Proposal to Support the Preliminary Design of the Long-Baseline Neutrino Experiment (LBNE)

X. Bai[r], T. Bolton[j], J. Brack[f], R. Breedon[c], D. Cline[d], S. Dye[h], H. Gallagher[s], J.L. Harton[f], G.A. Horton-Smith[j], J. Klein[m], V. Kravtsov[f], T. Kutter[k], C. Lane[g], J.G. Learned[h], K. Lee[d], K. McDonald[o], K. McFarland[p], R. McKeown[b], Y. Maravin[j], J. Maricic[g], A. Marino[e], S. Matsuno[h], J. Matthews[l], S.R. Mishra[q], D. Naples[n], V. Paolone[n], R. Petti[q], C. Rosenfeld[q], M. Sanchez[i], I. Stancu[a], R. Svoboda[c], W. Toki[f], R. Van Berg[m], G. Varner[h], R.J. Wilson[f], E. Zimmerman[e]

[a]*University of Alabama,* [b]*California Institute of Technology,*
[c]*University of California at Davis,* [d]*University of California at Los Angeles,*
[e]*University of Colorado,* [f]*Colorado State University,*
[g]*Drexel University,* [h]*University of Hawaii,* [i]*Iowa State University,*
[j]*Kansas State University,* [k]*Louisiana State University,*
[l]*University of New Mexico,* [m]*University of Pennsylvania,*
[n]*University of Pittsburgh,* [o]*Princeton University,*
[p]*University of Rochester,* [q]*University of South Carolina,*
[r]*South Dakota School of Mines and Technology,* [s]*Tufts University*

(Dated: May 13, 2010)

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EXECUTIVE SUMMARY

The Long Baseline Neutrino Experiment (LBNE) has been proposed to measure θ_{13}, to search for CP-violation in the lepton sector, and to determine the hierarchy of neutrino masses. The experiment will consist of an intense Fermilab neutrino beam, a large underground far detector, and a near detector complex located at Fermilab.

The neutrino beam is planned to have an intensity in the range of 700 kW, and will be energetically broad band in order to cover two oscillation minima. Options for both 60 and 120 GeV proton energies are being considered, along with various target, horn, and decay pipe options. The role of university personnel in the design and instrumentation of this beam is discussed in this proposal, and funds are requested to support people to participate in this effort.

The near detector complex must measure the incident neutrino beam characteristics prior to oscillations and the relative event rates of many neutrino interaction channels in order to reliably estimate the non-oscillated signal, background, and oscillated signal in the far detector. The goal is to limit the systematic uncertainty for oscillation analyses due to any process that can be measured at the near site. This requires the measurement of the neutrino fluxes, flavor composition, and neutrino-induced background processes to a high precision. In addition, this suite of detectors will monitor the position and intensity of the neutrino flux on a spill-by-spill basis.

There are two far detector options that are described by their proponents: liquid argon detector modules in the 20-kton range and water Cherenkov detectors in the 100-kton range. While some of the detector design work at the universities is being supported by R&D funds and "S4" funds from the NSF, many other tasks need to be done to realize a design for these detectors. The collaboration plans to settle on a reference far detector configuration by the end of 2010. This proposal will support university groups to participate in this activity.

In this document, we propose the physics studies to be carried out by university collaborators that are required to develop the preliminary design of LBNE and contributions to the near and far detector design and development. We propose to carry out this work over a three-year time period.

INTRODUCTION

Physics Goals

The last fifteen years have seen remarkable progress in the field of neutrino physics and astrophysics. Neutrino flavor oscillations have been discovered [1], implying that the mass of the neutrino is non-zero and that the mass and flavor states are mixed [2]. Several precision measurements of the mixing parameters have been made or are now in progress [3] and a new generation of experiments is now under construction [4]. The neutrino spectrum from the sun has been measured for ^8B and ^7Be neutrinos [5] and radiochemical experiments have measured the integral solar neutrino flux, including the pp reaction [6]. New experiments are being constructed to probe the absolute neutrino mass scale [7] and determine the basic structure of the neutrino sector of the Standard Model [8]. For the field of neutrino physics, this is truly the best of times.

How to build upon these discoveries has been a subject of several broad community studies over the past five years, culminating in a series of community town meetings sponsored by the Particle Physics Project Prioritization Panel (P5) in 2007–08. The subsequent report from P5, endorsed by HEPAP, called for a new neutrino initiative in the U.S. as part of a three-pronged program in particle physics over the next decade. The flagship of this initiative would be an intense neutrino beam from Fermilab to the Deep Underground Science and Engineering Laboratory (DUSEL) in South Dakota. In this proposal, we give a brief summary of the physics that could be addressed by such an experiment. More detailed descriptions can be found in the P5 report [9], the report of the Long Baseline Study Group [10], the Neutrino Science Advisory Group report [11], and the long baseline Theory White paper [12].

Under the assumption of three active Dirac neutrinos, neutrino oscillations are fully described by two Δm^2 values, three mixing angles, and one CP-violating phase angle. Two of the mixing angles, θ_{12} and θ_{23}, have been measured; however, the third mixing angle, θ_{13}, has only a limit, and the CP phase angle, δ_{CP}, is unknown. Motivated by the observation of neutrino oscillations with atmospheric and accelerator neutrinos ($\Delta m^2_{23} \sim 2 \times 10^{-3}$ eV^2) and with solar and reactor neutrinos ($\Delta m^2_{12} \sim 8 \times 10^{-5}$ eV^2), there is now the intriguing question of the absolute ordering of the neutrino masses. In addition, there is intense theoretical speculation that neutrinos might profoundly violate CP symmetry.

The question of CP violation in the lepton sector is especially important because it may play a role in understanding the baryon asymmetry of the universe. If the mass of the neutrino is due to a "see-saw" [13] type mechanism, whereby the light left-handed neutrinos are mixed with heavy right-handed partners, then CP violation in the neutrino sector could lead to a significant baryon/anti-baryon asymmetry in the early universe. The origin of this observed asymmetry has puzzled scientists for many decades, and it may be that there is a "neutrino solution" to the problem [14].

The ordering of neutrino masses is not known because, in general, neutrino oscillation effects in vacuum depend only on the magnitude of Δm^2 and not the sign. For solar neutrinos, propagation of the neutrino beam through the sun induces "matter effects" which *are* sign dependent. From measurements at different energy thresholds we know that $m_2 > m_1$. We do not know if m_3 is significantly higher ("normal" hierarchy) or lower ("inverted" hierarchy) than the mass of the closely spaced (m_1, m_2) pair. A new "matter effects" experiment is needed to resolve this ambiguity.

In addition to these two fundamental questions, there is also a good deal of speculation about the unexpected symmetry in the neutrino mixing angles. The current values are close to the so-called "tri-bi-maximal" symmetry values [15]. Is this just a coincidence, to be rejected by more precise measurements, or is this really a clue to new physics beyond the Standard Model? A new experiment is needed that is capable of improving the measurements of θ_{23} and θ_{13} significantly. This can be done by increasing the data collection capability of the "far" detector in addition to reducing the systematics by precision measurements of the beam at the "near" detector.

There is a significant program of fundamental physics that can be pursued in addition to that made possible by the FNAL neutrino beam. This includes extending the search for proton decay and making fundamental measurements in astrophysics and cosmology.

The possibility that the proton is unstable has intrigued physicists since the early 1970s. In the context of a unified picture of the fundamental particles (quarks and leptons) and interactions (strong, electromagnetic, and weak), proton decay appears as a consequence. Attempts of Grand Unification are strongly supported by the meeting of the strengths of the three forces that is predicted to occur at high energies ($\sim 10^{16}$ GeV) in the context of supersymmetry. One of the most crucial predictions of Grand Unification is that the proton must ultimately decay into a lepton and a meson, revealing quark-lepton unity. A large neutrino detector located at a deep underground location would be able to extend the search for proton instability by an order of magnitude or more for many possible decay modes.

Supernova explosions throughout the universe left behind a diffuse background of neutrinos that may be detected on Earth. The flux and spectrum of this background contain information about the rate of supernova explosions (and consequently the star formation rate) in the past. Since the existence of such a flux is a robust prediction of most models of stellar formation, observation of this flux would provide a key indication that our general idea of how stars came to be formed and in what epoch is correct, much like the measurement of solar neutrinos has provided strong confirmation (after our knowledge of neutrino oscillations improved) of the nuclear reaction processes in the sun. These neutrinos have never been detected, but a large, sensitive detector located deep underground should be able to make this observation based on almost all models.

A program of galactic supernova burst detection is also planned. While the detection of 20 neutrinos from SN1987A was stunning in that it confirmed the basic idea of stellar collapse into a pulsar, a galactic supernova observed with the detectors considered here would yield flavor- and time-resolved spectra that would provide a detailed record of the collapse mechanism. In addition, if a low enough threshold is achieved it might be possible to observe the predicted "day/night effect" in solar neutrinos, providing further confirmation of our ideas about matter effects in neutrino oscillations.

We propose to participate in the design and construction of LBNE by joining with the consortium of national laboratories and universities already committed to pursuing this scientific program. In the following sections, we provide a general overview of the experiment and a description of the individual contributions we plan to make to the effort. This participation would be in collaboration with existing efforts in three major categories: (1) development of the specification and conceptual design of a suite of "near detector" experiments, (2) development of the design of an intense neutrino beam with Fermilab, and (3) design of a suite of "far detector(s)" at the underground site. In each of these cases, there is significant effort already supported through DOE or NSF. *This proposal is important in that it would provide funding for university groups to participate in LBNE who do not cur-*

rently have sufficient support from DOE project funds or NSF S4 grant funds. To evaluate the work proposed here in the context of the whole project, we will give a brief overview of the experiment and its current status, followed by a detailed description of the work to be supported under this proposal. In some cases, mostly redirection of existing university operations funding is needed; in others, supplemental funding is requested in addition to redirection. One group (Iowa State) is led by a new assistant professor and is requesting new support from the DOE for participation in LBNE. This proposal is submitted under the auspices, and after review by, the LBNE Science Collaboration.

Experiment Overview

The LBNE project will use protons from the main injector at Fermilab to produce a neutrino beam by impinging the protons on a target encased in a magnetic horn system [10]. The horn system will be pulsed in time with the beam and will focus pions (and other charged mesons) down a decay region of several hundred meters producing a beam primarily of ν_μ or $\bar{\nu}_\mu$, depending on the chosen polarity of the horns. Downstream of a beam absorber and several hundred meters of earth will be a near detector (ND) hall. There will be detectors in the ND hall to measure the neutrino flux and neutrino interactions, detectors in the target hall to measure the neutrino-parent hadron flux, and detectors in the region around the beam dump to monitor the muon flux that is correlated with the neutrino flux. Collectively, we call this suite of detectors the near detector complex. The far site is anticipated to be in the proposed Deep Underground Science and Engineering Laboratory (DUSEL) in the Homestake mine in Lead, South Dakota. This site is about 1300 km from Fermilab. The primary oscillation analysis channel is the appearance of ν_e ($\bar{\nu}_e$) in the ν_μ ($\bar{\nu}_\mu$) beam. The appearance probability for vacuum-oscillations is given by

$$
\begin{aligned}
P_{\mu e} \simeq\ & \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 (1.27\frac{\Delta m^2_{13} L}{E}) \\
& \mp \sin 2\theta_{13} \sin\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin (1.27\frac{\Delta m^2_{12} L}{E}) \sin^2 (1.27\frac{\Delta m^2_{13} L}{E}) \\
& + \sin 2\theta_{13} \cos\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin (1.27\frac{\Delta m^2_{12} L}{E}) \sin (1.27\frac{\Delta m^2_{13} L}{E}) \cos (1.27\frac{\Delta m^2_{13} L}{E}) \\
& + \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 (1.27\frac{\Delta m^2_{12} L}{E}),
\end{aligned}
$$

where the $\Delta m_{ij}^2 = m_j^2 - m_i^2$, the θ_{ij} are the mixing angles, δ is the CP violating phase, E is the neutrino energy in GeV, and L is the distance from the point of production to the point of detection in kilometers. The critical parameter controlled by experimentalists is L/E. The baseline of 1300 km will allow the LBNE project to achieve unprecedented sensitivity in ν_e appearance for oscillations at a Δm^2 of 2×10^{-3} eV^2. At this distance, the oscillation maxima we expect to probe are at neutrino energies of about 2.1 GeV (1st maximum) and 700 MeV (2nd maximum). The LBNE neutrino beam is being designed to have a large flux between 500 MeV and 2.4 GeV. The large distance allows separation of the CP violation phenomena from the matter effects in the $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ signals. The detection of CP violation requires a very large detector at the far site to obtain sufficient data to see a small asymmetry between neutrinos and antineutrinos. The current beam concept is for a 700-kW beam utilizing Main Injector protons at 60 or 120 GeV, and a new switchyard, target hall, and 250-m decay pipe to be added onto the existing Fermilab complex. Site evaluation is underway, and a reference beam design is being developed.

