I. INTRODUCTION

An opportunity exists at Los Alamos National Laboratory to improve the limit on the electric dipole moment (EDM) of the neutron by more than two orders of magnitude to 4×10^{-28} $e$cm. The current limit is one of the most stringent in all of physics, $d_n < 1.1 \times 10^{-25}$ $e$cm, and represents 45 years of experimental effort. Nevertheless, the motivation for improving this value has never been stronger. The continuing reason for interest stems from the observation of a violation of time reversal (T) invariance in the neutral kaon system. Many theories have been developed to explain the kaon problem, but most have been ruled out by their prediction of a sizable EDM for the neutron. Today, new classes of highly popular models, *e.g.* supersymmetry, predict values for the EDM that are within the potential reach of experiment.

One of the most elegant explanations of the neutral kaon system is the introduction of a complex phase into the Cabibbo-Kobayashi-Maskawa mixing matrix of the standard model of electroweak interactions. This additional phase is T violating but predicts an immeasurably small value for the neutron EDM, $< 10^{-31}$ $e$cm. However, this phase may not be the entire story. If the observed baryon-antibaryon constitution of the universe is due to T violation, the range of predicted values for the neutron EDM is 6×10^{-28} $e\text{cm} < d_n < 2 \times 10^{-25}$ $e$cm.

This letter of intent announces our goal to make at least two orders of magnitude improvement in the measured value of the EDM of the neutron so as to challenge both the theories of supersymmetry and of T violation as the origin of the cosmological asymmetry observed in the ratio of baryons to antibaryons. We will pursue this objective in two phases. During the first, we will demonstrate the feasibility of the technique by experimentally verifying our ability to meet the specifications for the most challenging parts of our design. The final phase will consist of building the detector and making the measurement.

With the installation of a 10-cm x 10-cm supermirror guide (see below), the Lujan Center at LANSCE will become among the most intense sources of 8.9 Å neutrons in the world. Coupled to the superthermal He source (see below), it will have the greatest density of bottled UCN anywhere and 250 times greater than the current EDM experiment. Historically, the pursuit of the neutron's EDM has required that the experiment be developed by people at the site for many years. Los Alamos has a team that is pursuing this work and one of them, Steve Lamoreaux, is amongst the leading American scientists in UCN and EDM physics as well as a coinventor of the idea. A good source of neutrons, a new technique, and an enthusiastic team all contribute to making LANSCE an excellent place to pursue the goal of this experiment.

We believe that this experiment will be limited by the number of cold neutrons that illuminate the measurement cell. Hence, if the Long Pulsed Spallation Source (LPSS) is built at LANSCE, a factor of 6 more neutrons would be available and should produce a further improvement by a factor of 2.5. The ultimate neutron-intensity would arise from refurbishing the Institut Laue-Langevin reactor with a guide similar to the one proposed for the Lujan center. The resulting UCN density would be 24 times that of the Lujan center and would yield a factor of 5 better result than we intend at the Lujan Center. Such an upgrade would be very expensive and would only be considered if there were a proven experiment. If the National Spallation Neutron Source is built, it woul be another attractive source of neutrons.

The next section will describe the proposed experiment as well as giving a road map of the article by R. Golub and S. Lamoreaux [Phys. Rep. **237**, 1 (1994)], referred hereafter as GL. The following section will describe our beamline specifications and beam request. Next, there will follow a discussion of the major equipment required to carry out the experiment. Our schedule for performing the development work, constructing the detector, and making the measurement is given in Sec. V. Section VI addresses the technical challenges of the experiment and our plans for demonstrating the proposed technique. The remaining section deal with our collaboration, our vision of a reviewable proposal, and the resources required for success. Finally, for convenience, we attach the GL paper as an appendix.

II. THE PROPOSED EXPERIMENT

A. Overview

A detailed description of the fundamental physics regarding the new proposed experimental technique is given in the GL article; a brief overview of the technique will be given here.

The basic idea is to produce and store UCN in a superfluid ^{4}He bath that contains a small concentration of polarized ^{3}He; the polarized ^{3}He serves as a UCN polarizer, magnetometer, and UCN spin precession analyzer. In principle, this new experiment can achieve a factor of over 250 improvement in the experimental limit for the neutron EDM in conjunction with the upgraded LANSCE spallation-neutron source, or even higher with a more powerful source such as the LPSS or ILL reactor.

This factor results from the possibility of an increased electric field (a factor of 5) due to the excellent dielectric properties of superfluid ^{4}He, an increase in total UCN stored (250 fold improvement at the Lujan Center), and an increased storage time (up to 10 times) due to the low temperature of the walls; the combined improvements give a direct increase in sensitivity by a factor of 100 in the shot noise limit, as based on Eq. (6.26) of GL, in one year of operation. However, the current experimental EDM bound is largely limited by magnetic field systematics, and is about a factor of 2.5 greater than the shot noise. With the proposed experiment, which should not have the magnetic field systematics, a net factor of 250 improvement might be possible at the LANSCE spallation source, leading to an EDM limit of 4×10^{-28} $e$cm; the use of ^{3}He as a volume comagnetometer is crucial to the elimination of magnetic field systematics.

The so-called "superthermal process" for producing UCN in superfluid ^{4}He was proposed by Golub and Pendlebury and a number of aspects of the physical processes involved have been demonstrated. Briefly, the dispersion relation for the free neutron, relating kinetic energy $\hbar\omega$ to momentum $\hbar k$, is a parabola:

$$\omega = \hbar k^2/2m. \tag{1}$$

This curve crosses the Landau-Feynman (L-F) dispersion curve for elementary excitations in superfluid ^{4}He at $2\pi/k^* = 8.9$ Å, and $E^* = \hbar\omega = 11°$K. The crossing point is in the linear region of the L-F curve. (The curves also intersect at $k = 0$). Neutrons in this range of wavelength are readily produced by a liquid deuterium or liquid hydrogen moderator.

Since both energy and momentum are conserved in the scattering process, neutrons at or near rest can only absorb phonons of energy E^*, where the dispersion curves cross. This process is proportional to the 11°K phonon density which is strongly suppressed by the Boltzmann factor, $e^{-E^*/T}$ when the superfluid temperature is less than 1°K. By the same argument, only neutrons with energy near E^* can scatter into the UCN energy region by emission of a single excitation.

