Project Description

September 20, 2004

1 Introduction

1.1 Status of Neutrino Oscillations and Next Steps

1.2 Reactor experiment: Contributions and comparisons

For a three active neutrino scenario, neutrino oscillations are described by six physics parameters: $\theta_{13}, \theta_{12}, \theta_{23}, \Delta m^2_{12}, \Delta m^2_{23}$, and the CP violation phase, δ. In addition, a full description also requires knowing the hierarchy of mass state 3 relative to 1 and 2, *i.e.* the sign of Δm^2_{23}. Of the six parameters, $\theta_{12}, \sin^2 2\theta_{23}, \Delta m^2_{12}$, and Δm^2_{23} are fairly well known and will be addressed with greater precision through the current and planned long-baseline programs (SuperK, Minos, T2K, Nova and CNGS). This leaves for determination θ_{13}, δ, the value of θ_{23}, and the mass hierarchy. Reactor measurements directly measure θ_{13} and are necessary to determine θ_{23}, which are prime ingredients needed in order to move towards determining δ_{CP} and the mass hierarchy.

The leading order dependence of the oscillation probability for reactor and long-baseline measurements is given by

$$P_{reactor} = 1 - P(\nu_e \to \nu_e) \simeq \sin^2 2\theta_{13} \sin^2\left(1.27\Delta m^2_{31} L/E\right) + \cdots$$

$$\begin{aligned} P_{long-baseline} &= P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(1.27\Delta m^2_{31} L/E\right) + \\ &+ \text{ Other terms with CP viol. and matter effects} \end{aligned}$$

The higher order corrections for the reactor probability are quite small for the Braidwood experimental layout and so a measurement of $P_{reactor}$ directly constrains the mixing parameter θ_{13}. On the other hand, the full expression for the long-baseline probability introduces many degeneracies and correlations between the physics parameters θ_{23} and δ_{CP}, plus the mass hierarchy through matter effects even before experimental uncertainties are taken into account [**?**, **?**]. Therefore, a measurement of $P_{long-baseline}$ corresponds to sizeable regions in the physics parameter space. For this reason, a reactor experiment is ideal for determining θ_{13} and, in combination with the offaxis data,constraining θ_{23}.

As will be shown in the following sections, the Braidwood experiment will have a sensitivity equal to or better than $\sin^2 2\theta_{13} = 0.01$ at the 90% CL. For most of parameter space, this experiment is better at constraining the true value of $\sin^2 2\theta_{13}$ than either the T2K or Nova experiments even with the intensity upgrades being proposed as shown in Fig. 1. The size of θ_{13} sets the scale for which the off-axis experiments can start to probe CP violation and the mass hieracrchy. A combination of T2K and Nova will start to give some information about these effects if $\sin^2 2\theta_{13} > 0.05$ and, as shown in Figure 2, with enhanced beam rates will have complete coverage if $\sin^2 2\theta_{13} > 0.01$. Thus, an unambiguous determination of $\sin^2 2\theta_{13}$ at the 0.01 level from a reactor experiment is a crucial ingredient in planning the strategy for a neutrino oscillation program, as well as for accessing the phenomenology of neutrino mixing.

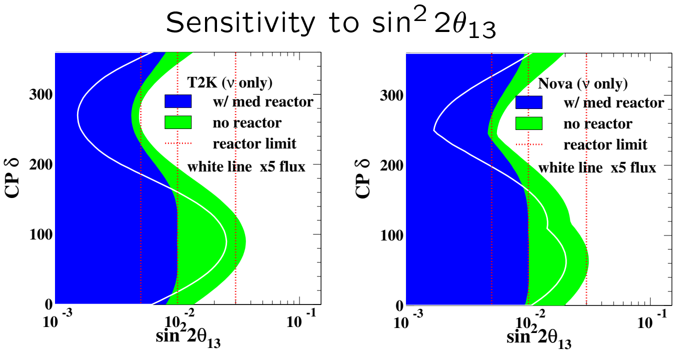

Figure 1: 90% C.L. upper limit regions for various oscillation measurements for an underlying null oscillation scenario where $\sin^2 2\theta_{13} = 0$ ($\sin^2 2\theta_{23} = 0.95 \pm 0.01$, $\Delta m^2 = 2.5 \pm 0.01 \times 10^{-3}$ eV^2 and $\delta_{CP} = 0^0$). The left (right) plot is for the T2K (Nova) long-baseline experiment. The vertical dotted line in each plot correspond to the 90% C.L. upper limit from a Braidwood reactor measurement. The grey region (white curve) is the 90% C.L. allowed region for the long-baseline experiments for a three year neutrino only run with nominal ($\times 5$) beam rate.

2 Strategy to reach sensitivity of $\sin^2 2\theta_{13} = 0.01$ in reactor experiment

2.1 Overview of Braidwood Experiment

In reactor oscillation experiments the oscillation is observed as a deficit of neutrino interactions near the oscillation maximum. The inverse β-decay process is used to identify neutrinos. In inverse β-decay an electron anti-neutrino interacts with a proton (a hydrogen nucleus in the mineral oil based target material) producing a positron and a neutron. The positron promptly deposits its energy in the scintillator and annihilates with an electron. The neutron thermalizes is and captured, releasing energy as the capturing nucleus works its way to the ground state.

In past reactor experiments the limiting sources of systematic error came from the uncertainty in the neutrino flux and inverse β-decay cross section. In this project these systematic limits are overcome by comparing the neutrino interaction rate in a detector which is near the oscillation maximum to an identical detector located closer to the source where the oscillation probability is very small. The resulting near to far comparison will allow a number of common systematic uncertainties, including flux and cross section, to cancel, thus permitting a precise relative measurement.

The Braidwood reactor oscillation experiment is designed to reach a sensitivity to $\sin^2 2\theta_{13}$ of $\sim$0.01 (Figure 3a show the sensitivity of the baseline configuration), with the capability to push below this limit in the longer term should the mixing angle turn out to be small.

In a reactor experiment with identical near and far detectors the effects that may limit sensitivity are the uncertainty in the background rate, the relative normalization of the near and far detectors, and statistics. The error due to background will be controlled with large cosmic ray shielding and with robust veto systems (section 2.2.3 and 2.2.4 AUTOMATE!!), that efficiently reject backgrounds and provide large samples of tagged background events that can be used measure the background rate and energy spectrum. The relative normalization error will be addressed with the implementation of rigorous controls during detector fabrication to ensure acceptance and total hydrogen content are nearly identical, the use of comprehensive calibration systems (section 2.3 AUTOMATE!!), and by using movable detectors for cross calibration (section 2.5.1). Finally, statistics will be improved, with respect to past experiments such as CHOOZ [?] and Palo Verde [?], by using larger detectors and a longer run.

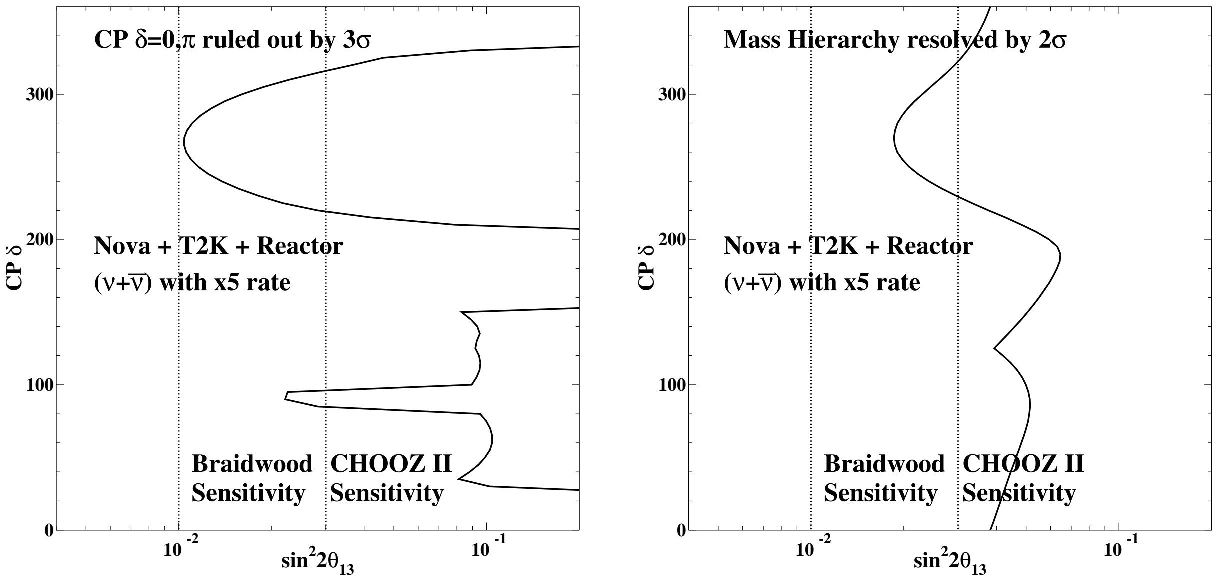

Figure 2: Regions of true CP phase δ versus true $\sin^2 2\theta_{13}$ where: (Left) a combination of data can observe CP violation at the three standard deviation level and (Right) the combination of data can resolve the mass hierarchy at the two standard deviation level. The assumed data is a combination the T2K, Noνa and a Braidwood reactor experiments. For both plots, the T2K and Nova data sets are assumed to be with upgraded beam fluxes ($\times 5$ the nominal rate) as would be expected with upgrades or a new proton driver. The vertical line in both plots represent the 90% C.L. $\sin^2 2\theta_{13}$ sensitivities for the Braidwood experiment. For these plots, $\Delta m^2 = 2.5^{-3}$ eV^2

We will endeavor to make the detector environments at near and far sites as identical as possible to facilitate understanding of the relative background rates from natural radioactivity and cosmic-ray spallation. Thus, each detector site will be located at a depth of 450 mwe in caverns excavated from low-radioactivity dolomite limestone with a uniform and well-understood overburden, taking advantage of the flat terrain around Braidwood.

Neutrino oscillation experiments using disappearance signals are very difficult and in the past have required additional information and redundancy to make them definitive. This has been clearly demonstrated in the Super-K atmospheric measurements where the oscillatory behavior was seen in the azimuthal dependence and in the recent KamLAND experiment where spectral distortion made the case. It is clear that redundancy is a key feature of a convincing experiment and we regard it as crucial to be able to measure

Source of Error	Error
Near to Far Detector Relative Normalization	0.6%
Far Detector Statistics	0.2%
Near Detector Statistics	0.04%
^{9}Li and ^{8}He Correlated Decays	0.2%
Other Background	0.5%

Table 1: Projection of the statistical and systematic errors. In considering the sensitivity of a simple counting experiment it is reasonable to combine these errors in quadrature. With a shape based analysis is one is less sensitive to relative normalization error and the background errors are improve with an understanding of the background energy spectrum. On the other hand greater statistics are needed in a shape analysis to get the bin-to-bin statistical errors low enough to be sensitive to small differences between bins.

the decrease in overall flux as well as the distortion of the $\bar{\nu}_e$ spectrum in order to firmly establish neutrino oscillations. This has led us to a design involving multiple, large (65 tons fiducial volume) detector modules which can be moved between near and far positions for both direct cross-calibration and for flexibility to optimize the configuration for the particular value of the mixing angle. Each detector module would be surrounded by a system of passive and active shielding, built within the caverns, to identify and suppress neutrons caused by muon spallation. Two such modules at each site will also allow redundant measurements under what should be "identical" configurations to directly verify that the inferred flux numbers are, indeed, reproducible at the anticipated level. Finally, the use of movable, self-contained modules will allow construction and testing to proceed at a surface facility in parallel with the civil construction.

The size of each module is based on the maximum, spherical volume (7 m in diameter) that can be easily accommodated within an 8 m diameter tunnel. The target volume will be filled with a mineral based scintillator and doped with gadolinium to enhance neutron capture. The target will be contained in a clear acrylic sphere of 5.2 m in diameter and is viewed by 1000 photomultiplier tubes (PMTs) attached to the outer steel vessel. The volume between the concentric steel and acrylic spheres will be filled with an undoped mineral oil that is intended to shield the target scintillator from radioactivity in the steel vessel and PMT glass. The use of large fiducial volume detectors is both economical and provides important handles on systematic uncertainties, such as the radial-dependence of radioactive backgrounds and external neutrons, with a large part of the fiducial volume located far from any containment walls.

Table 1 lists our reasonable expectations for the main sources of error. The projected sensitivity of the baseline detector and run scenario is shown in Figure 3a.

The large detector mass will allow a rapid, high statistics, relative flux measurement to be followed by a measurement of spectral distortion with an additional 2-3 years of running, should the value of $\sin^2 2\theta_{13}$ be greater than ∼0.01. We regard this capability as being absolutely essential to establish a believable observation, followed by a precision measurement of the mixing angle. Should $\sin^2 2\theta_{13}$ turn out to be smaller than 0.01 and no firm flux suppression is established after 2-3 years of operation, up to 4 modules (a total of 260 tons fiducial volume) could then be deployed at the far location, allowing a sensitivity to values below 0.01 to be reached with a further ∼4 years of operation. This scenario would correspond to an integrated exposure in excess of the so-called "Reactor II" model of reference [**?**] (sensitivity shown in Figure3b). This present proposal is unique in its design of a flexible system capable of reaching this level of sensitivity.

Another unique feature of the current proposal is that the significant overburden at the near site, together with the large detector mass, will allow the possibility for other physics topics, such as a precision measurement of $\bar{\nu}_e - e$ elastic scattering at MeV energies (section ???).

2.2 Backgrounds

2.2.1 Overview

The $\sim 30\ \mu$s coincidence between e^+ annihilation and n capture on Gd provided by the $\bar{\nu}_e p \rightarrow e^+ n$ signal reduces all serious background sources to a neutron capture on Gd in association with an uncorrelated or a correlated in-time energy deposition from another neutron or a radioactive decay in the detector. The correlated background has long been recognized as the most important. It arises almost entirely from cosmic ray muon spallation that creates the radionuclides ^{9}Li and ^{8}He inside the detector, and from spallation events in the experimental enclosure walls or shielding system that produce fast neutrons which then enter the detector. ^{9}Li/^{8}He each produce a neutron in their beta decays that mimics the antineutrino signature closely. Their 100-200 ms half-lives mean that it is difficult to veto these events by using a simple muon track coincidence without introducing prohibitive dead time. Fast spallation neutrons can enter the signal sample through a sequence of hard elastic scatters with protons in the detector that produce 1-8 MeV of visible energy, mimicking a positron signal, that is then followed by the capture of the neutron through thermalization. Spallation neutrons also dominate the uncorrelated backgrounds, which occur when a

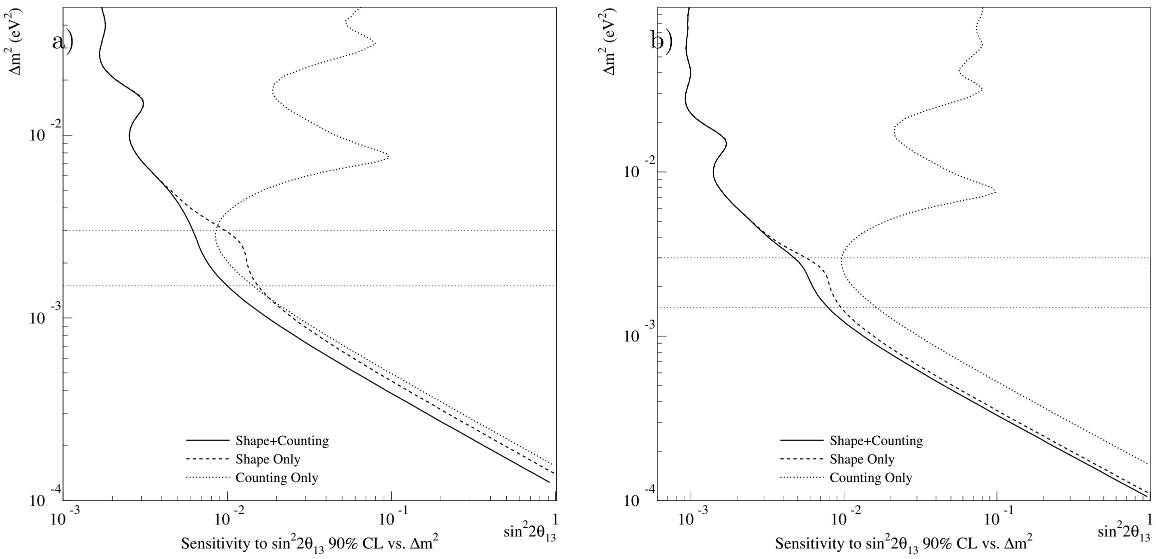

Figure 3: The 90% CL sensitivity to $\sin^2 2\theta_{13}$ as a function of Δm^2 for a) the baseline experiment (3 years, 130 tons of far fiducial mass), and b) for an upgraded exposure of 9750 GW·ton·years.

neutron capture by chance takes place in coincidence with an energy deposition in the detector initiated by radioactive decay or by an independent spallation event.

