.3 K [11]. In the near future, the production rate and storage time of UCN will measured, the polarized ^3He system will be tested, and the HV characteristics of the ^4He will be examined. A relatively low rate of background counts induced by neutron and gamma-ray activation in the measurement cell is presumed to be a significant advantage for using a spallation source over a reactor.

The anticipated experimental cycle of 1000 seconds will be divided as follows. In the first 40 seconds, the measurement cell will be loaded with ^4He and highly-polarized ^3He, where the spins are aligned with the magnetic and electric fields. From then until about 450 seconds, the cell will be filled with polarized neutrons whose spins are parallel to those of the ^3He. A short $\pi/2$-pulse will flip the spins to be perpendicular to the fields and the species will begin to precess. They will precess for another 500 seconds; during this time, the ^3He magnetization is measured by the SQUID and the absorption is measured by light in the photomultiplier tube. Finally, when necessary, the cell will be emptied to replace the somewhat depolarized ^3He with a new charge.

A conceptual apparatus to perform these tasks is shown in Fig. 1. The central part of the apparatus is where the measurement is made. There are two measurement cells containing roughly 3.5 l of ^4He doped with ^3He. These cells contain the wave length shifters and are coupled to photomultiplier tubes via light guides. The electric-field ground is provided by the plates surrounding the cells, and the high voltage is put on the central plate by a capacitor that amplifies the voltage. Outside the ground plates is the housing for the SQUIDs. The magnetic field is generated by a $\cos\theta$ magnet with a radius of 30 cm. Magnetic shielding from the Earth's field to the micro-gauss level will be required. This shielding is comprised of four layers of conventional shielding and an innermost superconducting shield. Of course, the entire apparatus is contained in a large cryostat to maintain 0.5 K, 4K, and 77 K temperature regions. The dimensions are roughly 2 m in length by 0.5 m in diameter. The important items not shown in the picture are the large dilution refrigerator that sits above and the Bi filter and neutron state selector that sit upstream of the cryostat.

The full apparatus requires a significant facility. The size is about 10 m along the beam and ±4 m perpendicular to the beam. The height is 5 m and requires a crane with a lift height of 7 m. A vibration-isolation pad is needed to prevent microphonic noise from affecting the SQUIDS. T_0 and frame overlap choppers will be needed to select only the 8.9-Å neutrons. Finally, the cryogenics will use about 150 kW of power and could consume between 100-2000 l/wk of liquid helium, depending on the success of recycling plans.

Though this experiment is very challenging (many details are not discussed here), it is one that will illuminate the mechanisms for baryogenesis in the universe and extensions to the standard model in a way that cannot be reached by other experiments.

References

[1] E. M. Purcell and N. F. Ramsey, *Phys. Rev.* **78**, 807 (1950).
[2] L. D. Landau, *Nucl. Phys.* **3**, 127 (1957).

[3] I. B. Kriplovich and A. R. Zhitnitsky, *Phys. Lett.* **B145**, 490 (1982); M. B. *Gavela et al.*, *Phys. Lett.* **B109**, 215 (1982).
[4] A. G. Cohen, D. B Kaplan and A. E. Nelson, *Annu. Rev. Nucl. Sci.* **43**, 27 (1993); I. I. Bigi and A. I. Sanda, CP Violation (Cambridge Univ. Press, 2000) 349.
[5] I. I. Bigi and A. I. Sanda, CP Violation (Cambridge Univ. Press, 2000) 269.
[6] M. D. Cooper and S. K. Lamoreaux, Lett. of Intent to LANSCE (1997).
[7] R. Golub and S. K. Lamoreaux, *Phys. Rep.* **237**, 1 (1994).
[8] P. G. Harris *et al.*, *Phys. Rev. Lett.* **85**, 904 (1999).
[9] P. R. Huffman *et al.*, *Nature* **403**, 62 (2000).
[10] T. Krist *et al.*, *Physica* **B213**, 939 (1995).
[11] S. K. Lamoreaux *et al.*, submitted to *Europhysics Letters*; LANL ArXiv, cond-mat/0110097.

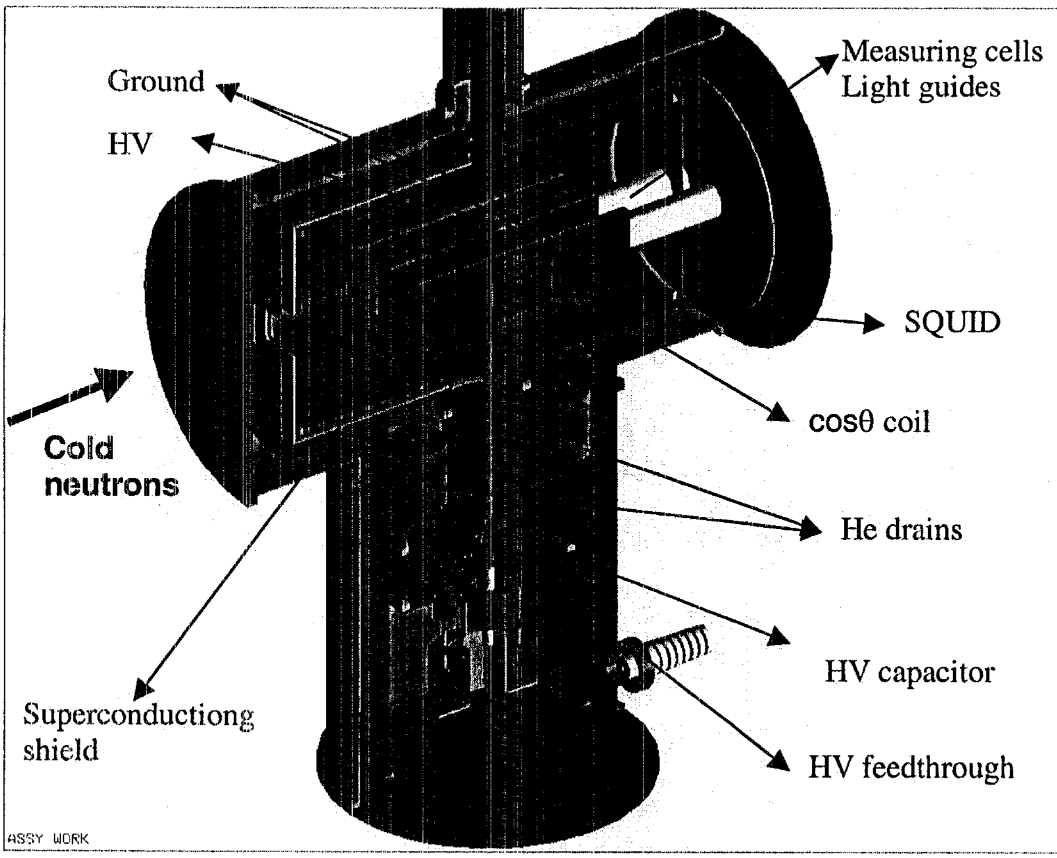

Fig. 1. Conceptual design of the central cryostat of the EDM experiment.