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A New Search for the Neutron Electric Dipole Moment

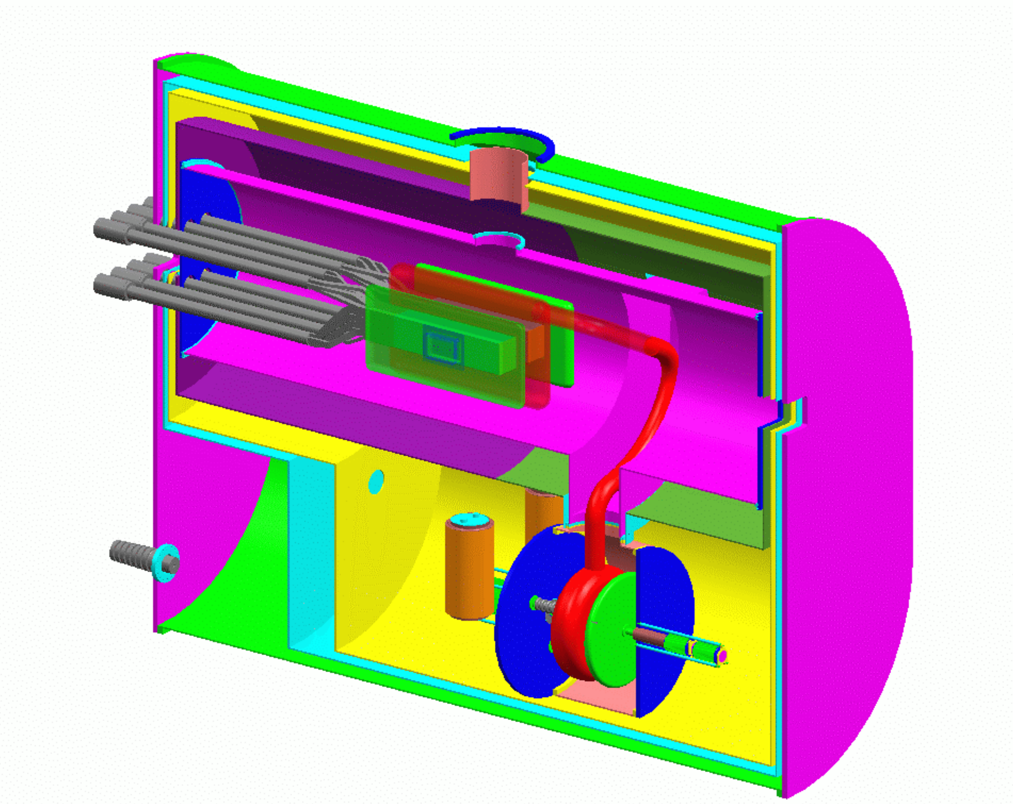
Funding Proposal for R&D

submitted to

The Department of Energy

prepared by

The EDM Collaboration



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A New Search for the Neutron Electric Dipole Moment - R&D Project

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A New Search for the Neutron Electric Dipole Moment

R&D Project Summary

This proposal is a request for funds to perform research and development for a new search for the neutron electric dipole moment (EDM). The full experiment directly impacts our knowledge of electroweak and strong interactions by searching for physics beyond the Standard Model. The experiment uses novel techniques to achieve unprecedented sensitivity, improving current knowledge by a factor of 50 or more. In order to insure the technical feasibility of the experiment, the EDM collaboration has embarked on a multi-year R&D program whose goal is to experimentally demonstrate its crucial aspects.

The full project is described in detail in the pre-proposal, which is available on the web at http://p25ext.lanl.gov/edm/pdf.unprotected/EDM_proposal.pdf. This proposal focuses on the R&D project. To put the R&D work into context and make this document self-contained, Appendix A reproduces the measurement overview.

The R&D project will produce some first-class science as part of the feasibility study; these results may have applications to other fields. A prime example is the study of the diffusion coefficient of ^{3}He in superfluid ^{4}He that has already been published. These measurements are a critical step towards understanding the uniformity of the ^{3}He in the experiment and the evaporative removal of unpolarized ^{3}He from the bath. The technique of neutron tomography also has utility in measuring other properties of He mixtures, and the measurements also are relevant to the mechanisms of heat coupling to the ^{3}He. New results can be expected in a number of areas, e.g. depolarization rates of ^{3}He at low temperature, the hysteresis curves of ferromagnetic materials at sub-Kelvin temperatures, and so forth.

The EDM collaboration has been working toward a schedule that begins project construction funding in FY'05. This proposal asks for startup funds for FY'03-04. Since FY'00, substantial LDRD funds from Los Alamos have been applied toward the R&D. As the collaboration has grown, more questions can be addressed experimentally at one time, and matching funds from DOE are needed to keep to the schedule.

The request is for $601k over two fiscal years. These funds will establish two new cryogenics test beds, one at Duke University for measurements above the lambda point of He, and one at the University of Illinois for 1-K measurements. The relaxation of ^{3}He polarization will be measured at both facilities. The low temperature properties of ferromagnetic shields will also be examined at Illinois. In addition, the UC Berkeley group will develop the optical Kerr effect as a tool for non-invasively monitoring voltages of 0.35 MV. Preliminary studies of ferromagnetic materials will begin at Caltech on a borrowed 4-K cryostat. The storage time for ultra-cold neutrons will be studied at NIST. Particle identification of neutron-absorption products will be studied at a dedicated dilution refrigerator at the HMI and will be examined at NIST with similar optics to the EDM experiment. Beyond the specific measurements, considerable engineering is required to bring our pre-conceptual design up to the level of detail required by a full conceptual-design report (CDR). The goal is to have the CDR ready near the end of FY'04. In the project description, we explain the subset of tasks that are covered by this proposal, but Appendix B lays out the work breakdown structure for the full R&D plan.

The EDM team comprises physicists from fifteen institutions. They possess a variety of skills that are needed to make the full measurement a success, and they are well positioned to demonstrate the feasibility during the R&D phase. The physics goals of the EDM search are compelling; they are of interest to atomic, nuclear, particle and cosmological physics. We request funds to do the R&D that will produce other interesting results as a byproduct.

A New Search for the Neutron Electric Dipole Moment

R&D Project Description

TECHNICAL WORK

Introduction

The EDM experiment will rely on measuring the precession rate of neutrons held in a bottle filled with a dilute mixture of ^{3}He in superfluid ^{4}He at 0.5 K. A thorough knowledge of the properties of materials at cryogenic temperatures is necessary. The necessary studies are being performed in a variety of cryogenic systems to allow parallel development of the project. There are ten sub-systems that are part of the R&D project, and they make good use of the manpower available across the collaboration.

The following description of the R&D work needed to prepare the EDM experiment is limited to the topics for which funding is requested during FY'03-04. This work is embedded in a larger project that is funded out of operating funds from the participating institutions. In particular, a substantial Los Alamos LDRD grant has funded several critical efforts. Duke University and the University of Illinois are making some contributions of hardware from complementary projects. Some of the studies only require scientific skills, e.g. the simulations to be performed at the University of Maryland and the Hungarian Academy of Sciences. No funds are requested for these because no new equipment is required.

Appendix B is the output of a project file for the complete R&D effort. The work breakdown structure (WBS) allows the placement of each of the elements included here into the full context of the project. Only a brief explanation of the R&D plan is presented here, but a complete set of details for both the R&D and the experiment can be found in the pre-proposal at http://p25ext.lanl.gov/edm/pdf.unprotected/EDM_proposal.pdf.

^{3}He Depolarization Studies at High Concentrations

An effort is beginning at Duke to measure the polarization relaxation time of ^{3}He in a cell of the type to be used in the EDM experiment. The deuterated-TPB wavelength shifter coating the walls is a particular concern in case it depolarizes the ^{3}He. The measurement can be performed by using a weak magnetic field to induce the ^{3}He spin-precession and observing the strength of a nuclear magnetic resonance (NMR) signal as a function of time. The precession is much easier to observe if the concentration of polarized ^{3}He is relatively large. A high concentration is most easily obtained with a rubidium exchange source. Even though these sources produce only 70% polarization, the absolute signal size will be much larger than that obtainable by a quadrupole source as planned for the full EDM measurement.

These measurements of the relaxation will be made near 4 K. To study the possible temperature dependence of the relaxation rates suggested by the literature, the apparatus will be moved to the University of Illinois refrigerator, where measurements can be done down to about 1 K. From these, we will be in a good position to extrapolate the results to 0.3 K planned for the EDM measurement. The work at Duke (WBS 11.1-11.3) and Illinois (WBS 11.4-11.5 and 12) will be supported from this grant. Most of the money will buy pumps and cryogenic sensors plus some technician support at Illinois.

The Illinois cryostat will also be used for the study of ferromagnetic materials at cryogenic temperatures. If the data indicate that a measurement of the ^{3}He relaxation time is needed at 0.3 K, the HMI refrigerator will be available in 2005.

Magnetic Shielding

The SQUIDs, which measure the precession of the ^{3}He atoms, require extremely good magnetic isolation from the environment to see the small precession signal. In addition to a conventional magnetic shield like the ones used in the previous neutron-EDM experiments, this project will employ a superconducting magnetic shield. The superconducting shield is expected to trap stray fields during its cool down. Additionally, a superconducting shield has non-optimal boundary conditions for sustaining a uniform field inside a cosθ magnet. Both of these difficulties can be solved if a ferromagnetic shield is used in conjunction with the cosθ coil. There is very little data on the properties of ferromagnetic materials in the sub-Kelven range, but it is already known that the hysteresis curve is considerably modified in the transition from room temperature to liquid nitrogen temperatures. This grant will support (WBS 13) a series of measurements at 4 K and 1 K of the properties of various ferromagnetic materials to be undertaken by the Caltech and Illinois groups. The Caltech team will begin preliminary studies in a borrowed 4 K cryostat before the work moves to Illinois. In addition to cryostat, magnetic monitors and several candidate substances will be bought. The goal will be to identify an appropriate material for the boundary matching to the magnet.

UCN Production Rate, Storage Time, and Decay Product Identification

The production rates and storage times of UCNs in the EDM apparatus are crucial parameters of the experiment. The UCNs are produced in ^{4}He via the superthermal process, where cold neutrons lose energy by phonon generation in the medium. The final density of UCNs is given as the product of the production rate and storage time. The rate for UCN production in ^{4}He has been measured in the NIST–lifetime experiment and is in good agreement with theory. The storage time in a bottle of LHe coated with deuterated wavelength shifter is unmeasured but is expected to be long. The storage time has an important influence on the sensitivity of the overall measurement. A preliminary experiment was mounted at FP11 of the Lujan Center at LANL, and the production rate agreed with the NIST experiment within errors.