These neutron-driven background rates may be theoretically uncertain to $\delta B/B \sim 50\%$ for fast spallation neutron production, and perhaps a factor of 3 for radionuclide production. This places high demands on the signal-to-background ratio, perhaps $S/B \sim 100$ in each Braidwood detector after event selection cuts, in order to achieve an overall 1% sensitivity on $\sin^2 2\theta_{13}$, and, at the same time, calls for a designed-in capability to measure backgrounds in place. Despite these challenges, extrapolations from previous experiments and other studies indicate that these requirements can be met, provided that the detectors are at sufficient depth, that an effective active and passive shielding scheme is implemented, that radioactive impurity levels are kept under control, and that a robust triggering and data acquisition system is implemented.

The $\sin^2\theta_W$ determination calls for measuring the rate for $\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$ production without benefit of the positron-neutron capture coincidence. Requirements for the rejection and monitoring of spallation backgrounds are at least as high as for the $\sin^2 2\theta_{13}$ extraction; and substantially more stringent requirements on radioactive impurity levels must be imposed. The weak mixing angle measurement also necessitates development of more aggressive analysis strategies than for $\sin^2 2\theta_{13}$ that employ tight visible energy and reconstructed event vertex cuts. These issues are discussed elsewhere in this document.

The remainder of this section provides more details on background rate calculations; suppression strategies for fast neutrons, cosmogenic radionuclide sources, and intrinsic radioactivity; and in situ background measurement techniques.

2.2.2 Muon Flux and Neutron Production

All estimations of cosmogenic backgrounds require an accurate characterization of the muon flux at the detector. This mandates development of a good Monte Carlo generator tuned to external data and to the local geology as determined from bore hole samples (which are currently being obtained at the Braidwood site). Preliminary calculations[8] that employ a muon flux at the surface tuned to data and using GEANT4 to propagate the muons through a flat "standard rock" ($A = 22$, $Z = 11$, $\rho = 2.65$ g/cm^3) overburden appropriate for Braidwood yield flux and rate values for muons given in Table 2. The values are consistent at the 15% level with computations with the MUSIC[9] package that employ the Gaisser parameterization[10],

Quantity	D=300 mwe	D=450 mwe
$\bar{\nu}_e$ interaction rate– near detector	74 day^{-1}ton^{-1}	55 day^{-1}ton^{-1}
$\bar{\nu}_e$ interaction rate– far detector	1.8 day^{-1}ton^{-1}	1.8 day^{-1}ton^{-1}
mean muon energy	61 GeV	83 GeV
muon flux	0.46 m^{-2}s^{-1}	0.16 m^{-2}s^{-1}
6.5 m detector muon rate	15 Hz	5.4 Hz
inclusive neutron production rate	303 day^{-1}ton^{-1}	138 day^{-1}ton^{-1}
6.5 m detector neutron rate	0.39 Hz	0.18 Hz
^{12}B/^{12}N production per day	8.0 day^{-1}ton^{-1}	3.7 day^{-1}ton^{-1}
^{8}He/^{9}Li production per day	0.034-0.15 day^{-1}ton^{-1}	0.016-0.07 day^{-1}ton^{-1}

Table 2: Muon and cosmogenic neutron properties expected at two candidate Braidwood depths. Muon rates and energies are from Ref. 8. Inclusive neutron rates are obtained by convolving these muon rates with production spectra from Ref. 12. The upper numbers for radionuclide rates are obtained by assuming the same excluse/inclusive production ratios at KAMLAND as obtained from Ref. 13. The lower rates are from Horton-Smith's model described in Ref. 14.

and with determinations by CHOOZ[11] for similar depths.

Muons with energies between 50-200 GeV, the energy range where the muon flux peaks, produce neutrons through several processes of comparable importance, including direct muon-spallation, nuclear photodisintegration, and spallation by secondary pions and neutrons from muon-nucleus induced hadronic showers. Inclusive production rates are estimated by convoluting cosmic ray muon spectra with neutron muo-production formulae provided by Wang et al[12].

Of particular interest are the long-lived $\mu+^{12}C,^{13}C$ spallation products ^{9}Li$\big(Q = 13.6$ MeV, $\tau_{1/2} = 178$ ms$\big)$ and ^{8}He$\big(Q = 10.7$ MeV, $\tau_{1/2} = 119$ ms$\big)$, with 49.5% and 16.1% branching fraction $\beta + n$ decay modes, respectively. The correlated electron ionization/neutron capture signature from these radionuclides can easily mimic the $\bar{\nu}_e p \rightarrow e^+ n$ signal. Furthermore, the decays occur so long after the passage of the initiating muon track that simple veto schemes are ineffective in removing them from the signal sample. Production estimates for ^{9}Li/^{8}He are obtained by assuming that the ratio of radiocuclide to inclusive spallation neutron is the same as in KAMLAND[13]. The radionuclides ^{12}B $\big(Q = 13.4$ MeV, $\tau_{1/2} = 20.2$ ms$\big)$ and ^{12}N $\big(Q = 17.3$ MeV, $\tau_{1/2} = 178$ ms$\big)$ production rates are given as well since they provide spallation rate monitors and serve as useful calibration sources; their rates are estimated by the same procedure. Horton-Smith has argued[14] that this technique overestimates radionuclide production rates at shallow sites (in particular, Chooz) by a factor of $4 - 5$ because the bulk of the production at KAMLAND is due to hard secondary neutrons spallating nuclei in the detector; and the production rate for these energetic secondaries decreases more rapidly with energy than the inclusive neutron rate in scaling to the softer cosmic ray spectra of Braidwood or Chooz.

2.2.3 Fast Neutron Shielding

Fast neutron correlated backgrounds can be reduced by combination of active and passive shielding that surrounds the detector. Active shielding in the form of scintillation counters or wire chambers, provides a muon veto and muon tracking information for use in offline analysis. The ~ 1 mwe of passive shielding between the active shield and that detector and the ~ 90 cm thick outer buffer layer of mineral oil inside the detector attenuates the flux of spallation neutrons reaching the detector from the surrounding rock. Several R&D tasks must be carried out to optimize the shielding, including: (1) establishing the required size and coverage of the active shield; (2) establishing whether the passive shielding needs to provide 4π coverage; (3) establishing whether the active shielding must extend beyond the enclosure walls, especially along the top; (4) establishing the required veto efficiency of the active shield; (5) establishing the tracking resolution needed for the active shield; (6) choosing the best technology choice for the active shield; and (7) determining how the shielding is to be installed and supported– especially the $\sim$ 100 tons above the detector and the $\sim$ 100 tons that will need to be moved in place between the detector and the surface shaft once the detector is installed.

2.2.4 Suppressing Cosmogenic Radionuclides

Backgrounds from spallation-produced radionuclides produced inside the detector are harder to eliminate due to the long half-lives of ^{9}Li and ^{8}He and the nearly identical detector response of these correlated $\beta - n$ decay pairs to the e^+n antineutrino production signal. Fortunately, measurements at CHOOZ[11] and KAMLAND[13] indicate that ^{9}Li/^{8}He cross sections are tolerably small ($S/B \gtrsim 10$ with no cuts); and there are some prospects for improving the precision of these measurements on the short term at KAMLAND. It would be valuable, however, to obtain further constraints on these and other radionuclide production rates at depths more similar to Braidwood's at something like the VSPLAT facility.

Possible extra handles[13] that might be available using the data itself include: (1) an ability to remove events off-line in which the positron-like primary ionization signal is spatially correlated with the track position of a muon passing through the detector within a specified time window before the event of interest, and (2) an ability to remove events offline in which the neutron capture is correlated with a muon-induced shower detected either in the detector or the veto system. Implementing the former procedure requires study of the muon tracking resolution, the neutrino detector vertexing resolution, the optimal time window, and the data acquisition scheme. Implementing the latter requires similar studies plus development of a procedures to identify a muon-induced shower using the veto system either alone or with the neutrino detector.

In principle, it is possible to discriminate via pulse shape analysis neutron-generated proton recoils from the ionization/annihilation signal from $\bar{\nu}_e$-induced positrons, although this technique has enjoyed limited use to date. Implementing this scheme in Braidwood would require an R&D program in fast neutron and recoil proton response in the scintillator. oil, and a method to monitor and calibrate the technique during actual data taking.

2.2.5 Controlling Intrinsic Radioactivity

Beta and gammas from U, Th, and K decay chain products in the PMT glass, scintillator., support structures, and atmosphere can produce $\geq$ 1 MeV energy depositions in the detector that can form an accidental coincidence with a stray neutron produced by neutron spallation in the external rocks. For the $\sin^2 2\theta_{13}$ measurement, procedures must be developed to limit U/Th levels to $\sim 10^{-12}\left(10^{-10}\right)$ g/g concentrations in the scintillator(acrylic); the tolerances for K are two orders of magnitude looser. These levels are well above those achieved by KAMLAND, BOREXINO, and SNO (although these experiments do not use Gd-doped scintillator.); and they have been achieved in the past by the Palo Verde and Chooz experiments. A procedure must be developed to insure that the Gd does not carry contaminants into the system; this will likely require a method for cleaning the scintillator. and Gd separately before making the final mixture, as was done in Palo Verde and Chooz. Assuming these levels can be achieved in the scintillator and acrylic, then the singles rate is expected to be dominated by PMT radioactivity, where K(U/Th) levels of 60 ppm(30 ppb) can be achieved using low radioactivity glass. The critical detector parameter for determining the singles rate from radioactivity is the thickness of the outer mineral oil buffer. This must be studied carefully using Monte Carlo techniques both to optimize the overall experimental S/B (a thinner buffer means more signal and more background), and to account for the complicated PMT geometry at the outer wall, the mineral oil-acrylic wall interface, and other non-trivial material and geometric effects

2.2.6 *In Situ* Monitors

Background rates *must* be measured; and it is therefor imperative to design the triggering and data acquisition system to tag and record as many of the important types of these interactions as possible. For both types of spallation backgrounds this can be accomplished by ensuring that the data acquisition system is capable of tagging muon tracks in coincidence with a delayed neutron signature. Issues to decide include the aforementioned required tracking resolution of the veto system and the specific triggering schemes. Extending the area of the active veto beyond the size of the enclosure roof would permit better studies of fast neutron production in the surrounding rock.

Uncorrelated background rates can be measured in the data by examining neutrino candidate events in which the neutron-like energy signal comes in at many capture time constants after the positron-like signal, or by selecting events using the "swap" technique[15], wherein the positron selection criteria are interchanged with the neutron selection criteria. An ability to tag the 164(0.3) μs time correlated ^{214}Bi-^{214}Po(^{212}Bi-^{212}Po) $\beta\alpha$ decays from the ^{238}U(^{232}Th) chain will allow constraints to be placed contributions from radioactivity in the oil and acrylic.

2.3 Calibration

For a two-detector reactor experiment, we need only understand the differences in acceptance between the two, and not the absolute detection efficiency. The detection efficiency ultimately depends upon what cuts we choose in our final analysis, but we will assume here only cuts on the positron and neutron energies and the coincidence time between the two detectors. The difference in overall detection efficiency between the two detectors then depends primarily on a small number of response parameters:

1. The number of hydrogen targets
2. The Gd loading fraction
3. Scintillator light output, including aging effects
4. Detector optics, including the attenuation lengths of the different media (five for a three-zone detector, three for two-zone), PMT angular and wavelength response, Rayleigh scattering, and diffuse and specular reflection off of all media
5. Number of working PMT's, as well as their individual gains and efficiencies
6. Number of working electronics channels and individual efficiencies
7. The livetime of each of the two detectors

All of these items may change with time, and furthermore can create position dependences within the detector which in turn may depend on time. The parameters can be measured individually and then used in the context of a detector model (such as a Monte Carlo simulation) to predict the relative detector efficiencies, or they can be measured in an integral way by using a source identical or nearly so to the antineutrino signal. In practice, we expect that we will use both approaches, and in so doing not only be able to calibrate the two detector efficiencies relative to one another but determine the systematic uncertainty on the calibration.

The primary goals of the calibration program are therefore:

- To measure differences in the two integral detector responses directly through radioactive source deployments, *in situ* calibrations (spallation products and neutrons from reactor antineutrinos), and possibly detector movement
- To measure the individual response parameters in order to build detector models for use in the efficiency calibration and the determination of the relative systematic uncertainties between the detectors
- To provide an analytic form of the detector response so that each event's measured PMT hits, charges, and times can be re-mapped into event energy [1]

[1] We note that with a two-detector experiment, such an explicit reconstruction of event energy is not strictly necessary. The differential response function for the two detectors can be cast to map neutrino energy into observed hits and charges, rather than into observed energy, removing the energy calibration step.

For the first goal, we will need to be able to deploy various radioactive sources at many positions within the volume of both detectors (using the same physical source for each detector). We also need to be able to accurately tag cosmic-ray spallation products, so that they can be used as calibrations and checks which can illuminate the entire active detector volume.

For the second and third goals, we will need to deploy optical sources of various wavelengths both inside and outside the active volume, at as many points as are necessary to measure the bulk optical properties of all the detector media. We will also need to develop a full detector model which includes the light generation (both scintillation and Cerenkov light), propagation (using the measured optical parameters), and detection.

2.3.1 Proposed Work

Well before the design of the detectors and calibration systems, several basic questions need to be answered: How many positions within the detector volume will sources need to be deployed? How well does the angular and wavelength distribution of optical sources need to be known—and how well can they be known in a low-cost, practical system? How well must the source position be known to calibrate the position-dependence of the response functions? Can there be differences between the detectors which are not seen by *in situ* calibrations like the inverse β-decay neutron capture peaks, and cosmic-ray spallation nuclei? How well matched do radioactive sources need to be to the expected signal and backgrounds, in order to be useful?

Much of the work to answer these questions will necessarily be done by simulation. For such a simulation to be useful, it must be based upon input parameters taken from measurements of the actual detector media. We would therefore like to being a research program whose goal is the measurement of many of these properties, and we list the many of the most important of these below.

<u>Photomultiplier Tubes</u>

Based upon the experience from detectors like the Sudbury Neutrino Observatory, we believe that a large part of the point-to-point variations in response will be due the response of the PMT's to light at different angles. For events occurring near the edge of the active volume, the near-side PMT photocathodes will on average be illuminated by high incidence angle photons. For events nearer the center, the photons tend toward normal incidence. The position sampling we will use for source calibrations will therefore depend on how steep the PMT response is with incidence angle, and this response is something we must measure now.

In addition to angular response, to build a complete model we will need to measure the charge and timing spectra (including any late- and pre-pulsing) for the various PMT's we may consider using in a complete experiment. Stability issues—such as the gain variation as a function of high voltage setting or PMT age, the PMT noise rates as function of temperature, light illumination, and age, and possible failure modes all need to be investigated and measured.