A UCN source based on this process operates by the following principle. 8.9 Å neutrons can easily penetrate the walls of the storage container, and enter the superfluid bath. These neutrons then downscatter, producing UCN which are trapped in the container if the kinetic energy is less than the effective neutron potential of the wall, U_F. ($U_{\rm F}$ for liquid ^{4}He is about 20 neV, much less than the potential for most solid materials, so we can assume it is zero in the following discussion.) UCN produced in this way will remain in the superfluid He bath until they are lost through one of the possible loss mechanisms, which include β-decay, absorption by ^{3}He, loss in the wall, etc. The UCN will reach a saturation density

$$\rho_{\rm UCN} = P\tau, \tag{2}$$

where τ is the total loss rate,

$$\tau^{-1} = \tau_\beta^{-1} + \tau_3^{-1} + \tau_{\rm wall}^{-1} + ... \tag{3}$$

and P is the UCN production rate (UCN/(cm^3 sec)) due to the above mentioned downscattering process:

$$P = 7.2 \frac{d^2\Phi}{d\lambda d\Omega} \frac{1}{\lambda_{\rm u}^3} \delta\Omega \text{ n cm}^{-3}\text{ s}^{-1}, \tag{4}$$

where the neutron spectral density is specified at 8.9 Å, $\lambda_{\rm u}$ is the shortest UCN wavelength that can be stored in the container, and $\delta\Omega$ is the source solid angle subtended at the superfluid bath.

The neutron-superfluid ^{4}He system is in some sense a two-level quantum system, and the production of UCN by the emission of a phonon can be compared to the spontaneous emission of radiation by an excited atom.

Attempts to make a UCN source based on the superthermal process in ^{4}He have so far been met with technical difficulties, primarily in regard to extraction of the UCN from the bath. Invariably and inevitably, the thin material windows used to contain the liquid He, but allow the UCN to pass, become covered by condensible gases, decreasing $U_{\rm F}$ and/or the UCN absorption. Typically, extracted densities have been a factor of 10 to 100 below that expected. Indirect measurement through the upscattering rate has confirmed that the expected density does indeed exist within the bath.

The extraction problems encountered so far can be avoid by performing an EDM search directly in the liquid helium of the superthermal source. Such a system has a number of advantages; for example, because of the excellent dielectric properties of liquid helium, increasing the applied electric field by nearly an order of magnitude might be possible. Also, it appears feasible to use a dilute solution of polarized ^{3}He as a UCN polarizer, spin analyzer, detector, and magnetometer. ^{3}He only absorbs neutrons when the total spin is zero because the reaction occurs via the 0^+ excited state, as follows

$$^3\text{He} + \text{n} \rightarrow \text{p} + \text{T} + 764 \text{ keV}. \tag{5}$$

The polarization and cryogenic transport of polarized ^{3}He have been studied. Furthermore, energetic charged particles produce ultraviolet scintillations in liquid helium with about 4 photons per keV of deposited energy. The reaction between ^{3}He and neutrons in the liquid helium are thus easily detected, giving a detection of reactions with nearly 100% efficiency. See J. Doyle and S. K. Lamoreaux, Europhysics Lett. **26**, 253 (1994) for an application of these techniques to a measurement of the neutron β-decay lifetime which may lead to a factor of 100 improvement in accuracy.

The ^{3}He serves as a UCN polarizer by absorbing neutrons in the singlet state. To be effective, this rate of absorption should be slightly higher than other UCN loss mechanisms in the system. This condition implies a ^{3}He concentration of 10^{-9}, or about 10^{13} atoms/cm^3. Such low densities of polarized ^{3}He can be produced with a hexapole state selector, with essentially perfect polarization. Other techniques for producing higher densities have the polarization limited to 70%; since the ^{3}He serves three functions, it is expected that the experimental sensitivity varies as at least the cube of the ^{3}He polarization. This presumption agrees with detailed calculations. It has been shown by solving the Schrödinger equation in the presence of a spin dependent absorption probability that this technique is slightly less sensitive than the conventional bottle technique, however, this loss of sensitivity is more than made up for by elimination of the extraction losses and increase in electric field.

In the following discussion, let the subscript 3 refer to the ^{3}He atoms, and subscript n refer to the UCN. In the case where both species are polarized, the spin-dependent loss rate can be written

$$\frac{1}{\tau_{\rm abs}} = \frac{1}{\tau_3}(1 - \vec{p_{\rm n}} \cdot \vec{p_3}) = (1 - p_n p_3 \cos\theta_{\rm n3})/\tau_3, \qquad (6)$$

where $\theta_{\rm n3}$ is the angle between the spin polarization vectors, $\vec{p_{\rm n}}$ and $\vec{p_3}$, where $|\vec{p_{\rm n}}| \leq 1$ and $|\vec{p_3}| \leq 1$. Each loss (nuclear reaction) produces a scintillation pulse; the scintillation rate thus becomes a measure of the angle between the polarization vectors.

One could search for a neutron EDM by using the above UCN production/ polarization technique. After the UCN are polarized (along a static field of magnitude B_0), the UCN and ^{3}He spins could be flipped by $\pi/2$; the spins then precess about the static field and there will be a modulation in the scintillation rate:

$$\phi(t) \propto (1 - \vec{p}_3 \cdot \vec{p}_{\rm n})$$

$$= 1 - p_3 p_{\rm n} \cos[(\gamma_3 - \gamma_{\rm n})B_0 t + \Phi], \qquad (7)$$

where $\phi(t)$ is the time-dependent scintillation rate, Φ is an arbitrary phase, and the gyromagnetic ratios are

$$\gamma_{\rm n}/2\pi \approx -3 \text{ Hz/mG}$$

and

$$\gamma_3/2\pi \approx -3.33\text{Hz/mG}.$$

The EDM of ^{3}He is expected to be quite small; thus, if an electric field is applied along B_0 there will be a change in the frequency of the scintillation rate modulation. Unfortunately, the problem of measuring the magnetic field remains (although the effects are only 1/10 as large since the gyromagnetic ratios are nearly equal) and it has been demonstrated that experiments are presently limited by magnetic systematic effects. It might be possible to use superconducting quantum-interference device (SQUID) magnetometers to detect the precessing ^{3}He magnetization, so that the ^{3}He could then serve as a direct magnetometer. However, the sensitivity is at best marginal, but recent technical advances have led us to reconsider this option.