The storage time τ has the following contributions from different neutron loss mechanisms:

$$\frac{1}{\tau} = \frac{1}{\tau_{\mathrm{n}}} + \frac{1}{\tau_{\mathrm{w}}} + \frac{1}{\tau_3} + \frac{1}{\tau_{\mathrm{up}}} + \frac{1}{\tau_{\mathrm{hole}}}$$

The neutron lifetime is, of course, fixed at τ_n = 886 s. Losses on the wall τ_w are the quantity of particular interest. The neutron losses on ^{3}He may be eliminated by the use of ultra-pure ^{4}He. Neutron upscattering has a T^{-7} behavior, which makes τ_{up} very long at low temperatures. The time τ_{hole} for a UCN to escape through the ^{4}He-fill hole is proportional to the cell volume. A practical cell-access hole is 0.5 mm in diameter, and from kinetic theory, $\tau_{hole} \cong$ 200 s for a 50-cm^3 cell and > 4000 s for a several-liter cell.

The FP11 measurement is consistent with losses due to the fill hole in a 50-cm^3 cell. To deduce the value of τ_w, the characteristic wall-loss time, requires a much larger storage vessel to eliminate the importance of the fill-hole losses. The NIST cryostat is well suited to this task, and the collaboration plans a measurement in the Fall of 2003 that will be funded by this proposal (WBS 2.3-2.5). A storage cell will be built to match the NIST cryostat.

Neutron decays and other beta decay processes are backgrounds for the EDM experiment, which could be removed if discriminated from absorption on ^{3}He. The HMI EDM collaboration members have used a dedicated dilution refrigerator on a dedicated neutron beam line to provide evidence that the ^{3}He absorption can be tagged by identifying final state particles. A new measuring cell is needed to continue this work. Furthermore, the NIST team has succeeded in reducing the signal-to-backgrounds ratio to unity for the neutron-lifetime experiment. By adding a small amount of ^{3}He to the cell, both the neutron-decay and the absorption scintillations should be visible with optics similar to that of the EDM experiment. The collaboration will characterize this effect in the new test measurements at NIST. This work (WBS 2.4.3 and 2.6) will be funded from this proposal.

Electric Fields and High Voltage

The planned strength of the electric field is 50 kV/cm, and it has a requirement of 1% uniformity. The ANSYS finite-element code has been used to set the size of the HV electrodes. They need to be roughly 27 cm x 77 cm. The geometry described in the pre-proposal meets the uniformity requirement taking into account the presence of a dielectric (the measurement cell wall) in the gap.

The scheme for generating roughly 350 kV across the electrodes in a cryogenic environment cannot involve large cables to room temperature. The proposed scheme is to utilize a variable-capacitor voltage amplifier. The idea is to charge the plates to a lower voltage at small distance between capacitor plates, disconnect the supply, and increase the gap between the plates to obtain the desired voltage. A full-scale capacitor is under construction at LANL to validate the concept and to provide a HV test bed.

During the experiment, the value of the electric field must be measured. The UC Berkeley group has proposed using the optical Kerr effect to measure electric-field strength. This grant will provide a laser, optical components, electronics, and a data acquisition computer (WBS 10). They are doing preliminary tests down to 1.4 K and much lower voltages but field strengths up to 100 kV/cm in their laboratories. Eventually the Berkeley group will evaluate the technique in the LANL apparatus.

Project Development

A significant piece of this grant will be used to prepare the conceptual design report (CDR) for the experiment. The Los Alamos LDRD program is not permitted to fund the preparation of a CDR. Substantial engineering (WBS 18.9-10), estimated to be about one man-year, is needed before the full project could be expected to pass a technical, cost and schedule review.

The full proposal will contain a WBS of the construction project. The task (WBS 19) of further characterizing this major project for the CDR requires engagement of a professional project planner. A significant refinement of the cost and schedule is expected from a strong interaction of the project planner with the engineers and with vendors. This position is estimated to average two days per week throughout the R&D project.

The collaboration intends to submit a full proposal following a successful review by NSAC in their evaluation of the national neutron program. If the proposal is favorably reviewed, we are counting on critical decision zero from DOE so that we can start work on the CDR and stay on schedule for a FY’05 construction start.

Expendables

The cost (WBS 20.2) of the liquid He, LHE, for operating the cryogenics systems is also requested.

COST AND SCHEDULE

The costs for the R&D project consist of two parts. In FY'03, this proposal funds the technician and engineering time, as well as the equipment purchases, necessary to design and validate the equipment to make measurements that are required to prepare the EDM experiment. During FY'04, the costs will largely be engineering time to establish the design and costs for the CDR. Additionally, funds are requested to employ a part-time project planner to refine the WBS and baseline of the full experiment. The cost for LHe is spread over both years.

Appendix B is a schedule from Microsoft Project for the full R&D project, both the part funded by this proposal and the parts funded by existing contracts. In particular, a substantial Los Alamos LDRD grant is assumed for supporting much of the research. This grant of $1.5M per year is being requested, with a decision for FY'04-06 expected by July 2003. Most of the LDRD funds will go for salaries, but roughly $200k per year will go towards equipment. The rules expressly prevent the use of LDRD funds for proposal and CDR preparations.

The WBS elements funded by this request are shown in red. Appendix B has two parts. The first shows tasks and the assumptions for the calculation of the budget and schedule. The financial units are thousands of dollars. The Project file employs the same rules for contingency and lag time as discussed in the pre-proposal, which are consistent with DOE standard practices. The burden rate for each institution has been used. The second part shows the dependencies of the tasks.

In summary, this proposal requests funds to be given to Los Alamos to be redistributed in the following way:

Institution	Principle Investigators	FY'03 ($k)	FY'04 ($k)
UC Berkeley	D. Budker	38	0
Caltech	B. Filippone, R. Mckeown	25	0
Duke	H. Gao	76	2
HMI	R. Golub	21	0
Illinois	D. Beck	131	12
Los Alamos	M. Cooper, S. Lamoreaux	0	281
NIST	P. Huffman	6	9
Totals		297	304

The table is made by zeroing all costs unassociated with this request and by using the cash flow feature of Project.

The schedule calls for the completion of the R&D project by the end of FY'04 in time for a technical, cost and schedule review that is needed for construction funding in FY'05. A table of the R&D milestones follows:

15.4	Publication of Results	8/28/01
2.2	Preliminary Storage Time and Rate Demo	1/13/02
18.3	Pre-proposal Submission to DOE	4/2/02
3.3	3He Source Ready to Test	12/27/02
1.5	Working DR	1/11/03
18.6	R&D Proposal Submission to DOE	3/8/03
11.1.6	4 K Cryostat Assembled	6/29/03
18.8	Proposal Submission to DOE	7/7/03
14.3	Cycling Demonstrated	8/29/03
3.7	3He Source Completed	9/8/03
12.4	1 K Cryostat Ready for Use	9/29/03
9.3	HV System Ready for Tests	10/8/03
2.5	UCN Storage Demonstration	11/13/03
17.3.3	Importance of Background Quantified	11/28/03
5.5	3He/4He Cryostat Completed	11/29/03
17.1.5	Cold Neutrons Simulated	12/27/03
17.2.4	Light Collection Modeled	12/27/03
10.6	Kerr Effect Demonstrated	2/5/04
9.5	HV System Demonstrated	4/5/04
4.6	3He Transport Understood	5/27/04
7.5	Magnetic Shielding Study Complete	5/27/04
13.5	Ferromagnetic Shield Understood	6/24/04
8.3	SQUID / 3He Systems Demonstrated	7/26/04
18.11	Conceptual Design Review	9/28/04
11.6	Depolarization Lifetime Understood	2/18/05
16.7	3He Removal Understood	6/21/05

Again, the parts of the table in red pertain to the work funded by this proposal. Two elements, measurement of the ^{3}He relaxation time at 1 K (WBS 11.6) and the demonstration of evaporative ^{4}He purification (WBS 16.7), will run into FY'05. Both of these results imply modifications of the engineering plan, but neither threatens the success of the full experiment.

Summary

This proposal requests $600k over two years to fund the R&D at the collaborating institutions that is needed to prepare the EDM experiment. This work strongly compliments work of the Los Alamos team. The proposal also funds the preparation of the CDR. Granting these funds is crucial to keeping the EDM experiment on a schedule for a construction start in FY'05. A start in FY'05 is well matched to a full evaluation of the technique at Los Alamos and the startup of the Spallation Neutron Source.

Appendix A

Chapter IV. PROPOSED MEASUREMENT — OVERVIEW

This experiment is based on a technique to measure the neutron EDM, which is qualitatively different from the strategies adopted in previous measurements (see Chapter III). Chapter IV provides an overview of the general strategy, however, many crucial technical details that are essential to the success of the measurement are deferred until Chapter V.

The overall strategy adopted here[1a], is to form a three component fluid of neutrons and ^{3}He atoms dissolved in a bath of superfluid ^{4}He at ~300 mK. When placed in an external magnetic field, both the neutron and ^{3}He magnetic dipoles can be made to precess in the plane perpendicular to the B field. The measurement of the neutron electric dipole moment comes from a precision measurement of the difference in the precession frequencies of the neutrons and the ^{3}He atoms, as modified when a strong electric field (parallel) to B is turned on (or reversed). In this comparison measurement, the neutral ^{3}He atom is assumed to have a negligible electric dipole moment, as expected for atoms of low atomic number [1a].

A. General Features

1. Frequency Measurement

As discussed in Chapter III, over the forty-year history of experimental searches for the neutron EDM, d_n, a number of different techniques have been employed. However, in the last two decades the measurements have focused on the use of UCN constrained to neutron traps. The primary method is to study the precession frequency of neutrons with aligned spins in the plane perpendicular to a static magnetic field, B_0. Application of a static electric field, E_0, parallel (anti-parallel) to B_0 can change the Larmor precession frequency, ν_n, in proportion to the neutron EDM, d_n. The precession frequency is

$$\nu_n = -\left[2\mu_n B_0 \pm 2d_n E_0\right]/h \equiv \nu_0 \pm (\Delta\nu/2) , \qquad \text{(IV.1)}$$

where the minus sign reflects the fact that $\mu_n < 0$.