<u>Scintillator</u>

The model we use to predict the source response within the detector (which will be used to determine which sources are needed for calibration and what we can learn from them) depends directly upon the distribution of scintillation photons as a function of particle energy and species. We therefore need a measurement of the scintillator photon creation as soon possible.

The attenuation length, scattering length, and index of refraction all need to be measured and optimized for a full detector.

If the scintillator can change either in its optical or light creation properties, the two detectors may evolve separately. We therefore need to begin studies of how much the scintillator does change, in what ways it changes, and how predictable the changes are.

The scintillator timing for various mixtures also needs to be measured and input to the simulation, to determine how well the position of events can be reconstructed.

The neutron capture efficiency as a function of the Gd loading will also be critical for the simulation model, and will help to tell us how well we need to measure the capture efficiency between the detectors and the time dependence (if any) of that efficiency.

In addition, we will need to develop of a directly way of measuring the source strength of our neutron source (either an Americium-Beryllium source and/or a ^{252}Cf source) to much better than 1%, so that the relative capture efficiency between the two detectors can be measured and checked.

Acrylic and Oil

The same optical properties which need to be measured for the scintillator will need to be measured for the remaining media in the detector. For a 3-zone detector, the unloaded scintillator will also have to be measured.

2.4 Two-Zones vs. Three-Zones

We have adopted in this proposal a 'baseline design' which has two inner zones: an active Gd loaded scintillator volume, and an outer mineral oil volume. Although we believe that in a two detector experiment a two-zone design is superior to the three-zone designs discussed by other groups [**?**], part of our work under this proposal will be to determine both the efficacy of the two-zone design and the relative cost implications of two- and three-zone designs.

The motivations for a three-zone detector seem on the face of it to be excellent: the middle volume filled only with scintillator 'flattens out' the radial dependence of the energy response to neutrons. Figure 4 illustrates the basic idea. The top panel of the figure shows the energy response for neutron captures as a function of the volume-weighted radius $R_V^3 = (R/R_{\rm av})^3$ in a two-zone detector. The 8 MeV Gd capture peak and the 2.2 MeV H capture peak are clearly visible. There is also a 'wash' of events falling away from the Gd peak which becomes more populated as R_V^3 gets closer to 1.0. By contrast, the bottom panel of Figure 4 shows the response for a three-zone detector, and we see that the entire tail on the Gd capture peak is confined to a very narrow region near $R_V^3 = 1.0$. The basic point is well-known: the middle scintillation region of the three-zone detector 'catches' the neutron-capture γ rays which otherwise would leak into the mineral oil buffer and produce relatively minimal Cerenkov light.

Understanding the neutron response in the two-zone detector is therefore in principle more difficult—small changes in the detector's optical and energy response can lead to relatively large changes in the number of detected neutrons, as the tail moves above and below the analysis threshold for neutron detection. We might therefore expect that the calibration requirements for a 1% disappearance measurement are more manageable in a three-zone detector.

The second motivation for a three-zone detector is that events created near the edge of the loaded volume can produce positrons which leave and annihilate outside. In a two-zone detector, the annihilation γ's for such positrons can produce at most a single γ which interacts in the scintillation region, thus the annihilation 'edge' at 1 MeV in the positron spectrum is broken, and the positrons can leak down to zero energy. In a three-zone detector, these events only occur at the edge of the middle region, and are thus eliminated simply by requiring the neutron energy to be consistent with Gd capture.

The third motivation for a three-zone detector is that the middle scintillation region provides an additional way of tagging fast neutrons. A large fraction of these will produce a recoil proton in the middle scintillation region before entering the inner loaded scintillation volume. These events can then be cut by the tag from the middle region, even if they produce a time-correlated event pair in the inner region.

All of these motivations are well-grounded, but become far less compelling in a two-detector experiment in which only *relative* response uncertainties matter. For example, an understanding of the neutron response can be made using the neutrons themselves—the neutron peak is narrow enough that it provides an excellent measure of the overall detector response. Most importantly, unlike any potential calibration source, the neutrons integrate over the detector volume and livetime in exactly the way we need. In our simulations, we have found that matching the neutron peaks between the near and far detectors reduces even huge (10%) differences in the energy scale between the two detectors, and we are investigating whether we can also use the overall shape of the neutron peak to investigate potential scale non-linearities.

Our simulations have also shown us that the total positron leakage below the annihilation edge in a

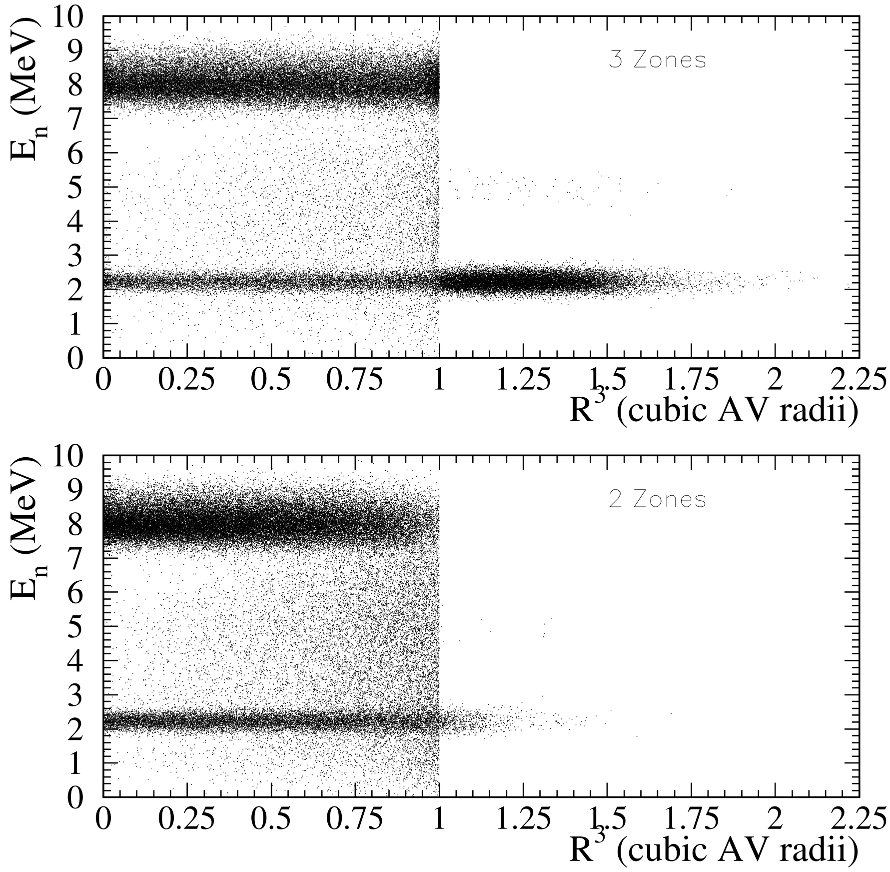

Figure 4: Simulated energy of neutron capture events vs. R^3, where $R^3 = 1$ is the radius of the inner scintillation volume.

two-zone detector is a few percent or less (and of course gets smaller with a large fiducial volume), and depends almost entirely on geometry. We expect therefore to know this already small fraction very well.

The middle region in a three-zone detector which tags the external neutrons can be effectively replaced in a two-zone detector just by a larger fiducial volume. The events which would have produced recoil protons in the middle volume followed by a coincidence pair in the inner volume will now produce a triple and therefore be tagged in a two-zone detector just as effectively.

The three-zone detector also has many drawbacks. In addition to the obvious construction difficulties, the three-zone detector introduces two new optical media (the scintillator and its container) which will need to be calibrated in order to understand the response to the neutrino signal and backgrounds (there is no neutron signal which can be used in the middle volume). The optical calibrations cannot be done by sources only in the mineral oil buffer and the inner volume—there is no way to untangle the covariances in the attenuation lengths. Sources will have to be deployed in the middle volume, and how this could be done (and with what cost in mechanical apparatus) would have to be explored. The new media will also attenuate the light somewhat, reducing the energy resolution and making it somewhat harder to see the positron annihilation edge or to separate signal from background. Lastly, the addition of a container for the middle volume also has the danger of adding backgrounds and increasing the accidental rate.

2.5 Cross Checks

The relative normalization of the near and far detectors is sensitive to several parameters: the target hydrogen density, the target volume, the detector efficiency, and the energy scale calibration through analysis cuts. In-situ calibration systems — such as radioactive sources, and laser or lead light sources — will play a large roll in understanding the efficiency and energy scale, but the hydrogen density and target volume cannot be determined in this way. The Double-CHOOZ collaboration [?] has proposed using various control and measurement procedures during detector assembly to ensure that the target vessels and target chemistry are identical, but even in their best case scenario they are only able to get the uncertainty on the relative normalization down to 0.6%. While we intend to implementing similar procedures during assembly, the Double-CHOOZ plan does not provide a way to verify that the assumed precision of these methods is correct. The plan for Braidwood is to construct movable detectors which will allow an independent, high precision measurement of the relative detector normalization.

2.5.1 Moving Detectors

The reactor neutrino flux itself provides one of the best means of determining the relative normalization of near and far detectors. The neutrino interactions sample the detector volume uniformly, and the energy, spatial and temporal characteristics of the events are, by definition, exactly matched to the events under study. The trick is to use the near detector site, where the interaction rate, or flux, is 30 times larger than at the far site. By placing two detectors side-by-side in the near detector hall where both detectors experience the same flux, one can determine their relative normalization ($\equiv \frac{N_1}{N_2}$), at that moment in time, with the statistical precision determined by the number of events observed:

$$\sigma_{relative} = \sqrt{\frac{1}{N_1} + \frac{1}{N_2}} \approx \sqrt{\frac{2}{N}} \qquad (1)$$

where N_1 and N_2, the number of events observed in detectors 1 and 2, are approximately equal ($N_1 \approx N_2 \equiv N$), as would be expected for identical detectors. Given the Braidwood neutrino flux, the baseline detector size and near site location, an uncertainty of 0.25% could be achieved in fewer than 100 days of side-by-side calibration running (less than 10% of the proposed experimental run).

Using this direct measurement of the relative normalization in conjunction with concurrent measurements of the detector efficiency and energy scale, one can determine the target volume and hydrogen content. If the target temperature is maintained at a consistent value, the hydrogen content and target volume should be constants. Therefore these measurement values can be used to determine the relative normalization to high precision even when the far detector is located in the far position.

If during the course of the experiment the detector efficiency can be shown to be stable and the analysis, which is insensitive to any fluctuations in the energy scale calibration, can be defined then the uncertainty in relative normalization will reach the lower limit set by the side-by-side calibration. This hypothesis could be firmly established by comparing side-by-side calibrations runs taken early in the experimental run to those taken at the end.

2.5.2 Multiple Detectors

The requirement of movable detectors puts limits on the detector size and weight. These limits are set by shaft and tunnel apertures, and by the capacity of the crane or other lifting system. Multiple detectors allow one to achieve the desired target mass within the constraints set by a practical and cost effective facility design. In the Braidwood experimental baseline, two far detectors are assumed. Each detector is 7 m in diameter and weights about 165 metric tons. The corresponding target mass is 65 tons per detector or 130 tons total target mass. The baseline also calls for two near detectors. The use of multiple near detectors is motivated primarily by the potential to measure the weak mixing angle. Multiple near detectors may also be advantageous for testing the transferability of calibration methods against the neutrino flux.

If the relative normalization uncertainties between n far detectors are uncorrelated, when the results from the different detectors are combined the overall effective relative normalization is reduced by $\frac{1}{\sqrt{n}}$. The requirement of uncorrelated uncertainties is satisfied if the uncertainty come from independent measurements such as separate side-by-side calibration runs.

Multiple-movable detectors allow for greater flexibility in operating the experiment. For example, if it turns out that $\sin^2 2\theta_{13}$ is very small, then it is possible to redeploy the second near detector as a far detector (or to build additional far detectors) to increase sensitivity to the spectral shape distortion [**?**]. Figure 3b shows the sensitivity to $\sin^2 2\theta_{13}$ as a function of Δm^2 for a scenario where the first two years of the run there are two far detectors and the next four years there are four far detectors. In this configuration the experiment is sensitive to values of $\sin^2 2\theta_{13} \sim 0.005$ to 0.008 in the allowed range of Δm^2. This scenario corresponds to an exposure of 9750 GW·ton·years, which is 20% larger then the shape deformation sensitive example from Huber *et al.* [**?**], known as "Reactor II."

2.6 Questions and proposed R&D

If the Braidwood experiment is to be done in timely fashion, three areas will require substantial R&D support during the coming year. These areas, discussed in detail in Sections 3.1?? - 3.3?? below, are: 1) engineering studies to prepare an accurate cost estimate and schedule for civil construction at the Braidwood site; 2) mechanical engineering for the spherical detectors and their support and transport; and 3) R&D on the properties, stability, chemical compatibility and large-scale production and handling of Gd-based liquid scintillator.

Complementary to these major projects are investigations of important questions that can be pursued by collaborating institutions largely with funds from their base grants. Most of these investigations involve simulations or obtaining data for inputs to simulations; they are ideally suited for supervised participation by undergraduates. Support of these undergraduates is an important part of the education and outreach component of this proposal.

The paragraphs below present questions to be addressed by these 0smaller-scale investigations.

Detector design. As discussed in Section 2.5??, the baseline detector design has two zones, rather than the three zones discussed by other groups. The two-zone design has distinct advantages in simplicity of construction and deployment of calibration sources, and preliminary studies indicate that its performance will be satisfactory in an experiment in which uncertainties in relative (rather than absolute) detector response matter. But before we commit to this baseline design, we must explore its implications carefully with more detailed simulations. So far, most of our results have come from a fast parametric Monte Carlo program; these results must be confirmed and extended with a full GEANT4 simulation, a major task. In particular, the issues of blurred positron threshold and possible compromising of the ability to tag fast neutrons must be thoroughly investigated. Significant Monte Carlo studies will also be devoted to optimization of various detector parameters, such as mineral oil buffer thickness and photocathode coverage.

Backgrounds, muon veto/tagging system and neutron shielding. As discussed in Section 2.2??, the ability of the detectors to reduce uncertainties from backgrounds must be thoroughly understood through careful simulation studies of cosmic-ray spallation processes and radionuclide (^{9}Li and ^{8}He) generation.It is especially important to design the detectors and muon veto/tagging systems to measure background shapes and magnitudes *in situ*. R&D questions in this category (presented in Section 2.2??) include issues of optimal coverage of active and passive shielding, tracking resolution and technology, and engineering of support structures.

Calibration. Intercalibration of detectors (discussed in Sections 2.3?? and 2.4??) will use three standards: radioactive sources, optical sources, and *in situ* signals from cosmic-ray spallation products and neutrons from reactor antineutrinos. Detailed questions for investigation include: How reliable and precise are energy calibrations with radioactive sources? How precise is neutron capture relative efficiency calibration with sources? How many source positions are necessary? How well must we know the positions of sources and the angle and wavelength distribution of optical sources? How will sources be deployed? Can there be differences between detectors that do not show up in *in situ* calibrations?

Scintillator properties. In addition to the substantial R&D project of developing and mass-producing a suitable Gd-doped scintillator, the characteristics and responses of the scintillator(s), and also of the non-scintillating oil, must be measured and characterized for inputs to simulations. These properties include: radioactivity levels; scattering and extinction lengths and index of refraction as a function of wavelength; Gd-capture probability and aging properties as a function of Gd loading and mixture; median and distribution of scintillation light output (including quenching effects) for positrons, electrons, gammas, neutrons, and recoil protons; and time spectrum of generated light.

Photomultipliers. Detailed measurements of sample PMT's must be made to select a vendor and to characterize them for input to simulations. Quantities to be studied include quantum efficiency; background radioactivity; dependence of PMT gain on high voltage, and gain stability and sample-to-sample variations; rates, spectrum, and dependence on temperature and on-off cycling of dark noise; "flashing" probability; failure modes; timing characteristics such as transit-time jitter and pre- and after-pulsing; wavelength-dependent angular response; and light reflection coefficients.