The current options for the far detector are a water Cherenkov detector with a fiducial mass of several hundred kilotons and a liquid argon time-projection chamber (TPC) with a fiducial mass of several tens of kilotons. Water Cherenkov detection is a leading candidate technology because it minimizes the cost per kiloton of fiducial mass and can separate charged-current (CC) ν_μ interactions from CC ν_e interactions. In addition, the mature technology has a long history culminating with Super–Kamiokande, a 50-kton detector in the Kamioka Mine in Japan [16]. Building a detector of a few hundred kilotons is, therefore, viable with a minimum of research and development (R&D). The design issues are largely ones of cost vs. physics optimization rather than fundamental viability, so the current LBNE plan is to build at least 300 kton of fiducial mass of water Cherenkov detector in multiple modules, each at least 100 kton in fiducial mass. Liquid argon TPCs show great promise in achieving better background rejection from neutral current π^0 events than water Cherenkov detectors, but require a significant R&D program to establish the viability of constructing sufficiently large detectors to serve the physics needs of the LBNE project. A phased program at Fermilab is underway including the ArgoNEUT and MicroBooNE experiments, and the collaboration is considering a liquid argon TPC option instead of, or in addition to, a water Cherenkov detector.

In addition to the far detectors, one or more near detectors are required to characterize the neutrino beam at the production point. An oscillation analysis requires a detailed knowledge of the absolute flux, energy spectrum, and intrinsic ν_e contamination. At the energies considered for this beam, a fundamental knowledge of the interaction parameters associated with nuclear effects and non-quasi elastic final states is also required. Thus a near detector is planned to make detailed measurements of the beam at the end of the decay pipe. There are several options being considered, including (1) liquid argon TPC, (2) MINERVA-like tracking detector, and (3) a suite of high resolution tracking detectors.

Sensitivity

The collaboration is currently embarked on settling on a set of reference designs and configurations necessary for a planned CD-1 review in later 2010 or early 2011. The sensitivities shown below are for a preliminary beam design consisting of a 120-GeV proton beam, MINOS-like horn and target design, a 300-kton water Cherenkov detector or 50-kton liquid argon detector, and a far detector site located 4850 feet underground at DUSEL. (Note that a shallow liquid argon detector may not be sensitive to, or may have reduced sensitivity for, non-beam related physics.) The tables and plots below are from several studies and preliminary calculations based on estimates from extrapolated data from existing Cherenkov detectors such as Super-Kamiokande, SNO, and MiniBooNE, and from assumptions on the performance of liquid argon TPC from simulations and small prototypes.

Neutrino Physics

The current generation of neutrino oscillation experiments has essentially no sensitivity to the value of $\delta_C P$ and only limited sensitivity to the mass hierarchy (only if the value of θ_{13} is close to 10^o). A major goal of this experiment is to be sensitive to the mass hierarchy and CP violation even if θ_{13} is as small as 3^o, roughly the sensitivity of the new generation of experiments now being built.

Using a preliminary beam design and assuming equal running of neutrinos and antineutrinos, Table I gives the expected sensitivity for a 300-kton water Cherenkov detector for 60×10^{20} and 120×10^{20} protons on target (POT). Note that 60×10^{20} POT represents roughly six years of actual run time (100% duty factor) for a 700-kW 120-GeV beam. Performance

Detector	POT($\times 10^{20}$) at 120 GeV $\nu + \overline{\nu}$	assumed hierarchy	Sensitivity		
			$\sin^2 2\theta_{13} \neq 0$	mass hierarchy	CPV
300-kton water	60+60	normal	0.006	0.01	0.012
300-kton water	60+60	inverted	0.005	0.01	0.011
50-kton argon	60+60	normal	0.006	0.009	0.009
50-kton argon	60+60	inverted	0.004	0.01	0.007

TABLE I: Sensitivity of LBNE for specific combinations of run time, assumed mass hierarchy, and far detector configuration. Water Cherenkov π^0 rejection efficiencies are extrapolated from Super–Kamiokande, and liquid argon rejection efficiency is assumed to be 100%. The sensitivity for $\sin^2 2\theta_{13} \neq 0$ is for rejection of the null hypothesis at 3σ for all values of δ_{CP}, while the mass hierarchy sensitivity is the $\sin^2 2\theta_{13}$ value that would allow discrimination between the normal and inverted mass hierarchy at 90% c.l. for all values of δ_{CP}. For CP violation, the sensitivity quoted is the value of $\sin^2 2\theta_{13}$ for which 50% of the possible values of δ_{CP} can be measured at better than 3σ. For all cases, a 5% uncertainty on the background is assumed, along with a Δm^2_{23} value of 2.4×10^{-3} eV^2.

parameters for the detector are extrapolated from Super-Kamiokande, including the effects of the higher beam energy for DUSEL. A 5% uncertainty is assumed for backgrounds (e.g., intrinsic ν_e in the beam). To reach the ultimate sensitivity goal with a realistic duty factor (0.67), a 16-year run would be required. This could be reduced by a factor of three if the beam power is increased to 2 MW (as planned for "Project X").

If a liquid argon detector is practical and is shown to be near 100% efficient for reducing the background from misidentifying neutrino-induced π^0 events, then a similar sensitivity could be obtained with a 50-kton detector. The collaboration is currently studying the possibility of employing one or more such detectors at the far site.

Thus, if the current round of θ_{13} experiments makes a positive measurement, then this experiment will settle the mass hierarchy problem in addition to making a definitive statement regarding CP violation by neutrinos.

Nucleon Decay

The stability of the proton has been questioned since the early 1970s in the context of a unified picture of the fundamental particles—the quarks and leptons—and interactions—the strong, electromagnetic, and weak. Grand Unification attempts are strongly supported by the dramatic meeting of the strengths of the three forces that is predicted to occur at high energies ($\sim 10^{16}$ GeV) in the context of supersymmetry, and recently by the magnitude of neutrino masses that is suggested by the discovery of neutrino oscillations. One important prediction of Grand Unification is that the proton must ultimately decay (with a lifetime in the range of 10^{35-36} years for some theoretical models) into a lepton and a meson, revealing quark–lepton unity.

Proton decay final states depend on the details of a given theory. Experimentally, the modes $p \rightarrow e^+\pi^0$ and $p \rightarrow \nu K^+$ are common benchmarks. The former represents the lightest anti-lepton plus meson final state, typical for the case where the first generation of quarks and leptons are grouped in a single multiplet, as in SU(5). The latter is typical of supersymmetric grand unified theories where dimension-5 operators induce decays that span generations, hence requiring a strange quark. Current limits from Super-Kamiokande for these two modes are 8×10^{33} years and 2×10^{32} years, respectively [17].

Currently, no experiment has ever detected a candidate event in the region of total momentum and invariant mass expected for $p \rightarrow e^+\pi^0$. Background estimates from the SK collaboration are 0.2 ± 0.1 events/100 kton/year using their particular analysis. The selection efficiency or the SK analysis was estimated to be $45\% \pm 19\%$, dominated by nuclear effects. It should be noted that the presence of free protons in water presents a 2/10 chance for an event with ideal back-to-back kinematics far from the background region. For a run of 20 years we would expect to reach a sensitivity of 10^{35} years (90% CL). Based on experience with 20% photon coverage in the SK-2 and IMB (5% coverage), we expect the sensitivity to $p \rightarrow e^+\pi^0$ to be relatively unaffected by PMT coverage.

For the $p \rightarrow K^+\nu$ mode, the K^+ is below the Cherenkov threshold, requiring a search for kaon decay at rest. There is significant atmospheric neutrino background in the dominant (63%) decay mode of $K^+ \rightarrow \mu^+\nu_\mu$. SK uses the prompt nuclear de-excitation gamma ray (6.3 MeV) from the residual ^{15}N nucleus to reject background events. Analysis of the hadronic mode, $K^+ \rightarrow \pi^+\pi^0$ (21%) is hampered by the fact that $\beta_{\pi^+} = 0.87$, so that the amount of Cherenkov light emitted is near the detectable threshold. Expectations are that background events could be seen in this mode at a rate of 0.8 events/100 kton/year. The combined efficiency for the prompt gamma tag of both kaon decay modes is $14\% \pm 2\%$ with an expected background of 1.2 ± 0.4 events/100 kton/year. Experience with SK shows that the performance of this analysis is sensitive to the amount of photon coverage. For a run of 20 years we would expect to reach a sensitivity between $1 - 2 \times 10^{34}$ years.

For a liquid argon detector, the sensitivity per kiloton for $p \to e^+\pi^0$ and other related decay modes is worse than water, due to the larger nuclear effects and lack of free protons. For $p \to K^+\nu$ however, the sensitivity per kiloton can be significantly better. The highly-ionizing kaon tracks will be visible, along with the decay into either the muon or pion modes. Assuming 100% background rejection and 100% efficiency, a 20-year run of a 50-kton liquid argon detector would result in a sensitivity (90% c.l.) of 9×10^{34} years.

Cosmological Supernovae

Supernova explosions throughout the universe left behind a diffuse background of neutrinos that may be detected on Earth. The flux and spectrum of this background contains information about the rate of supernova explosions (and consequently the star formation rate) in the past. Since the existence of such a flux is a robust prediction of almost all models of stellar formation, observation of this flux would provide a key indication that our general idea of how stars came to be formed and in what epoch is correct, much like the measurement of solar neutrinos has provided strong confirmation (after our knowledge of neutrino oscillations improved) of the nuclear reaction processes in our own sun.

The best signal of supernova relic neutrinos in water Cherenkov detectors are the positrons resulting from the inverse β decay reaction with antineutrinos well above the reactor ($\sim$10 MeV) and well below the atmospheric ($\sim$100 MeV) antineutrino background. Above $\sim$20 MeV, the dominant background is due to the decay of sub-Cherenkov threshold μs from atmospheric neutrino interactions. This could be greatly reduced by tagging the neutron which accompanies each inverse β reaction by observing the γ rays associated with its capture.

Figure 1 shows the existing limit on the flux of diffuse SN background neutrinos from Super–Kamiokande and the predictions from several published models. The model differ-

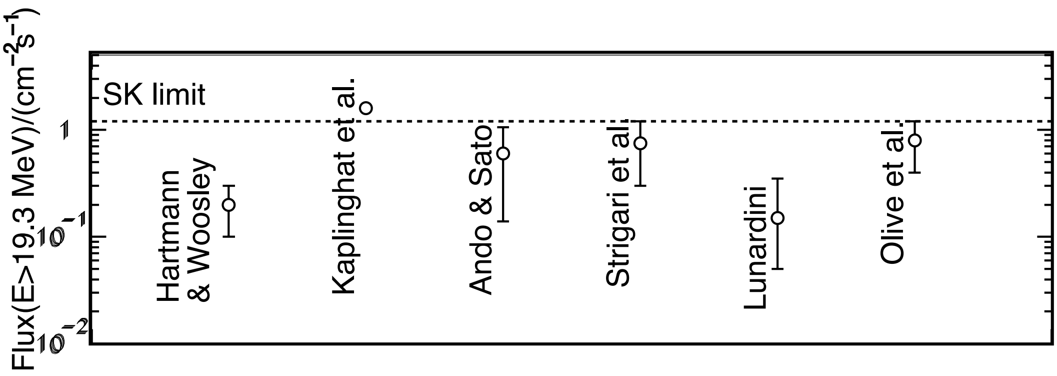

FIG. 1: A sample of theoretical predictions for the anti-electron component of the diffuse SN neutrino flux above the Super-Kamiokande (SK) neutrino threshold. The dashed line is the SK flux limit (reprinted from C. Lunardini [18]).

ences are mainly due to (1) different collapse model and (2) different stellar formation model. It is evident that an order of magnitude improvement in sensitivity is sufficient to cover most models. Thus a 300-kton detector loaded with gadolinium and at sufficient depth should be able to unambiguously detect this neutrino flux [19].

Galactic Supernovae

A nearby core-collapse supernova will provide a wealth of information via its neutrino signal. The neutrinos are emitted in a burst of a few tens of seconds duration, with about half in the first second. Energies are in the few tens of MeV range and luminosity is divided roughly equally between flavors. The observed neutrino signal will shed light on a variety of topics. The time, energy, and flavor distribution of the detected neutrinos will give information on the astrophysics of core collapse: one can learn about the explosion mechanism, accretion, neutron star cooling, and possible transitions to quark matter or to a black hole. An observation in conjunction with a gravitational wave detection would be especially interesting. A nearby core collapse will also give information on the properties of neutrinos. In particular, oscillations in the core can provide information on oscillation parameters, mass hierarchy, and θ_{13}, possibly even down to very small values inaccessible to

100-kton water	No. of interactions
Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$	23000
CC $\nu_e +^{16,18}\mathrm{O} \rightarrow^{16,18}\mathrm{F} + \mathrm{e}^-$	1000
NC $\nu +^{16}\mathrm{O} \rightarrow \nu +^{12}\mathrm{O}^*$	1100
ES $\nu + e^- \rightarrow \nu + e^-$	1000
50-kton LAr	
CC $\nu_e +^{40}\mathrm{Ar} \rightarrow e^- +^{40}\mathrm{K}^*$	3100
CC $\bar{\nu}_e +^{40}\mathrm{Ar} \rightarrow e^+ +^{40}\mathrm{Cl}^*$	260
NC $\nu +^{40}\mathrm{Ar} \rightarrow \nu +^{40}\mathrm{Ar}^*$	15000
ES $\nu + e^- \rightarrow \nu + e^-$	500

TABLE II: Summary of expected core collapse signals at 10 kpc. The expected number of events scales by distance as $1/D^2$, where D is the distance to the supernova. These numbers are for no oscillation effects. Oscillation effects will very likely strongly influence the charged current ν_e and $\bar{\nu}_e$ event rates.

accelerator experiments [20]. Observation of a neutrino burst also allows one to set limits on coupling to axions, large extra dimensions, and other exotic physics [21]. Finally, because the neutrinos emerge promptly after core collapse, in contrast to the electromagnetic radiation, which must beat its way out of the stellar envelope, an observed neutrino signal can provide a prompt supernova alert [22]. This will allow astronomers to find the supernova in an early light turn-on stage, which may yield information about the progenitor (in turn important for understanding oscillations). Table II shows the number of events expected from a galactic supernova at 10 kpc in a 100-kton water detector and 50-kton liquid argon detector.