Thus the frequency shift, $\Delta\nu$, as the direction of E_0 is reversed, is:

$$\Delta\nu = -4\mathrm{d_n E_0/h} , \qquad \text{(IV.2)}$$

In the case of B_0 = 1 mG and E_0 = 0, the Larmor precession frequency is $\nu_0 = 2.92\text{Hz}$. With E_0 = 50 kV/cm, and using a nominal value of $d_n = 4 \times 10^{-27}$ e cm, the frequency shift, as the electric field is reversed, is:

$$\Delta\nu = 0.19\mu\text{Hz} = 0.66\times10^{-7}\nu_0 \ . \tag{IV.3}$$

Note that for the current measurement, it is the absolute frequency shift, $\Delta\nu$, that is critical, not the fractional frequency shift. For a known electric field, E_o, the uncertainty in d_n is:

$$\delta d_n = h\frac{\delta\Delta\nu}{4E_o} \tag{IV.4}$$

2. Statistical and Systematic Errors

The immediate challenge of an EDM measurement of $\Delta\nu$ is to generate as large an electric field as possible in the presence of a weak *B* field, and to measure a precession frequency shift with an absolute uncertainty $\delta\Delta\nu$ at the sub μHz level. Other issues include production of a large neutron sample size as well as having a precise knowledge of the spatial and temporal properties of B_0 and E_0.

Consider a measurement sequence in which N_0 neutrons are collected in a trap over a time T_0, followed by a precession measurement for a time T_m. This measurement cycle can be repeated *m* times for a total measurement time: t = m T_m. A single cycle takes a time: $T_o + T_m$ and the time to perform m cycles is: m ($T_o + T_m$).

From the uncertainty principle we have

$$\delta\Delta\nu \geq \frac{1}{2\pi T_m\sqrt{N}} \qquad \text{per cycle}$$

The statistical contribution to the uncertainty in the EDM for the set of *m* measurements is:

$$\sigma \geq \frac{\hbar/4}{E_0 T_m\sqrt{Nm}} = \frac{\hbar/4}{E_0\sqrt{T_m N t}}\text{ecm} \ . \tag{IV.5}$$

Here $N < N_o$ is the effective number of neutrons contributing to or detected in the measurement. Equation IV.5 is useful since it gives a lower bound on the statistical error. In practice it only gives an order of magnitude estimate for the statistical error of a generic experiment due to the ambiguity in the value of N. For the experiment discussed here, we do the proper analysis of the statistical error in Section V.H.

Consider the parameters typical of this proposed LANSCE measurement as discussed below: E_0 = 50 kV/cm, T_o = 1000 sec, T_m = 500 sec, $N = 4.0 \times 10^6$ neutrons / measurement cycle and $m = 5.7 \times 10^3$ repeated cycles (1500 sec / cycle and 100 days of live time). Three other parameters, also discussed below, characterize the three neutron loss mechanisms:

Beta decay: τ_β=887sec, wall losses: τ_{wall}=1200sec,
and n - ^{3}He absorption: τ_3=500sec

Using Eq. (IV.5) with the overestimate, $N = N_o$, gives for one standard deviation uncertainty: $\sigma \geq 10^{-28}$ e cm. See however, the more realistic calculation (including shot noise) given in Section V.H, which gives a 2σ limit of 9 x 10^{-28} e cm.

One can compare this result to the error on the 1990 Smith [1], ILL measurement where they achieved:

$$d_n = -3 \pm 5 \times 10^{-26} \; e \text{ cm},$$

where the error is from both statistical and systematic contributions. For the more recent Harris [2], ILL measurement they achieve:

$$d_n = -1 \pm 3.6 \text{ x } 10^{-26} \; e \text{ cm}.$$

For statistical errors, note that the quality factor, $E_0\sqrt{(T_m N)}$ in Eq. (IV.5), gives a relative reduction in σ by a factor of 50 to 100 at LANSCE, in comparison to the Smith [1] ILL measurement and to the Harris [2] ILL measurement.

The challenges in designing this trapped UCN experiment were to maximize N_0, T_m, and E_0. In addition it is crucial to develop uniform, stable, and well measured B_0 and E_0 fields over the sample volume since these are a major source of systematic errors. The method developed to measure the errors related to B_0 are discussed below. More generally, issues related to systematic errors, such as v x E effects, pseudo-magnetic fields, gravitational effects, spatial differences in UCN/ ^{3}He distributions, etc., are discussed in detail in Section V.H.

In the technique adopted here, there are three critical issues that are addressed in this overview:

1. Optimize the UCN trap design for large N_o, long trap lifetime, and large E_0.

2. Make a precision measurement of the B_0 field, averaged over the neutron trap volume and valid for the neutron precession period.
3. Make a precision measurement of the neutron precession frequency, ν_n.

The overall layout of the experimental apparatus is shown in Fig. IV.1

B. Neutron Trap Design

We use the strategy for loading the trap with UCN suggested first by Golub [3]. It relies on using UCN locally produced inside a closed neutron trap filled with ultra-pure, superfluid ^{4}He, cooled to about 300 mK. When this neutron trap is placed in a beam of cold neutrons (E = 1 meV, v = 440 m/s, λ = 8.9 Å, see section V.A), the neutrons interacting with the superfluid may be down-scattered to $E < 0.13\ \mu$ eV, v < 5 m/s with a recoil phonon in the superfluid carrying away the missing energy and momentum.

The properly averaged UCN trapping (production) rate [4], as discussed in Section V.B, gives a nominal trapped UCN production rate, P, of

$$P \sim 1.0 \text{ UCN/ cm}^3 \text{ sec}$$

In order to minimize neutron absorption by hydrogen, deuterated polystyrene coatings have been developed for the surfaces of the trap (see discussions in [5]). The goal for the mean life of a neutron in a trap filled with pure ^{4}He and operated at 300 mK is about 500 sec as a result of losses by neutron beta decay and neutron wall interactions.

In T_0 = 1000 sec of UCN production, the neutron density will reach $\rho_n \sim 500$ UCN/cm^3 in the ^{4}He. Note that at other facilities with more intense sources of cold neutrons this density could be considerably higher. This UCN production technique and the UCN production rate calculations for a ^{4}He filled UCN trap have been tested and validated by Golub [3], and at the neutron lifetime experiment now in progress at NIST [6] (see Section V.B).

The details of the proposed geometry for the target region of the experiment are shown in Figs. IV.1 and IV.2, with two trap volumes, one on each side of the high-voltage central electrode. Thus two orientations of the electric field for a fixed B field will be measured simultaneously. Superfluid ^{4}He is a very good medium for high electric fields (see [7] and section V.E) and experience has shown that the deuterated polystyrene surfaces are very stable under high E fields [5]. Independent bench tests are planned in order to evaluate the trap performance under these conditions. The goal is to operate at an E field strength of 50 kV/cm (about four times greater than other recent EDM measurements).

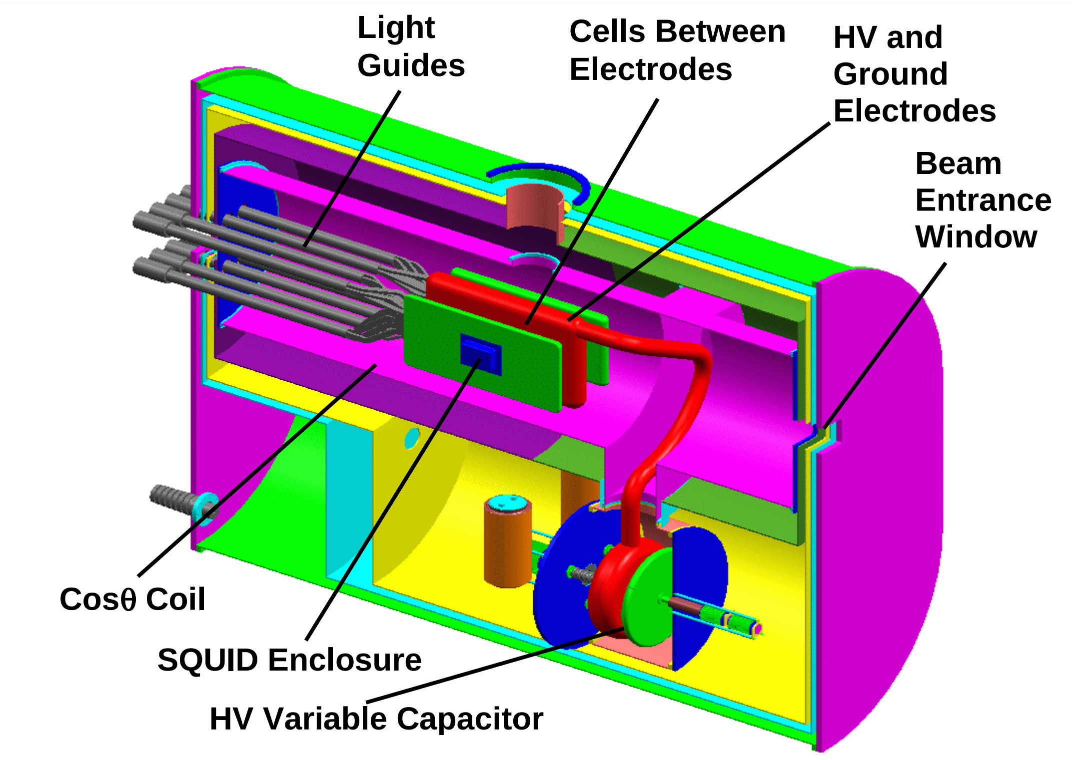

Fig IV-1. Experimental cryostat, length ~ 3.1 m. The neutron beam enters from the right. Two neutron cells are between the three electrodes. Scintillation light from the cells is monitored by the light guides and photomultipliers.

Properties of the magnetic and electric fields are discussed in Section V.E. The region in the cryostat but outside the UCN cells (see Fig. IV-1) will also be filled with ^{4}He because of its good electrical insulating properties. Note: The ^{4}He fluid in the region outside the two UCN cell volumes will contain ^{3}He atoms at normal concentrations (see below). Any UCN produced there will be absorbed in coatings on the vessel wall to prevent wall activation.

C. Measurement of the *B* Field with a ^{3}He Co-Magnetometer

Knowledge of the *B* field environment of the trapped neutrons is a crucial issue in the analysis of systematic errors in the measurement. The ^{4}He-UCN cells will sit in the uniform *B* field of a Cos Θ magnet with a nominal strength of 1 mG (up to 10 mG). The *B* field must be uniform to 1 part in 1000 (see Section V.E). These features of the *B* field must be confirmed by direct measurement in real time.

The magnetic dipole moment of ^{3}He atoms is comparable to that of the neutron (see Table I-B) such that the ^{3}He magnetic dipole moment is only 11% larger than that of the neutron. In addition, the EDM of the ^{3}He atom is negligible due to the shielding from the two bound electrons [1a] i.e. Schiff shielding [8]. These properties make ^{3}He an excellent candidate as a monitor of the *B* field in the volume where the UCN are trapped, or if B is stable, as a reference for precession frequency measurements.