Electronics. Possible architectures for readout electronics must be evaluated for suitability and cost. It appears attractive to record the amplitude of signals from each PMT as a function of time, during a time window centered on a trigger. It is planned to test candidate systems with a laboratory prototype of the detector using the baseline scintillator and photomultiplier tubes. Most of this work can be done with funds already available.

Alternative design concepts. Members of the Braidwood collaboration are interested in investigating alternative designs that use measurements of both Cherenkov and scintillation light to suppress backgrounds. This might be done with a slow scintillation mixture with somewhat lower light production levels in order to separate the prompt Cherenkov signal with timing information. The effective photocathode coverage would have to be increased to $\sim$50% with more PMT's and light concentrators. The potential advantages of this technique are: 1) eliminating the recoil proton signals by which fast neutrons can produce correlated background, and 2) direct tagging of positrons, especially at low energies, since their annihilation would yield another ∼MeV of visible energy in the scintillation signal, but none in the Cherenkov component since the resulting scattered electrons from the annihilation gammas would be below threshold.

3 Elastic Scattering Measurements at Reactor Experiments

The availability of a high statistics, high precision reactor neutrino experiment provides an ideal environment to search for new exotic physics. In particular, one can use neutrino-electron scattering to make precision tests of what is predicted by the Standard Model. Neutrino-electron scattering is sensitive to one of the most fundamental parameters in the Standard Model of particle interactions, the weak mixing angle. Deviations from theoretical prediction would be evidence of new physics processes at work.

The differential cross-section for $\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$ scattering is given by the following expression [1]:

$$\frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi}[(g_V + g_A)^2 + (g_V - g_A)^2(1 - \frac{T}{E_\nu})^2 + (g_A^2 - g_V^2)\frac{m_e T}{E_\nu^2}] + \frac{\pi\alpha^2\mu_\nu^2}{m_e^2}\frac{(1 - T/E_\nu)}{T} \tag{2}$$

where E_ν is the incident $\bar{\nu}_e$ energy, T is the electron recoil kinetic energy, and the vector and axial vector coupling constants are given by:

$$g_V = 2\sin^2\theta_W + \frac{1}{2} \qquad g_A = -\frac{1}{2} \tag{3}$$

The electron scattering cross-section allows a direct measurement of the weak mixing angle θ_W. As such a process is purely leptonic, it is void of uncertainties associated with nuclear structure or strong interactions. A high precision future measurement of the weak mixing angle is motivated, in part, by the result report by the NuTeV experiment, who measures a 3σ deviation from Standard Model predictions [2]. Various exotic models to explain the measurement have been put forward, and those which best explain the result require a follow-up experiment which probes the neutral weak couplings specifically using neutrinos. The proposed measurement is also interesting as an additional precision study at $Q^2 = 4 \times 10^6$ GeV^2. The two existing low Q^2 measurements are from atomic parity violation [3], and Moller scattering [4]. A careful, controlled measurement of neutrino-elastic scattering should provide a measurement of the weak mixing angle at the level of 1%.

The technique of using reactor neutrinos to measure the weak mixing angle measurement has been pioneered by Reines, Gurr, and Sobel [5]. The weak mixing angle measurement comes mainly from tagging electrons that possess an energy greater than 3 MeV. Above this energy threshold, many of the environmental backgrounds are reduced or removed entirely. In order to make a precision measurement, the incoming neutrino flux has to be known to better than 0.5%. Current uncertainties in nuclear fuel burning limit one's knowledge of the neutrino flux and spectrum to no better than 2%. Thus, it is necessary to use inverse beta decay events ($\bar{\nu}_e + p \rightarrow e^+ n$) as a normalization constraint. These events can be tagged by the subsequent neutron capture on Gadolinium. The inverse beta decay cross-section for low energy neutrinos is given by the following expression:

$$\sigma(E_{e+}) = \frac{2\pi^2}{m_e^5 f \tau_n} p_{e+} E_{e+} \tag{4}$$

Here, $E_{e+}(p_{e+})$ is the energy (momentum) of the outgoing positron, f is the free neutron decay-space factor, and t_n is the neutron lifetime. The total uncertainty on the cross-section is 0.2%, making it an ideal process by which to normalize electron scattering events.

To reduce the uncertainties associated with neutrino electron scattering, careful control must be placed on the backgrounds and systematics associated with counting the number of electrons and their subsequent recoil energies. Further details regarding background rejection and error reduction techniques can be found in Reference [6]. A total uncertainty of 1.3% is, in principle, achievable with sufficient flux, adequate overburden, and a careful calibration program. We believe such a measurement will greatly complement a θ_{13} measurement program at reactor experiments.

In addition to being a direct probe to the weak mixing angle, neutrino-electron scattering is also sensitive to other exotic physics. More notably, the differential cross-section $\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$ depends also on the neutrino magnetic moment, μ_ν. The Standard Model prediction for the neutrino magnetic moment is very small, $\mu_\nu \sim 10^{-19}\mu_B$. Thus, a positive measurement of μ_ν beyond this prediction would be a strong indication of new physics. The current limit from reactor experiments on the neutrino magnetic moment is less than $1.3 \times 10^{-10}\mu_B$ at the 90% confidence level [7]. Reactor experiments may be able to probe at this level of sensitivity or greater.

The precision measurement of the antineutrino-electron elastic scattering cross section has more stringent requirements on certain detector issues, such as contamination levels and energy calibration, than the oscillation measurement. R&D on these issues will proceed over the next two years, and modest funding for this is being requested separately as a part of base grant proposals. Here we provide some initial information on these studies.

With respect to contamination, the issue is U and Th, since the measurement is restricted to the 3 to 5 MeV range. Purification of scintillator to the requisite level is well understood from KamLAND and Borexino experience. However, the question of U and Th contaminants in the rare earth metal Gd, used as a dopant, remains open. For a similar rare earth metal, Yb, a satisfactory contamination level of 10^{-12} has been achieved, leading us to believe that with R&D this can also be attained with Gd using similar methods. Even less contamination is desirable and so work will continue to aim for purities beyond the 10^{-12}.

On energy reconstruction, it is desirable to find a method which an calibrate the detector in the energy window for both β^+ and β^- events. Possible sources and methods for deployment are under consideration. The plan is to bench test these ideas over the next year. The ambitious goal is 0.3% (for comparison, SNO calibrated their detector energy scale to 1%).

Other issues are also under study. One example is fiducial volume error, which is greatly reduced by the fact that we are measuring elastics scatters with respect to the inverse beta decay rate. Another is spallation issues, which may lead us to narrow our energy window to 3.5 to 5 MeV, which sacrifices statistics for better control of the spallation, as well as reducing the background from contamination.

4 Proposed Engineering and R&D for Cost and Schedule Determination

In the following sections, we Engineering and R&D tasks for which funding is requested in this proposal.

4.1 Proposed civil engineering

4.1.1 The Braidwood Site

The Braidwood Nuclear Station is located about 90 km southwest of Chicago. The plant is built next to an old coal strip mine which has been converted into a cooling lake. The terrain at Braidwood is very flat with a change in elevation of less than two meters over the region of interest. The plant consists of two reactors each with a rated maximum thermal energy of 3586 MW. Averaged over the last eight years both reactors have operated with a capacity factor of greater than 90% and capacity factor has continually improved throughout this period. The two reactors are separated by about 100 meters running north-south (see Figure 5). The reactors sit in the middle of a rectangular security area. All experimental facilities must be located outside this security fence. Outside the fence, the point of closest approach is on the east side at a distance of about 200 meters from the reactors.

To achieve the required cosmic ray shielding, the detectors will be located at the bottom of shafts, one at the near site and one at the far site. (Figure 6 shows the proposed layout of the facility.) The shafts will be dug to a depth of 115 to 170 meters (300 to 450 meters water equivalent (mwe)). Geological data collected during the planning and construction of the plant [16] show a rock formation, known as the Galena/Platteville, that begins at a depth of about 85 meters and extends to nearly 200 meters. The Galena/Platteville formation is made up of dolomitic limestone, a rock type that is typically good at supporting tunnel structures. In addition, the radioactivity of limestone is typically low compared to most other rock types. The low intrinsic radioactivity of this specific rock group is confirmed by several gamma surveys performed during the original site characterization studies [16]. It is in this layer that the detector rooms will be constructed. The actual depth will be determined by the results of a core boring study that is currently in progress. The rock cores and bore holes will provide data on rock strength and water flow rates which will be used to determine the feasibility and cost of civil construction and maintenance as a function of depth. From a physics point of view, deeper shafts are preferable since background rates and dead time decrease with depth. On the other had, depth may be a cost driver for the experiment and it may not make sense to go below where background uncertainties are the limiting systematic. Continuing this cost benefit analysis will be a high priority in the coming year.

4.1.2 Baseline Design

In the baseline design the detectors halls are located due east of the reactors on the line that is equidistant from both reactors. The near detector hall is just outside the security fence (∼200 meters) and located 175 meters (450 mwe) below the surface. Therefore the neutrino path length distance is approximately 270 meters. The far detector hall is 1500 meters due east of the reactors and is also down 175 meters which results in a neutrino path length of about 1510 meters. The baseline calls for two detectors at each site, each with an outer diameter of 7 meters. Each detector will be surrounded on 5 sides by a veto system that has an array of active cosmic ray detectors outside about a meter of passive shielding. Each detector sits inside a veto which is housed in an excavated room of dimensions 12 meters wide, 11 meters high and 32 meters

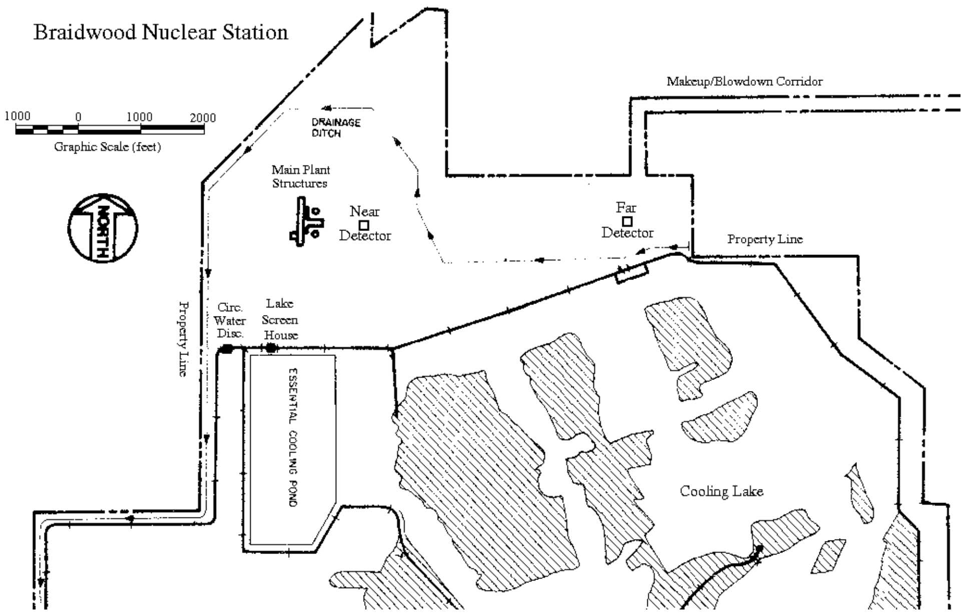

Figure 5: Drawing of the plant and surrounding area showing the approximate locations of the near and far detectors with respect to the plant and cooling lake.

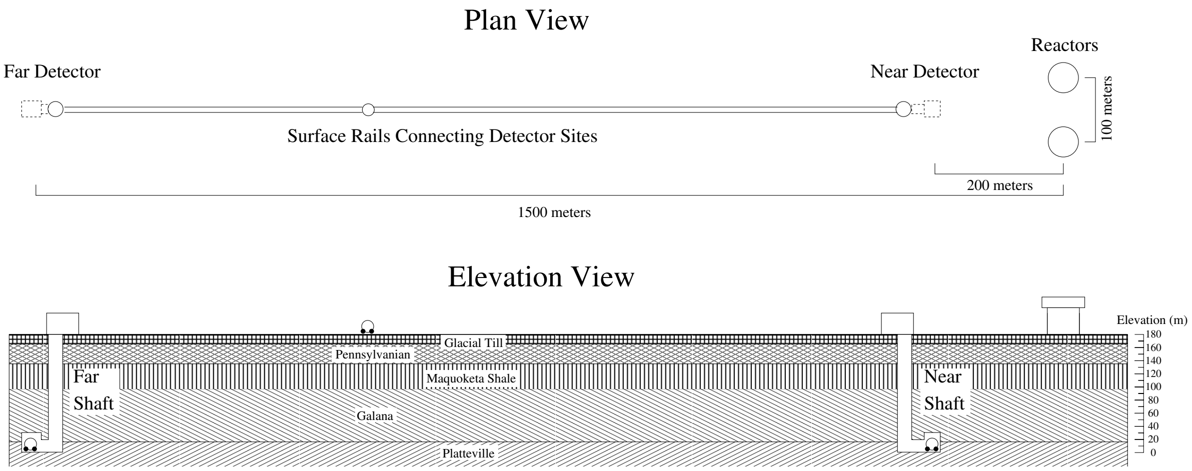

Figure 6: Plan and elevation views of the proposed layout of the experimental facility are shown. The elevation view shows the the major geological strata and their approximate elevation, in meters above sea level. Buildings, shafts and detectors are not drawn to scale.

long. Each room holds two complete detector-veto systems.

Ten meter diameter shafts connect the surface to the detector level at both the near and far sites. Each shafts contains two elevators, ventilation ducts, electrical and data cables, as well as pumps and water pipes for removing water from the shaft sump. The detector halls are connected to the shaft by a tunnel stub. At the far end this stub will be approximately 10 meters in length, which is the minimum required for structural integrity. The near tunnel stub will be about 45 meters long, because surface infrastructure at the near site does not allow construction of the shaft directly above the detector hall location.

In March of 2004, the collaboration commissioned a study of the cost and schedule of constructing an underground neutrino facility at the Braidwood site. The study was conducted by the consulting firm of Don Hilton and Associates. The results of the study were presented in such a way that cost of specific tasks could be broken out into manageable units (cost/meter of shaft, of tunnel, etc.) and rearranged to optimize the physics potential per unit cost. Table 3 show the estimated cost of the baseline civil construction as determined using the results of the Hilton study. The 17% scale factor for EDIA (Engineering, Design, Inspection and Administration) is consistent with industry standards for a project conducted under a design and build contract [17]. The 25% contingency assumes that the rock conditions along the full length of each shaft have been fully characterized, which will be the case when the shaft core borings are completed this October. The Hilton study estimates that each shaft and detector hall will take about 18 months to complete, with about 3 months on each end to mobilize and demobilize. The work on the two shafts can either be done serially or in parallel, so the civil construction should take between 2 to 3 1/2 years to complete.

4.1.3 Civil Engineering Needed for a Proposal Design Report

Developing the Scope for a Design and Build Contract Package The current plan for civil construction is to use a design and build contract [18]. In a design and build situation the collaboration specifies the layout, requirements and baseline design and the final design is determined by the contractor. This allows contractors the freedom to select techniques that they are already familiar with or to use equipment that they already own. The contractors know best how to use local labor, methods and means most cost-effectively. This can potentially result in a faster and less expensive overall project. The design and build process requires that the collaboration focus, early on, on developing a well-defined set of requirements that gives bidding contractors the maximum design flexibility. This will be a major activity in the next year as the collaboration prepares a full proposal.