Other Physics

In addition to the physics program outlined above, a deep detector would be able to continue the solar, atmospheric, and VHE neutrino investigations of Super–Kamiokande with an order of magnitude increase in data, and muon-induced backgrounds reduced a factor of 10 or more due to the greater depth. This program would include (1) looking for matter effects in the ^8B solar neutrino flux, (2) looking for evidence of tau neutrino interactions in atmospheric neutrinos, (3) a search for a sterile neutrino component in atmospheric neutrino oscillations, (4) looking for neutrinos from WIMP annihilation in the sun, and (5) searching for other exotic physics (e.g., mass-varying neutrinos and GRB neutrinos). Thus, the collaboration supports the development of a broad physics program enabled by large detectors at the 4850 level of DUSEL.

This Proposal

While the LBNE project provides funds for design and engineering work, support for university physicists to work on the experiment must come from individual university grants. Thus, we propose to join the existing effort to design the beam, far detector, and near detector complex for LBNE. The work outlined in this proposal represents only a fraction of the total effort required, and so must be considered in that context. Briefly, the existing efforts are centered around the LBNE project, which is a joint NSF-DOE effort that is working towards the CD1 level of design by late 2010 (note: CD0 was received in January 2010). This project is supported by a combination of DOE project funds and NSF design funds. Currently, the LBNE Science Collaboration consists of 46 institutions and 200+ physicists and engineers. This proposal outlines a plan to redirect existing resources at universities coupled with a request for increased operational support for travel and people to participate in this community-wide effort. *There is no overlap with effort already funded through the DOE project or NSF S4 solicitation.* The work outlined in this proposal has been planned in coordination with the LBNE project management and the science collaboration. Letters of endorsement are included as an appendix. It should be explicitly noted that this proposal does not cover equipment or M&S costs associated with the actual construction of the experiment, but only the physicist effort required for design and planning. Engineering and other technical support are not covered, as this work will be supported directly by the DOE project funds or NSF S4.

The work proposed here spans the entire range of the project scope: near detector, far detector, and beam design and instrumentation. There is a section for each institution that describes the work to be done and how it fits into the overall experimental design effort. Each institution then lays out the budget for doing the work, and indicates the part that can be covered by redirection of existing funds and the part that would require additional funding. The expectation is that, although this proposal is presented as a coherent plan, the individual requests will be separately evaluated by the DOE. This proposal provides the information needed to evaluate these requests in the context of the whole project. It includes only HEP-supported university groups; effort from NSF-supported groups, DOE nuclear physics groups, and national lab groups will be requested via separate proposals.

PHYSICS PLAN

In this section, we outline the physics studies required to support the preliminary design of LBNE.

Near Detector Studies

The primary purpose of the near detector (ND) complex is to maximize the oscillation physics potential of the far detector. The complex should, therefore, be useful for analyzing ν_e appearance, the primary oscillation channel, and ν_μ disappearance. In addition, the complex should be able to monitor the intensity and direction of the beam on a spill-by-spill basis. We anticipate the need for detectors to measure the post-target hadron (PTH) flux and both the muon flux and neutrino flux due to the decay of the PTH flux. The requirements of the ND complex will depend on the neutrino flux produced by the beam, the beamline configuration, and the anticipated performance of the far detector. Close coordination with the beam working group and the far detector working groups is critical for a successful design.

There are three focus areas that constitute the organization of the work required to define the near detector complex: strategy, beamline, and neutrino. The strategy focus area integrates studies required to define how the ND data will be used in oscillation analyses. This requires close coordination between the ND, beam, and far detector working groups both in the initial planning stages and throughout the design process as the beam and far detector designs undergo iterative changes. The beamline focus area constitutes any measurements of hadron or muon fluxes in the region after the target and horn configuration to just beyond the beam absorber at the downstream end of the decay region. It also includes any measurements of hadron production off of the target performed externally. The neutrino focus area consists of any measurements of neutrino interactions in the neutrino hall downstream of the decay region.

For each focus area, there are two sets of tasks: work to be performed for CD-1 and work to be completed after CD-1 in support of the preliminary design of LBNE. Much of the work on the latter set of tasks will commence before CD-1 is granted.

Strategy Focus Area

The LBNE project plans to measure ν_e appearance and ν_μ disappearance with unprecedented sensitivity. In order to accomplish this goal, we must design the ND complex to answer all necessary questions important for the oscillation analyses. To properly determine what information is needed from the ND complex, we have liaisons with both the beam working group and the far detector working groups. The measurements that will be made by the ND complex may take place at several locations including

- in the vicinity of the target,
- in or near the decay region,
- after the beam dump,
- in the ND hall located several hundred meters downstream of the beam dump.

These measurements will be of several different particle types in a wide energy range. In addition, measurements done in the target or decay regions will likely be of high particle intensities in a high radiation environment.

There are two tasks that we must complete to determine and validate the global ND requirements and specifications:

- determine how ND data will be used in the oscillation analyses; and
- determine an analysis strategy to handle any neutrino spectral differences between the near and far sites.

Simply stated, ND data will be used to predict the event rates and energy spectra of all processes contributing to the signal and background in the far detectors. ND data are required because the neutrino flux cannot be precisely determined from measurements of the proton beam current, and even if the neutrino flux were known precisely, present neutrino interaction models in the few GeV neutrino energy regime have large uncertainties. Whether or not a given process contributes to the background or signal depends on the capabilities of the far detector technology, so we must separately evaluate neutrino interactions for each possible far detector scenario.

If the neutrino spectra at the near site were identical to the spectra at the far site under the assumption of no neutrino oscillations, we could in principle simply make high precision measurements of the neutrino flux and spectra and all interaction processes and be able to predict the event rates and event topologies in the far detector under any neutrino oscillation scenario.

A neutrino hall constrained to be on the Fermilab site will not see a point source of neutrinos like the far detector will. Therefore, the neutrino spectra even in the absence of oscillations will be different far to near. We must determine what the impact of the difference on the sensitivity will be. If it is large, we must develop a plan to mitigate the impact.

There are three options we will consider to address this problem. If we build an off-site near detector hall far enough away from the target station and decay region, the far–near neutrino spectral ratio will be very close to unity for all neutrino energies. In addition, the neutrino interaction rates would become more manageable, allowing for a broader range of technologies to be considered for neutrino detection. The political issues surrounding acquiring land off of the Fermilab site to build such a facility coupled with the high cost of excavation make this possibility somewhat remote. A second option is to use a hadron hose in the decay region. A hadron hose would mix pion momenta to such an extent as to smear out the geometrical dependencies of the neutrino spectra. This option also has its own challenges, as building a robust device that can withstand the exposure to intense radiation over years without requiring frequent replacement could be daunting. Finally, we will study the efficacy of making near detector neutrino measurements with a series of special runs with different horn currents. MINOS has used horn-on vs. horn-off running to evaluate the impact of their high-energy tail at the far site.

There are several studies we will carry out to address the first task for CD-1. For a given precision on the ND measurement of each neutrino interaction process, we will determine the impact on the LBNE sensitivity to neutrino oscillation parameters. We will study not only the impact due to uncertainties on the total cross-sections, but also the impact due to uncertainties on final-state interactions (FSI) in the nucleus. FSIs significantly modify the kinematic distributions and even charge-states of the outgoing particles and thus have a large impact on the fraction of events from a particular neutrino interaction mechanism that contribute to signal or background. Since the far detectors are still under design, we will use response parameterizations for the far detectors in the first stage. Using the results of this study, we will define the order of importance of each neutrino interaction channel and communicate this with the team developing the near neutrino detector design.

While we will look carefully at all contributions to the systematic uncertainties of the oscillation analyses, we can already list several sources of systematic uncertainty which must be addressed by our study:

- the absolute neutrino fluxes at the near site
- NC pion production at the near site
- NC gamma production at the near site
- CC quasi-elastic scattering at the near site
- CC pion production at the near site
- the intrinsic ν_e component of the beam

The expected performance of the far detector will play a crucial role in the expected systematic uncertainties. After CD-1, we will refine our understanding of the ND requirements as we develop a better understanding of what the far detector capabilities will be. For a water Cherenkov far detector, we must understand, for example

- What is the quantitative impact of sub-Cherenkov threshold particles on the systematic uncertainty for the oscillation analyses?
- How well can single π^0's be identified in the far detector?
- With what statistical precision can π^0's and single γ's misidentified as ν_e's be subtracted from the far detector ν_e sample?

For the liquid argon option of the far detector, the above questions might be less relevant; however, the current plan is to use all CC events for oscillation analysis. A careful evaluation of the impact of FSIs on the reconstructed neutrino energy as well as the efficiency and energy resolution on neutron detection will be important. For both technologies, we will revisit these estimates as the designs and capabilities are refined.

The first two options to address the second task would result in similar or identical far and near neutrino spectra. In these cases, the oscillation analysis described above is sufficient to determine the precision required to measure various neutrino interaction channels in the near detector. The exploration of these two options will be discussed in the Neutrino Focus Area and Beamline Focus Area sections, respectively. The third option, on the other hand, requires significantly more analysis. The first step is to quantify what the impact of doing no special runs is on the sensitivity of LBNE to all relevant oscillation parameters. In this step, we will also learn if the order of importance of each neutrino channel has changed due to the energy dependence of the far–near spectral ratio. Next, we will explore how varying the horn current impacts the resultant neutrino spectrum at the near site and how special runs with non-standard currents and with the horn off can help us eliminate the limitations on the LBNE sensitivity due to the far–near spectral ratio. This exploration will carry-on beyond CD-1.

Beamline Focus Area

This focus area incorporates in-situ and external measurements of hadron production off of the LBNE target to precisely determine the flux, spectrum, and composition of the generated neutrino beam. Additionally, measurements of the neutrino beam stability and profile on a spill-by-spill basis using the muon flux after the beam absorber are studied here.

Determining the LBNE neutrino source flux is one of the most difficult challenges facing the LBNE program. The near detector system, although providing an important cross check on the flux and cross-section models, will not provide a complete determination of the neutrino flux at the far detector location. Many experiments have attempted to use quasi-elastic neutrino interactions to measure the neutrino flux because the theoretical uncertainties on the quasi-elastic cross-section were expected to be small. Recent measurements [28] [39] of the axial mass, M_A, are significantly different from those of previous experiments and indicate a need to approach the use of quasi-elastic interactions as a measure of the neutrino flux with caution. Clearly, a more direct approach is welcome. By measuring the momenta and intensities of the parent mesons of the neutrinos, we can infer the neutrino flux directly. Thus, the extrapolation of the flux to the far detector will rely on the knowledge of the spatial distribution and momenta of meson decays in the decay region.

While there are several factors that influence these spatial and momenta distributions, the largest uncertainties on neutrino fluxes come from the simulation of the hadronic cascade through the target, horn, and decay region. Ideally one would instrument the decay region so that the complete distribution of decays could be measured in situ; however, the environment in the decay region poses a number of problems for instrumentation, such as radiation damage and high fluxes of particles. Typical rates exceed 10^8 particles per square centimeter per main injector proton pulse that limit measurements to simple ones, for example, total ionization.

Past experiments have adopted several strategies to constrain the meson production. The first step is to measure meson production cross-sections for primary proton interactions on the target material in a separate experiment [32][33]. In order to constrain the problem further one could mount an experiment to measure meson production rates of the complete target/horn setup. This would require careful planning such that the initial horn testing, prior to installation in the LBNE underground area, be done in a beamline upstream of a particle spectrometer capable of measuring meson production by the target/horn system. The measurement of those yields should be possible in a low rate environment. Such measurements would provide direct constraints on the hadron cascade simulation and the beam flux simulation.

There are two tasks required to define the specifications for the hadron detectors, both of which require close contact with the beam working group. First, it is quite likely there will be significant differences in the un-oscillated neutrino spectra between the near neutrino hall and the far site. Trying to account for differences in background rates due to the far–near spectral ratio differences presents a significant complication for neutrino oscillation analyses.

We will study the viability and the advantages and disadvantages of using a hadron hose for LBNE. The hose consists of a segmented wire which runs down the length of the decay pipe and is pulsed in time with the beam. The induced magnetic field mixes the momenta of the hadron flux and generates a more uniform far–near neutrino energy spectrum. This idea was proposed for MINOS [40], but was discarded as too expensive. It also increased the intrinsic ν_e background. For LBNE, the length of the decay pipe will be less than half the length of the NuMI decay pipe, so the total impact on the project cost might not be significant. The beam intensities for the LBNE project will be much higher, however. Trying to replace a broken segment might be extremely difficult. We will study its capabilities and especially its viability in this extreme environment.

The second task is to determine the optimal strategy to make hadron measurements in situ and externally. Under the assumption that the hadron hose is not viable, we will have to make hadron measurements for the standard target/horn configuration and also for special configurations designed to change the energy spectrum of the neutrino flux to more precisely study backgrounds with the ND. Through discussions with the beam working group, we will study the likely beam scenarios and give input where warranted.