To exploit this, the pure ^{4}He superfluid is modified by adding a small admixture of polarized ^{3}He (with spins initially aligned with the B_o field). The amount is $\approx$ 1 x 10^{+12} atoms / cm^3 and fractional density of X = 0.4 x 10^{-10}. This mixture is prepared in a separate reservoir and then transferred to the neutron cells. The result is a three-component fluid in the cell with densities: ρ_n = 5.0 x 10^{+2}/ cc, ρ_3 = 0.8 x 10^{+12} / cc, and ρ_4 = 2.2 x 10^{+22} / cc.

The UCN cells will be adjacent to SQUID coils mounted in the ground electrodes as discussed in Section V.F and V.H. The spins of the ensembles of ^{3}He and neutrons are aligned (see below) and are initially parallel to the B_0 field. An "RF coil", positioned with its axis perpendicular to B_0 (see Section V.E), is then used to rotate the neutron and ^{3}He spins into the plane perpendicular to B_0. We discuss the resulting n-^{3}He interaction below.

As the spins of the ^{3}He atoms and the neutrons precess in this plane, the SQUID coils will pick up the signal from the large number of precessing ^{3}He magnetic dipoles; the corresponding neutron signal from 500 UCN/cm^3 is negligible. Analysis of this

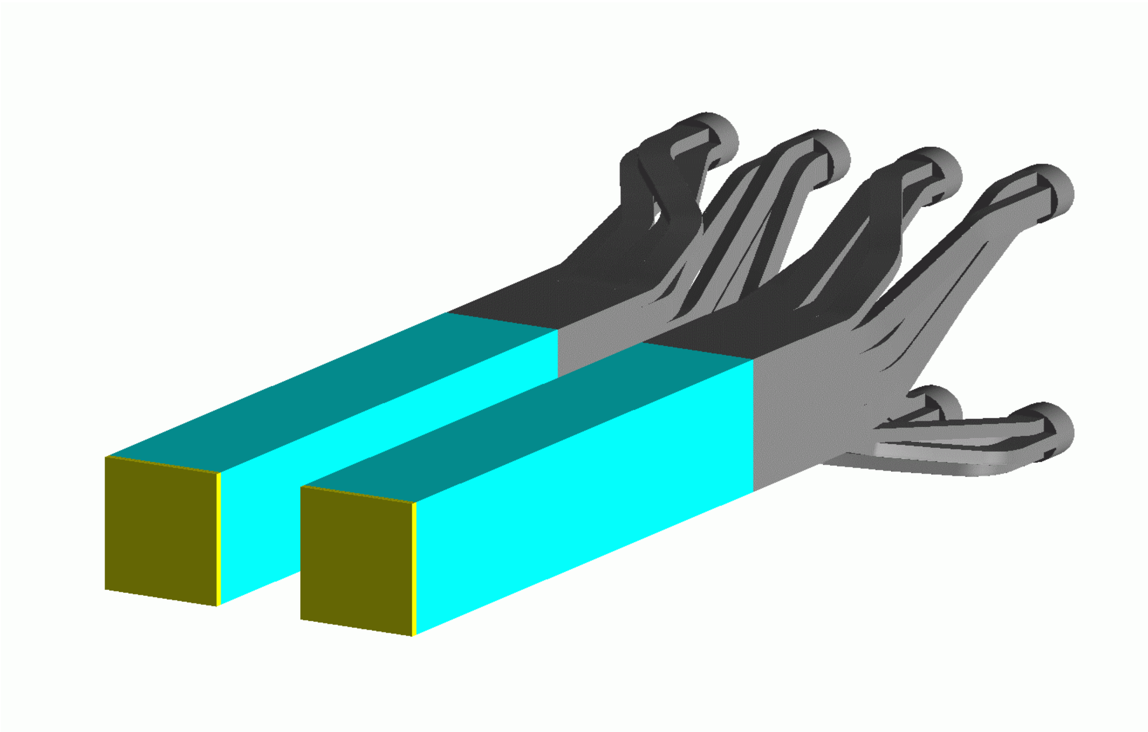

Fig IV-2. Two cell design with light guides which connect to the photomultiplier tubes outside the cryostat. Each cell has a nominal volume of 4 L.

sinusoidal signal will directly measure the ^{3}He precession frequency, ν_3, and thus the magnetic field, B_0, averaged over the same volume and time interval as experienced by the trapped UCN's.

$$B_0 = \frac{\nu_3}{2\mu_3} \ . \tag{IV.6}$$

In summary, the addition of the ^{3}He atoms to the measurement cells and the SQUIDs to the electrodes, provides the opportunity for a direct measurement *in situ* of the *B* field averaged over the cell volumes and the time period of the measurement.

D. Measurement of the UCN Precession Frequency

Knowledge of the neutron EDM depends on a precision measurement of the change in the neutron precession frequency for the two orientations of the electric field. Consider N_0 UCN trapped in a cell. Because the magnitude of the precession frequency shift, $\Delta\nu_n$, due to the interaction of the neutron EDM with the electric field, is extremely small,

<1 μ Hz, it is imperative to measure it with great precision. The technique adopted here is to make a comparison measurement in which ν_n is compared to the ^{3}He precession frequency, ν_3. The technique relies on the spin dependence of the nuclear absorption cross section for the reaction:

$$n + {}^3\text{He} \rightarrow p + t + 764 \text{ keV}. \qquad \text{(IV.7)}$$

The nuclear absorption reaction products (and the neutron beta decay products) generate scintillation light in the ^{4}He fluid, which can be shifted in wavelength and detected with photomultipliers.

The absorption cross section is strongly dependent on the initial spin state of the reaction:

Spin State	Cross Section, σ_{abs}, barns [10] (v = 2200 m/sec)	(v = 5 m/sec)
$J = 0$	$\sim 2 \text{ x } 5.5 \times 10^{+3}$	$\sim 2 \text{ x } 2.4 \times 10^{+6}$
$J = 1$	~ 0	~ 0

There are two options here. In **option A**, where the cell is irradiated with an unpolarized cold neutron beam, we take $\sigma_{abs} = 2.4 \text{ x } 10^6$ b as the average ^{3}He absorption cross section for UCNs. The mean life of the neutron in the trap due to ^{3}He absorption alone, τ_3, is given by:

$$1/\tau_3 = \rho_3[\sigma_{abs} v]_{UCN} = \rho_3[\sigma_{abs} v]_{thermal} \;. \qquad \text{(IV.8)}$$

The ^{3}He density, ρ_3, is adjusted to give τ_3 = 500 sec. This corresponds to:

$$\rho_3 = 0.85 \times 10^{+12} \;\; {}^3\text{He} / \text{cm}^3.$$

The net neutron mean life in the trap is 250 sec, due about equally to losses by ^{3}He absorption, by neutron beta-decay, and by wall interactions.

In this scheme, the only neutrons that survive are those with spins parallel to the polarization vector of the ^{3}He (and aligned with the B_o field). In the process, half the neutrons in the trap have been lost. We are assuming here 100% ^{3}He polarization and that there is no polarization loss in the traps.

An alternative approach, **option B**, is to pre-select the cold neutron beam according to spin direction, with an upstream spin selector, and to direct neutrons of each of the two transverse spin orientations to each of the two cells. Although there may be flux losses in the spin selector apparatus, the subsequent loss of neutrons to ^{3}He absorption in a cell will only occur if there is not perfect ^{3}He or neutron-beam polarization or if there is loss of polarization in the cell as time passes. Over all this approach makes the measurement less sensitive to the ^{3}He polarization in the cells (see Section V.D).

As noted, there are three neutron loss mechanisms in the cells which lead to: τ_β = 887 sec, τ_3 = 500 sec, τ_{cell} ~ 1200 sec. During the precession process in the cell, as a result of all three loss mechanisms, the net neutron mean life is: $1/\Gamma_{avg}$ = 250 sec. On the other hand, during the UCN production phase in which a cold polarized beam of neutrons is aligned with the polarized ^{3}He in the cell, there are no absorption losses and the mean neutron life in the cell is 500 sec. Effects due to time dependent polarization changes in the cell are neglected in this discussion (section V.C and V.H). This second strategy, **option B**, is being evaluated and is discussed in Section V.A.

To start the precession process, independent RF coils are used to reorient the neutron and the ^{3}He spin directions into the plane perpendicular to B_0 where they both precess about B_0, initially with their spins parallel. Thus the aligned ^{3}He and UCN components are trapped in the cell and continue to precess for up to a time, T_m, at which point the cell is flushed so a new measurement cycle can begin.

However, because the magnetic dipole moments of the neutron and ^{3}He are slightly different,

$$\mu_{^3\mathrm{He}}/\mu_\mathrm{n} = 1.11 \ ,$$

the ^{3}He spin vectors will gradually rotate ahead of the neutron spin vectors and destroy the alignment. As the precession continues, the absorption process will alternately appear and disappear.

This absorption process can be observed as scintillation light generated by the recoiling charged particle reaction products in the ^{4}He superfluid. The scintillation light is emitted in a broad spectrum centered at 80 nm, and is easily transmitted to the wall of the cell where a deuterated tetraphenyl butadiene-doped polystyrene surface will absorb it and re-emit it at 430 nm. This wave-shifted light can be collected with light pipes and transmitted to photomultiplier tubes outside of the *B* field region (see Section V.C).

The net scintillation light signal, $\Phi(t)$, due to a constant background, Φ_{bgd}, beta decay, and ^{3}He absorption, and with polarizations P_3 and P_n, can be written as (see V.H):

$$\Phi(t)=\Phi_{bgd}+N_o\exp(-\Gamma_{avg}t)\left\{\frac{1}{\tau\beta}+\frac{1}{\tau 3}(1-P_3P_n\cos[(\nu_3-\nu_n)t+\phi])\right\}$$

Equation IV.9

where we neglect the loss of both neutron and ^{3}He polarization during the measurement period. Here Γ_{avg} is the overall neutron loss rate for the cell including both wall losses and neutron beta decay as well as absorption. The neutron scintillation rate has a time dependence coming from both the decaying exponential factor and the sinusoidal dependence on: $\nu_3 - \nu_n$ = 0.3 Hz.

The resulting photomultiplier signal gives a direct measure of the neutron precession rate, ν_n, when combined with a knowledge of ν_3.

In summary, the introduction of $0.8 \times 10^{+12}$ polarized ^{3}He atoms/cm^3 into a cell containing $5 \times 10^{+2}$ UCN/ cc allows one to directly measure the average B_0 field and to confirm the polarization of the UCN. It also permits a direct and precise measurement of the orientation of the UCN spin relative to the ^{3}He spin as they precess over a time interval, T_m = 500 sec (two neutron mean cell life times). It is this time-dependent absorption sinusoidal light signal which must be carefully analyzed for changes in its period as the E_0 field is reversed.