In the above description, it is evident that a perfect experiment would be possible if the magnetic moments of the ^{3}He and neutron were equal; the fact that the magnetic moments are equal to within 10% reduces the sensitivity to background field by an order of magnitude, and if the moments were exactly equal, there would be no effect at all. Unfortunately, we have no direct control over the physics responsible for the observed magnetic moments; however, these moments can be artificially modified by using "dressed atom" techniques to make them effectively equal.

In the presence of a strong oscillating magnetic field (RF), the magnetic moment will be modified, or "dressed", yielding an effective gyromagnetic ratio

$$\gamma' = \gamma J_0(\gamma B_{\rm RF}/\omega_{\rm RF}) = \gamma J_0(x), \qquad (8)$$

where γ is the unperturbed gyromagnetic ratio, $B_{\rm RF}$ and $\omega_{\rm RF}$ are the amplitude and frequency of an applied RF field, and J_0 is the zeroth-order Bessel function. This effect can be qualitatively understood by taking the average of the spin in an RF field. Consider a spin pointing along $\hat{z}$ at $t = 0$. Now apply an RF field along $\hat{x}$; the spin precession frequency is time dependent,

$$\omega(t) = \dot{\theta(t)} = \gamma B_x(t) = \gamma B_{\rm RF} \sin\omega_{\rm RF} t,$$

so that the angle relative to $\hat{x}$ is

$$\theta = \gamma(B_{\rm RF}/\omega_{\rm RF})\cos\omega_{\rm RF} t.$$

The average spin projection $\langle P_z \rangle$ along $\hat{z}$ is given by

$$\langle P_z \rangle = \frac{1}{T}\int_0^T \cos[\gamma B_{\rm RF} t \cos\omega_{\rm RF} t] dt$$

$$= J_0(\gamma B_{\rm RF}/\omega_{\rm RF}) = J_0(x).$$

A more sophisticated treatment shows that a spin will respond to a small (compared to the RF amplitude) static field along $\hat{x}$, with an average magnetic moment $\gamma' = \gamma J_0(x)$; our simple estimate gives a picture of how the oscillating field dilutes the magnetic moment.

In practice, the oscillating field is at right angles to the static field B_0 around which the spins are processing. In the absence of the oscillating field, one would see scintillation due to reactions occurring at a rate given by (7). Thus, there is an oscillation in the scintillation rate at the difference in the precession frequencies ($\delta\omega = (\gamma_{\rm n} - \gamma_3)B_0$). If the RF dressing field is now applied, the effective magnetic moments become modified, and

$$\delta\omega = (\gamma_{\rm n} J_0(\gamma_{\rm n} x) - \gamma_3 J_0(\gamma_3 x))B_0. \qquad (9)$$

This formula has the property that $\delta\omega = 0$ when $\gamma_{\rm n} x \approx 1.19$; this condition is referred to as "critical dressing". This cancellation can be achieved in practice with a dressing field frequency of order 1 kHz and amplitude of 100 mG, and a spin precession frequency on the order of a few Hz.

If the neutron EDM is non-zero, the neutron precession frequency will be shifted by an amount $2d_{\rm n}EJ_0(\gamma_{\rm n}x)$ (since the dressing dilutes the net spin projection). Thus, the value of $x=x_{\rm c}$ to give $\delta\omega=0$ is changed. By measuring the value of $x_{\rm c}$ vs. electric field direction, a neutron EDM would be evident. The important point is that the effect of static magnetic fields is canceled.

Experimentally, the neutron and helium spin vectors could be kept nearly parallel; the scintillation would increase or decrease as x is varied away from the value $x_{\rm c}$ such that $\delta\omega=0$. Over the course of a storage period, x could be sinusoidally modulated at a low frequency $\omega_{\rm m}$ and the value $x_{\rm c}(\pm E)$ inferred from variations in the scintillation rate which occur at harmonics of ω_m. If the average value of $x\neq x_{\rm c}$, there will be a first harmonic to the scintillation rate growing linearly in time. If $x=x_{\rm c}$, there will be only a second harmonic component. In practice, a feedback system might be used to force the first harmonic signal to zero; the second harmonic then serves as a system calibration. (Note that the modulation in x and the subsequent modulation in the scintillation rate are 90° out of phase because the spin vectors must precess before the effects due to a change in x are manifest).

The sequence of events during a measurement cycle is 1) The cell is filled with pure ^{4}He with the electric field on (for example), 2) The cell is filled in a few seconds with polarized ^{3}He, 3) The cell is illuminated by cold-neutrons for roughly one neutron lifetime (900 s), 4) A $\pi/2$-RF pulse is given to flip the neutron and ^{3}He spins, 5) The RF dressing field is turned on with the appropriate modulation of its frequency, and 6) The scintillation light is observed for roughly one neutron lifetime.

B. Layout of the apparatus

A prototype schematic of a proposed apparatus is shown in Fig. 1, roughly to scale, with the measurement cell having a diameter of about 20 cm. A supermirror guide delivers 8.9 Å neutrons to the apparatus. UCN are produced directly in the cell; the side of the cell where the cold neutrons enter is made of deuterated plastic, while the rest is made of normal plastic. These walls form a cold neutron trap and increases the UCN production rate by a factor of more than two.

The high voltage enters from the bottom to ensure there is no superfluid gap near the entry region.

A SQUID pickup loop surrounds the measurement cell; an electromagnetic copper shield between this loop and the cell will guard against high voltage induced noise. The measurement cell and SQUID pickup loop is surrounded by a superconducting shield.

A polarized ^{3}He fill/empty line with a crude (not superfluid tight) valve allows introduction and removal of ^{3}He which must be done for every measurement cycle. Introduction of the polarized ^{3}He is simple, but its removal after each cycle is more difficult. We are exploring options in this regard.

For simplicity, we have not shown the magnet coils and the hexapole source of polarized ^{3}He. Three magnets are necessary, the DC field coil, the RF field coil, and an RF coil for the $\pi/2$ pulse at the beginning of the measurement cycle. The scale of the hexapole source is of the order of 1 m and is outside this view.