Description of Work	Quantity	Units	Unit Cost	Subtotal	Total
General Mobilization	1	each	$3,286,691	$3,286,691	$3,286,691
Shaft					
mobilization	1	each	$512,165	$512,165	
pregrout overburden	15	meters	$7,538	$113,074	
excavate & line soil	15	meters	$62,891	$943,360	
excavate & line rock	160	meters	$42,262	$6,761,941	
water ring	1	each	$87,445	$87,445	
surface facilities	1	each	$104,532	$104,532	
equipment	1	each	$664,844	$664,844	
sump room	1	each	$226,295	$226,295	
decommissioning	1	each	$412,289	$412,289	
Shaft Total	2	each	$9,825,945	$19,602,870	$19,602,870
Detector Room (each room houses 2 detectors)					
excavate	32	meters	$69,156	$2,212,981	
grout	32	meters	$5,641	$180,511	
Detector Room Total	2	each	$2,393,492	$4,786,984	$4,786,984
Tunnel					
excavation	55	meters	$28,237	$1,553,035	
grout	55	meters	$2,247	$123,585	
Tunnel Total	55	meters	$30,484	$1,676,620	$1,676,620
Subtotal					$29,353,165
EDIA	17	%			$4,990,038
Contingency	25	%			$8,585,801
Total					$42,929,004

Table 3: The cost of civil construction for the baseline project estimated using the study of Don Hilton and Associates.

In order to determine the requirements a significant baseline design study is needed. This study will include geotechnical, civil, electrical, and mechanical engineering. It will provide a framework for estimating cost and schedule, and for creating a bid package suitable for completing a design and build contract. The specific elements of this study, and their approximate costs, are discussed in the following paragraphs and they are summarized in Table 4. The cost estimate of this study is done to a precision of $25K where each unit of $25K represents 1 senior engineer-month or 2 junior engineer-months.

Geological and geotechnical engineering tasks will include the characterization of the ground units (or strata), and the determination of the ground water table and ground permeabilities in the various units. Viable options for excavation methods, rock support systems and water control will be identified. These studies are expected to cost approximately $75K.

Civil and structural engineers will determine the requirements for all surface work platforms and buildings. They will also determine all needed utility runs and access roads. Underground they will look at shaft lining and floor requirements. These studies have an anticipated cost of approximately $50K.

Electrical engineering tasks include determining the specifications for power and communications: power distribution, transformers, lighting, grounding, safety systems such as fire detection, phone and internet. The estimated cost of these studies is $25K.

The mechanical engineering studies will determine the requirements for heating, ventilation, and air conditioning (HVAC), fire protection, ground water pumping systems, and other utilities. The approximate spatial layout and routing of pipes and ducts will also be determined. The mechanical engineering cost is

Task	Cost ($\times$1000)
Geology/Geo-technical	\$75
Civil/Structural	\$50
Electrical	\$25
Mechanical	\$25
Drafting	\$75
Cost & Schedule	\$25
Other Costs	\$50
Management & Administration	\$75
Detector Moving Study	\$25
Contingency	\$100
Total	\$525

Table 4: This cost estimate is made in increments of \$25K where one unit of \$25K represents 1 senior engineer-month or 2 junior-engineer months.

assumed to be \$25K.

All engineering studies will result in a reviewed outline of the determined specifications, and text for the related sections of the bid and contract documentation. In addition these engineering studies will generate the drawings required to bid the contract. These will include scale-approximate schematics of the layout of the surface buildings, shafts, tunnels, and chambers. Accurate scale drawings will be generated for the existing surface conditions; the spatial envelope of the minimum required excavations; and for the baselines of the electrical, mechanical and structural design. Drafting costs are expected to to be about \$75K.

In the course of these studies a methodology will be determined for estimating the cost and schedule. A risk analysis will be made to help in setting the appropriate contingency. These tasks have been allocated \$25K. In addition, \$50K has been allocated for "other costs." These costs include a land survey, evaluations of environmental safety and health requirements, and permitting.

Finally, \$75K is allocated to project management. These tasks will include coordinating with Exelon, the funding agencies and the institutions of the collaboration; conducting the engineering reviews; and contractor selection and pre-qualification.

Detector Moving Study The experiment baseline specifies movable detectors which allow for an important cross check of the relative normalization of the near and far detectors as discussed in Section 2.5.1. In addition movable detectors allow the detectors to be built on the surface in a single facility, during the civil construction. Without this capability, the project would incur additional costs from installing clean rooms and overhead cranes in each detector room. Also, transferring scintillator and other potentially toxic materials underground would present a significant environmental and safety hazard. Finally, detector construction, commissioning and testing could be conducted on the surface, during civil construction so that the detectors are ready to be installed as soon as the halls are complete.

The issue of how best to lift a 150 to 200 ton detector from the bottom of a 175 meter deep shaft, move it across 1300 meters of flat land, and lower it down a second 175 meter shaft must be addressed in the full proposal. The Fermilab Facilities Engineering Services Section (FESS) is currently in discussion with the Belding Walbridge Company about the cost and scope of such a study. Belding Walbridge is a contractor in heavy lifting and rigging and has worked with Fermilab in the past.

This study will divide up into two phases. In the first phase Belding Walbridge will develop a small number of initial schemes including sketches and order of magnitude cost estimates. In the second phase the collaboration will select one of these schemes for further development. This development will include scaled drawings; a detailed cost estimate that separates one-time costs – such as equipment – and recurring cost for each move operation; and a move schedule detailing the time required for each detector move. The estimated cost of this study is $25K.

4.2 Proposed Detector Engineering

4.2.1 Introduction

The important features of the experimental design are to locate two detectors about 200 m from the average core position, and another two identical detectors at a distance of about 1.5 km. Both detector sites will be at the bottom of 175 m shafts, thus requiring the detectors to be self-contained and movable.

Some preliminary engineering design studies have already been performed at several collaboration institutions to identify the critical issues involved in constructing such a detector. The details of these investigations can be found in [19] and [20]. Now that the experimental goals of this project have become better defined, a baseline design has been chosen. Detailed R&D work now needs to be applied to fully engineer this design and establish the procedures needed for assembly, transportation, and filling of the detectors. The following sections will detail the current baseline design features and identify the engineering and research that will be needed to successfully build these detectors.

4.2.2 Baseline Detector Design

The detectors of the Braidwood experiment are comprised of two main pieces. The innermost piece is a spherical detector containing the oil, scintillator, PMTs, etc. This detector is surrounded by a veto when in its underground cavern. The veto is comprised of one meter of passive shielding surrounded by an active muon detector. The spherical detectors are required to be able to move when completely assembled and full of oil. They first move horizontally on the surface of the earth from the assembly area up to 2 kilometers to the vertical access shafts. They are then required to be movable vertically from the surface down to the elevation of the detector caverns, and horizontally again from the base of the shafts to inside the veto shields. The veto system is installed inside the underground caverns and is not required to move with the detectors.

Spherical Detectors The baseline spherical detector contains 2 separate liquid zones: a central target filled with Gadolinium-loaded scintillator and an outer buffer region containing inactive mineral oil. The two liquid regions are separated by a single acrylic sphere, greatly simplifying the assembly procedure compared to a three zone detector. In addition, the dimensions have been enlarged slightly from previous studies to allow a total diameter of 7m for the entire detector and a radius of 2.6m for the acrylic sphere. This gives a target mass of about 65 tons for each detector. Figure 7 shows a 2D section through the detector cavern. The drawing is to scale per the baseline dimensions of the detector.

One of the challenges of building the acrylic sphere is in fully understanding the bonding process for the pieces of acrylic that make up the sphere. Bonding tests from SNO[21] indicate that bonds of 6000psi can be achieved, but the adhesive curing reaction is exothermic. Temperature variations and shrinkage during curing can induce residual stresses in the acrylic that could cause crazing, cracking or other problems for the sphere. Much research is needed to successfully build the acrylic spheres.

The liquid is contained by a steel spherical tank supported on a frame which allows the tank to be lifted by a crane while full of liquid, or moved horizontally either on the surface or inside the detector caverns. Engineering studies (referenced below) have identified several frame designs that minimize the distortion and stress of the steel sphere. To allow assembly of the acrylic sphere inside the steel sphere, the steel sphere must have a flange at some latitude and a removable lid that allows the acrylic sphere to be lowered through the top opening. The acrylic sphere is assembled to the steel tank lid and the tank sealed before any liquid is introduced to the detector.

Mounted to the inner surface of the steel sphere are 1000 photomultiplier tubes giving a total photocathode coverage of 25%. For PMT assembly to the steel sphere, there may also be a man-hole access flange near the bottom of the steel sphere. Typical assembly of PMTs in spherical vessels proceeds from the top of the vessel to the bottom, with scaffolding materials removed through the lower access port.

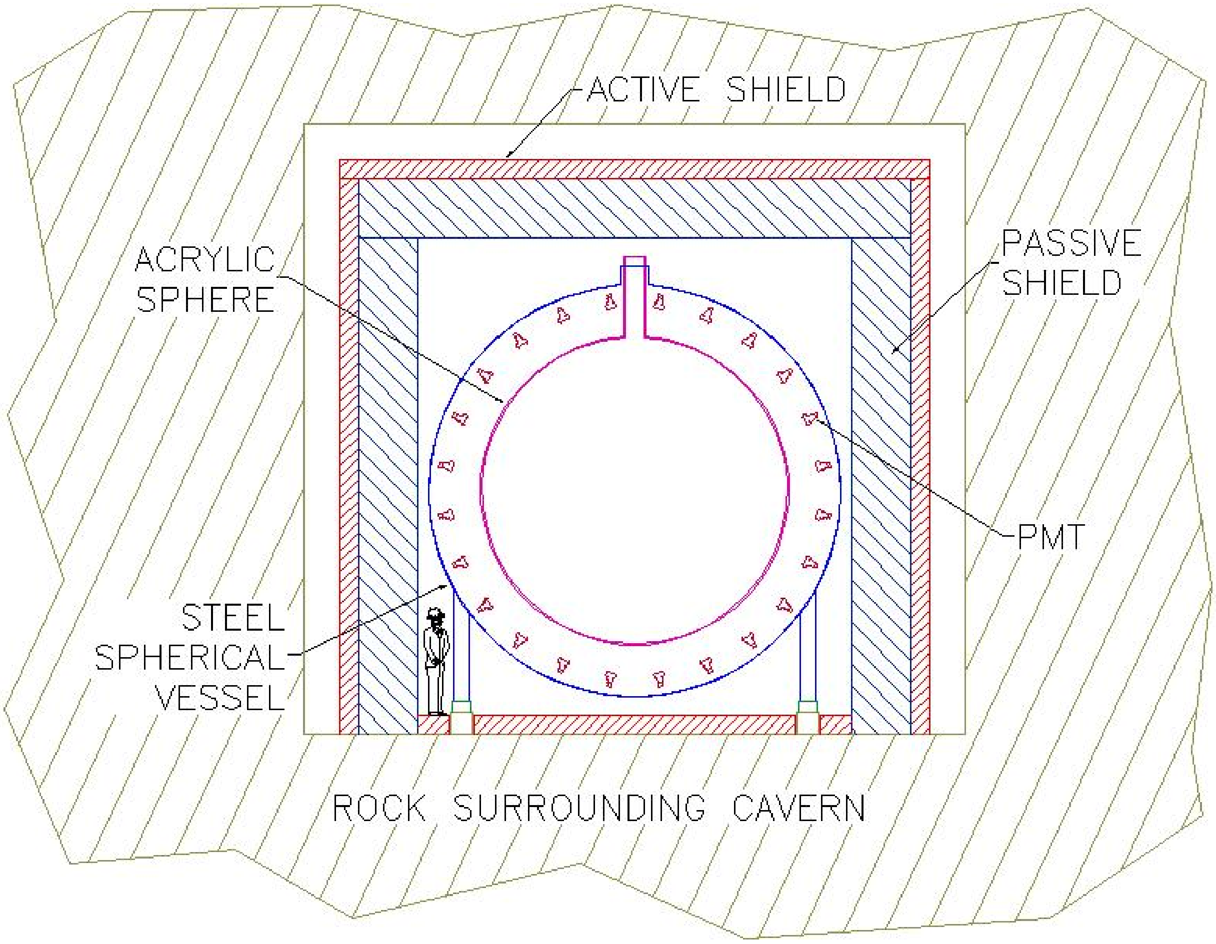

Figure 7: A cross-section through a detector cavern showing the spherical detector surrounded by the veto system. The drawing is to scale.

The acrylic sphere will be supported from the removable lid of the steel sphere, and one of the big challenges of the design is to create supports for the acrylic sphere that minimize the stress on the acrylic while minimizing the optical distortion from the supports seen by the PMTs.

To control the stress and deflection of the acrylic sphere during filling of the detector, a liquid flow control system will need to be designed to match the liquid level of the mineral oil with the Gadolinium-loaded scintillator filling the acrylic sphere. Care must also be taken to insure that the chemistry and physical properties of the entire volumes of oil and scintillator are identical for all four detectors.

Another challenge will be the design of a radioactive source positioning system for characterizing the optical performance of the detectors.

Figure 8 shows a possible configuration for the pieces that make up the acrylic sphere. Figure 9 shows one of the frames studied to support the steel sphere. Figure 10 shows a finite element model of an alternative support frame that also provides mounting points near the floor for rollers to move the detectors. Figure 11 shows a concept of how the acrylic sphere might be lowered into the steel sphere after attachment to the removable lid, and another alternative support structure.

Veto System The Veto system is conceived in two layers. Closest to the spherical detectors would be a layer of passive shielding, at least 1 meter water equivalent in thickness. Outside of the passive shielding would be a layer of active shielding to provide a muon veto.

The passive shielding needs to be a hydrogen-rich material to slow fast neutrons, and studies will have to

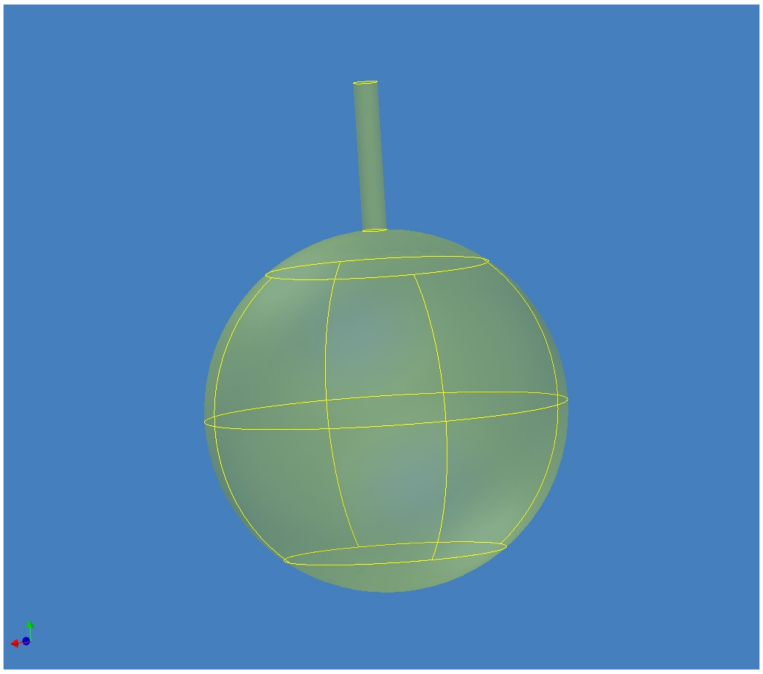

Figure 8: A model of the acrylic sphere showing the chimney and the possible segmentation of pieces. The figure comes from [19] and is courtesy of Vic Guarino at ANL.

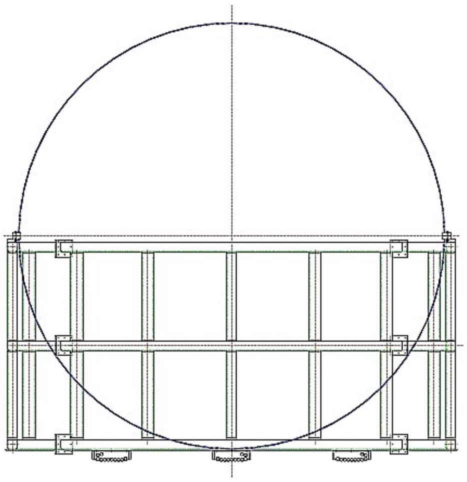

Figure 9: Conceptual design of a framework that allows the detector to be rolled on a floor with Hilman rollers. The separation between the upper and lower sections of the steel sphere happens at the equator in this design. The figure comes from [19] and is courtesy of Vic Guarino at ANL.