For this two component fluid of neutrons and ^{3}He dissolved in the ^{4}He super-fluid we measure:

$$\nu_3 = -2\mu_3 B_0 \ , \qquad \text{(IV.10)}$$

obtained from the SQUID signal, and

$$\nu_n = -[2\mu_n B_0 + 2E_0 d_n]/h \ , \qquad \text{(IV.11)}$$

obtained from the combination of the scintillation light and the SQUID signals. Thus analysis of the shape and the time dependence of the scintillation light signal, throughout the precession period, is critical to the precision of the EDM measurement.

Note that when E_0 = 0, the two measurements (SQUID and scintillation signals) can be crossed checked since they should both give the common value of B_0. Alternatively, for a stable B_0 field and when $E_0 \neq 0$, the SQUID measurement provides a reference clock against which a shift in the scintillator spectrum can be measured.

E. Discussion of Errors

The most vexing problem in the design of a neutron EDM measurement is the control of systematic errors. This is amply illustrated by the discussion of previous neutron EDM measurements reviewed in Chapter III. This overview addresses only a few aspects of the problem; the details are deferred to the main discussion in Section V.H.

1. Statistical Errors

The gross analysis of the statistical errors presented above, equation IV.5, suggests that the proposed technique gives an improvement in the figure of merit $E_0\sqrt{(T_m N_o)}$ by a factor of 50 – 100 over recent UCN measurements at ILL. Subsidiary measurements planned for LANSCE, involving cell fabrication tests, cold neutron flux measurements, and maximum usable E field tests, will verify whether this gain can be fully realized.

2. Systematic Errors

The analysis of systematic errors is a challenging and detailed exercise and is at the heart of a successful EDM measurement. The major concerns are related to knowledge of the magnetic and electric fields (since both time-dependent field strengths and nonparallel E and B fields, have the potential to produce a false EDM signal), any differences in the two cells, and any contribution of background sources to the scintillation light spectrum.

The ^{3}He-precession measurement allows the magnetic field to be sampled in time and space throughout the precession period and over the volume of the UCN traps. The major limitations come from the quality, stability, and background of the SQUID signals. Bench tests of the performance of the SQUID coils at these low temperatures and in the LANSCE noise environment are in progress as discussed in Section V.F. The goal is a B_o field uniform to 0.1 % over the cell volume.

The electric field properties are equally critical. The goal for the electric field uniformity is < 1 % as discussed in Section V.E. In order to achieve the high fields consistent with the dielectric properties of the superfluid ^{4}He medium, a program for performing bench tests of the maximum useable electric field is being developed. Issues of leakage currents and sparks are critical and in the end will dictate the upper limit at which the applied voltage can operate.

Other issues related to the properties of the cold neutron beam, pre-selection of the neutron spin, and the role of gamma-ray and neutron induced backgrounds, are discussed in Sections V.A and V.C. The optimum sequence in the measurement cycles in order to cancel systematic shifts in the data also has to be evaluated.

F. Measurement Cycle

By way of clarification and review, we describe the measurement sequence over the 1500 sec measurement cycle, as currently envisioned, with some additional details included.

1. **Cold neutron beam preparation.** Cold neutrons (v= 440 m/s, 1 meV) from the LANSCE liquid-hydrogen moderator, are transported by neutron guides through a frame overlap chopper, T_o chopper, and a Bi filter. This system (see Section V.A) filters out unusable neutrons and gamma rays. In addition the beam is divided into two guides that transport the cold neutrons downstream and through the cryostat wall to the two cells. We are currently evaluating techniques to install a spin filter in the guide (**option B** in the above discussion) to permit pre-selection of the neutron spin state. Spin rotators make both beams have their spins aligned with the ^{3}He atoms in the measuring cells. The technology to divide the beam is available, but the cost in loss of flux and beam line floor space is still being evaluated. The splitter is discussed in Section V.A and Appendix A.

   For the purposes of this discussion of the measurement cycle, we assume that the beam is split into two components matched to the neutron cell sizes and that the beam spin filter is implemented. We further assume that E_o and B_o are on and stable during the entire cycle.

2. **^{4}He and polarized ^{3}He transfer to the cells.** – START OF A 5-STEP CYCLE. During a previous measurement phase (step 5 below), polarized ^{3}He (~99% polarization and density fraction X ~ 10^{-10}) from an atomic beam apparatus, is mixed with ultra-pure superfluid ^{4}He in a reservoir separate from the target cells. Now, with the beam shutter closed, the mixture is transferred to the measurement cells. A small holding field continues to be used to maintain the polarization during the transfer, < 10 sec. The ^{3}He polarization is selected in the polarized source to be either parallel or anti-parallel to the magnetic field, Bo, generated by the cos Θ magnet. The ^{3}He-spin vectors are the same in both cells, but, by construction, the electric

fields are opposite of each other, regardless of the sign of the potential on the high-voltage electrode.

3. **Cold neutron beam irradiation and production of the UCN in the cells.** The beam shutter is opened, allowing the cold neutrons to irradiate the cells, some of which produce UCN. The two cells, each filled with superfluid ^{4}He (2.2 x 10^{22}/cm^3) and polarized ^{3}He (0.8 x 10^{+12} /cm^3), are irradiated for T_o = 1000 sec. A trapped sample of UCN is built up with a production rate of P = ~ 1 UCN / (cm^3 sec). The mean life of these neutrons in the cells is ~ 500 sec due to both beta decay and wall losses alone. Assuming that the initial sample of neutrons has been fully polarized, the large n-^{3}He cross section in the J = 0 state will reduce only slightly the population of neutrons during the UCN collection process. Neutrons properly aligned with the ^{3}He will suffer no absorption losses. The number density produced in T_o = 1000 sec grows to ρ_n ~ 500 UCN/ cm^3 (actually 430/ cm^3 when corrected for beta decay and cell losses) in each of two cells of volume = 4000 cm^3 per cell. At the end of the UCN fill period, the beam shutter is closed.

4. **Rotation of both magnetic moments into the transverse plane.** The spin vectors are rotated into the plane perpendicular to B_o and E_o by pulsing an "RF" coil at 3.165 Hz for 1.58 sec (see Section V. E). Both the neutrons and the ^{3}He start to precess about B_o in order to conserve angular momentum.

5. **Precession Frequency measurements.** The critical precession frequency measurement occurs over the next T_m = 500 seconds. At the start of the measurement there are 4 x 10^{+6} neutrons in the two traps. The SQUID detectors measure the ^{3}He precession, ν_3, at about 3 Hz over a set of 1500 signal periods. The scintillator detection system measures $\nu_3 - \nu_n$ = 0.3 Hz over a set of 150 signal periods. The neutron sample continues to decrease with a mean life of 250 sec due to all loss mechanisms and is reduced to 116 UCN/cm^3, i.e. a total of 0.5 x 10^{+6} neutrons at the end of the measurement cycle. As discussed in detail in Section V.H, this corresponds to a sensitivity of

$$\sigma \sim 7 \times 10^{-26} \text{ e cm} \quad \text{in one cycle.}$$

In parallel with the precession measurement, the mixing reservoir is refilled with pure ^{4}He and polarized ^{3}He in the correct proportions.

6. **Empty the cells.** Valves are opened to drain the cells in about 10 sec, and the ^{3}He-^{4}He mixture is sent to a recovery reservoir for purification.
END OF THE CYCLE, return to step #2.

7. **Repeated cycles.** A single cycle takes about To + T_m = 1500 sec plus some transfer times. The cycle can be repeated about m = 5.7 x 10^{3} time in 100 days, which gives a two σ limit of < 9 x 10^{-28} e cm in one hundred days.

   Over this 100-day period one expects to follow a program of electric field reversals, spin reversals, magnetic field reversals, etc. to study and remove systematic effects.

Altogether this measurement involves the interplay of many technical and practical issues: polarized UCN and ^{3}He production, precision measurements of frequencies, UCN trap design, electric and magnetic field measurements, etc. These issues are discussed in detail in the following segment, Chapter V.

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Appendix B

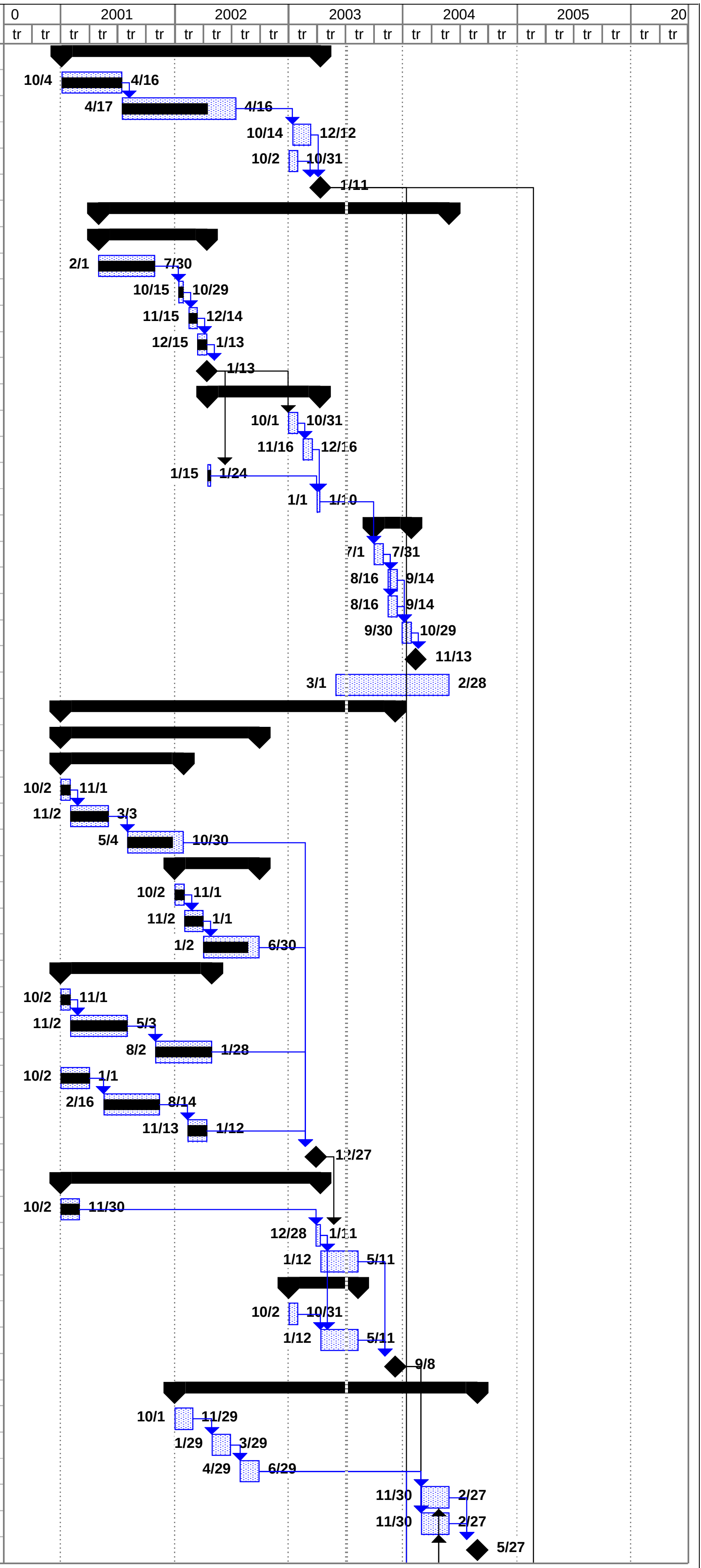
Work Breakdown Structure from Microsoft Project