C. The main sections of GL relating to this proposal

Sections 3.1-3.2 gives an overview of the experiment, similar to that above. The polarization of UCN by selective absorption with polarized ^{3}He is discussed in Sec. 3.3.

In Sec. 3.4, it is shown that a hexapole spin filter can produce polarized ^{3}He at a rate sufficient for the proposed experiment. Such a source would use a 1°K atomic source and a hexapole focusing system about 1 m long. A similar source has been recently built for ^{3}He spin echo.

Section 3.5 gives an overview of the work on scintillations produced in liquid helium; at the time of writing GL, it reported the most current work. Our subsequent studies have indicated a number of features of the scintillation process not recognized in the original work, but there are no new features that would indicate any serious difficulty.

Sections 3.6-3.8 give an overview and qualitative discussion of the use of ^{3}He as a comagnetometer.

Section 4 gives a full quantum mechanical treatment of the dressed spin system, and the expected time dependence of the scintillation signal. Of particular interest are Sec. 4.4 and 4.5 where the effects of varying static field, both parallel and perpendicular to the applied field, are determined, and shown to only affect the dressing in second order.

In Sec. 5, a discussion of the interaction of ^{3}He with UCN is given. This interaction is a complicated issue because it contains both real and imaginary components; the spin dependent real part gives rise to a pseudomagnetic field which, for the anticipated ^{3}He concentration, is of order 10 mHz. Any component of the ^{3}He polarization along the static field (e.g., resulting from an imperfect spin flip) will give a randomly varying effective field, which although not necessarily a systematic problem, can introduce additional noise to the system between ^{3}He fillings that will likely not be reproducible. Also, the dressed spin system evolution will be affected by both the real and imaginary parts of the interaction. Section 5.4 shows some deleterious effects of the pseudomagnetic field can be eliminated by a suitable feedback system.

In order to contend with the possibility that a finite ^{3}He polarization remains along the static field after the spin flip, we propose reversing the high voltage polarity over the course of a 1000 second single measurement cycle. However, there is a ^{3}He magnetization problem only insofar as the spin flip is imperfect; in principle, the spin flip could be perfectly adjusted by use of a SQUID magnetometer to determine the final ^{3}He magnetization direction, or by other suitable calibration methods. The required accuracy of the spin flip is 10^{-4}.

Section 6 presents a detailed calculation of the dressed spin system noise when operated in a modulated fashion with feedback to keep the first harmonic signal zero. The primary result is that the uncertainty in the neutron EDM, after a measurement time T (which we take as one year) is

$$\sigma(d_n) = \frac{\hbar}{4eEJ_0(x_c)}\frac{2\pi m}{\sqrt{3}}\frac{1}{\sqrt{\Phi_p \tau V}}\frac{1}{\sqrt{\tau T}} \tag{10}$$

where E is the applied electric field strength, $J_0(x_c) = 0.65$, m is the number of times the electric field is reversed during a measurement cycle, Φ_p is the UCN production rate due to the superthermal process, V is the measuring cell volume, and τ is the UCN lifetime due to wall loss and beta decay, assuming no polarization relaxation. In this section, it is shown that the experimental sensitivity depends critically on the ^{3}He polarization, dropping by a factor of two in going from 0.99 to 0.95 polarization.

The sensitivity can be compared to the case for the current UCN limit based on the use of separated oscillatory fields (SOF),

$$\sigma(d_n') = \frac{\hbar}{2\alpha e E'}\frac{1}{\sqrt{\tau'\rho' V' T}} \tag{11}$$

where $\alpha = 0.64$ is the polarizing efficiency, and $\rho' V'$ is the number of UCN detected per cycle. Comparing these two limits gives a relative sensitivity

$$\frac{\sigma(d_n)}{\sigma(d_n')} = \frac{\pi m \alpha}{J_0(x_c)}\frac{E'}{E}\sqrt{\frac{V}{V'}\frac{\tau'}{\tau}\frac{\rho'}{\Phi_p \tau}} \approx m\pi\frac{E'}{E}\sqrt{\frac{\rho'\tau'}{\tau^2\Phi_p}} \tag{12}$$

for $V \approx V'$, so with $m = 2$, we see a direct factor of six reduction in sensitivity as compared to Ramsey's method of SOF. This reduction is due in part to the fact that for SOF, all neutrons had the entire storage time to accumulate a spin precession phase, compared to the continuous monitoring case as proposed for the dressed spin system. However, the sensitivity is inversely proportional to the storage lifetime for the case of the dressed field technique because the initial UCN density depends linearly on it.

Taking the case $\tau = 10\tau' = 880$ s, $E = 5E'$, $\Phi_p = 2$/cc/s as expected at the upgraded LANSCE source, and $m = 2$, with $\rho' = 4$/cc, we find an improvement in the shot noise limit by a factor of about 100.

Section 7 addresses technical issues relating to the proposed experiment. Section 7.1 points out that the simplest operating technique will be to produce UCN directly in the measurement vessel as opposed to coupling an external UCN source to the apparatus.

The most important sections here are 7.2, 7.3, and 7.4. In Sec. 7.2, an estimate of the ^{3}He diffusion time in a superfluid ^{4}He bath, due to phonon scattering, is estimated. This characteristic time relates to the required static and AC magnetic field homogeneity requirements, as discussed in Secs. 7.3 and 7.4, respectively. In the situation where UCN are produced in situ, there is no real serious limit to the lower operating temperature, so we might choose 0.3°K, which alleviates many of the field homogeneity problems.

High voltage issues are discussed in Sec. 7.4, while the scintillation properties of charged particles in liquid helium are discussed in Sec. 7.5. Section 7.6 gives an overview of existing cold neutron sources and anticipated UCN densities that can be expected.

Finally, Appendix C outlines the "tomography" technique we plan to employ to determine whether the polarized ^{3}He gives a sufficient volume average of the measuring cell.