Measuring hadron production is a first step. Both K2K and MiniBooNE carried out measurements on their target materials at HARP which ran at CERN [37]. HARP was a multi-detector high performance system which included a TPC, RPCs, drift chambers, threshold Cherenkov detectors, time-of-flight detectors, and an electromagnetic calorimeter. It may be possible to collaborate with them to measure primary production cross sections. In addition, the MIPP experiment has recorded data that might be of some use, or possibly the MIPP apparatus might be reused to make measurements specific to LBNE. If a MIPP-like detector system could be set up downstream of a functioning target/horn system, a complete map of meson production could be made for mesons that exit the target/horn system. This would provide the most reliable flux values and should be considered carefully. This is likely to be the only method that could determine the neutrino flux with the necessary precision.

For in situ measurements, K2K used a Cherenkov threshold detector to measure pion momenta above 2 GeV, corresponding to measuring information about neutrinos created at 1 GeV and above. This detector could only be run at 1% of the normal intensity. To measure the azimuthal symmetry of the hadron beam, K2K could roll in a detector named the IonoCopter. This detector consisted of two sets of ionization chambers placed on a rotatable ring. This system was run with full intensity beam, but did not measure pion momenta.

It is likely we will have to consider scenarios where we use less sensitive but more robust equipment for full intensity runs and roll in sensitive equipment for special low-intensity runs. We would then correlate the different intensities using the more robust ionization chambers. The muon monitors and detectors may be indispensible for such a validation.

We will also consider mechanisms to roll detector systems into and out of the target region. If left in place, the detectors would destructively interfere with the production of the neutrino beam and would become useless after long irradiation times. A conceptual design of a spectrometer that could provide a complete understanding of the meson decays in the decay region will be explored. This would require a facility that allows the simultaneous operation of the target/horn, provide an incident beam to the target of the appropriate energy, and allow for a spectrometer downstream of the target/horn. The use of existing equiment in order to reduce costs will be researched. It is likely that much of the needed equipment is already available from previous experiments like MIPP.

We will investigate several types of muon measurements that may help us achieve our goals. Muons after the hadron beam dump can provide information about the profile and flux of the neutrino beam on a pulse-by-pulse basis. Off-axis muons can be used to determine the kaon component in the beam.

We will investigate the requirements and specifications for two arrays of detectors. The first array is a muon monitor located downstream of the beam dump at the end of the decay pipe. It would monitor the profile and intensity of the neutrino beam on a pulse-by-pulse basis. The second array would be off-axis and would ascertain the kaon component in the beam.

Several experiments including K2K [41] and MINOS [42] have used an array of detectors to measure the post-beam dump muon flux to monitor the position of the neutrino beam. Since muons and neutrinos have the same parents, the position of the neutrino beam is correlated with the post-dump muons. At K2K, the post-dump muon flux was about 10^4 muons/cm^2 per spill. At LBNE, the fluxes are expected to be significantly more intense. There are five questions which will define our study of the requirements and specification of the post-dump muon monitor.

- With what spatial resolution must we know the beam profile?
- How well must we know the pulse-by-pulse intensity of the beam?
- How intense will the muon flux be after the beam dump?
- What other particles will be present in the post-dump muon flux?
- How intense will the radiation environment be after the beam dump?

Answering these questions will determine the required spacing and resolution of the muon monitor. They will also limit the technical options available due to the high radiation and requirement to measure high particle intensities. They may also indicate fundamental limitations if there is a large fraction of other secondary particles besides muons. If successful, the muon monitor will provide an independent measurement of the proton flux and neutrino beam profiles.

We will study the viability of an array of muon detectors to determine the kaon flux in the hadron beam. A measure of the kaon flux can be done by directly observing the muons produced via kaon decay in the decay pipe. The higher kaon mass allows an enrichment of the kaon flux by measuring off-axis muons. The off-axis muon measurement also constrains the on-axis kaon rate, which for electron appearance measurements are crucial. MiniBooNE had limited success with this method due to high backgrounds. Here, the following questions will guide our study: How well must we know the kaon component in the beam? How well correlated are the muon flux as a function of angle and the kaon component of the beam for LBNE?

K2K used ionization chambers and silicon pad detectors for its muon monitor. T2K is using a similar array, but plans to replace the silicon detectors with a solid state option that is more radiation hard. We will investigate these technical options for the LBNE muon monitor.

MinibooNE attempted to measure off-axis muons from the decay pipe. The Little Muon Counter was built for this purpose and was positioned 7 degrees off-axis. The fiber hodoscope, with a permanent magnet for momentum measurement, worked well. However, beam–air interactions in the decay pipe produced large backgrounds, reducing the sensitivity of the measurement. They were still able to produce an upper limit on the kaon contribution that was consistent with the central value estimate from the on-axis neutrino data.

To make a better measurement for LBNE, we propose to study the building of a muon spectrometer that views the decay pipe slightly off the proton beam axis. We anticipate the decay pipe will be filled with helium gas, so we will simulate the anticipated backgrounds in this scenario.

Neutrino Focus Area

The heart of the ND effort will be the neutrino detectors. To accomplish the physics goals of LBNE, the near neutrino detectors must measure the ν_e contamination in the beam and any NC processes that could mimic the ν_e appearance signal. Additionally, we must plan thorough high-precision measurements of many CC processes that will contribute to the CC quasi-elastic ν_μ signal in the far detector, such as CC single pion production. The CP non-conservation measurement goals of the experiment require us to perform charge-separated measurements of the neutrino beam and will likely require a magnetic field. We will develop strategies to carry out all measurements that will be useful for the oscillation analysis physics goals of LBNE.

One of the first tasks of the proposed activity will be to specify quantitatively the requirements for the neutrino detectors in the near detector complex. These detectors will need to measure the incident ν_μ, $\bar{\nu}_\mu$, ν_e, and $\bar{\nu}_e$ fluxes and measure the cross sections for both charged-current reactions and neutral-current reactions that mimic ν_e charged-current events (e.g., involving photons) in the far detector. In order to perform these measurements, the detectors must have excellent energy, position, and angular resolutions and excellent particle identification (better than the far detector) for muons, electrons, photons, pions and protons. In addition, the target material for the detectors should include both water and liquid argon, so that the cross-section measurements in the near neutrino detectors match the far detector cross-sections. Other important considerations are the intense neutrino flux at the near location, which leads to an event rate of approximately 0.2 neutrino events per ton per spill, and the cost of the neutrino detectors. The inclusion of a magnetic field would allow the separate determination of fluxes and cross sections for both neutrinos and antineutrinos. Finally, the detectors should have good timing resolutions in order to distinguish events and measure the beam microstructure timing.

The proposed activities will study various technical options for the neutrino detectors. We will evaluate a water Cherenkov detector, a fine-grained tracking argon detector, a fine-grained tracking water detector, and a muon ranger. The two options for a fine-grained argon detector are to re-use the MicroBooNE liquid argon TPC or to use a custom-designed modular liquid argon TPC. For a fine-grained water detector, there are also two options: a MINERνA-style detector with plastic scintillator strips interleaved with water layers and a NOMAD-style detector with drift chambers or straw tubes.

The water Cherenkov detector is not well suited for reconstructing multiple tracks occurring at the same time; however, by reducing reflections and using fast phototubes and electronics, it may be possible to constrict an event to < 100 ns, so that 10 or more separate neutrino events could be reconstructed over the 10 μs beam spill. Background from beam muons ($\sim$10 muons/m^2 per spill) will have to be considered for this option. We will also explore the usefulness of using a water Cherenkov detector during special low-intensity runs.

For the liquid Ar TPC, we can mimic the design of the MicroBooNE detector or possibly even move MicroBooNE to the near detector location. The success of the MicroBooNE detector and associated R&D is crucial for liquid argon to remain a viable possibility for the LBNE far detector.

The MINERνA detector technology is another interesting option to consider. With MINERνA turning on and operating over the next year, we will study its performance capabilities (reconstruction resolutions and particle identification efficiencies) in the NuMI beam. As in the case of MicroBooNE, we can mimic the design of the MINERνA detector or move MINERνA to the near detector location. Finally, we will also consider a NOMAD-style detector with drift chambers or straw tubes serving as an active target.

A downstream spectrometer consisting of steel plates interspersed with particle detectors will be considered for measuring muons from ν_μ charged-current interactions. The plates will be magnetized so that muon momenta will be determined from both the muon range in the plates and the deflection of the muons going through the plates. The angular acceptance of the spectrometer should be as large as possible in order to measure muons from the various upstream detectors. We will study the possibility of using the MINOS detector as a downstream muon detector.

Prior to CD-1, detailed Monte Carlo simulations will be performed for the different fine-grained technology options in order to determine the resolutions, cross-section sensitivities, and particle identification efficiencies that are achievable. Note that detailed simulations already exist from ongoing experiments (e.g., MiniBooNE, MINERvA, and T2K), so that it should be relatively straightforward to modify these simulations for the LBNE neutrino detectors. For each fine-grained candidate technology, we will evaluate each important process as determined by studies done in the Strategy Focus Area. For each process, we will determine what size fiducial volume and what granularity is required in order to attain a given sensitivity to neutrino oscillation parameters. We anticipate these processes to include:

- NC pion production
- NC gamma production
- CC quasi-elastic scattering

- CC pion production at the near site

After CD-1, we will have to carefully consider any special running plan (e.g., varying the horn currents) to sharpen our requirements on the fiducial volume of these detectors.

Before CD-1, we will calculate the fiducial volume requirements for the fine-grained detector options and for a water Cherenkov detector in the case of locating these detectors at an off-site location where the far–near neutrino spectral ratio is close to unity.

Far Detector Studies

There are two technologies being pursued for the LBNE far detector: water Cherenkov and liquid argon time-projection chamber (TPC). Water Cherenkov detectors are a mature technology as evinced by the success of the 50-kton Super-Kamiokande detector. In the case of liquid argon TPCs, there is no existence proof of a large-scale detector; however, they offer the possibility of a significant improvement in precision over water Cherenkov detectors while still being potentially viable on a large scale.

Water Cherenkov

There are several questions that drive the detector simulations that we plan to carry out:

- What PMT coverage is required to optimally carry out the long-baseline neutrino oscillation analyses?
- How does the shape of the cavern influence performance?
- Is a veto detector required?
- How would PMT implosion shells affect performance?
- How would light concentrators or waveshifter plates enhance the performance?
- What quantities can be calibrated and what is the impact on the long-baseline neutrino oscillation analyses?

We will develop detector simulations based on experience with previous experiments, such as Super-Kamiokande, SNO, and MiniBooNE, that incorporate all known important quantities to predict the physics performance of various configurations of the water Cherenkov detectors. These quantities include PMT performance, light concentrators/wavelength shifter performance, light absorption and scattering in the water, and cavern shape. We will use analysis tools adapted from Super-Kamiokande, SNO, and MiniBooNE and standard physics interaction simulations such as NUANCE, NEUT, and GENIE in order to evaluate the impact of all relevant quantities on the long-baseline neutrino oscillation sensitivity. We will continue to develop the tools to optimize them for the relevant reference detector geometries.

An important optimization problem to be addressed is PMT coverage. A large part of the cost of building any large water Cherenkov detector is the PMT cost. We know that it is possible to make attenuation lengths in water on the order of 100 m. Engineering considerations, including the quality of the rock and maximum possible spans, will limit the size and constrain how many cavities should be built for a given mass. The sampling required by the reconstruction algorithms will set a requirement for the number of PMTs needed and their associated cost. Additionally, algorithms will be modified or tuned to work better at lower PMT density. Work similar to this was done for both the Super-K and T2K experiments by members of this collaboration. By leveraging this knowledge, we will study the expected quantitative performance for vertex reconstruction, particle ID, track reconstruction, and so on necessary for physics analyses.

We will similarly address the issue of the cavern shape on performance. Cavern shape also might play a crucial role in the cost-optimization of LBNE.

Another vital question to answer early on will be whether a veto is needed, because omitting one will mean substantial cost savings. Beam neutrino physics is not especially sensitive to cosmic background, thanks to beam timing. Galactic supernova burst physics is also relatively insensitive to cosmic ray background, since signal to background will already be high within the few tens of second burst period. However, distant supernovae and relic supernova neutrino searches will be crucially dependent on rejection of cosmic muon-related background. Although one can make back-of-the-envelope estimates based on Super-K experience, the angular distribution and rate of muons will differ at the DUSEL site due to different depth overburden shape. Furthermore, one must understand muon rejection capability based on track reconstruction given a particular assumed PMT coverage. Therefore, to reliably determine the required veto capability for the fully-planned physics reach and for a given detector configuration, we need both a detailed detector simulation and cosmic ray background model.

Several components attached to the PMTs could inhibit or enhance light collection. These will be studied in detail. First, Super-Kamiokande currently uses acrylic implosion shields around each PMT to prevent a chain reaction of PMT implosions. By creating a barrier between the fiducial volume and the PMT, they have a small negative impact on light collection.

The average distance between a Cherenkov-light emitter and a PMT is larger here than in Super-Kamiokande. In addition, we might use lower photocathode coverage. The impact of implosion shields will be simulated in detail. Previous and current large underground detectors such as IMB, SK, SNO, and Borexino have successfully implemented light concentrators or waveshifter plates to enhance light collection by a factor of 1.3 to as much as 2.5 at just a few percent of the PMT cost. Improved light collection leads to a number of benefits such as significantly improved energy resolution and vertex reconstruction, and improved particle identification and pulse shape analysis. Alternatively, some devices might lead to a loss of fiducial volume or other downsides, so their performance must be thoroughly understood and evaluated.

We will simulate a variety of options to optimally design these devices to best address our physics goals. Simulations will test the length and geometric field of view for light concentrators and side plate dimensions and thickness for waveshifter plates, based on parameters in the existing literature and upon the experience of our group members.