ID	WBS	Task Name	Base Cost	% Contingency	% Burden	Loaded Cost	Duration	Lag	Qtr 4
1	**1**	**Dilution Refrigerator (DR)**	**$390.30**	**0**	**0**	**$516.17**	**830 days**	**0 days**	
2	1.1	Specify Refrigerator	$37.50	25	80	$84.38	195 days	0 days	**10/4**
3	1.2	Procure Refrigerator	$303.00	5	3.5	$329.29	365 days	180 days	
4	1.3	Acceptance Test Refrigerator	$40.80	25	80	$91.80	60 days	30 days	
5	1.4	Ancillary Equipment	$9.00	15	3.5	$10.71	30 days	23 days	
6	1.5	Working DR	$0.00	0	0	$0.00	0 days	0 days	
7	**2**	**UCN Storage Time / Rate in Cell**	**$32.80**	**0**	**0**	**$82.49**	**1123 days**	**0 days**	
8	**2.1**	**Measurement in LANSCE Beam**	**$15.80**	**0**	**0**	**$56.88**	**347 days**	**0 days**	
9	2.1.1	Setup of Old Dilution Refrigerator	$7.90	100	80	$28.44	180 days	0 days	
10	2.1.2	Setup at Beam	$7.90	100	80	$28.44	15 days	0 days	
11	2.1.3	Measurements	$0.00	0	0	$0.00	30 days	0 days	
12	2.1.4	Analysis of Data	$0.00	0	0	$0.00	30 days	0 days	
13	2.2	Preliminary Storage Time and Rate Demo	$0.00	0	0	$0.00	0 days	0 days	
14	**2.3**	**Meaurement Cell**	**$3.00**	**0**	**0**	**$4.61**	**361 days**	**0 days**	
15	2.3.1	Design Cell	$0.00	0	0	$0.00	31 days	15 days	
16	2.3.2	Fabricate Cell	$1.00	50	0	$1.50	31 days	15 days	
17	2.3.3	Fabricate TPB	$2.00	50	3.5	$3.11	10 days	10 days	
18	2.3.4	Assemble Cell	$0.00	0	0	$0.00	10 days	5 days	
19	**2.4**	**Measurements in NIST Beam**	**$0.00**	**0**	**0**	**$0.00**	**121 days**	**0 days**	
20	2.4.1	Setup at Beam	$0.00	0	0	$0.00	31 days	15 days	
21	2.4.2	Storage Time Measurements	$0.00	0	0	$0.00	30 days	15 days	
22	2.4.3	Particle ID Measurement	$0.00	0	0	$0.00	30 days	15 days	
23	2.4.4	Analyze Data	$0.00	0	0	$0.00	30 days	15 days	
24	2.5	UCN Storage Demonstration	$0.00	0	0	$0.00	0 days	0 days	
25	2.6	Particle ID feasibility	$14.00	50	0	$21.00	365 days	0 days	
26	**3**	**Hexapole 3He System**	**$319.60**	**0**	**0**	**$517.46**	**1072 days**	**0 days**	
27	**3.1**	**Beam Injector**	**$93.80**	**0**	**0**	**$169.25**	**637 days**	**0 days**	
28	**3.1.1**	**Cryogenics System**	**$56.40**	**0**	**0**	**$92.18**	**394 days**	**0 days**	
29	3.1.1.1	Design Cryogenics	$12.50	50	80	$33.75	31 days	0 days	**10/2**
30	3.1.1.2	Procurement Cryogenics	$36.00	25	3.5	$46.58	122 days	61 days	**11**
31	3.1.1.3	Assemble Cryogenics	$7.90	50	0	$11.85	180 days	180 days	
32	**3.1.2**	**Nozzle**	**$37.40**	**0**	**0**	**$77.07**	**272 days**	**0 days**	
33	3.1.2.1	Design Nozzle	$12.50	50	80	$33.75	31 days	0 days	
34	3.1.2.2	Fabricate Nozzle	$17.00	25	3.5	$21.99	61 days	0 days	
35	3.1.2.3	Assemble Nozzle	$7.90	50	80	$21.33	180 days	180 days	
36	**3.2**	**Filter / Analyzer**	**$220.80**	**0**	**0**	**$343.04**	**484 days**	**0 days**	
37	3.2.1	Design Magnets	$12.50	50	80	$33.75	31 days	0 days	**10/2**
38	3.2.2	Procure Magnets	$100.00	25	3.5	$129.38	183 days	90 days	**11**
39	3.2.3	Assemble Magnets	$7.90	50	80	$21.33	180 days	90 days	
40	3.2.4	Design Vacuum System	$12.50	50	80	$33.75	92 days	45 days	**10/2**
41	3.2.5	Procure Vacuum System	$80.00	25	3.5	$103.50	180 days	90 days	
42	3.2.6	Assemble Vacuum System	$7.90	50	80	$21.33	61 days	30 days	
43	3.3	3He Source Ready to Test	$0.00	0	0	$0.00	0 days	0 days	
44	**3.4**	**3He Detector**	**$5.00**	**0**	**0**	**$5.18**	**832 days**	**0 days**	
45	3.4.1	Procure Detector	$5.00	0	3.5	$5.18	60 days	0 days	**10/2**
46	3.4.2	Install Detector	$0.00	0	0	$0.00	15 days	0 days	
47	3.5	Measure Source Intensity	$0.00	0	0	$0.00	120 days	120 days	
48	**3.6**	**Measure Source Polarization**	**$0.00**	**0**	**0**	**$0.00**	**222 days**	**0 days**	
49	3.6.1	Build RF Spin Flipper	$0.00	0	0	$0.00	30 days	22 days	
50	3.6.2	Measure Spin Dependent Transmission	$0.00	0	0	$0.00	120 days	120 days	
51	3.7	3He Source Completed	$0.00	0	0	$0.00	0 days	0 days	
52	**4**	**Polarized 3He Transport System**	**$17.90**	**0**	**0**	**$36.86**	**970 days**	**0 days**	
53	4.1	Design Transport	$0.00	0	0	$0.00	60 days	60 days	
54	4.2	Procure Transport Parts	$10.00	50	3.5	$15.53	60 days	30 days	
55	4.3	Build Transport into Cryostat	$7.90	50	80	$21.33	62 days	30 days	
56	4.4	Measure 3He Transferred to Cryostat	$0.00	0	0	$0.00	90 days	90 days	
57	4.5	Measure 3He Polarization in Cryostat	$0.00	0	0	$0.00	90 days	90 days	
58	4.6	3He Transport Understood	$0.00	0	0	$0.00	0 days	0 days	