III. BEAMLINE SPECIFICATIONS AND BEAM REQUEST

The EDM apparatus would best be situated on a beamline which views the coupled liquid H_2 moderator. In order to insure the highest fluence of neutrons at 8.9 Å, we will employ a neutron guide to conduct the cold neutrons to the ^{4}He filled UCN vessel. The first section will reside within the shutter mechanism to insure that the guide is fully "illuminated" up to its acceptance angle at 8.9 Å. It is anticipated that the design and installation of the shutter/guide mechanism will be the responsibility of LANSCE. The design goal of this shutter/guide system is to provide a neutron beam with dimension 10 cm x 10 cm. The maximum fluence would be obtained if this first section is a supermirror. To our knowledge, only the upgraded flight pathes 12 and 13 come close to meeting these desires.

Because we need only long wavelength neutrons, we will install a pyrolytic-graphite Bragg filter immediately following the shutter. Pyrolytic graphite acts as a low pass filter with a cut off at 6 Å. Filtering the beam as far upstream as possible will reduce both backgrounds and activation at the apparatus. The filter will be followed by a neutron shutter consisting of a ^{6}LiF loaded plate that can be mechanically inserted in the beam. The UCN fill and measurement cycle needed for the EDM apparatus requires that the neutron beam be closed during the free precession period. The primary shutter/guide system is not appropriate for this purpose.

Following the filter and shutter will be a section of "curved" neutron guide (actually a polygonal approximation to a curve) that will obscure the direct line of sight to the source. We imagine this to be a 10 cm x 10 cm cross-section supermirror guide with a radius of curvature of approximately 60 m and a length of about 5 m.

There are three distinct phases to the EDM project; a research and development phase, a construction phase and a data collection phase. The neutron beam requirements for each of these phases are quite different. During our research and development phase (approximately FY'98, FY'99), we will require access to a cold neutron beam for test purposes approximately 2 months per year. During the construction phase (FY'00, FY'01, FY'02), our needs are less certain but may require a few weeks to a month per year. During the data collection phase (FY'03, FY'04, FY'05), we wish to be installed on the beamline full time, and due to the complexity of the setup, we will request sole use during this period.

IV. MAJOR EQUIPMENT

A. Cryogenic cell of superfluid ^{4}He surrounded by a ^{4}He temperature stabilization bath

The layout of the proposed neutron-superfluid ^{4}He system is shown in Fig. 1. The UCN storage vessel is 20 cm in diameter and 10 cm in height; this dimension is constrained by the maximum high voltage we can supply and by the gravitational density gradient of the UCN. The 20-cm diameter of the cell is designed to match the 10-cm x 10-cm neutron guide. One method we are considering for getting the scintillation light out of the cell would be to make the walls from transparent plastic. The walls must conduct heat so that the liquid ^{4}He in the cell can be cooled in a reasonable time. These requirements limit the potential materials for the walls as well as their thickness.

The size of the cell and the need for at least five penetrations (^{3}He/^{4}He in and out, HV and return, and SQUID) would cause temperature gradients in the superfluid ^{4}He that would produce convectional flows of the ^{4}He and thus an unequal distribution of ^{3}He atoms. Our plan is to prevent the gradients with a second superfluid ^{4}He bath outside the UCN storage cell. This bath will contain all the shielding (passive or active) as well as the RF and SQUID pickup coils. This superfluid bath will have two different functions; it will form a thermal buffer bath around the UCN storage cell and it will also serve as a thermal link between the mixing chamber of the dilution refrigerator and the ^{4}He bath in the UCN storage cell. The dilution refrigerator is required to be able to vary the temperature of the UCN cell between $0.3 - 0.5°$K.

B. Light collection system; wave-length shifter, fiber optics and photomultiplier tubes

The two charged particles from the ^{3}He(n,p)T capture reaction produce scintillation light in the vacuum ultra-violate (XUV) region through the deexcitation of short-lifetime ^{4}He quasi-molecules. The n-^{3}He reaction is estimated to produce ≈4 XUV photons per keV in liquid ^{4}He. It is not possible reflect these XUV photons or to transmit them through the plastic walls; therefore, a wavelength shifter (WLS) must be used first to convert the XUV light to the visible region.

One idea is to evaporate WLS on the inside wall of the transparent UCN storage cell or dope WLS into the wall material. The plastic wall can then serve as a light collector. The light from the walls is conducted out from the cryostat using fibers viewed by photomultiplier tubes (PMT). This light conversion-counting system may be able to be designed to have a total quantum efficiency of about 1%.

A promising candidate for our WLS is tetraphenyl butadiene (TPB). It has a high fluorescence efficiency, near 100 %. It emits light at 440 nm and it can be easily evaporated or used as a dopant for plastics. The technology for making deuterated TPB is in hand. Thus a coating on the inside surface of the cell can shield the UCN from hydrogen and give the type of cell lifetimes the experiment requires.

Another requirement of the walls is that they do not depolarize the ^{3}He. This issue is the subject of an experimental investigation that we are undertaking.

C. Magnetic shield

The purpose of the magnetic shield system is to provide a small (few milligauss), but very uniform static magnetic field across the free precession volume. The field must be spatially uniform to insure negligible T_2 relaxation and temporally uniform to insure an immunity to systematic effects. We imagine that the static magnetic field will be created and maintained by persistent currents in a superconducting shield. This shield will surround the experimental vessel and will in turn be surrounded by a multilayer Mu-metal shield. We have not yet decided whether to a) produce the uniform field within the superconducting cavity by applying a homogeneous field to the vessel before making it superconducting, which gets frozen in after cooling, or b) including a set of windings within the superconducting shield that are energized after cooling. For example, to implement the first plan, we would line the inside surface of the inner layer of the Mu-metal shield with a coil of uniform pitch (cosine coil). Such a coil produces a very uniform magnetic field inside the shield.

The procedure for producing the uniform field begins with the superconducting shield kept above its transition temperature and the cosine coil off. The Mu-metal shields are demagnetized, providing a very low magnetic field within the inner shield. The cosine coil is then energized, creating a small uniform field on and inside the superconducting shield. The superconducting shield is now cooled to below its superconducting transition. The field within the superconductor is then maintained by the persistent currents in the superconductor. The cosine coil can now be turned off and any external field changes will not (ideally) perturb that internal field distribution.

Necessarily, the superconducting shield will need a number of penetrations to allow access to the experimental vessel. Such penetration will compromise the efficacy of the shield and we anticipate that a considerable effort will be required to design the optimal system.