Water Cherenkov detectors are essentially calorimeters, yet they have successfully been used for tracking. In addition to sophisticated reconstruction algorithms, an extensive calibration program is required. Specification of the calibration requirements is a major task of the collaboration in the design process. There are many aspects of detector performance that must be measured and/or controlled in order to relate detector measurements to physics. Based on experience at Super-K, IMB, SNO, and MiniBooNE, some of these are

- PMT relative gain, timing, and including the slope offset and signal-size dependence
- PMT relative efficiency
- Water scattering and absorption length as a function of wavelength

- Electronics threshold/energy threshold
- Absolute energy scale and energy resolution
- Trigger efficiency and detector response asymmetry
- Particle ID efficiency and vertex resolution as a function of position and energy

Most of these are time dependent, and some may also be temperature dependent. Many of these depend upon the exact detector configuration (e.g., particle ID and vertex resolution) and many are correlated. We will develop a specific calibration plan to address each one of these items. In addition, we will develop full simulations of each calibration device required to measure the above quantities.

Liquid Argon

An integrated R&D plan for a very large Liquid Argon Time Projection Chamber (LArTPC) has been prepared by the LArTPC Planning Group[43]. The integrated plan includes both hardware and physics R&D for a LArTPC for LBNE, focusing on a 20-kton design referred to as LAr20. (It should also be noted that a smaller LArTPC could be employed as a near detector for LBNE.) The integrated plan outlines existing components, current activities, and new efforts required to fully demonstrate the LBNE LArTPC option. Here, the physics R&D component of the LArTPC integrated plan is excerpted.

Physics R&D challenges for LAr20 are summarized as follows:

– "Analysis tools: Develop tools to simulate and reconstruct neutrino interactions."

– "Surface operation of a physics experiment: Test feasibility to reconstruct data in a detector exposed to cosmic ray backgrounds on the surface."

– "Physics results: Produce publishable physics results with a large experiment."

Much physics R&D relevant to LArTPC development is being done in connection with the following:

– The ArgoNeuT 175-L LArTPC, now taking data in the NuMI beam.

– The MicroBooNE collaboration, which has completed the conceptual design for a 100-ton active volume LArTPC to run in the on-axis Booster Neutrino Beam (and off-axis in the NuMI beam).

– The Liquid Argon Software group (LArSoft), a coordinated software development effort for all planned and running U.S. LArTPCs, providing tools for simulation, reconstruction, and analysis. LArSoft has active contributors from ArgoNeuT, MicroBooNE, and LAr20 collaborators.

ArgoNeuT's first data collection period spans October 2009 to March 2010. "ArgoNeuT's ∼10k events will allow for development of analysis tools [LArSoft], and first measurements of neutrino cross sections on argon as well as data to better understand signal and background identification for LAr20."

MicroBooNE has both a physics program and LArTPC physics R&D goals. Its primary physics goals are to perform a variety of precision cross-section measurements at sub-GeV neutrino energies and to resolve the low energy excess observed by the MiniBooNE experiment. Its physics development goals include the following:

– "Test ability to run on the surface for non-neutrino-beam physics."

– Provide data useful to "refine sensitivity estimates for LBNE/LAr20 program."

– "Develop tools for analysis." [LArSoft]

Much physics R&D applicable to LBNE can be done in the context of existing programs. These common activities are spelled out in the integrated plan as follows:

> • "Collect and analyze neutrino interaction data on Argon. This will be done first with ArgoNeuT which will collect ∼10k of neutrino interactions and later with MicroBooNE, which will collect >100k neutrino interactions and perform a suite of low energy cross section measurements. The neutrino interaction data from MicroBooNE will be used to
>
> – "Measure neutrino cross sections for LAr20 experiments including rare processes
>
> – "Measure signal-like proton decay events and backgrounds to proton decay running on the surface

- “Test cosmic ray background rejection while running on the surface
- “Develop data compression schemes for continuous data taking
- “Develop Supernova triggering capabilities

- “Develop analysis tools for simulation and fully automated reconstruction for neutrino interactions and proton decay events. This will be done in the context of a software framework for the reconstruction and analysis of interactions in liquid argon, LArSoft, which is under active development. This framework is designed to provide universal algorithms for use by any LArTPC and currently supports the Bo[44] and ArgoNeuT test stands as well as the MicroBooNE experiment. The modularity is accomplished by designing algorithms that are agnostic as to a particular LArTPC geometry so that the geometry for a specific LArTPC can be supplied at run time. The LArSoft developers group includes collaborators working on the test stands, as well as the MicroBooNE and LBNE experiments.

  “The scope of LArSoft is to perform all offline simulation, reconstruction, and analysis tasks. LArSoft can currently perform the following tasks: i) simulation of interactions in the detector, ii) tracking of particles through the detector, iii) simulation of readout electronics, iv) displaying of events. The simulation of interaction in the detector includes neutrino interactions using the GENIE package [http://www.genie-mc.org], cosmic ray interactions using the CRY package [http://nuclear.llnl.gov/simulation], and simulation of specific particles using LArSoft specific routines. The tracking of particles through the detector is accomplished using Geant4 [http://geant4.web.cern.ch/geant4]. The simulation of the readout electronics is different for each LArTPC, and the addition of different electronics for each new LArTPC is straight-forward.

  “The next challenge for the developers is to create reconstruction algorithms. A mature algorithm to identify individual signals on each wire of a LArTPC already exists. The next steps are to develop algorithms to group those signals into reconstructed tracks and showers. Discussions of various techniques and algorithms have started, and progress is expected over the next 4 to 6 months."

Some of the work noted above addresses issues with importance beyond the existing programs. As noted in the integrated plan, "No fully automated reconstruction package yet exists for LArTPC detectors. In addition, the only neutrino data yet collected with a LArTPC come from the exposure of a 50-L prototype in the NOMAD beam at CERN in the 1990s, and now with the ArgoNeuT test." These issues are being addressed in the context of MicroBooNE, ArgoNeuT, LArSoft, and other efforts.

While many of the physics studies needed for LBNE LAr detectors can be addressed in conjunction with ArgoNeuT and MicroBooNE, some LBNE-specific LAr physics R&D is also needed:

- A number of near term (6–9 month) studies are outstanding, including "hand-scanning" studies to be repeated with the latest simulation to address the issue of performance vs. wire spacing (a key cost driver), and other MC studies to address key near-term questions for LBNE.

- As the LArSoft software improves and the LAr20 conceptual design develops, design and performance studies need to be performed: optimization studies of the far (and near) LArTPC detectors, simulation of cosmic ray events for the shallow and deep options at the far site (and the shallow near site), and related sensitivity studies with updated efficiency and background assumptions.

- In the integrated plan, it is noted "no LArTPC has been calibrated in a test beam to allow measurement of electromagnetic and hadronic showers," which is identified as the largest "physics R&D risk" in the integrated plan, rated "medium". To address this, the option is raised to perform a "LArTPC calibration test" in a test beam, such as the MTest facility at Fermilab, in order to calibrate response to electromagnetic and hadronic showers. This is not part of ArgoNeuT or MicroBooNE. Physics studies should simulate such a test and determine how best to use test beam data from a modestly-sized calibration test LArTPC to calibrate the much larger LAr20.

In summary, studies for the LArTPC option for LBNE are proposed to be pursued in the context of ArgoNeuT, MicroBooNE, and LBNE-specific efforts. An integrated plan of hardware and physics R&D exists which unifies these efforts [43]. The physics component of that plan has been summarized and excerpted here for the benefit of the reader.

University of Alabama Contribution

The University of Alabama will participate in the development of the far detector complex with a focus on the water Cherenkov detector(s). The PI has had extensive experience with event reconstruction in mineral oil based imaging detectors (LSND, MiniBooNE and Double Chooz), as well as particle identification using artificial neural networks (ANN) and boosted decision trees (BDT) algorithms. Jason Goon (postdoctoral fellow) has previously worked on the SNO data analysis and is currently involved in the development of the Double Chooz laser calibration system. Both the PI and the postdoc have significant experience in Monte Carlo (Geant-4) simulations. The PI is currently co-leading the far detector water Cherenkov simulations group together with Chris Walter (Duke University).

Within this project we propose to participate in simulating and evaluating one or several of the water Cherenkov detector configurations in order to understand the dependence of the energy, position and angular resolution, as well as the particle identification performance on the detector geometry, phototube coverage, number of channels, etc. In particular, we plan to implement the maximum likelihood event reconstruction developed for MiniBooNE to the LBNE water Cherenkov detectors, as these algorithms are independent on the configurations enumerated above – although their performance obviously does. In first order, different algorithms will be developed for different event hypotheses (e.g., electron, muon, neutral pion, etc.) and likelihood ratios will be used for particle identification. More sophisticated methods, such as ANNs and BDTs, will be developed as needed. Our studies will not only address these issues, but will also investigate the different types of calibrations needed in order to fully measure *in situ* the underlying parameters needed for these reconstruction algorithms, such as charge and time likelihoods, effective attenuation length, scattering, reflections, etc. The group will also contribute to the overall simulations effort, as needed, and plans to get involved with some aspects of the calibration hardware which are directly related to tracking.

Personnel and Resources

This effort will be lead by Ion Stancu (Associate Professor) and will involve Dr. Jason Goon (postdoctoral researcher), as well as graduate students. Throughout the study we expect to have only one graduate student directly involved with LBNE at any time, each working on the project for a duration of up to one year. This group has a cluster of about 100 CPUs (shared with two other neutrino groups), which will provide adequate but limited computing support for initial calculations.

Requested Support

We would like to request support for the following:

(1) One full-time graduate student (as described above). The graduate student would work on the simulations and algorithms development for LBNE for up to one year, and then on MiniBooNE or Double Chooz data analysis.

(2) Half a postdoc support – to be stationed at Fermilab and dedicate the other half of her time to the MiniBooNE data analysis to ensure continued publications and conference exposure.

(3) Travel support to attend LBNE meetings – a total of about 8–10 trips per year for the PI, postdoctoral fellow and the graduate student.

(4) Funds to enhance our computing capabilities – namely the purchase of 5 additional blades (an additional 20 individual CPUs).

Caltech Contribution

The LBNE group at Caltech proposes to perform studies related to several aspects of the LBNE experiment. A major effort will be in conducting simulations of a variety of Water Cerenkov Detector geometries with the primary goal to optimize the sensitivity of the long baseline electron neutrino appearance experiment to the discovery and measurement of the CP violating phase and the mass hierarchy. A second activity will involve study of the use of a liquid argon TPC, such as the miniBooNE detector, as a near detector for monitoring the neutrino flux. In addition, we propose to provide input to the nuclear physics associated with neutrino interactions in the various far and near detector designs under consideration.

Water Cerenkov Simulation Studies

The water Cerenkov technology offers some important advantages as the LBNE far detector. The previous experience with Super-Kamiokande provides an important benchmark that serves as a starting point for many of the design features for LBNE. This benchmark does offer a proof of principle, some information on the technical capabilities, an example of a particular construction technique, and a basis for cost estimation. However, one should be mindful of the fact that Super-K was in fact designed for a very different purpose (nucleon decay searches) than the primary goal of LBNE. Thus it is essential to consider a range of variations on the design parameters in order to be sure that we optimize the LBNE design to maximize the sensitivity to the long baseline electron neutrino appearance measurement. Important considerations include the following:

- the primary signal is an electron-like shower in the energy range 0.5-5 GeV,
- the events of interest are primarily quasielastic charged current interactions, and the electrons produced propagate primarily in the forward direction (i.e., directed away from Fermilab),
- a major limitation of the water Cerenkov technology is its limited ability to reject neutral current π^0 background.

Our emphasis will be on simulation studies involving variations in a.) the geometric shape of the detector, b.) the distribution of photomultipliers, c.) the amount of photocathode coverage, and d.) the effect of enhanced light collection methods. (The development of enhanced light collection methods is a task covered by S4 funding from NSF. This work will focus on integrating the results of that work into a combined study to optimize the LBNE design.) In addition, these variations may have some (positive or negative) effects on other LBNE physics goals, and these effects must be quantitatively studied.

LAr near detector as flux monitor

An important function of the near detector system for LBNE is to provide a measurement of the flux of the muon neutrino beam. The neutrino interactions observed in the near detector will generally be associated with processes involving nuclei and nucleons. These processes with hadronic systems involve issues related to the structure of the nuclei and/or nucleons. While we have some empirical knowledge from other experiments, the theoretical limitations of QCD imply that there are substantial uncertainties associated with our knowledge of hadronic structure and its effect on the relevant cross sections. Several methods for mitigating these uncertainties are under consideration for the LBNE near detector system.

We have begun to study a promising method for a high precision determination of the neutrino flux using a liquid argon TPC. In particular, we have proposed the possibility that the coherent nuclear transition

$$\nu_\mu + {}^{40}\mathrm{Ar} \rightarrow \mu^- + {}^{40}\mathrm{K}^*(4.38\ \mathrm{MeV}) \tag{1}$$

can be used to accurately normalize the flux of the ν_μ beam at the near site for LBNE. The rationale is that this is a $0^+ \rightarrow 0^+$ Fermi transition where the nuclear matrix element is accurately known. Such analog Fermi transitions have been studied in detail in nuclear beta decay. Since the nuclear matrix elements are reliably known independent of nuclear structure (except for small radiative corrections, isospin violations, and effects related to nuclear wave function overlap), these decays enable a precise determination of the CKM matrix element V_{ud}. Thus the process has been the subject of a great deal of experimental and theoretical study. In particular, there has been much theoretical work related to the radiative and nuclear corrections (few percent), and the consistency of the resulting ft-values (the experimental quantity used to extract V_{ud}) at the $< 1\%$ level is viewed as an indication that the corrections are under good control. Thus one can expect that the corresponding corrections to $|M_F|^2$ for the $A = 40$ transition of interest here can be computed to an accuracy of $< 1\%$.