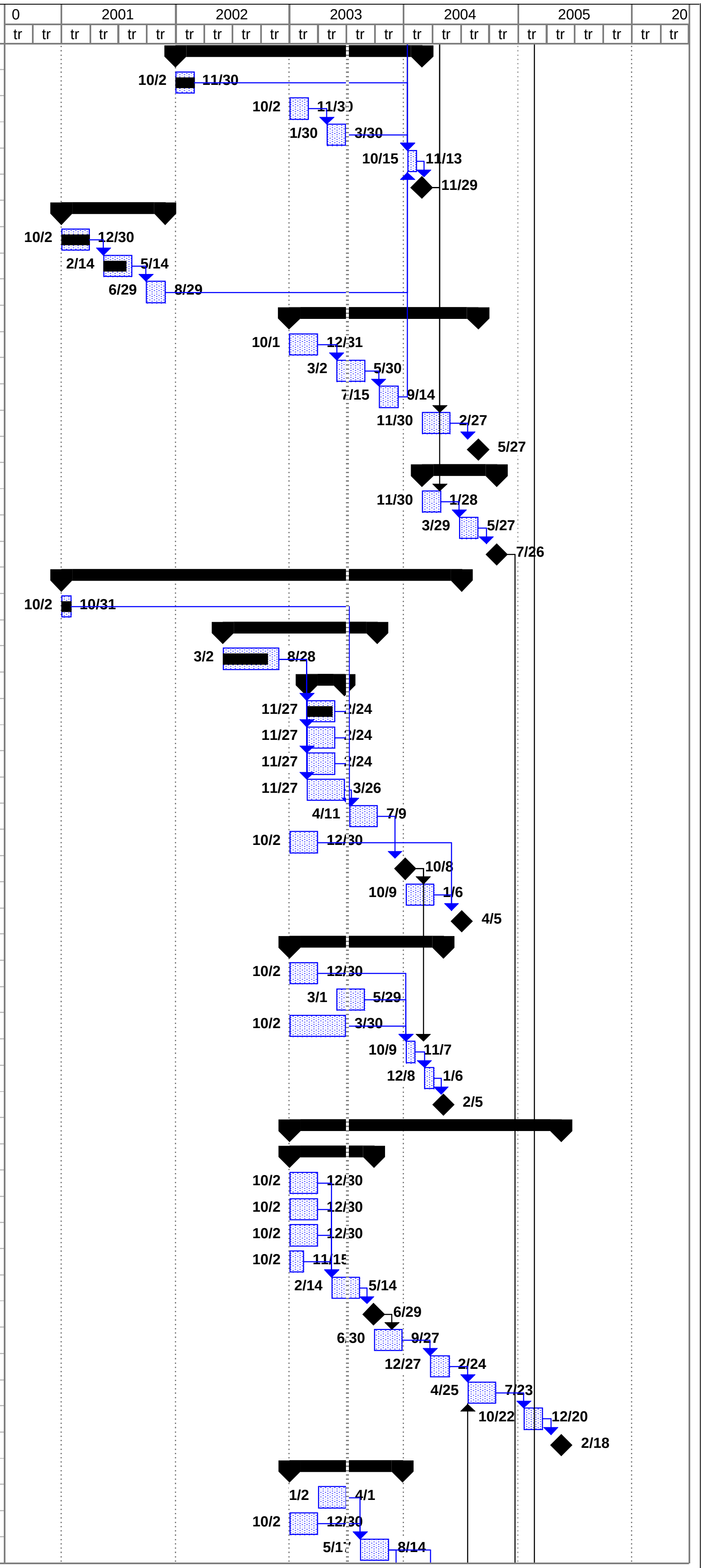
ID	WBS	Task Name	Base Cost	% Contingency	% Burden	Loaded Cost	Duration	Lag	Qtr 4
59	**5**	**Polarized 3He/4He Cryostat**	**$48.30**	**0**	**0**	**$106.17**	**789 days?**	**0 days**	
60	5.1	Purchase Cryostat	$5.00	25	3.5	$6.47	60 days	30 days	
61	5.2	Design Cryostat Insert	$12.50	50	80	$33.75	60 days	60 days	
62	5.3	Fabricate Cryostat Insert	$15.00	50	3.5	$23.29	60 days	30 days	
63	5.4	Assemble Cryostat	$15.80	50	80	$42.66	30 days	15 days	
64	5.5	3He/4He Cryostat Completed	$0.00	0	0	$0.00	1 day?	0 days	
65	**6**	**SQUID System Prototype**	**$4.00**	**0**	**0**	**$5.18**	**332 days**	**0 days**	
66	6.1	Procure SQUIDs	$4.00	25	3.5	$5.18	90 days	45 days	**10/2**
67	6.2	Assemble SQUID Electronics	$0.00	0	0	$0.00	90 days	45 days	
68	6.3	Install SQUID system Prototype	$0.00	0	0	$0.00	62 days	30 days	
69	**7**	**Superconducting Shield Prototype**	**$17.90**	**0**	**0**	**$36.86**	**605 days**	**0 days**	
70	7.1	Design Shield	$0.00	0	0	$0.00	92 days	60 days	
71	7.2	Procure Shield	$10.00	50	3.5	$15.53	90 days	45 days	
72	7.3	Install Shield into DR	$7.90	50	80	$21.33	62 days	30 days	
73	7.4	Measure Shielding Factor, Trapped Fields	$0.00	0	0	$0.00	90 days	90 days	
74	7.5	Magnetic Shielding Study Complete	$0.00	0	0	$0.00	0 days	0 days	
75	**8**	**SQUID Performance**	**$0.00**	**0**	**0**	**$0.00**	**240 days**	**0 days**	
76	8.1	Measure SQUID Response to 3He	$0.00	0	0	$0.00	60 days	60 days	
77	8.2	SQUID Measurements vrs Concentration	$0.00	0	0	$0.00	60 days	60 days	
78	8.3	SQUID / 3He Systems Demonstrated	$0.00	0	0	$0.00	0 days	0 days	
79	**9**	**High Voltage System Prototype**	**$123.10**	**0**	**0**	**$214.35**	**1282 days?**	**0 days**	
80	9.1	Power Supply	$0.00	0	0	$0.00	30 days	30 days	**10/2**
81	**9.2**	**HV System**	**$123.10**	**0**	**0**	**$214.35**	**495 days**	**0 days**	
82	9.2.1	Design HV	$19.00	0	80	$34.20	180 days	90 days	
83	**9.2.2**	**Procure HV Parts**	**$68.50**	**0**	**0**	**$88.62**	**120 days**	**0 days**	
84	9.2.2.1	Fabricate Outer Vacuum Vessel	$16.50	25	3.5	$21.35	90 days	20 days	
85	9.2.2.2	Fabrocate LN2 Shield	$12.00	25	3.5	$15.53	90 days	45 days	
86	9.2.2.3	Fabricate LHe Volume	$35.00	25	3.5	$45.28	90 days	45 days	
87	9.2.2.4	Procure HV Standoffs	$5.00	25	3.5	$6.47	120 days	30 days	
88	9.2.3	Assemble HV System	$31.60	50	80	$85.32	90 days	90 days	
89	9.2.4	Fabricate Alternate Electrodes	$4.00	50	3.5	$6.21	90 days	45 days	
90	9.3	HV System Ready for Tests	$0.00	0	0	$0.00	1 day?	0 days	
91	9.4	Perform HV Tests	$0.00	0	0	$0.00	90 days	90 days	
92	9.5	HV System Demonstrated	$0.00	0	0	$0.00	0 days	0 days	
93	**10**	**Kerr Effect Tests**	**$25.00**	**0**	**0**	**$38.28**	**492 days**	**0 days**	
94	10.1	Procure Laser	$15.00	25	3.5	$19.41	90 days	45 days	
95	10.2	Procure Electronics and Optics	$10.00	25	51	$18.88	90 days	45 days	
96	10.3	R&D at 4 K	$0.00	0	0	$0.00	180 days	180 days	
97	10.4	Measurements at 50 kV/cm 4 K	$0.00	0	0	$0.00	30 days	30 days	
98	10.5	Measurements at 1.5 K	$0.00	0	0	$0.00	30 days	30 days	
99	10.6	Kerr Effect Demonstrated	$0.00	0	0	$0.00	0 days	0 days	
100	**11**	**3He Depolarization in Cell**	**$64.50**	**0**	**0**	**$80.63**	**871 days?**	**0 days**	
101	**11.1**	**Construct 4 K Cryostat**	**$64.50**	**0**	**0**	**$80.63**	**271 days?**	**0 days**	
102	11.1.1	Build Exchange 3He Polarizing Cell	$25.00	25	0	$31.25	90 days	45 days	
103	11.1.2	Procure Cryostat	$34.50	25	0	$43.13	90 days	45 days	
104	11.1.3	Fabricate Magnetic Shield	$0.00	0	0	$0.00	90 days	45 days	
105	11.1.4	Fabricate NMR Apparatus	$5.00	25	0	$6.25	45 days	45 days	
106	11.1.5	4 K Cryostat Assembly	$0.00	0	0	$0.00	90 days	45 days	
107	11.1.6	4 K Cryostat Assembled	$0.00	0	0	$0.00	1 day?	0 days	
108	11.2	Measure Depolarization at 4 K	$0.00	0	0	$0.00	90 days	90 days	
109	11.3	Depolarization Measured for Coatings 4 K	$0.00	0	0	$0.00	60 days	60 days	
110	11.4	Measure Depolarization at 1 K	$0.00	0	0	$0.00	90 days	90 days	
111	11.5	Depolarization Measured for Coatings 1 K	$0.00	0	0	$0.00	60 days	60 days	
112	11.6	Depolarization Lifetime Understood	$0.00	0	0	$0.00	0 days	0 days	
113	**12**	**Refurbish 1 K Cryostat**	**$83.00**	**0**	**0**	**$128.43**	**363 days?**	**0 days**	
114	12.1	Procure Cryostat Instrumentation / Pumps	$53.00	10	0	$58.30	90 days	0 days	
115	12.2	Modify 1 K Cryostat	$30.00	25	87	$70.13	90 days	90 days	
116	12.3	Test 1 K Cryostat	$0.00	0	0	$0.00	90 days	45 days	

ID	WBS	Task Name	Base Cost	% Contingency	% Burden	Loaded Cost	Duration	Lag	Qtr 4
117	12.4	1 K Cryostat Ready for Use	$0.00	0	0	$0.00	1 day?	0 days	
118	**13**	**Ferromagnetic Shield Prototype**	**$15.00**	**0**	**0**	**$18.75**	**450 days**	**0 days**	
119	13.1	Procure Shield Materials	$5.00	25	0	$6.25	90 days	45 days	
120	13.2	Procure Magnetic Monitoring Electronics	$10.00	25	0	$12.50	90 days	45 days	
121	13.3	Measure Ferromagnetic Shields at 4 K	$0.00	0	0	$0.00	90 days	45 days	
122	13.4	Measure Ferromagnetic Shields at 1 K	$0.00	0	0	$0.00	90 days	90 days	
123	13.5	Ferromagnetic Shield Understood	$0.00	0	0	$0.00	0 days	0 days	
124	**14**	**3He Purification System**	**$23.70**	**0**	**0**	**$53.32**	**606 days**	**0 days**	
125	14.1	Refurbish HMI Purifier	$15.80	25	80	$35.55	92 days	330 days	
126	14.2	Test Purifier	$7.90	25	80	$17.77	62 days	62 days	
127	14.3	Cycling Demonstrated	$0.00	0	0	$0.00	0 days	0 days	
128	14.4	Produce Two Cell Fills of Ultrapure 4He	$0.00	0	0	$0.00	60 days	30 days	
129	**15**	**3He Diffusion Coefficient Measurement**	**$15.80**	**0**	**0**	**$28.44**	**331 days?**	**0 days**	
130	15.1	Setup at FP 11a	$15.80	0	80	$28.44	30 days	0 days	**10/2**
131	15.2	Diffusion with Neutron Tomography	$0.00	0	0	$0.00	30 days	0 days	**11**
132	15.3	Data Analysis and Paper Writing	$0.00	0	0	$0.00	150 days	0 days	
133	15.4	Publication of Results	$0.00	0	0	$0.00	1 day?	0 days	
134	**16**	**Evaporative 3He Removal**	**$49.55**	**0**	**0**	**$155.43**	**630 days**	**0 days**	
135	16.1	Design Evaporation Chamber	$12.50	100	80	$45.00	60 days	60 days	
136	16.2	Fabricate Evaporation Chamber	$10.00	100	3.5	$20.70	60 days	30 days	
137	16.3	Design SQUID Sensor Geormetry	$6.25	100	80	$22.50	30 days	30 days	
138	16.4	Fabricate SQUID Modifcations	$5.00	100	3.5	$10.35	30 days	30 days	
139	16.5	Assemble Evaporation Chamber and DR	$15.80	100	80	$56.88	60 days	30 days	
140	16.6	Measure 3He Removal Performance	$0.00	0	0	$0.00	60 days	60 days	
141	16.7	3He Removal Understood	$0.00	0	0	$0.00	0 days	0 days	
142	**17**	**Monte-Carlo Simulations**	**$0.00**	**0**	**0**	**$0.00**	**575 days?**	**0 days**	
143	**17.1**	**Cold Neutron Simulations LANSCE / SNS**	**$0.00**	**0**	**0**	**$0.00**	**361 days?**	**0 days**	
144	17.1.1	Transport Through Beam Elements	$0.00	0	0	$0.00	180 days	180 days	
145	17.1.2	Beam State Selector	$0.00	0	0	$0.00	180 days	180 days	
146	17.1.3	Transport in the Cryostat	$0.00	0	0	$0.00	180 days	180 days	
147	17.1.4	Activation Neutrons	$0.00	0	0	$0.00	180 days	180 days	
148	17.1.5	Cold Neutrons Simulated	$0.00	0	0	$0.00	1 day?	0 days	
149	**17.2**	**UCN and Light Collection Simulations**	**$0.00**	**0**	**0**	**$0.00**	**361 days?**	**0 days**	
150	17.2.1	UCN Absorption on 3He	$0.00	0	0	$0.00	180 days	180 days	
151	17.2.2	Light Propogation in Cell Walls	$0.00	0	0	$0.00	180 days	180 days	
152	17.2.3	Light Propogation in Guides	$0.00	0	0	$0.00	180 days	180 days	
153	17.2.4	Light Collection Modeled	$0.00	0	0	$0.00	1 day?	0 days	
154	**17.3**	**Data Analysis Simulations**	**$0.00**	**0**	**0**	**$0.00**	**546 days?**	**0 days**	
155	17.3.1	Beta Decay Backgrounds Only	$0.00	0	0	$0.00	90 days	0 days	
156	17.3.2	Complete Backgrounds Included	$0.00	0	0	$0.00	90 days	90 days	
157	17.3.3	Importance of Background Quantified	$0.00	0	0	$0.00	1 day?	0 days	
158	**18**	**Project Development**	**$135.40**	**0**	**0**	**$424.50**	**1455 days?**	**0 days**	
159	18.1	Conceptual Engineering	$75.00	50	80	$202.50	180 days	0 days	
160	18.2	Pre-proposal Writing	$0.00	0	0	$0.00	360 days	180 days	**10/2**
161	18.3	Pre-proposal Submission to DOE	$0.00	0	0	$0.00	0 days	0 days	
162	18.4	DOE Guidance	$0.00	0	0	$0.00	250 days	0 days	
163	18.5	R&D Proposal Preparation	$0.00	0	0	$0.00	60 days	30 days	
164	18.6	R&D Proposal Submission to DOE	$0.00	0	0	$0.00	1 day?	0 days	
165	18.7	Proposal Preparation	$12.50	50	80	$33.75	90 days	30 days	
166	18.8	Proposal Submission to DOE	$0.00	0	0	$0.00	1 day?	0 days	
167	18.9	CDR Engineering	$47.90	50	162	$188.25	138 days	69 days	
168	18.10	CDR Preparation	$0.00	0	0	$0.00	270 days	90 days	
169	18.11	Conceptual Design Review	$0.00	0	0	$0.00	1 day?	0 days	
170	**19**	**Management**	**$28.21**	**0**	**0**	**$92.39**	**102 days**	**0 days**	
171	19.1	Project Manager Before Construction	$28.21	25	162	$92.39	102 days	26 days	
172	**20**	**Expendables**	**$81.00**	**0**	**0**	**$124.65**	**1752 days**	**0 days**	
173	20.1	LHe at LANL	$60.00	50	3.5	$93.15	1752 days	0 days	**10/2**
174	20.2	LHe away from LANL	$21.00	50	0	$31.50	487 days	0 days	