D. Uniform milligauss DC and 1 Gauss RF fields

We envision a static field magnitude of order 5 mG; the required absolute field variation, assuming an operating temperature of 0.3°K and a cell mean free path of 10 cm (giving a ^{3}He diffusion time of 7 msec from Eq. (7.5) of GL, which is comparable to the UCN ballistic correlation time), is 5 μG, implying a field homogeneity of about 0.1%. Field gradients within passive ferromagnetic shields are better than 1 μG/cm; current-carrying windings can be arranged to give this level of accuracy for the generated static field.

The field requirements for the RF field are discussed in sec 7.3 of GL. In this case, it is the relative change of B_{RF} that is important. Under the same conditions as for the static field, we find that the fractional change in B_{RF} over the measurement cell is 0.1%.

The RF field coils must be located within the superconducting shield. If the superconducting shield is in the form of a hollow cylindrical section, with the static field along the cylinder axis, the RF field can be most conveniently generated by use of a sine distribution winding, i.e. normal to the static field, only with length and radius somewhat smaller than the inner diameter of the shield; the image currents will reduce the field generated by about a factor of two if the winding is on a form 25% smaller than the inner dimensions of the superconducting shield.

Uses of conducting materials within the RF field region must be avoided. The cell electrodes could be made from a fine wire mesh, or a thin low-conductivity film. The HV leads should also be made of very low conductivity material, which is, in fact, a desirable feature. The ^{3}He fill and empty line can be made of glass lined plastic.

E. Hexapole-filter source of polarized ^{3}He

Different sources of polarized ^{3}He are currently available. An optically pumped ^{3}He metastable source is inexpensive, compact, and easy to operate, and has been demonstrated to provide polarizations of 0.8 at fluxes of 10^{18} atoms/s. Such a source will be valuable for development and evaluation of the different components of the experiment. However, ^{3}He polarizations near 1.0 will be needed for the final experiment; this degree of polarization has only been demonstrated with Stern-Gerlach atomic beam type sources.

The atomic beam source employs a magnetic field gradient to separate the trajectories of atoms with different spin states. The axial magnetic field can be quadrupole, hexapole, or "two-wire" geometry. If a beam of ^{3}He passes through the magnet, the undesired spin state is either deflected or defocused, leaving only the desired state to exit an aperture at the end of the magnet. The performance of the atomic beam source is limited by the field gradient of the magnets, the emittance of the input beam, and the background ^{3}He pressure, which provides an unpolarized background component of ^{3}He and causes scattering of the beam.

An atomic beam source of polarized ^{3}He is operated at the University of Heidelberg. It employs a supersonic beam source of ^{3}He in the $1.3-4.2$°K temperature range with multiple stages of differential pumping to provide a very low emittance input beam and reduce background gas. It is a quadrupole polarizing electromagnet of length 40 cm and magnetic field intensity of 1.2 T. The source easily provides polarizations of 0.9 at a flux of about 10^{14} atoms/s.

F. ^{3}He-^{4}He purification

At the beginning of each measurement cycle, highly polarized ^{3}He must be admitted to the measuring cell. This procedure is most simply done by opening a valve connected to the polarized ^{3}He accumulation vessel.

After a measurement cycle, the spent ^{3}He must be removed from the system. The removal poses a problem because there is a binding energy for ^{3}He into superfluid ^{4}He, and the evaporating superfluid film that invariably flows up the fill line eventually reaches a high temperature region and evaporates; the gas generated by this evaporation recondenses into the bath, and forms a diffusion pump, driving the ^{3}He back into the bath also.

There are several methods to contend with this problem. One is to drain the superfluid He from the measurement cell after each cycle; the spent ^{3}He would be carried away with the liquid. There are about 5 liters of liquid He per cycle. The other is to have the ^{3}He fill line full of superfluid ^{4}He, and have a direct connection to a large superfluid vat external to the magnetic shield. A small heat source in the measurement cell could be used to produce a phonon wind that would drive the ^{3}He into this larger volume. The McClintock heat flush technique could be continuously operated on this larger volume. A prototype of our ^{3}He cleaner is in construction.

Another method to deal with the evaporation of ^{4}He is to line the transport tubes with a ring of Cs metal above the liquid surface. Cesium blocks the flow of the superfluid and, at the same time, inhibits nuclear spin relaxation on the walls.

V. SCHEDULE

A very successful "Workshop on a New Experiment to Measure the Neutron Electric Dipole Moment" was held in Los Alamos from March 13-14, 1997. Over 75 scientists from 13 countries attended. The workshop marked the beginning of serious work toward creating a viable project. Since that time, we have initiated prototype work to answer some of the outstanding technical challenges described below. In the fall of 1997, we hope to hold the first organizing meeting of the collaboration. At that time, we hope to have the nucleus of an international team that will begin taking responsibilities toward the development work or the designs needed for a proposal.

In parallel, the Los Alamos group has begun constructing equipment with the purpose of understanding features of the ^{3}He magnetometer. This work will continue through FY'99. We anticipate that other aspects of the experiment will be studied at other institutions over the same period.

During the spring of 1998, we will produce a conceptual design that will be the focus of our proposal. This design must be specific enough to answer the first level of engineering and cost questions. The collaboration will produce a full proposal by the end of 1998. We hope this proposal can be reviewed successfully early in 1999 to allow funding for construction in FY'00.

Based on a guess of the complexity of the apparatus, we anticipate three years to construct and test the detector in a laboratory. At this point, we would want to move to the Lujan Center for a three year period on one of the cold-neutron flight paths described above. During the extended beam period, we would develop and refine the technique as well as take about 10^7 seconds of data for a physics result. Once the method is established, the data analysis is rapid. Hence, we anticipate intermediate publications and a final result by 2005.

VI. FEASIBILITY AND TECHNICAL CHALLENGES

We have identified the most significant (we hope) technical challenges facing the experiment. Our approach is to study each area either with simulations or in the laboratory in order to make a convincing case in the proposal for the feasibility of the measurement.

As the collaboration grows, we expect many institutions to participate in the research necessary to settle the outstanding questions. At present, there is an active program at Los Alamos to begin the work. Some examples of areas that will be studied by the university collaborators include the magnetic and electric fields, the demonstration of the superthermal source density, and the hexapole source of polarized ^{3}He. The cell design is the type of development that will be done jointly.