We have estimated the event rate using the 70 Ton (fiducial mass) microBooNE detector at the LBNE near site. It appears that one would observe event rates of about 2440/year with a 0.7 MW beam. The event signature is a forward muon with no recoil nucleon, but with coincident gamma decays in the final ^{40}K nucleus. The summed energy associated with these gamma decays must be measured with few percent precision. Selecting these events in microBooNE will be challenging, but might be possible. We propose to develop appropriate simulations of LAr detectors relevant to studying the feasibility of this analog charge current process. Such simulation tools will be important for studying other exclusive nuclear processes if interest as well.

Nuclear effects

Many of the neutrino interactions observed with LBNE involve nuclear physics, particularly semi-leptonic nuclear processes with GeV incident leptons. Our group has had a long history of studying electron-nuclear interactions at these energies, with significant emphasis on weak interactions. We propose to provide support to LBNE studies that require knowledge of nuclear physics relevant to the cross sections of interest. In particular, even the most recent codes used for quasielastic neutrino interactions utilize a very simple 40 year old model of the nucleus known as the Fermi gas model. Much more sophisticated methods are now routinely used for analysis of electron scattering experiments, and we propose to incorporate these methods into the LBNE cross section models.

Future Efforts

After CD-1 is granted, we plan to participate in the development, assembly, installation and commisssioning of hardware for the far Water Cerenkov detector system. This work will likely be related to the PMT assemblies and the potential incorporation of enhanced light collection techniques.

Personnel and Resources

Our group has significant experience in hardware construction for neutrino and accelerator-based experiments as well as simulation and analysis. We have recently played important roles in the KamLAND and Daya Bay reactor neutrino experiments. We propose that this LBNE effort replace the KamLAND effort (previously supported by DOE-NP) as we continue to phase out our KamLAND activities over the next year. This effort well be led by Professor Robert McKeown and will include a senior research fellow, a postdoctoral scholar, as well as a graduate student and summer undergraduate.

Requested Support

We are seeking support for:

1. Salary support for the senior research fellow and postdoctoral scholar. Partial support related to 5% of Prof. McKeown's effort committed to this activity.

2. Support for one graduate student, as well as some summer support for an undergraduate student.

3. The group will attend domestic collaboration meetings (3 meetings per year), and some working group meetings, conferences and workshops in the US. We also request funds for attending 2 international conferences/workshops on neutrino physics.

4. Materials and supplies includes expendable lab supplies, computers, computer peripherals, communications hardware, and other miscellaneous items related to our participation in the LBNE project.

UC Davis Contribution

Scope of Work

The University of California, Davis, group proposes to work on project management and simulation studies of the water Cherenkov detector and to continue development of both a PMT testing facility and a prototype thin muon veto detector.

Project management: R. Svoboda serves as the NSF S4 PI for LBNE, with responsibilities for those elements of the water Cherenkov far detector being built by universities with NSF support. This includes the deck design, simulations, thermal model, magnetic compensation, PMT characterization, water systems, PMT production testing, electronics, and light collectors. UC Davis administers the NSF grant for the eleven institutions of the S4 group.

A major part of the work involves coordinating the activities of the NSF groups with the DOE-funded project. He is aided in this task by R. Breedon, a senior Research Physicist at UC Davis. Together, they arrange and conduct periodic work reviews, meet regularly with the DOE project team to plan and document work, and prepare regular reports to the NSF on progress.

In addition, Svoboda also serves as LBNE co-spokesperson. He is responsible for steering the scientific development of the LBNE project. In particular, he is responsible for ensuring, at every stage of the project, that the scientific goals of the U.S. HEP community are reflected in the major decisions and goals of the LBNE project.

Water Cherenkov far detector simulation: Work continues on the development of the water Cherenkov Geant4 simulation. UC Davis has been a major contributor in this effort, having developed much of the geometry routines for the detector shape, photomultiplier tube coverage, and rock walls. In addition, they have validated photon transport against theoretical models in Geant4 to the required sub-nanosecond accuracy.

Recently, they successfully modeled the detector noise rate due to radon in the water and gammas from the rock walls by adapting radioactive decay event generators from Double Chooz into the LBNE simulation. A study is now underway to determine the following:

1. The optimal running temperature for dark noise reduction while considering the account possible sources of background, such as from rock gammas and PMTs, that

could dominate;

2. The limits that should be imposed on radon levels in the water;

3. The limits that should be imposed on U/Th/K in the wall shotcrete.

Their student John Felde has been a star in getting studies done for the detector design in addition to building (with undergraduates and a visiting student from SDSMT) the UC Davis PMT magnetic test facility described below. Thus far, he is supported by NSF S4 funds. However, this support will end at the end this summer, and so UC Davis requests funds to let him continue developing the analysis code. John will also train a replacement student (likely a new student coming to the Davis gradute program from UC Berkeley) to take this over, since he will move at some point to Double Chooz to analyze data to use for his thesis.

In addition to the design specification work, Tim Classen has been adapting the neutrino interaction code GENIE to the LBNE far detector geometry and the FNAL beam source. Simulation studies underway include those on the impact of detector geometries on low energy neutrino physics and on the background originating from neutrinos interacting in the beam-side rock, an understanding of which would help in estimating the veto region required for the detector. This work will continue to be supported from our DOE grant. In addition, UC Davis has hired a new postdoc (Pooja Gupta) using NSF funds who will take this over when Tim moves to France to work on Double Chooz at the beginning of summer. No new funds are needed to continue this work.

Thin muon veto prototype: UC Davis will obtain LBNE project funds to build a model of a section of a proposed thin (0.5 m) muon veto detector for the large water Cherenkov detectors (WCD) for the benefit of beam-based neutrino physics at LBNE. On the beam side, the veto will identify rock muons entering the WCD. On the far side, the veto will detect muons that exit the WCD, which will help to reduce systematics in the analysis. The addition of a thin veto to the WCD design would allow the fiducial cut region in front of the large PMTs to be reduced from 2 m to 1 m, increasing the fiducial volume by $\sim$8% or permit a cost savings from a reduced cavern size and the number of PMTs for the same fiducial region. The prototype, to be built at UC Davis, will be used to show proof of concept and to test veto PMT layouts and measure the muon detection efficiency. A minimum 3 m x 3 m water tank lined with Tyvek with 0.5-m water depth will be constructed, which will be filled with purified water from a reverse osmosis de-ionization water system with recirculation loop and UV sterilization system. In addition, a position-adjustable cosmic-muon hodoscope with associated readout electronics and DAQ system will be constructed with a combination of new and borrowed materials. This prototype is being designed and constructed by Richard Breedon, who has moved half his effort from an LHC experiment to LBNE.

PMT test facility: UC Davis is developing a PMT testing facility to study the magnetic field effects on candidate PMTs, for which a model coil magnetic compensation system has been successfully constructed. The first round of magnetic field tests is ~90% complete and is awaiting the delivery of the final electronics needed to run the test. The new student would be in charge of operating this test stand. This facility was built using NSF funds.

Future Efforts

R. Svoboda will be LBNE co-spokesperson and NSF S4 PI for at least another two years. Thus he will continue to be active in the planning and management of the experiment in addition to directing the Science Collaboration. A teaching buy-out was not included in the S4 proposal, but in order to wear these two hats at once, relief from teaching is crucial. In addition, Research Physicist R. Breedon is helping to manage the S4 design work and fold it into the DOE LBNE Project. It is envisioned that this work will continue, with 50% of Breedon's effort supported by the NSF S4 and LBNE Project. Note that Breedon is leading the effort to build a full-scale mock up of the LBNE water Cherenkov detector veto region to optimize the design based on high level physics requirements. This effort will also continue.

Over the next two years UC Davis will test all the candidate PMTs for their performance in geomagnetic-scale fields. These data will be used in the simulation for the WCD to design a magnetic field compensation system in collaboration with RPI. Note that typical large PMTs can be seriously affected (on the 15%–25% level) by such fields if not properly compensated. This work is being done under the auspices of the NSF S4.

Other work includes the simulation work of Tim Classen and Pooja Gupta. This will continue for at least another two years, as the design is taken from CD-1 to CD-2. Note that Gupta is also starting to work with the beam group at FNAL, and this may continue if the collaboration proves fruitful. Gupta's and Classen's work will need support to continue after the S4 expires at the end of FY12.

UC Davis will also have a working full-scale mock-up of the WCD veto region, complete with muon hodoscope, by the end of 2010. This will allow the determination of the size of the fiducial region needed to distinguish neutrino events originating in the rock from those occurring in the detector. This is very important in determining the sensitivity of the experiment. This work is not covered under the S4 grant.

Subcontract with SDSMT

Being a new LBNE member institution, the South Dakota School of Mines and Technology (SDSMT) would be subcontracted through UC Davis during the course of the proposed research. The SDSMT group proposes to perform studies primarily focused on the far water Cherenkov detector and work closely with scientists in UC Davis, BNL, FNAL, and PSL. In particular, the following investigations will be conducted.

<u>Measure the group velocity of light in water as a function of wavelength.</u> In water Cherenkov detectors, the event reconstruction resolution relies heavily on light propagation in water. Cherenkov light emitted by charged particles in water has a continuous wavelength distribution (Fig. 2, left). The light group velocity in certain media depends on the index of refraction and has a complicated dependence on the wavelength, temperature, and pressure. Taking the change of the group velocity between 375 ± 50 nm wavelength (Fig. 2, right), for example, one expect to see a difference of about 1 ns or more in the arrival time of detectable photons propagating 50 m in water. In a WCD of several hundred kilotons, such as the LBNE far detector, this wavelength dependence will affect the timing pattern of the events, hence further affecting the event reconstruction. Their first project will be to set up a sub-ns timing system with a 50-m water path to measure the group velocity of light as a function of wavelength at a given pressure and temperature. They can then compare their data with calculations, such as in Fig. 2, to attempt to understand this effect over a 50-m distance.

In this project, X. Bai will be responsible for the experiment design and will investigate proper light sources and electronics for a sub-nanosecond system. He will be working together with a graduate student and with BNL in setting up the electronics system. R. Corey will be responsible for the water treatment system, building up a water path at different lengths up to 50 m. The measurement and analysis will be the main topic of a master's

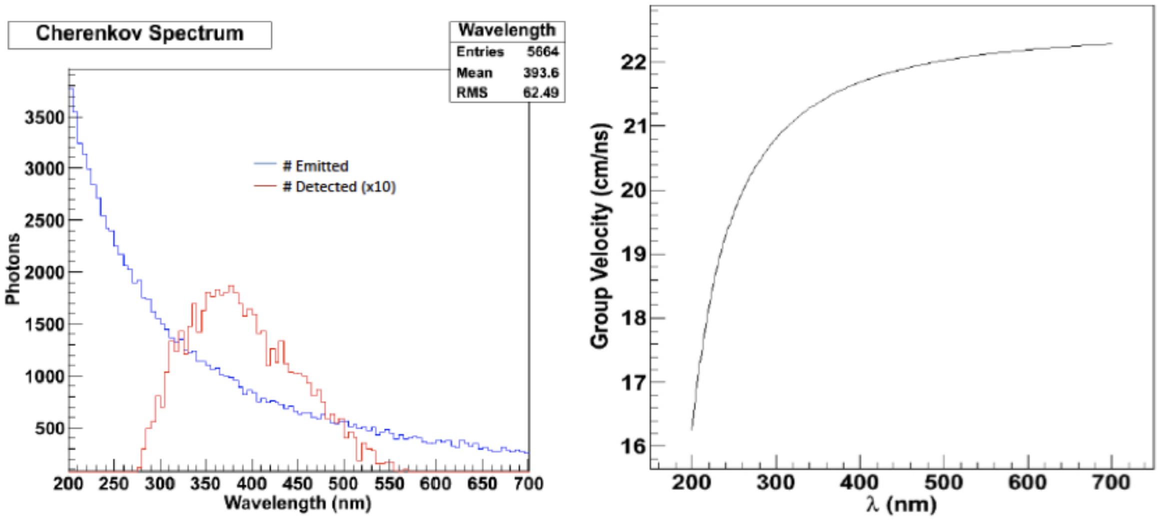

FIG. 2: Left: The spectrum of Cherenkov radiation in water. Both emitted and detected photons are simulated. The distribution of the detected photons reflects the quantum efficiency of the PMTs. Right: Light group velocity as a function of wavelength in water.

degree student thesis.

Measure the signals from PMTs immersed in water. To test the electronics and monitor PMT unit performance over long time, SDSMT is currently investigating the borrowing of an appropriate water tank from FNAL. A programmable LED pulser is under test. Several plastic scintillate detectors in their lab can be used to measure the PMT response to muons. A facility of this kind close to the eventual detector site could become quite important for timely testing of devices throughout the long-term deployment and operation of LBNE. While PSL, BNL, and FNAL are investigating PMT properties from different manufacturers, designing electronics, and building up technical capability for mass production and testing, SDSMT will cooperate with these three labs closely and measure the signals from PMTs immersed in water. This will support the electronics testing and monitoring of PMT unit performance over a long time, such as glass properties in contact with ultra-pure water. According to their current plan, in FY11 50 PMTs will be assembled and pressure tested in PSL and BNL. After that, they will be sent to SDSMT to measure the signal from them in the water tank. In FY12, this number will increase to about 500.