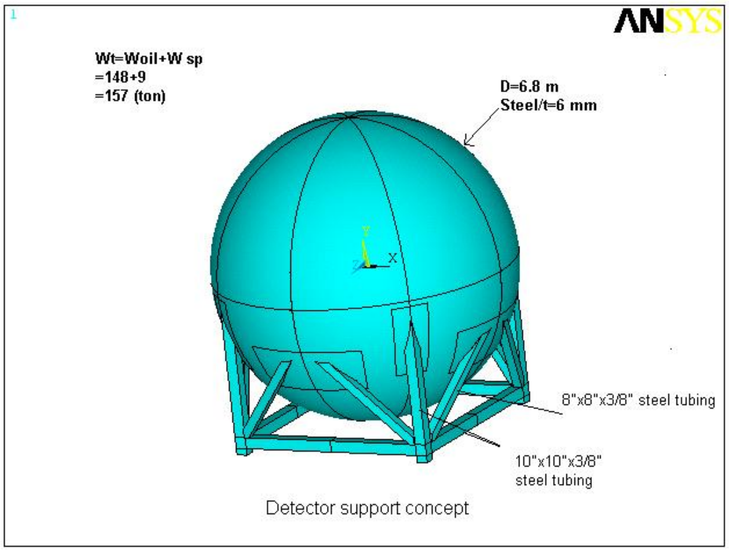

Figure 10: A FEA model of another support design that transfers loads to the elevation of the floor where rollers would be used to move it horizontally. The figure comes from [20] and is courtesy of Ang Lee at FNAL.

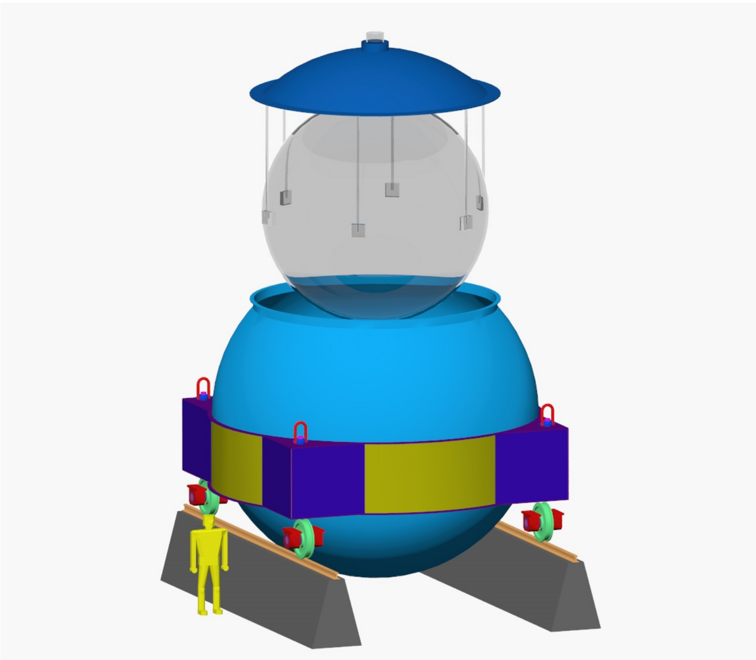

Figure 11: Rendering showing the acrylic sphere suspended above the steel tank from the steel tank's removable lid. This rendering shows another conceptual design for a support structure for the detector. Depending on the results of the study of how the detectors will be moved on the surface, there may be reasons to mount the detectors on rails. This support concept shows the rollers at an elevation above the floor and rails mounted on concrete foundations. The flange allowing the lid to come off is above the equator of the steel sphere in this design. The figure is courtesy of Larry Bartoszek, Bartoszek Engineering.

answer the question of how much hydrogen density is enough for the purpose of this experiment, and what material satisfies the requirement at an affordable price. Several ideas have been discussed, such as concrete blocks and water-filled tanks. Water tanks with PMTs inside them could combine the function of active and passive shields.

There are several choices for the technology of the active shield, such as plastic scintillator paddles, wire chambers, or the liquid scintillator system described in reference [22]. Again, cost-benefit studies will have to be done to determine the technology of choice for the Braidwood experiment. To create a baseline for the cavern for civil engineering estimates, we have assumed a minimum thickness of 0.3 meters for the active shield and sufficient space around it for assembly and maintenance.

4.2.3 Baseline Detector Preliminary Cost Estimate

Table 5 below shows a very preliminary cost estimate for the detectors and veto systems. No costs are included for any detector horizontal or vertical motion systems as these technologies have not been determined. Costs have been scaled from recent MiniBooNE construction experience. A Braidwood spherical detector is one fifth of the volume of the MiniBooNE detector. Some items, such as the steel tanks, PMTs and cables, can be expected to scale as the ratio of the surface area of the Braidwood tank to the MiniBooNE tank, a factor of .34. A few sub-systems do not depend on the number of detectors built because only one item would be needed for any number of detectors.

The MiniBooNE muon tracking system covers approximately 11.8 square meters and is based on plastic scintillator technology. The area required to be covered by a single Braidwood muon tracking system is approximately 486 square meters. The estimate for the cost of the muon tracking system came from scaling up the MiniBooNE cost of approximately $2100 per square meter of coverage. A different technology choice for this active veto might bring the cost down.

No costs for the full engineering effort are covered in the estimate below.

4.2.4 Summary of Major Detector Design Tasks for the Coming Year

There are many aspects of the detector system that will need study and engineering in the coming year to be able to submit a proposal for the full engineering of the Braidwood Experiment. Listed below are the major tasks expected to be accomplished in the next year.

- *Design of Acrylic Sphere:* Work is needed to test bonding methods, develop and prototype a final design for the support structure, and perform a detailed structural analysis.

- *Design of Outer Steel Sphere:* A set of specification drawings needs to be prepared to go out for bid to the steel tank vendors such as Chicago Bridge and Iron and Matrix Service, Inc. Experience from experiments such as MiniBooNE provides a clear path to spherical tank construction.

- *Calculation of Pressure Variation Inside Detector:* During the movement of the detector lateral accelerations will result in variations of the pressure distribution inside each sphere. Calculations are needed to determine this variation in order to see the maximum pressure that the PMTs will be subjected to and if a potential shock wave effect could occur because of very high accelerations. Also, the potential for damage due to a PMT imploding needs to be investigated. Studies done for MiniBooNE after the Super-Kamiokande disaster will also be useful because the PMTs for Braidwood are the same size as MiniBooNE's.

- *Development of Assembly Procedure:* A procedure is needed for assembling the detector. This involves designing the fixtures, tools, and procedures for mounting the steel sphere inside its support structure, mounting the PMTs, and assembling the acrylic sphere inside the outer steel sphere.

Description	Est. Cost
Spherical Detectors	
Steel tank	$340,000
Acrylic vessel	$500,000
Oil	$89,000
Gd-loaded Scintillator	$640,000
Oil plumbing system	$100,000
Temp regulation system, N2 purge	$40,000
PMTs	$870,000
PMT supports	$100,000
Cable system	$7,000
Tank support system	$50,000
Detector electronics	$150,000
DAQ	$50,000
Assembly Labor	$65,000
Radioactive Source Scanning System	$100,000
Muon System	
Passive shielding	$100,000
Muon tracking system	$1,000,000
Subtotal per Detector and Veto	$4,201,000
Contingency (30%)	$1,260,000
Total for one Detector System with cont.	$5,462,000
Total for four Detector Systems with cont.	$21,847,000
Items independent of number of detectors	Est. Cost
Attenuation Length Tester	$29,000
Storage Tank Farm on Site	$750,000
Subtotal of above items	$779,000
Contingency (30%)	$234,000
Subtotal of above items with contingency	$1,013,000
Overall Total with contingency	$22,859,000

Table 5: Preliminary Cost Estimate for one spherical detector and its associated veto system for the Braidwood Reactor Neutrino Project, and total cost for four detectors.

- *Design of PMT Mounts:* The method for mounting the PMTs inside the steel sphere has to be developed. This work will have to be coordinated with the tank specification drawings as any features on the inside of the steel tanks may be the responsibility of the tank vendors.
- *Design of Detector Support Structure:* While preliminary work has gone into the design of an external support structure, the details of how this will fit into the restrictions imposed by the civil construction shafts and tunnels have yet to be worked out. Furthermore, the underground movement system will need to be fully designed and tested to ensure reliable operation.
- *Investigation of Materials Compatibility:* The potential of liquid scintillator causing chemically induced defects in the acrylic is significant. Acrylic is known to work well as long as the percentage of pseudocumene is kept sufficiently low. When the final chemical composition of the liquid scintillator is defined, careful investigation will be needed to ensure that no chemically induced crazing or stresses develop. This is discussed in more detail below.

- *Scintillator Handling/Storage and Detector Filling Procedure:* By filling the inner and outer spheres simultaneously, stresses on the acrylic vessel will be greatly reduced. This will require accurate control of the fluid flow rate. Also, to achieve the desired similarity between the separate detectors, it is required that the liquid in each detector be identical which can only be achieved if the liquid is mixed on site and the detectors filled at the same time. This will require the design of a large chemical storage and deployment system at the experimental site.
- *Conceptual design of the Source Positioning System:* The source positioning system allows a radioactive source to be positioned within an as-yet unspecified volume of the Gd-scintillator zone. This system needs to be specified in terms of volume required to access, repeatability, absolute position uncertainty, and other elements characteristic of robotic positioning systems. The specific need for this system needs to be studied and understood with an eye to potential cost savings.
- *Conceptual and Preliminary Design of the Veto System:* The technology of the Veto system is currently completely unspecified, for both the passive and active muon shielding. Since this system is highly integrated with the civil construction of the underground caverns, much work is needed to put it on a par with other more developed aspects of the detectors.

4.2.5 Cost Estimate of Detector Design R&D

Table 6 gives a rough breakdown of engineering and M & S costs by sub-system for the detectors. The work represents a mixture of labor rates for Engineering, Engineering Assistants and Drafting. The M & S column is a break-out of detail from the Total Cost Column. The M & S dollars are added to the labor dollars in the total cost column for each item so the M & S shown is not intended to be added again to the overall total.

Task Name	M & S	Work (hours)	Total Cost
Spherical Detectors			
Steel tanks	$0	160	$14,400
Acrylic vessels	$0	378	$35,000
Oil	$10,000	168	$26,800
Oil plumbing system	$0	364	$34,600
PMT system	$0	200	$19,400
Cable system	$0	160	$9,000
Tank support system	$0	320	$29,200
Detector electronics	$0	104	$10,400
Radioactive source scanning system	$0	616	$55,600
Muon System			
Passive shielding	$0	498	$44,300
Muon tracking system	$0	538	$47,800
Subtotal	$10,000	3,678	$408,125
Contingency (25%)	$0	0	$81,625
Total	$10,000	3,678	$408,125

Table 6: Estimate of detector engineering and M & S costs for the Braidwood Reactor Neutrino Project expected to be performed in FY05

4.3 Liquid Scintillators, Material Compatibility, and Chemical and Radioactive Contaminants

4.3.1 General Considerations

Organic liquid-scintillators (LS) have been the detection medium of choice for antineutrinos since the discovery experiment of Reines and Cowan. There are several requirements that a multi-ton LS neutrino detector must satisfy: It must (1) be chemically stable for long periods of time, (2) be optically transparent, i.e., have a large attenuation length, (3) have high light output, (4) contain ultra-low concentrations of contaminants, chemical as well as radioactive, and (5) be chemically compatible with the vessel in which it is contained.

The advantages of adding an element such as Gd to the LS (to form "Gd-LS") are:

- Only a small concentration of Gd in the liquid is required, 0.1-0.2% by weight, because some naturally occurring Gd isotopes have huge (n,g) cross sections, 104 barns.

- The energy released by the neutron capture is large, 8 MeV, and is distributed among a few emitted g rays, giving a distinctive angular distribution.

- The delayed coincidence time between the e+ and n signals is shortened from 200 ms for n-capture in H to 30 ms (depending on the concentration of Gd in the LS).

However, there are several potential disadvantages to overcome:

- Trying to add inorganic salts of Gd, such as GdCl3 or Gd(NO3)3, directly to the LS will not work. It is well known that the CHOOZ experiment was forced to shut down when the optical properties of its LS + Gd(NO3)3 mixture deteriorated, degrading the quality of its output signal. The observed yellow color of the CHOOZ Gd-LS was likely produced by oxidation of the organic liquid by the nitrate.

- It is not trivial to synthesize a chemical complex of Gd that will be soluble in the organic LS, which is usually a non-polar aromatic compound (i.e., contains phenyl groups and primarily C and H). This type of LS is generally immiscible with aqueous solutions.

- The Gd-LS for a neutrino experiment must be chemically stable for very long time periods,   years, as opposed to the shorter times needed for the more traditional uses of Gd-LS, for detecting high fluxes of neutrons from nuclear reactors and spallation neutron sources. "Chemical stability" means the absence of (slow) chemical reactions, such as hydrolysis and/or polymerization, which can lead over time to cloudy suspensions in the LS or formation of gels or precipitates.

- Lanthanides, such as Gd3+, often contain naturally occurring radioactive impurities, such as Th4+ and U4+ and U6+ (as UO22+). Purification steps will have to be developed and used to reduce these radioactive species to concentrations 10-12 g/g. Concentrations of other non-radioactive chemical species that can adversely affect the optical properties of the Gd-LS will also have to be strictly controlled.

- Most of the envisaged purification steps will have to be applied before and during the synthesis of the Gd-LS. Most chemical separation schemes that would be used after the Gd-LS has been put into the detector vessel would be unsuitable because they would likely remove some of the Gd as well as the other inorganic impurities. Even vacuum techniques for removing Rn from the Gd-LS could cause problems by changing the concentrations of the volatile organic liquid components in the LS.

- The chemical compatibility of the organic LS with the material of the detector vessel is another important factor to study. Acrylic is known from SNO R&D to be attacked by many chemical liquids.

Nylon, as used in Borexino and in KamLAND, is known to be resistant to some LS, such as PC and mineral oil. Another aspect of this problem that should be realized is that chemical attack and/or leaching of the vessel by the LS could introduce unwanted impurities, organic as well as inorganic, from the vessel into the liquid and adversely affect the LS properties.

- The requirement of achieving a 1% precision in this theta-13 experiment magnifies the above challenges inherent in preparing the Gd-LS. For example, the concentrations not only of Gd but also of LS (i.e., the concentrations of target H atoms for the antineutrino capture), must be identical in the near and far detectors. Special care will thus have to be given to the batch-wise preparation of the Gd-LS and to the chemical quantitative analyses of these batches.