ID	WBS	Task Name
1	**1**	**Dilution Refrigerator (DR)**
2	1.1	Specify Refrigerator
3	1.2	Procure Refrigerator
4	1.3	Acceptance Test Refrigerator
5	1.4	Ancillary Equipment
6	1.5	Working DR
7	**2**	**UCN Storage Time / Rate in Cell**
8	**2.1**	**Measurement in LANSCE Beam**
9	2.1.1	Setup of Old Dilution Refrigerator
10	2.1.2	Setup at Beam
11	2.1.3	Measurements
12	2.1.4	Analysis of Data
13	2.2	Preliminary Storage Time and Rate Demo
14	**2.3**	**Meaurement Cell**
15	2.3.1	Design Cell
16	2.3.2	Fabricate Cell
17	2.3.3	Fabricate TPB
18	2.3.4	Assemble Cell
19	**2.4**	**Measurements in NIST Beam**
20	2.4.1	Setup at Beam
21	2.4.2	Storage Time Measurements
22	2.4.3	Particle ID Measurement
23	2.4.4	Analyze Data
24	2.5	UCN Storage Demonstration
25	2.6	Particle ID feasibility
26	**3**	**Hexapole 3He System**
27	**3.1**	**Beam Injector**
28	**3.1.1**	**Cryogenics System**
29	3.1.1.1	Design Cryogenics
30	3.1.1.2	Procurement Cryogenics
31	3.1.1.3	Assemble Cryogenics
32	**3.1.2**	**Nozzle**
33	3.1.2.1	Design Nozzle
34	3.1.2.2	Fabricate Nozzle
35	3.1.2.3	Assemble Nozzle
36	**3.2**	**Filter / Analyzer**
37	3.2.1	Design Magnets
38	3.2.2	Procure Magnets
39	3.2.3	Assemble Magnets
40	3.2.4	Design Vacuum System
41	3.2.5	Procure Vacuum System
42	3.2.6	Assemble Vacuum System
43	3.3	3He Source Ready to Test
44	**3.4**	**3He Detector**
45	3.4.1	Procure Detector
46	3.4.2	Install Detector
47	3.5	Measure Source Intensity
48	**3.6**	**Measure Source Polarization**
49	3.6.1	Build RF Spin Flipper
50	3.6.2	Measure Spin Dependent Transmission
51	3.7	3He Source Completed
52	**4**	**Polarized 3He Transport System**
53	4.1	Design Transport
54	4.2	Procure Transport Parts
55	4.3	Build Transport into Cryostat
56	4.4	Measure 3He Transferred to Cryostat
57	4.5	Measure 3He Polarization in Cryostat
58	4.6	3He Transport Understood



ID	WBS	Task Name
59	**5**	**Polarized 3He/4He Cryostat**
60	5.1	Purchase Cryostat
61	5.2	Design Cryostat Insert
62	5.3	Fabricate Cryostat Insert
63	5.4	Assemble Cryostat
64	5.5	3He/4He Cryostat Completed
65	**6**	**SQUID System Prototype**
66	6.1	Procure SQUIDs
67	6.2	Assemble SQUID Electronics
68	6.3	Install SQUID system Prototype
69	**7**	**Superconducting Shield Prototype**
70	7.1	Design Shield
71	7.2	Procure Shield
72	7.3	Install Shield into DR
73	7.4	Measure Shielding Factor, Trapped Fields
74	7.5	Magnetic Shielding Study Complete
75	**8**	**SQUID Performance**
76	8.1	Measure SQUID Response to 3He
77	8.2	SQUID Measurements vrs Concentration
78	8.3	SQUID / 3He Systems Demonstrated
79	**9**	**High Voltage System Prototype**
80	9.1	Power Supply
81	**9.2**	**HV System**
82	9.2.1	Design HV
83	**9.2.2**	**Procure HV Parts**
84	9.2.2.1	Fabricate Outer Vacuum Vessel
85	9.2.2.2	Fabrocate LN2 Shield
86	9.2.2.3	Fabricate LHe Volume
87	9.2.2.4	Procure HV Standoffs
88	9.2.3	Assemble HV System
89	9.2.4	Fabricate Alternate Electrodes
90	9.3	HV System Ready for Tests
91	9.4	Perform HV Tests
92	9.5	HV System Demonstrated
93	**10**	**Kerr Effect Tests**
94	10.1	Procure Laser
95	10.2	Procure Electronics and Optics
96	10.3	R&D at 4 K
97	10.4	Measurements at 50 kV/cm 4 K
98	10.5	Measurements at 1.5 K
99	10.6	Kerr Effect Demonstrated
100	**11**	**3He Depolarization in Cell**
101	**11.1**	**Construct 4 K Cryostat**
102	11.1.1	Build Exchange 3He Polarizing Cell
103	11.1.2	Procure Cryostat
104	11.1.3	Fabricate Magnetic Shield
105	11.1.4	Fabricate NMR Apparatus
106	11.1.5	4 K Cryostat Assembly
107	11.1.6	4 K Cryostat Assembled
108	11.2	Measure Depolarization at 4 K
109	11.3	Depolarization Measured for Coatings 4 K
110	11.4	Measure Depolarization at 1 K
111	11.5	Depolarization Measured for Coatings 1 K
112	11.6	Depolarization Lifetime Understood
113	**12**	**Refurbish 1 K Cryostat**
114	12.1	Procure Cryostat Instrumentation / Pumps
115	12.2	Modify 1 K Cryostat
116	12.3	Test 1 K Cryostat



ID	WBS	Task Name
117	12.4	1 K Cryostat Ready for Use
118	13	**Ferromagnetic Shield Prototype**
119	13.1	Procure Shield Materials
120	13.2	Procure Magnetic Monitoring Electronics
121	13.3	Measure Ferromagnetic Shields at 4 K
122	13.4	Measure Ferromagnetic Shields at 1 K
123	13.5	Ferromagnetic Shield Understood
124	**14**	**3He Purification System**
125	14.1	Refurbish HMI Purifier
126	14.2	Test Purifier
127	14.3	Cycling Demonstrated
128	14.4	Produce Two Cell Fills of Ultrapure 4He
129	**15**	**3He Diffusion Coefficient Measurement**
130	15.1	Setup at FP 11a
131	15.2	Diffusion with Neutron Tomography
132	15.3	Data Analysis and Paper Writing
133	15.4	Publication of Results
134	**16**	**Evaporative 3He Removal**
135	16.1	Design Evaporation Chamber
136	16.2	Fabricate Evaporation Chamber
137	16.3	Design SQUID Sensor Geormetry
138	16.4	Fabricate SQUID Modifcations
139	16.5	Assemble Evaporation Chamber and DR
140	16.6	Measure 3He Removal Performance
141	16.7	3He Removal Understood
142	**17**	**Monte-Carlo Simulations**
143	**17.1**	**Cold Neutron Simulations LANSCE / SNS**
144	17.1.1	Transport Through Beam Elements
145	17.1.2	Beam State Selector
146	17.1.3	Transport in the Cryostat
147	17.1.4	Activation Neutrons
148	17.1.5	Cold Neutrons Simulated
149	**17.2**	**UCN and Light Collection Simulations**
150	17.2.1	UCN Absorption on 3He
151	17.2.2	Light Propogation in Cell Walls
152	17.2.3	Light Propogation in Guides
153	17.2.4	Light Collection Modeled
154	**17.3**	**Data Analysis Simulations**
155	17.3.1	Beta Decay Backgrounds Only
156	17.3.2	Complete Backgrounds Included
157	17.3.3	Importance of Background Quantified
158	**18**	**Project Development**
159	18.1	Conceptual Engineering
160	18.2	Pre-proposal Writing
161	18.3	Pre-proposal Submission to DOE
162	18.4	DOE Guidance
163	18.5	R&D Proposal Preparation
164	18.6	R&D Proposal Submission to DOE
165	18.7	Proposal Preparation
166	18.8	Proposal Submission to DOE
167	18.9	CDR Engineering
168	18.10	CDR Preparation
169	18.11	Conceptual Design Review
170	19	**Management**
171	19.1	Project Manager Before Construction
172	**20**	**Expendables**
173	20.1	LHe at LANL
174	20.2	LHe away from LANL