The issues related to the magnetic fields will certainly require careful study. However, as they were discussed above in Sec. IV-D, there is no reason to repeat the arguments here.

A. Neutron density

Using Eq. (4) with a minimum UCN wavelength of 700 Å as expected for deuterated polystyrene, and taking $\delta\Omega = 0.01$ str as expected for a supermirror guide, we find a production rate of

$$P = 2.1 \times 10^{-10} \frac{d^2\Phi}{d\lambda d\Omega}.$$

The spectral flux density, for the present LANSCE decoupled moderator, is 3×10^{-3} n/(p eV str cm^2) at 1 meV. With a coupled moderator, the output per proton at 1 meV might increase by up to a factor of 6. It is also expected that the current will be 200 μA; there should be a flux of 5.2×10^9 n/(cm^2 s Å) at 1 meV. Furthermore, with the flux trap for the cold neutrons, the effective flux can be increased by a factor of about 2.4. Taking all these factors together gives a net production rate

$$P = 2.62 \text{ UCN/cm}^3\text{s}.$$

Thus, we see a reasonable UCN production rate at the upgraded LANSCE spallation source, when coupled by a supermirror guide to a fully coupled moderator; the polarized UCN density in this case, assuming a storage time of 800 sec, is about 1000/cc, or 250 times that in the current experiment.

Simulations of the source and supermirror guides are underway as part of overall UCN development at LANSCE. A paper has been submitted to Nuclear Instruments and Methods that reports the results of Monte-Carlo studies of the cold-neutron flux trap for a number of different reflectors. In particular, the type of hydrogenated materials we are considering for our cell walls were studied, and the factor of at least two enhancement in UCN density reported here is taken from that paper.

The measurement of the neutron lifetime underway at the National Institute of Standards and Technology uses the superfluid He source to produce the neutrons in their magnetic trap. This experiment will provide verification of the densities available to the EDM experiment.

B. Electric field across the measuring cell

In Sec. 7.4 of GL, high voltage issues are considered. We are presently considering a 10-cm cell electrode separation and 500 kV applied, which gives a factor of 5 increase in electric field as compared to the current experiment.

With 1 mm gaps, a number of workers have found the superfluid ^{4}He dielectric strength to be roughly 40 kV/mm; we are considering fields of order 5 kV/mm. However there is a "gap effect"; that is, the dielectric strength falls for increasing gap size. Also, all early measurements were made with free electrodes; we are proposing that there be a cylindrical UCN containment wall between the electrodes. This issue remains to be studied, but the proposed 500 kV across the cell seems reasonable; the bulk dielectric strength of Plexiglas is about 100 kV/cm; at low temperatures in a clean environment, surface leakage effects should be minimal.

The high voltage leads must penetrate the cryogenics. The engineering of these leads must ensure that their contact with the electrodes does not produce a heat source at the cell. A heat source would produce phonons that will affect the ^{3}He distribution in the cell.

C. Observation of the scintillation light

We have taken an aluminum cylinder of 5 cm in diameter by 15 cm in length and filled it with 2.5 atm of ^{4}He containing about 6% Xe and 1% ^{3}He. The round walls were lined with an aluminized mylar sheet coated with TPB. The ends of the cylinder were each viewed by a PMT through a quartz window. This apparatus was placed in a cold-neutron beam collimated to a diameter of 4 mm. Roughly 99% of the pulses from the PMT were associated with neutrons capturing on the ^{3}He. By comparing the ratio of coincidences to singles, we found the mean number of photoelectrons to be about 1.5 per tube. This value is roughly understood from the solid angle subtended by the tube, the Fresnel reflection from the quartz and PMT interfaces with gases, and the quantum efficiency of the photocathode. Fortunately, liquid He produces about 4 times as many XUV photons as gaseous He. In order to maximize the number of photoelectrons per neutron capture, the path for getting the light to the PMT must be carefully designed.

We are considering two designs for getting the light out of the measuring cell. The first takes advantage of the fact that we wish to surround the cell with a hydrogenated plastic to reflect the cold neutrons back into the cell. A 2-cm wall would work well as both the reflector and as a light guide. The cell wall would be coated with deuterated TPB and coupled to as many as 8 PMT via fiber optics. A Monte-Carlo study of this coupling indicates that a total of 30 photoelectrons (mean value) can be observed.

An alternate design would be to place a coil of fiber optics in the cell whose core is wavelength shifter. The outside of the fiber would be coated with a clear, deuterated plastic. In this arrangement, visible light produced by the TPB would largely be captured in the fiber and propagated to the ends. Potentially, a number of fibers might be used to keep the total length of the coils from exceeding many absorption lengths.

D. ^{3}He magnetometry

In order to introduce the polarized ^{3}He into the measurement cell, it must be transported through the gas handling manifold without losing polarization. Volume depolarization can occur if the ^{3}He atoms pass through a rapidly changing or vanishing B field. This depolarization is mitigated by ensuring that, throughout the volume, a non-zero B field is present which varies slowly enough that the spin of the thermal atoms can follow it adiabatically. Surface depolarization can be minimized by choosing proper wall coatings for the transport system. This technology has been demonstrated by several groups using polarized helium and xenon for medical imaging.

Using the collimated, cold-neutron beam incident on the gas cylinder described in the previous section, we traced the count rate from PMT coincidences as a function of position across the circular cross section. We observed a variation in count rate that was roughly explainable by a circular cross section. We also found that the small discrepancies could easily be explained by taking into account the places where the aluminized mylar sheet containing the TPB had pulled away from the wall.

Based on this measurement, we have estimated the sensitivity such a measurement would have to any other distribution of ^{3}He in a chamber other than uniform. In particular, we considered a low concentration of ^{3}He in liquid ^{4}He and a percentage of that ^{3}He attached to the walls. Discounting systematic effects, the statistical power of the technique would allow the observation of 1% of the ^{3}He distributed along the wall if the total concentration of ^{3}He is 10^{-9} of liquid ^{4}He. Thus this "tomography" of the ^{3}He appears to be a useful technique even at the concentrations of interest.

We are assembling a cryogenic apparatus to address a number of the problems associated with the ^{3}He magnetometry. In the first phase, we will admit unpolarized ^{3}He into the cryogenic cell and map out its distribution using tomography. If there is any adherence to the walls or concentrations produced by heat sources, they should be observable. A byproduct should be a measure of the diffusion time of the ^{3}He into the ^{4}He.