The SDSMT group is currently working with UC Davis on LUX water shield PMT (total of 20) testing and calibration. After this is done later this year, the lab equipment will be dedicated to LBNE PMT testing. R. Corey and X. Bai will oversee and participate in the local activities on this task. Two SDSMT senior undergraduate research assistants will participate in this project. Graduate students, engineers, and technicians from UC Davis, BNL, PSL, and FNAL will provide support and make contributions when needed. Depending on LBNE project planning, with additional funding support, they will be able to build up local capability to do the electronics testing and signal measurements for a larger number of PMTs in the future by working closely with PSL, BNL, and FNAL.

Investigate potential PMT unit mass production sites near DUSEL or in Rapid City. Given the convenience of being only 50 miles from DUSEL, the SDSMT group is assisting with the survey of LBNE PMT unit production sites near DUSEL or in Rapid City. X. Bai is working with the LBNE PMT task leader Paul Mantsch and has finished the first survey of light industrial space in the Rapid City and Homestake regions. Connection with SDSMT and local high technology business administration has been established. Funding requested in this proposal will enable X. Bai and R. Corey to continue working on this under the LBNE PMT task manager.

Personnel and Resources

Prof. Robert Svoboda (PI) is co-spokesperson of the experiment and is involved with PMT evaluation, calibrations, and simulation of the water Cherenkov far detector. Research Physicist Richard Breedon is assisting with project management and is constructing the thin muon veto prototype. Postdoctoral Researcher Pooja Gupta is working on the simulation study of the rock muon background. Postdoctoral Researcher Tim Classen is adapting the neutrino interaction code GENIE to LBNE. Graduate Student John Felde, whose support is running out in June, is developing both the Geant4-based WCD simulation and the PMT test facility. The construction projects benefit from the involvement of UC Davis physics departmental engineer John Thompson.

The SDSMT group currently consists of two physics faculty members, Xinhua Bai and Robert Corey. X. Bai has rich experience with PMT testing and water Cherenkov detector calibration and simulation through many years of work with the Pierre Auger Project and the Ice Cube Project. R. Corey has strong background with hardware and instrumentation. Once the funding starts, they will recruit a graduate student dedicated to LBNE. Other resources from SDSMT available for this proposal include (1) 800 sq ft lab space in the PI's lab at SDSMT, (2) Light sources: LED pulser, picosecond fast laser diode pulser including driver, and heads of different wavelengths, (3) Plastic scintillator detectors and high voltage suppliers that can be used to tag muons for the PMT study in the water tank at SDSMT, (4) Analysis and simulation computers, and (5) Electronics including NIM electronics, digital oscilloscope.

Request for Support

UC Davis is requesting support for the following:

1. Teaching buy-out for R. Svoboda for two quarters each in FY11 and FY12 to allow time for project management responsibilities.
2. The support for one graduate student whose present S4 support is running out.
3. Travel support for R. Breedon for project management activities. He will attend the DUSEL review in Rapid City SD in April, the LBNE collaboration meeting in Lead SD in May, the LBNE S4 review in Washington D.C. in July, and an estimated two other trips for a total of five trips. Similar travel is projected for the following years.
4. The support for one SDSMT FTE faculty: X. Bai (20%) and R. Corey (80%).
5. Support for one SDSMT graduate student including tuition remission over 3 years.
6. Equipment and lab supplies for the measurement of light group velocity and future testing at SDSMT:

    A small water treatment system and plumbing;

    Sub-nanosecond VME electronics + one DAQ computer;

    Fast photon detectors (e.g., microchannel plates (MCP), photo-diodes), cables, fibers, connectors, PVC pipes, liners, etc.
7. Travel support for three SDSMT group members to join collaboration meetings and participate in training in PSL/FNAL/BNL, at the level of two trips at five days each and two persons per year.

UCLA Contribution

Motivation and Scope of Work

The UCLA group proposes a simulation study of the physics potential of the proposed 20-kton LAr far detector and also a study of one near detector option with a magnetized LAr TPC of a strong magnetic flux of 0.5 T to support the LBNE measurements.

One option of the LBNE far detector being considered is a 20-kton evacuated liquid Argon TPC, to be located in a shallow depth at DUSEL with drive-in capability. The UCLA team will study the physics potential for a 20-kton LAr detector at the shallow site, including the following:

- The potential to detect p $\rightarrow$ k + $\bar{\nu}$ using veto detectors and the high space and time resolutions at the 300 ft or possibly 800 ft depth; and
- The detection of a supernova pulse in the 20-kT detector at the shallow site.

The study is to look into the backgrounds at the respective depths of the 20-kton LAr detector with an appropriate veto system to set limits for the proton decay search and to quantify the energy threshold and resolution of spectral measurements for all neutrino species. A large volume LAr TPC of tens of meters is capable of measuring energy information from charged particle track lengths of supernova neutrino interactions. These simulation studies will also be important for the optimization of the TPC structures and the wire planes.

We also propose the study of a magnetized LAr near detector necessary to achieve the beam flux precision to below the 3% level. We anticipate that the electron and anti-electron neutrino beam fluxes will have to be measured with good charge identification to give the necessary high precision on the beam flux at the far detector. A 125-ton or 50- or 10-ton magnetized liquid Argon TPC near detector of similar module structure to the far detector will be key to achieving small systematic errors in the beam flux at the far detector site. A LAr near detector will provide extremely high quality event identification of events for the high precision flux measurement. Magnetizing the detector with a field of 0.1 to 0.5 T will allow the capability of charge identification. The study will be necessary for the optimization of the mass and magnetic flux of the near detector.

This work will be performed on the order of two to three years time to provide information for the CD-2 baseline study. UT Dallas, another member of the LBNE, will be joining us in this effort in the future.

In the muon neutrino beam, the dominant component is muon neutrinos with smaller numbers of anti-muon neutrinos and electron neutrinos, each with its corresponding energy spectrum. Precision determination at the near detector of the electron neutrino flux and spectrum to a few percent level is then crucial to the measurement of the electron neutrinos at the far detector. Unlike muons, electrons shower and are easily multiple scattered. In the energy range $1 \leq \mathrm{E} \leq 3$ GeV, electrons and positrons will give off a bremsstrahlung shower of mesons, leptons, and gammas in the liquid Argon. Subsequent to the bremsstrahlung, an electron or positron at below 1 GeV will still form a good enough ionization track in the liquid Argon medium for the TPC until the electron or positron energy becomes too low and multiple scattering becomes dominant [**?**]. A good sub-centimeter tracking resolution will be sufficient for these measurements. The magnetized TPC will allow for unambiguous determination of charge.

In addition, magnetization with a high field will enable better containment of tracks within the fiducial volume. For particles with 300 MeV/c momentum, a 1-T field is required to bend tracks of 1-m radius. It has been worked out for 3 σ sign discrimination that the B field should be [**?**]

$$B \geq \frac{0.2}{\sqrt{x[\mathrm{m}]}}[\mathrm{T}], \tag{2}$$

where x is the electron track length.

A magnetic field of up to 0.2 T can be energized by water-cooled copper coils implying a track length of only 1 m. Realistic simulation of these events will be important in the determination of the detector size and field strength, and also the required wire spacing.

Results from the simulation study will lead to a detector design with subsequent hardware R&D in the future. We possess a cylindrical cryovessel of ≈1.5 m outer diameter and ≈0.9 m height (Figure 2) approximating to 2 tons of liquid Argon. The TPC described below for the LANNDD-VD can be built for this cylindrical vessel. In addition, coils can be wound around externally to provide a field strength of at least 0.1 T. Hardware R&D work on the order of two to three years time will be necessary for the CD-2 baseline design.

The LANNDD-VD detector

A LANNDD-VD module is configured as a scaled down single cell device made with the same criteria of the full scale 20 kton. The purpose of this detector is to optimize and test in practice the construction criteria, to verify its stability at room and at LAr temperature and to develop dedicated details, as thermal bridge supports and no-heat conducting HV and signal feed-throughs, to be proposed as a model for the future full scale detector. The cryostat design is based on reduced size square walls with thicknesses properly scaled down in order to constitute a concrete model for the full scale detector and to be tested in such a way to verify the positive results of the finite element analysis made on the CAD model for LANNDD.

The overall structure of the detector is schematically described in Figure 3. The detector is configured as a cubic TPC sited inside a cubic cold vessel. The cold vessel is inserted in a warm vessel with insulation vacuum in-between. Both cold and warm vessels, with every element made by stainless steel, are built with a square pipe cubic frame with faces closed by double layer walls. This configuration allows building rigid walls with thin metal layers and, mainly for the full scale multi-cell detector, verifying in a practicable way the vacuum tightness of the outer and inner vessels by checking it in between the double layer walls.

Software

There has been much effort into software development at Fermilab called LArSoft for the LBNE and related liquid Argon detector projects. The LArSoft package will be modified for our own studies.

Personnel and Resources

The simulation and optimization work on the near detector will be headed by Kevin Lee under Prof. David B. Cline working in collaboration with Prof. Ervin Fenyves and his students at UT Dallas. K. Lee has previously carried out wavelength shifter fiber survival study for the NO A project. He has been involved recently in the liquid Argon near detector hardware R&D. In addition, 0.5 time of our graduate student, Y. Meng, will be on the LBNE.

Request for Support

We request in new funding support:

- 0.5 time for K. Lee, 2 graduate students, 2 part time undergraduate students at UCLA to assist the work on the physics simulation and detector optimization studies. The undergraduate students will help in the scanning of the track events.
- A minimal funding for 3 computers and data storage in the first year
- Travel to the collaboration meetings a total of 8 to 10 trips per year

Colorado Contribution

Scope of Work

The University of Colorado group proposes to participate in beamline design and instrumentation for LBNE.

The first component of the University of Colorado's efforts will be to perform physics studies to determine the LBNE requirements for uncertainties on the π and K production from the proton beam striking the target. Recent ν_e appearance searches [**?**][**?**][**?**] have looked for an excess in the total number of ν_e events; LBNE will go beyond this and will determine the oscillation parameters using the detailed shape of the energy spectrum of the ν_e appearance events. Questions to be addressed here are the required accuracy on the π^+ production and the π^+/K ratio to keep the resulting systematic uncertainty on the shape of the ν_e appearance spectrum below the level of the statistical uncertainty for either a large water Čerenkov or liquid argon detector. These studies are important for determining whether existing hadron production cross section measurements will be sufficient for LBNE or if new experiments must be performed.

Another component of the Colorado effort will be to participate in the design of muon monitors, located in the rock just after the decay pipe. The primary purpose of these monitors is to monitor the beam direction, to measure the pulse-by-pulse beam intensity, and to make an in-situ measurement of the muon flux to evaluate potential misalignments of the beamline components such as the target and horns. There are a number of physics studies that must be performed. Firstly we must determine how well we need to determine the beam direction and the pulse-by-pulse beam intensity for the systematic effects on the ν_e appearance measurement to be small. This leads into a number of design studies that must be conducted, including determining what area the muon monitors must cover, and with what resolution. We also need to understand the particle flux after the beam dump to understand how intense the radiation environment will be. The muon monitors currently used in the NuMI beamline [**?**] are located in alcoves in the rock, which means that only muons above a certain momentum threshold will reach each monitor. This gives some sensitivity to pion energy spectrum, and can potentially be used to determine the neutrino flux independently of the interactions seen in the near detector [**?**][**?**]. This is important since this measurement does not depend on the uncertainties in the neutrino interaction cross sections as the near detector measurements do. Therefore it will be necessary to study the optimal placement for the muon monitors within the rock for the LBNE beam.

As these design studies are going on, we propose to study the technical design of the muon monitors. The silicon detector components will likely not withstand the high radiation environment after the LBNE absorber. One area of interest to us is the potential use of diamond detectors in the muon monitor system, as diamond detectors are at least an order of magnitude more radiation tolerant than silicon detectors [**?**][**?**]. It will be necessary to evaluate their performance and stability for potential use in the LBNE beam.

The muon detector R&D effort will also include studies of a potential new technique to monitor decays of stopped muons in the rock downstream of the absorber. This would involve arrays of smaller detectors at varying depths in the rock. The detectors would be optimized for observing single decays of muons at rest after the beam spill, yielding a total rate and timing distribution. This technique has several advantages over conventional ionization-based monitoring. First, the muons observed at a particular depth all have the same range and therefore come from a narrow distribution of initial energy; muon ionization detectors, by contrast, observe a total flux integrated above a threshold. Second, the observation of individual muon decays after the beam spill is over would allow absolute rates to be measured reliably; fitting the observed decay rate to the muon lifetime would provide independent confirmation of the muon signal and allow background subtraction. Finally, the small, modular nature of these detectors may allow them to be built with less expensive infrastructure: rather than large alcoves, only an access corridor and small core holes for the detectors may be needed. However, this is an untested technique and basic questions about its feasibility must be answered in the initial R&D stage. In particular, detailed simulation of the migration of neutrons through the rock must be made to ensure that a suitable post-spill time window exists when the muon decay rates are measurable. Detector work will include studies of radiation-hard scintillation and Cherenkov counters as well as methods for gating off the detector during the beam spill to prevent lingering saturation effects.