4.4 Research to date at BNL on metal-loaded LS

4.4.1 In-LS

Since 2000, the Solar-Neutrino/Nuclear-Chemistry Group in the BNL Chemistry Department has been involved in R&D of chemical techniques for loading metallic elements, such as In3+ and Yb3+, up to concentrations of several % by weight, into organic LS (in collaboration with R. S. Raghavan of Bell Labs). This research, in a project called LENS-Sol, has as its main goal the development of a detector capable of observing low-energy neutrinos from the solar pp and 7Be branches, via neutrino capture on the In (with a Q-value of 0.114 MeV). The principle of the chemistry is straightforward, namely to prepare an organometallic complex of In that is soluble in the LS. But the execution has been difficult, with many problems to solve and details to master. Several organic complexing agents come to mind, for example (i) carboxylic acids (RCOOH) that can be neutralized with inorganic bases such as NH3 to form metal carboxylates, (ii) organic phosphorus-oxygen compounds, such as organic phosphates or phosphine oxides, that can complex neutral inorganic species such as InCl3, and (iii) organic diketones, such as acetyl acetonate. Compounds from groups (i) and (ii) were selected as candidates for testing proposed chemical procedures at BNL. Much of their organometallic chemistry has already been developed in the fields of separations chemistry and chemical treatment of the nuclear fuel cycle. After extensive laboratory R&D, procedures have been worked out for the purification of the chemical components and synthesis of the metal-LS by solvent-solvent extraction. Much of the focus has been on the carboxylic acids, because they are produced in bulk by the chemical industry and have lower cost and ease of chemical disposal, as compared with the phosphorus-containing compounds. Several carboxylic acids, with side chains containing from 1-8 carbons, have been studied. The best candidate found to date is methylvaleric acid, MVA. Reproducible results with MVA have been found for samples of In-LS, where In concentrations are in the 5-10% range and the organic solvent, PC, is the LS. Many methods, instrumental and chemical, have been developed at BNL to analyze the resulting In-LS samples. Among these are (1) measurement of the attenuation length both by UV-Visible absorption spectrophotometry with 10-cm optical cells and by a dual-beam, long-pathlength (¿1 meter) blue laser system; (2) measurement of the light yield, S%, relative to the pure PC liquid scintillator; and several chemical determinations of the In-LS, such as of the concentrations (3) of the In3+ by a colorimetric method, (4) of the total RCOOH by acid-base titrations, (5) of the uncomplexed RCOOH by IR spectroscopy, (6) of the H2O by Karl-Fischer titrations, (7) of the NH4+ and Cl- by electrochemistry, and (8) of different In species in the organic liquid by IR spectroscopy.

4.4.2 Gd-LS

Early in 2004, because of the developing interest of the BNL Group in theta-13 experiments, the procedures that had been developed for In-LS were successfully applied to the preparation of some initial samples of Gd-LS. Samples of 3% Gd-LS in PC were made and then diluted to Gd concentrations, 1%, 0.5%, and 0.1%. Figure 12 shows the 10-cm absorption spectra and the absorbance values, R at 430 nm, for these samples. These R-values translate into 1/e attenuation lengths of 5 to 15 meters. Figure 13 shows the

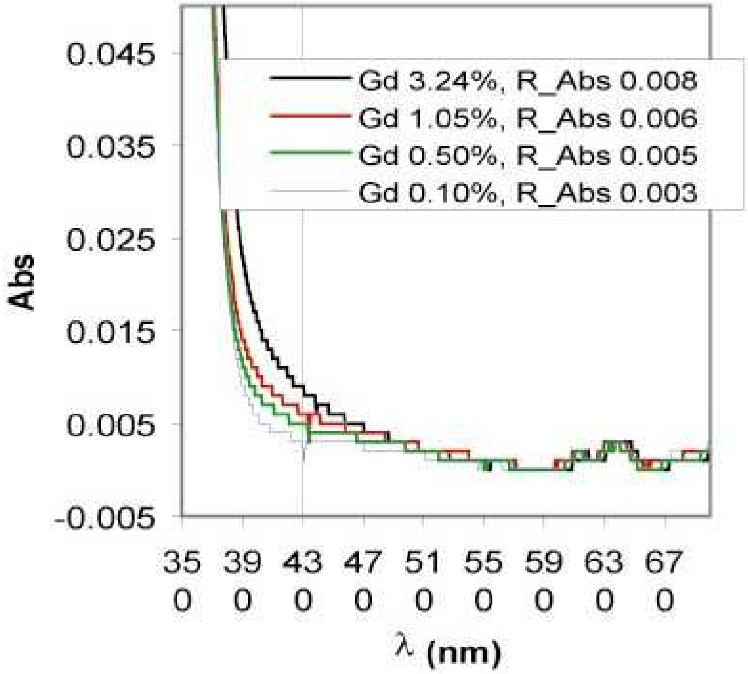

Figure 12: Absorption spectra of BNL Gd-LS.

Compton-scattering light-yield curves, produced by an external source of 137Cs irradiating these samples. The 0.1% Gd-LS has a light yield relative to pure PC of 94%. The properties of these samples are also being monitored over time, to search for any degradation of the Gd-LS. Over a period of the first few months, the properties of these samples have not changed. Some samples of commercially available Gd-LS were obtained, Bicron BC-521 with 1% Gd in PC and BC-525 with 0.5% Gd in mineral oil, and compared with the BNL samples. The light yields of the respective BNL and Bicron were found to be comparable, but the attenuation lengths of the BNL Gd-LS were more than two times larger than the Bicron samples, probably reflecting the care put into the BNL pre-synthesis purification steps.

4.4.3 Future Research at BNL on Gd-LS

These initial results on Gd-LS are very encouraging for the theta-13 project and merit further R&D. The BNL Group plans to increase its efforts in the short term. One major focus will be to optimize, simplify and finalize the chemical procedures to synthesize the Gd-LS. Issues of chemical purifications and of the control and assay of radioactive impurities will have to be addressed. There are two approaches to making batches of the Gd-LS: (a) preparing each batch at the desired final Gd concentration, 0.1-0.2%, or (b) preparing more concentrated batches, at least 1-2% Gd, and then diluting with the organic LS to the desired concentration. The two approaches are not identical, with regard to possible long-term effects such as hydrolysis, polymerization, and effects on the optical properties of the final Gd-LS. Approach (b), however, may simplify preparation of larger volumes of Gd-LS. In the long term, consideration will have to be given to designing and building chemical systems that (i) are closed to prevent ingress of air, which can degrade the LS, and (ii) are automated to replace many of the procedures that are currently done in the laboratory by hand. After that, one will have to increase the scale of the syntheses, from the present 0.5-1 liter per batch to at least 5-10 liters per batch. A goal has been set in the collaboration of accumulating 200 liters for prototype tests. As the BNL R&D continues, all of the analytical methods that have been described

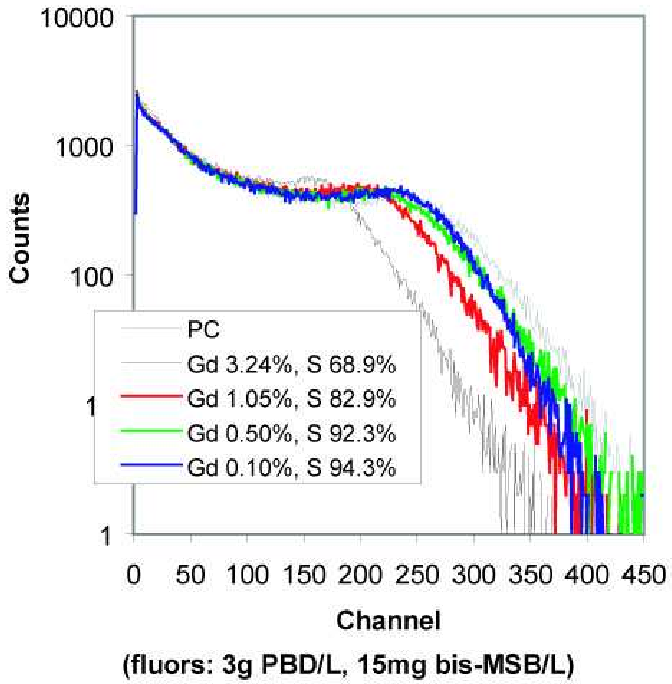

Figure 13: Light yields of BNL Gd-LS.

in Section 4.4.1 for In-LS will be used to determine the chemical and physical properties of the Gd-LS. The timing characteristics of the light signals produced by the Gd-LS may also be investigated, such as the pulse widths and decay times. Another important issue to study is the compatibility with the detector vessel material of the Gd-LS and of the unloaded LS that will be used in the buffer region. In addition to PC, other organic liquid scintillators are known, such as phenyl cyclohexane (PCH) and various types of mineral oil. It has been reported that a mixture of 20% PC - 80% mineral oil, and possibly even 40% PC - 60% mineral oil, will not attack acrylic. These claims will have to be verified. Once the project gets into planning for the full-scale experiment, or possibly for an intermediate-size prototype, the volumes of liquids being produced will be on the level of tons. Industrial cooperation will likely be required. At that juncture, it will be very important to have a quality control program already developed and in place in the collaboration so as to verify the quality of the materials that will be supplied by the vendors, e.g., pure solvents, starting materials for the Gd-LS syntheses, or even commercially manufactured Gd-LS. There are many topics to investigate. The BNL Group is relatively small and may have more ambitious plans than it can accomplish in a reasonable time span. It intends to cooperate with other groups in the collaboration to leverage its efforts. It will also provide samples of Gd-LS for measurements that will be done at other institutions and/or participate in exchanging samples between different institutions ("round robin") to get independent measurements of key quantities, such as attenuation lengths and light yields. The BNL Group is funded by DOE's Office of Nuclear Physics, for its ongoing research in SNO and for exploring new research directions, such as LENS-Sol and Theta-13. While no funds for scientific support are being requested from NSF for BNL, this proposal does contain a request for the cost of purchases of chemicals and materials to be used in R&D on the synthesis of the Gd-LS. That amount for the first year is $20,000.

5 Education and Outreach: Now and Future

We request funding to support Education and Outreach associated with the R&D phase of the experiment and sketch our plans for the future.

5.1 Immediate Plan: Braidwood Undergraduate Program

This proposal requests funding to support undergraduates to participate in the Braidwood R&D and design efforts. This is an optimal time to involve undergraduates for several reasons. There are many self-contained projects requiring only undergraduate level educational background that will come to fruition on the timescale of a few months or a semester. Also, the working groups are small. so an undergraduate's work can have a big impact. The R&D time period provides an opportunity for young physicists to observe the dialog that occurs in the real process of experimental design, which is a great departure from the typical "cookbook" experience of undergraduate laboratories. Lastly, in principle, a student starting as a Braidwood undergraduate now can follow this experiment through its full development from R&D to first analysis, if he or she chooses to continue on the experiment as a graduate student. This is a rare educational opportunity to see a particle physics experiment from start to finish, and will place the student in a good position to lead an experiment through all of its phases in the future.

Successfully enfranchising undergraduates on an experiment takes planning and thought because their time is limited by classes, they are less experienced than older students, and they may be intimidated by the research environment. However, the collaborators on Braidwood have a strong past record for successfully integrating undergraduate research into the experiment (see synergistic activities of the collaboration members).

A wide range of projects have been identified. Examples include: a study of adapting KamLAND style tracking and energy signature cuts to Braidwood geometry in order to suppress ^{9}Li and ^{8}He backgrounds; study of fast spallation neutron signatures in the detector, paying particular attention to quenching effects in proton recoil, in order to tag and measure this background source; investigation of drift chamber designs that might form a part of a muon tracking system to be installed within the active veto (specifically addressing Ar:CO_2 gas mixtures, pressure, wire voltage and wire diameter); processors for readout; continued sensitivity studies; and construction of test-stands for the scintillator oil and the phototubes.

We propose to run a "Braidwood Summer School" at the start of the summer as an introduction for the students. This will be modeled on the successful MiniBooNE program of 10 classes in June, designed to introduce students to all aspects of the experiment. At the end of the summer, when undergraduates on MiniBooNE are asked to evaluate their experience, the classes are routinely identified as very valuable. Because Braidwood does not yet have a central location for office space, the classes will be condensed into an intensive 3-day series to be held at the University of Chicago. A day-trip to Braidwood will be part of the class schedule, followed by a 2-day Braidwood Collaboration meeting. At the end of the summer, the effectiveness of the school and the summer project will be evaluated via both student and adviser surveys. Based on these, we will adjust the program in following years.

Upon returning to their host institution, students will also participate in existing educational programs, including Research Experience for Undergraduates (REU) programs at Chicago, Columbia and Michigan. Also, we will connect our undergraduates to programs for teachers. For example, the Kansas State group runs a highly successful outreach program for teachers at rural high schools, which includes special lectures on Kansas' Wolf Creek reactor and reactor-based neutrinos physics which will be valuable to the undergraduates of the Braidwood group at KSU.

We request funding for two students for each U.S. University that does not have an REU program in experimental particle physics. For those with an REU, we ask for funding for one student in addition to the student who will come through the REU. The total is 11 students. For each student, we plan to supply a summer stipend of \$3650 which includes travel allowance for expenses between the student's home and the host institution, but does not include housing. We ask for \$1800 for housing for each student. We ask for

\$350/student to cover cost of attending the summer school at the University of Chicago. Thus, the total for summer support per student is \$5800, or \$63,800.

5.2 Plans for the Future

The Braidwood Undergraduate Program is expected to be only one aspect of our outreach plan. The final plan is expected to have three constituencies: 1) students and teachers, 2) people in the local area, and 3) the population at large. During the R&D phase of the experiment, the full education and outreach plan will be designed. An initial outline is given here.

The key to success will be in good planning and project management, lead by an expert who will make this a primary part of his effort on the experiment. Paul Nienaber, Assistant Professor at St. Mary's University in Minnesota, will take on this position. He has years of experience in this area, both through his work as project manager for Education and Outreach for the MiniBooNE experiment and as a Visiting Scientist at Fermilab cooperating with Public Affairs and the Education Office (see attached bio).

The program for undergraduates has been described above. We also plan to hire teachers to work with us during the summer and to involve high school students in the effort. Geneva High School junior Hannah Newfield-Plunckett, hired by the Columbia group, has entered the Intel Science Talent Search using the results of her work on parameterizing backgrounds for the reactor experiment.

Work in the local area falls into three categories: Presentations, Media Relations and a Welcome Center. Braidwood collaborators would give presentations to local organizations and schools. We will work with the EXELON Corporation to establish an office for public affairs. Publicity releases will be sent to local papers, TV and radio stations describing the project and its progress. When justified, the releases will go to national media. Researchers will be made available for interviews. Local people will be utilized for construction where possible, and this, also, will be publicized. We would like to establish a modest "welcome center" that would provide inquiry-driven experiences. The location of this center must be be negotiated with EXELON, and we will be sensitive to their concerns. It could be in one of the experiment's utility buildings, in a building associated with EXELON, or at a nearby local science museum.

For the population at large, a web site will be created with will contain the information described above for talks. θ_{13}-specific activities will be bound into ongoing outreach efforts at universities and national laboratories. The site will be linked to education databases. A 1-2 page brochure on the experiment will be produced concerning physics, technology, and local aspects of the experiment.

6 Summary

In this proposal, we have described R&D work and engineering required to prepare a full proposal with well supported cost and schedule for the Braidwood Neutrino Experiment. Much of the technical R&D required to refine the detector design will be carried out by collaborating physicists using support of their base grants. This proposal requests funding three engineering/R&D tasks that are beyond the resources of the groups. We also request support for an education and outreach program to support additional involvement of undergraduates in this very exciting design phase of the experiment. The funding requests in this proposal are summarized in Table 7.

6.1 Collaboration Organization and Management of Grant

The Braidwood Collaboration includes Argonne National Laboratory, Brookhaven National Laboratory, The University of Chicago, Columbia University, Fermi National Accerator Laboratory, Kansas State University, Massachusetts Institute of Technology, University of Michigan, Oxford University, University of Pittsburgh, St. Mary's University of Minnesota, University of Sussex, and University of Texas at Austin. The collaboration includes physicists from an unusually wide range of backgrounds including neutrino physics (accelerator,

Table 7: Proposed budget. Education and outreach request includes 51% overhead; other items are free of overhead.

Category	Request in thousands of dollars
Civil engineering	525
Detector engineering	410
Liquid scintillator	20
Education and Outreach	95
Total	1050

reactor, and non-accelerator based experiments), collider physics, and fixed-target accelerator physics. E. Blucher (Chicago) and M. Shaevitz (Columbia) are cospokespersons of the group.

This grant will be managed by the PI in consultation with the Co-PIs. The PI will fulfill all NSF reporting requirements. Administrative support for the grant will be provided by The Enrico Fermi Institute of The University of Chicago.

6.2 Results from Prior Support and Group Plans

In the following sections, we summarize results of prior support for collaboration members, as well as the specific R&D plans for each collaborating institution.