In the second phase, the cryostat will be coupled to a metastable source and to a superconducting pickup loop attached to a SQUID. The transport and dilution properties of the polarized beam will be studied. A measurement of the bulk magnetization of the ^{3}He with the SQUID will allow a determination of the rate of depolarization in a cell. The apparatus will also provide a field test of the SQUID technology under realistic conditions.

There are two ways to determine the neutron EDM based on the layout of the proposed experiment. One is to use the "critical dressing" techniques described above in Eq. (9) and the other is to use Eq. (7) and measure B_0 directly by using a SQUID. The SQUID detector is the most sensitive detector of magnetic field known (10^{-15} T). With such sensitivity, it should be possible to detect the magnetic field from the precessing ^{3}He directly. This design change would simplify the experiment in that the very uniform RF field needed for critical dressing would not be required. However, the signal from ^{3}He will be small enough to be near the limit of the technology. Therefore a program to determine the feasibility of the SQUID option has been developed. It should also be mentioned that the SQUID will be able to provide a monitor of the ^{3}He density times polarization, another quantity which should be known.

Preliminary calculations have determined that with a 100 cm^2 pickup coil, approximately 0.01-0.1 Φ_0 ($\Phi_0 = 2\times10^{-15}$ Wb) will be intercepted. Assuming that 0.05 Φ_0 is coupled into the pickup coil, the desired signal-to-noise ratio in the measurement of the ^{3}He precession magnetization is achieved with a pickup coil sensitivity of $\approx 0.25\ \mu\Phi_0/\mathrm{Hz}^{1/2}$ at a temperature of 0.3°K. Also, the magnetic noise from the rest of the experiment would have to be kept below $\approx 40\ \mu\Phi_0/\mathrm{Hz}^{1/2}$ to give sufficient precision to the precession rate. While a SQUID with pickup coil sensitivity below this level has been produced before, it is near the limit of what has been done. To achieve the required sensitivity, we will most likely have to use superconducting electronics. A more daunting challenge is to keep the experimental noise below 40 $\mu\Phi_0/\mathrm{Hz}^{1/2}$. This requirement will necessitate some clever magnetic shielding, vibration isolation (to prevent motion of the pickup coil in B_0, which couples spurious flux to the SQUID), and the use of appropriate non-magnetic materials. Also, the effects of any leakage current from the high electric field must be well understood.

To address these concerns, we have begun construction of a test setup. The entire apparatus will be contained in a superconducting lead can to simulate the environment of the actual experiment. Measurements will originally be made at 4°K. The absolute noise level of the SQUID sensors, effects of vibration, leakage current, and the magnetic noise of various materials will be characterized with this setup in 1998. If the results are as we expect, in the following year work will begin on the superconducting readout electronics, and integration of the SQUID system into the actual experimental setup. This will enable us to make a final determination about whether or not a SQUID is suitable for a direct measurement of the precessing ^{3}He magnetic field. If the SQUIDs are determined to not be suitable, we will still be able to utilize them for the determination of ^{3}He polarization times density, and the method of critical dressing can be utilized for the determination of the neutron EDM.

VII. MANAGEMENT

A. Building the collaboration

At the time of this writing, there is no EDM collaboration. There is a team at Los Alamos working on developing the project. The workshop on the experiment developed a number of highly interested groups. We plan to rectify this situation by the time this letter of intent is reviewed. There will be an organizational meeting of the potential collaborators in November, 1997. At that time, groups will join, though we expect more groups to join as we move toward a proposal.

Some of our manpower and budgetary estimates are based on the experience of the MEGA collaboration, an experiment of comparable scale and complexity. We believe that between 5 and 10 principal investigators and their co-workers are appropriate to make the project a success. The early returns point toward an international character for our group.

Many issues will face the embryonic collaboration when it meets. Of course, the technical issues highlighted above are critical. In addition, we must refine our ideas for the proposal, the experimental development plan, and the schedule. A method, e.g. work breakdown structure (WBS), must be established for estimating the costs. Possible sources of funding must be identified, both in the United States and elsewhere. Finally, the management of the collaboration must be established.

B. The proposal

The proposal we aim for in a little over a year's time is a professional document with many uses to the collaboration. It will document the scientific and technical reasoning behind the technology choices made at the outset of the experiment. Though the design will continue to evolve, the proposal will be the basis. It is clear that the GL paper will continue to be a cornerstone of our work. The proposal will also be a document that can be reviewed by LANSCE, by other scientific bodies such as NSAC, and by funding agencies. Good reviews should allow the commencement of the construction phase.

Central to the document will be an advanced reference design (RD) of the apparatus. The degree to which the project is thought through will become clear by the level of detail in the RD. It should also reflect the results of the development program. Both experimental results and simulations will bolster the RD. The RD will allow the development of a WBS.

The WBS will provide the framework for collaboration organization. Institutions will be able to take responsibilities for identifiable parts of the project. The WBS will be a mechanism for a serious budget estimate that includes researched costing, contingency, engineering, etc.

Finally, the proposal should provide a funding plan. This plan should contain sources and funding profiles to allow for orderly construction. The funding should go to the institutions doing the work.

C. Resources required

Again, we have drawn on the experience of the MEGA project to estimate the resources needed. Table 1 is our estimate of the resources needed collaboration wide to carry out the EDM experiment. The numbers are necessarily crude at this stage of the project. The evolution of the project is by year. The numbers for people are in full time equivalents (FTE). Scientists include permanent employees at institutions and do not accrue as incremental costs to a funding agency. Some engineers and technicians are part of the construction costs. Postdoctoral fellows and students are employed in the traditional way.

For simplicity, we have made all the equipment funds during the years 2000-02 the same in table 1 and table 2, which is the analogous table specified to Los Alamos. These costs for construction in 2000-02 contain no overhead and are very rough. Without a detailed cost estimate or RD, it is impossible to assign a reasonable value to better than 50%. We currently do not know which agencies will be approached for funds or the institutional breakdown.

VIII. APPENDIX

R. Golub and S. K. Lamoreaux, Phys. Rep. **237**, 1 (1994).