Argonne National Laboratory

Group Members:
Physicists: M. Goodman, D. Reyna, L. Price, Engineers: J. Dawson, G. Drake, J. Grudzinski, V. Guarino

Results from Prior Support:

The Argonne group has mainly been working on the MINOS experiment for the last four years.Group members have made important contributions to the original conception of the experiment, beam design, project management, and technology decisions. Scintillator module construction techniques were designed at Argonne and the module factory for near detector modules was located at ANL. Cosmic ray analysis is underway. In addition, the group has recently completed analysis on the Soudan 2 experiment, including results on nucleon decay, atmospheric neutrino oscillations and searches for astrophysical sources of neutrinos.

Proposed Work:

- Site evaluation
- Detector Engineering

Brookhaven National Laboratory

Group Members:
Physicists:

Results from Prior Support:

Proposed Work:

The University of Chicago

Group Members:
Faculty. E. Blucher, J. Pilcher; Senior Scientist: K. Anderson; Postdoctoral Fellow: M. Worcester; Graduate Students: E. Abouzaid, M. Hurowitz, D. McKeen; Undergraduate Students: A. Kaboth, J. Seger

Results from Prior Support:

The Chicago group members listed above have been involved in the following major experiments: 1) the KTeV experiment at Fermilab, 2) The OPAL experiment at the CERN LEP facility, 3) The ATLAS experiment at the CERN LHC. Blucher has been spokesman of KTeV (E832) since 1997. His group has led the analysis of the direct CP violation parameter ϵ'/ϵ, and performed the recent determination of the CKM parameter $|V_{us}|$ based on measurements of the 6 largest K_L branching fractions and semileptonic form factors. The OPAL measurements have included many high precision tests of the electroweak theory, including the determination of the W-boson mass. Involvement in this experiment ended this year. The ATLAS experiment is under construction with startup planned in 2007. The Chicago group has finished construction of readout electronics for the hadron calorimeter and is now involved in the installation of the detector and in the preparation of analysis software.

Proposed Work:

- Site investigation. We will continue to work with other collaborating intstitutions to develop the Braidwood site. We have used $100K of seed money from the University to drill bore holes and for initial civil construction estimates.
- Monte Carlo development and studies. In collaboration with Kansas, the Chicago group has implemented many features of the experiment's simulation program. The group will continue to work on software development and on studies to optimize the detector configuration.
- Liquid scintillator studies. During the past year, the group has developed a small test cell for liquid scintillator. This work will be extended to a larger device using two of the 8 inch phototubes planned for the full experiment.
- Electronics design. The group will work to develop a data acquisition and trigger system for the experiment. One possibility is to exploit a modified version of the front-end electronics developed for the ATLAS hadron calorimeter.
- Mechanical design. Chicago's mechanical engineer, Elizabeth Pod, will collaborate on mechanical design work for the detector and veto system.

Columbia University

Group Members:
Prof. J. Conrad, Prof. M. Shaevitz, Postdoctoral Fellows: Z. Djurcic, J. Link, G. Zeller, Graduate Students: A. Aguilar-Arevalo, K. McConnel

Results from Prior Support:
The Columbia group has mainly been working on the MiniBooNE experiment for the last four years. Prof. Conrad is co-spokesperson for the experiment. MiniBooNE is a low energy neutrino experiment using the Fermilab 8 GeV proton booster accelerator. The experiment is set up to search for neutrino oscillation through numu disappearance and nue appearance in the region of the LSND anomaly and to make precise measurements of neutrino cross sections. Data taking started two years ago and is continuing. Preliminary results[**?**] have been presented on how well the data distributions agree with expectations and first neutrino oscillation results are expected in 2005. In addition, the group has continued data analysis on NuTeV experiment. New results were presented on structure functions[**?**] including a new NLO analysis of the strange quark sea[**?**] and on updated information on the weak mixing angle.

Proposed Work:

- The group has, over the past year, worked closely on the reactor site for the experiment and plans to continue an active role in the team supervising the civil construction engineering.

- Building on the past work for MiniBooNE, the Columbia group will investigate phototubes for the neutrino detectors. The group has been in contact with several photoube companies and plans to obtain samples of various tubes. Of particular importance is to evaluate the tubes for noise and radioactivity along with determining the useable photocathode coverage.
- In addition, the group is involved with a program to upgrade the VLAND detector, a small Gd-loaded scintillator detector, to measure spallation rates and energies by cosmic ray muons at depths appropriate for a reactor neutrino oscillation experiment. This will give accurate information for design work and in the end be useful for analyzing the actual oscillation data.

Fermi National Accelerator Laboratory

Group Members:

Physicists: H. Jostlein, C. Laughton, D. Finley, R. Stefanski

Results from Prior Support: As a group of experimentalists, we have not worked together in the past. However, we have a great deal of experience that will add directly to the support of this proposal. We have worked on complex detector systems (HJ at D0), underground tunneling at LHC, SSC and NuMI (CL), management of large projects (DF at NLC) and wqork on neutrino and charm production experiments (RS).

Proposed Work: The group will continue to develop post-conceptual design for the Braidwood site, especially in underground construction. They will also work to assure excellent relations with Braidwood.

Kansas State University

Group Members:

Profs. T. Bolton, G. Horton-Smith, N. Stanton; Post-doctoral fellow D. Onoprienko; Graduate student J. Foster; Undergraduates C. Borjas, N. Kinzie, J. Kondikas, D. Thompson.

Results from prior NSF and DOE support: The Kansas State group has a strong history of research in neutrino physics in addition to a program in energy frontier physics at the Tevatron and LHC colliders. Group members have made decisive contributions to measurements of neutrino oscillations, neutrino charm production, precisions neutral current cross sections, and rare processes on FNAL E531 (Stanton), FNAL E815-NuTeV (Bolton), FNAL E831-DONUT (Stanton), and KAMLAND (Horton-Smith). The group receives funding through the DOE HEP (DE-FG03-99ER41093) and DOE EPSCoR (DE-FG02-00ER45824) programs, and has received NSF EPSCoR(NSF EPS-9550487– "Kansas Alliance for Cosmology- Interdisciplinary Astrophysics") and NSF MRI(NSF PHY-0116649– "Development of the Silicon Vertex Detector for the Higgs Search at the Tevatron Collider") grants. The NSF EPSCoR funding helped establish the K-State Electronics Design Laboratory and to start a synergistic program in Cosmology at KSU. The MRI grant supports the contruction of the Layer 0 upgrade for the D0 detector at Fermilab.

Proposed Work:

- In the past year the group has led in the development of Monte Carlo simulation tools for the Braidwood experiment, implementing both a fast parametric program called RactorFsim and a Geant4 model of the detector. KSU proposes to continue aiding in the development of these programs as general purpose tools, and more specifically using them to refine background rate estimates and study rejection strategies for spallation neutrons.
- The group has also developed a test fixture over the past year to characterize the optical properties of scintillator oil. We propose to extend these studies to measurements of scintillator reponse to protons with energies below 14 MeV and neutrons with energies below 7 MeV using the tandem Van de Graaf accelerator at Kansas State's James R. McDonald Laboratory. These energies are important in understanding the detector response to spallation backgrounds; we note that the quenching properties of slow protons are particularly uncertain.

Massachusetts Institute of Technology

Group Members:
Faculty: P. Fisher, L. Osborne, G. Sciolla, R. Yamamoto; Senior Research Scientist: F. Taylor; Research Scientist: R. Cowan; Postdoc: S. Sekula; Graduate Student: T. Walker .

Results from Prior Support:
Over the past years, members of the group have collaborated on SLD (Cowan, Osborne, Taylor, Yamamoto) at SLAC, L3 (Fisher) at CERN. Group members are currently working on Babar (Cowan, Sciolla, Sekula, Taylor, Yamamoto) at SLAC and AMS (Fisher) at MIT, as well as the development of Gas Electron Multipliers for the NLC (Fisher).

Proposed Work: The group proposes to work on the design of the veto and shield systems for the Braidwood reactor neutrino experiment. Initially, the group will carry out Monte Carlo studies in order to determine baseline rates and the required precision. Subsequently, the group will investigate the relative advantages of gas-filled multi-wire proportional chambers and liquid or solid scintillators. This work will be carried out in collaboration with the other members of the Braidwood collaboration. Group members are also involved in studies of the physics impact of the measurement of the neutrino-electron scattering cross section, developing new methods for photon detection and the use of multiple small detector stations for higher precision electron anti-neutrino disappearance measurements.

University of Michigan

Group Members:
Faculty: B. Roe

Results from Prior Support:
B. Roe was spokesperson for Michigan effort on L3. The group built 100,000 wires of PWT for hadron calorimeter and produced more Ph.D. theses than any other L3 institution except for MIT. He is presently working on the miniBooNE experiment, expecially on the event reconstruction and particle ID, as well as beam MC and muon measurements in the hadron shield.

Proposed Work: Roe will work on MC simulations of events and backgrounds, and on event reconstruction software.

Oxford University (United Kingdom)

Group Members:
Faculty: S. Biller, N. Jelley; Postdoctoral Fellows: S. Peeters, N. Tagg; Graduate Student: G. Orebi-Gann

Results from Prior Support:
The Oxford SNO group provided central components for the analysis; in particular, the SNOMAN Monte Carlo and analysis code, which is used throughout the collaboration to analyze the data, is a UK responsibility. In detail, the group had major involvement in data-cleaning, phototube, electronic and timing calibrations and the RAL computing farm was used to process most of the calibration data, as well as general involvement in the analysis chain from verification to the results and their implications. The Oxford group also had considerable involvement in the determination of the background. Of crucial importance in determining the NC signal is an accurate measurement of the background signal coming from photodisintegration. High-energy -rays from the bottom of the thorium and uranium decay chains can dissociate deuterium, and the resulting signal is indistinguishable from the NC reaction. The amount of thorium and uranium was determined by radioassays (ex-situ) and also by looking in the data at the Cerenkov light produced by their decays (in-situ). Analysis of the CC spectrum from the salt phase will continue with the aim of lowering the threshold and allowing for correlations between the errors, both statistical and systematic. Studies on combining the data from all three phases will also be undertaken.

We will also continue to exploit the unique capabilities of SNO to explore exotic processes (such as n-nbar oscillations, nucleon decay etc).

N. Tagg has been part of the Oxford participation with the MINOS experiment, which has been closely involved in detector component production and testing; notably PMTs, front end electronics, and timing systems. They have been heavily involved in Monte Carlo, reconstruction, database, and calibration software. Oxford has also been pursuing analysis of calibration data as well as netural-current beam analyses.

Proposed Work:

We have begun to explore the possible use of both Cherenkov and scintillation light as a means to substantial suppress relevant backgrounds for the Braidwood experiment. This will continue through further discussions with the Brookhaven group along with bench-top tests and simulations here, in Oxford. We are also interested in exploring the use of muon spallation products for relative detector callibration and plan on becoming involved in the VSPLAT program along with Columbia. We will also continue to explore aspects of detector calibration using both fixed and deployed sources based on our experience with SNO. Finally, we have begun modifying aspects of the simulation code used for SNO to provide an independent, well-tested simulation of the Braidwood experiment to help provide input to various aspects of detector design.

University of Pittsburgh

Group Members:

Faculty: D. Naples, V. Paolone; graduate student B. Dhar; undergraduates: N. Madison, C. Pankow

Results from Prior Support:

The Pitt group's current main involvement is the MINOS long-baseline neutrino oscillation experiment. The group has designed the experiment's beam monitoring system hardware and is currently involved in near detector commissioning. The experiment will begin data taking at the end of this year. In addition, the members of the group are involved in ongoing analysis on two neutrino experiments; NuTeV (Naples) and DONUT (Paolone). Paolone has been spokesman for the DONUT experiment since 1997. Ongoing analyses include a search for exotic heavy neutral particles produced in the beam dump and analysis of a larger tau-neutrino interaction sample. Naples has been involved in the NuTeV experiment and made major contributions to Nutev calibration and to analyses. She has led neutrino oscillation measurements for both $\nu_\mu \to \nu_\tau$ and $\nu_e \to \nu_\tau$ and is currently leading analysis on structure functions in Nutev.

Proposed Work:

The focus of our effort has been estimation and understanding of spallation backgrounds. We have proposed to improve measurements of spallation backgrounds by using muons from the Numi beam at the Near detector site at Fermilab. These goals overlap with those of the VSPLAT (upgrade of VLAND detector) prototype detector planned. Thus, work on this prototype is a natural choice for our group to contribute to R&D efforts.

We plan to construct and operate the veto system for the VSPLAT experiment. Development of expertise on this system and related spallation background veto issues will lead to contributions to understanding and involvement in of this system for the Braidwood experiment.

University of Sussex (United Kingdom)

Group Members:

Faculty: E. Falk Harris

Results from Prior Support:

The University of Sussex has a highly active group working on the MINOS experiment, which is now completing its construction phase and is due to begin data-taking in April 2005. The Sussex MINOS group currently consists of Dr. P.G. Harris (group leader of the Sussex EPP group), E. Falk Harris (currently postdoctoral fellow), and one graduate student. The primary activity of the Sussex MINOS group is the calibration of the energy scale, paramount to the CC-spectrum measurement. In particular, the group has designed and developed a sophisticated light-injection calibration system for the detectors. Specifications included amongst other things tight constraints on stability, linearity, dynamic range, uniformity, temporal and wavelength profiles, and cost. This system (which was delivered on time, to specification, and approximately 30% under budget), is universally acknowledged within the collaboration as being an extraordinarily powerful and flexible tool for understanding and debugging the detectors, in addition to providing its primariy function of calibrating the optical readout chain of the detectors. The Sussex group also coordinates the overall calibration of the MINOS detectors, overseeing all aspects of the calibration from light injection and cosmic muons through to magnetic-field calibration and the incorporation of data from a separate Calibration Detector. (This responsibility in nominally shared between P.G. Harris and a collaborator in Texas, but in reality the effort is led entirely from Sussex, jointly by P.G. Harris and E. Falk Harris.) The group will remain heavily involved in the ongoing general calibration effort, and will also work on the CC analysis.

Proposed Work:

I would like to contribute to the simulation of the Braidwood experiment, by collaborating with the Oxford group on the modification of the SNO simulation code. I may have an opening to recruit an M.Sc. student ($\sim$ six man months of experimental work) to help in this effort over the coming year. I would also be interested in working on some aspect of the calibration of the Braidwood detectors; my MINOS experience is likely to be useful, for example, in addressing issues regarding relative calibration.

University of Texas at Austin

Group members:

Prof. Joshua Klein; Post-doctoral fellow: Dr. Melin Huang; Graduate Students: Stanley Seibert, Aubra Anthony; Undergraduates: Atiquar Rahman, Jaclyn Jerz

Results from Prior Support

The Texas group has primarily been involved in work on the Sudbury Neutrino Observatory (SNO). The SNO group is relatively new to Texas—Klein arrived from the University of Pennsylvania two years ago, where he spent the previous several years designing the SNO trigger system and acting as SNO's physics analysis coordinator. SNO is a heavy water Cerenkov experiment whose first results have resolved the 35-year old Solar Neutrino Problem. The Texas SNO group is now working on SNO's third phase, in which discrete ^{3}He proportional counters have been installed inside the heavy water volume. The group's focus is on a search for the MSW effect which will require pushing SNO's energy threshold as low as possible. To accomplish this goal, analyses on many fronts are being developed, including improvements to the SNO energy calibration, the position reconstruction of events inside the new counters, and the reduction and measurement of low energy backgrounds.

Proposed Work:

- The group has already begun work on simulations of possible detector configuations, with the primary goal being the exploration of relative calibration issues between the near and far detectors. A large fraction of this simulation work is being done by the undergraduate students.

- A small PMT testing facility which is being set up to study the timing of the SNO phototubes can be used to study the timing and charge characteristics of PMT's for the reactor experiment.

- The same PMT testing facility will be used to help develop optical calibration sources for the reactor experiment.

- The group's experience with the trigger and front-end electronics for SNO and input from the PMT and scintillator studies being done by the Collaboration will be used to assist in designs of the trigger and front-end electronics.

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