Future Work

We are also interested in performing studies of the design of LBNE beamline elements, such as the horns and decay pipe. For example, in the conceptual design phase over the next year it will be important to understand the tradeoffs between the size of the decay pipe and the neutrino fluxes and backgrounds at the first and second oscillation maxima. As LBNE moves into a technical design phase after CD-1 is granted, it will be important to optimize the size and shape of the magnetic horns to maximize the sensitivity to the physics parameters of interest. We currently have the preliminary LBNE beam simulation code installed on our computer cluster, and a group member has previous experience using a variant of this code for the MINOS experiment.

After LBNE is granted CD-1 approval, the University of Colorado group plans to participate in the development of detector hardware for the muon monitors and/or hadron production monitors. We also have the resources available to design and fabricate a large beamline device such as a magnetic horn, as was done by the group for the T2K experiment; a decision of what if any large component we will build will likely be made at the CD-2 stage.

Personnel and Resources

The LBNE group at the University of Colorado is composed of Prof. Eric Zimmerman, Prof. Alysia Marino, and Dr. Martin Tzanov (post-doctoral researcher). Robert Johnson will join the group as a post-doctoral researcher in Spring 2010 supported mostly on University funding. The group members have extensive experience in neutrino physics, including the SNO, MINOS, NuTeV, and MiniBooNE experiments. Currently the group is active in the T2K long-baseline neutrino oscillation study in Japan, where the University of Colorado group built one of the magnetic focusing horns. Marino is also currently serving as the LBNE Deputy Project Manager for Near Detector Beam Measurements.

Marino and Johnson are planning to devote approximately 30% of their research efforts to LBNE over the next 3 years. Zimmerman will devote 15% of his effort to LBNE until the summer of 2010, and then will increase the fraction to 30% as his effort on MiniBooNE ramps down. Tzanov will devote 40% of his research effort to LBNE beginning in the middle of 2010.

The University of Colorado HEP group has a large computing cluster with a dedicated professional system administrator. The University supports a technician whose skills include mechanical and electronics design. We also have access to professional machine shops and a high-bay area for the assembly of large detector components; that space is being upgraded at present with a modernized overhead crane.

Requested Support

- We are asking for travel support for Zimmerman and 1 postdoc to each attend 4 domestic LBNE collaboration meetings each year, for a total of 8 trips.
- Augmentation of the grant to allow hiring a new graduate student: the LBNE effort will thus be split across personnel who will work on both LBNE design and T2K data analysis.

Colorado State Contribution

Scope of work

The Colorado State University group proposes to participate in the physics group and instrumentation for the water Cherenkov far detector and a near detector contribution still under discussion.

Physics Working Group: Co-Spokespersons Svoboda and Diwan have asked Professor Robert Wilson to lead the newly formed Physics Working Group (PWG). The ultimate goal of the group is to clearly define the full extent of the physics potential of the experiment so the collaboration can prepare the strongest possible proposal. An essential step is to prepare a comprehensive set of target measurements (e.g., beam or astrophysical neutrinos, pi-zero, and K proton decay modes) or operational parameters (such as neutrino beam profile) that will be used as a common reference for all potential detector technologies. Wilson and a deputy (to be named) will work with the spokespersons and representatives of the existing detector and simulation groups to develop the benchmarks and will organize forums at which detector technology proponents will report on anticipated or measured performance for each of the benchmark processes. The use of a coherent set of parameters and benchmarks in simulations will allow the collaboration to compare the relative strengths of different detector configurations. To remain well-informed of the status and sophistication of the simulations addressing the performance metrics, the CSU group will attempt to maintain operational versions of all the simulation and analysis codes. Professors Wilson and Toki will work with a new post doc on this task.

Water Cherenkov far detector: The CSU group proposes to work on PMT characterization. Detailed knowledge of PMT response as a function of several variables is essential for both the choice of PMT to purchase in large quantities and for characterization of the chosen PMT to model its response. After production of PMT units begins in large numbers there will be routine testing of each PMT at various stages in the process from vendor to installation in the detector. Additionally, it may be prudent to characterize a small fraction of the units during production to ensure that there are no changes in response during the years of production—changes that are not detectable by the less detailed tests performed on every PMT. We propose here initially to work on the characterization before PMT choice and after selection, including periodic characterization during large scale production.

We propose to build a system capable of measuring quantum efficiency, angular response, and response as a function of position on the PMT face. We will make measurements with the PMT face in water. Single photo-electron response and linearity will be studied, along with timing characteristics including pre/after pulses. We have some instrumentation used in our development of the absolute (at a single wavelength) and (relative) multi-wavelength calibration of the Auger fluorescence detectors, and we will reuse much of that equipment including broad spectrum and LED light sources, optical table, absolutely calibrated photo-diode, dark box, and small optics. This proposal will allow us to reduce systematic effects for the new work, and to make the detailed studies needed for a meticulous PMT model.

There are three main areas of instrumentation that we propose to procure: (1) optical, (2) electronics, and (3) mechanical. All of the systems augment and take advantage of the existing Auger hardware.

1. The optical system includes a double monochromator for wavelength selection (in 1-nm steps), subtractive dispersion kit, exit mirror, grating mounts, and adjustable slits. Also needed are two integrating spheres and an optical fiber bundle to monitor the intensity and move the light spot on the photo-cathode. Existing optical table, dark box, and light sources (D2 and Xenon) will be used along with our NIST-calibrated photo-diode and other miscellaneous optics.

2. The electronics system will be VME-based similar to that used currently in the CSU-HEP lab. We need a dedicated VME crate with processor card, a VME waveform digitizer, and a VME controlled leading edge discriminator. These will be used with existing VME ADCs and TDCs. The new waveform digitizer will complement the existing electronics allowing more detailed pulse-to-pulse studies.

3. To allow qualification of the candidate PMT quantum efficiency and timing as a function of position on the photocathode, we will manufacture a test station capable of illuminating an approximately 1-mm-diameter spot on the face of the photocathode. This station will allow the spot to be positioned to approximately ± 2 mm of the desired position on the face of the PMT. Due to the long settling time of the PMT in darkness before tests can be made, this test stand will allow us to maneuver the illumination spot around the face of the PMT remotely without opening the dark box. Because it

is critical that we understand the performance of the PMTs while submerged in water, the test stand will be capable of testing the PMTs both in water and dry.

Future Efforts

The initial focus of the physics group will be preparation of the physics case for CD-1, including a coherent comparison of technology choices. Beyond that the group will continue to play a central role in optimizing the overall physics potential of the proposed detector and neutrino beam configuration. We plan to expand our participation in development of the water Cherenkov detector and, as one of the closest large research universities to Homestake, we may be able to provide a useful regional base for production and installation staging operations and management.

Personnel and Resources

Initial members of the CSU LBNE effort are as follows: Professors Robert Wilson (PI), Walter Toki, and John Harton; Senior Research Scientist Jeffrey Brack; Research Scientist Vladimir Kravtsov; Post Doc Alexei Dorofeev; and several graduate students (at modest levels). Wilson and Toki are current members of the T2K collaboration and have a long history with very long baseline and underground science initiatives. They were members of the UNO collaboration (led by Chang Kee Jung, Stony Brook University); Wilson was a member of the experiment advisory group and Toki was the coordinator for an extensive R&D proposal (not formally submitted). Wilson was Deputy Spokesman for the Henderson DUSEL collaboration, and project manager of the NSF S-1 and S-2 awards and editor of the Henderson DUSEL Project Development Plan. Kravtsov is also a member of T2K and has long experience with neutrino experiments in Russia. Harton, Brack, and Dorofeev are members of the Pierre Auger Observatory collaboration and have significant experience with PMT calibration for that experiment. The group has a very experienced HEP engineer, David Warner—we are currently discussing areas where he may contribute to LBNE project design and R&D efforts. The group has extensive experience with large and small photosensors. Redistribution of efforts from other projects is outlined in a separate document.

It is anticipated that new Assistant Professor Norman Buchanan (July 2010) will participate in LBNE. He is currently in discussions with NSF S4 project director Robert Svoboda (UC-Davis) to perform measurement and simulations to enhance the light-collecting capacity of PMTs in the water Cherenkov detector. This effort will be synergistic with the other CSU activities.

Requested Support

We are asking support for

1. Teaching buy-out support for Wilson fall semester 2010 to assist with CD-1 preparation (2 months salary+benefits).
2. The addition of one FTE post doc and one student to the grant. In practice, two of the three post docs in the group would together average to one FTE, with one on them spending a majority of his/her time for extended periods. Since all the post docs would also be working on closely related T2K physics and analyses, this should be an effective organization and attractive to candidates for the new position. A student has been identified (will shortly complete an MS) who wishes to work 100% on LBNE physics and simulations,; T2K students will spend some time rotating through LBNE tasks.
3. Travel: The most immediate need is support for the May collaboration meeting in Lead, when we need support for 4 travelers (Toki, Brack, Dorofeev, and Warner; Wilson will have travel support for 3 trips from an S4 sub-contract with UC Davis). For subsequent meetings (3 per year, generally at FNAL or Homestake) we anticipate 5 travelers on average (Wilson will attend all), in addition we expect about 3 other trips of 2 people to FNAL or collaborating institutions (such as related to pmt characterization task). For a total of 21 trips. If not teaching in the fall, Wilson will spend two extended trips ($\sim$10 days) to FNAL/BNL to assist with CD-1 preparation.
4. Computing hardware: Two computing nodes and modest additional data storage will be needed to supplement the existing cluster to host the comprehensive set of LBNE simulation codes.

5. PMT Characterization: A proposal for this equipment construction has been submitted to the PMT Project Manager (Paul Mantsch). Electrical design, assembly, operation, and analysis will come from redirection of effort scientific staff from a current DOE-supported project.

Drexel University Contribution

The Scope of Proposed Work

The Drexel University neutrino group proposes to perform hardware design and simulation studies primarily focused on the far detector and relevant consequences on the design requirements for the near detector. The proposed tasks will lead to improved vertex/ID resolution and improved absolute energy calibration in the low energy range relevant for supernovae searches. Specifically, the following investigations will be conducted:

- Assessing the effects of the particle vertex/ID resolution at the far detector on *the sensitivity of the oscillation parameters* with Monte Carlo simulations.

- Studying the capabilities of Winston cone light concentrators (LC) placed on the photomultiplier tubes as means for *improved vertex/ID reconstruction* at the far detector with Monte Carlo simulations.

- Designing a novel *hardware device: Cherenkov cones simulating light pulser (CSLP)*. The goal of the CSLP design is to build a device that will *improve* π^0 *rejection and particle vertex/ID reconstruction* by advancing the pattern recognition software through direct calibration with single and multiple rings. This investigation will also consider using the near (water Cherenkov) detector or an optional small water Cherenkov detector at a near site for CSLP optimization.

- *Investigating possible radioactive sources* for *calibrations in the energy range relevant for supernovae searches.* Both neutron and gamma source options will be studied since the former are relevant for the gadolinium-doped water Cherenkov detector option.

Baseline for simulation work

All of the proposed simulation studies (of the effects of vertex/ID reconstruction on neutrino sensitivity and those related to LC and CSLP) will be conducted using the LBNE water Cherenkov simulation being developed at Duke University in collaboration with Drexel and several other institutions. Drexel postdoctoral researcher Karim Zbiri has been working on developing the LBNE WC detector simulation that is based on the detailed, well-tuned simulation of the Super-Kamiokande 2 km water Cherenkov detector.

- **Motivation for vertex/ID sensitivity studies**

  Particle vertex/ID resolution, and in particular the effective rejection of events associated with NC (neutral current) events with single π^0 production, will have a critical effect on the capability of LBNE to reach its precision goals for neutrino oscillation parameters, CP-violation angle, and mass hierarchy. In a decay process of single π^0's resulting from NC neutrino scattering, one decay gamma is sometimes undetected (particularly in the case of asymmetric π^0 decay) or two overlapping gamma-ray Cherenkov rings are identified as a single ring. These single ring events can easily be mis-identified as CC electron neutrino events, which are a major source of background in the beam neutrino oscillation analysis. On top of that, the effect of overlapping gamma-ray Cherenkov rings becomes especially pronounced in the few-GeV region that coincides with the beam neutrino energy range.

  Assessing the capability of various pattern recognition algorithms and associated vertex/ID reconstruction will place requirements on the far detector design as well as on the precision with which the incoming flux of electron neutrinos must be known. Therefore, it will influence the design requirements of the near detector and the minimum level of precision of the electron neutrino flux measurement at the near site. This study will also include detailed analysis of matter effects on the electron neutrino flux at the far detector.

- **Motivation for LC vertex/ID improvement study**

  In the second study, we will investigate the potential of LCs for improving particle ID pattern recognition algorithms. The Drexel group is currently developing Winston cone-like LCs to be placed on all PMTs in the LBNE detector with the goal of increased light collection efficiency. The following question arises:

  Can the Winston cone-like light concentrators positively impact particle vertex/ID reconstruction, besides improving light collection efficiency?

  The proposed simulation study will answer this question by investigating several alternatives that will make the detector perform more like a digital camera, taking enhanced snapshots of parts of the particle tracks and therefore achieving better particle ID resolution. The following options will be simulated:

- Placing LCs on one or more subsets of PMTs, with varying orientation of the PMTs with respect to the detector's vertical axis.
- Combining several LC shapes (mostly varying the LC height) depending on the PMT location in the detector.
- Developing new pattern recognition algorithms that will take full advantage of the limited field of view of the PMTs with LCs as well as their specific orientation.

- **Motivation for building CSLP instrument and improved vertex/ID study**

  The CSLP device is envisioned as a battery-operated light pulser that will emit one or more light cones with tunable cone direction, cone opening, thickness of the cone envelope, and sharpness of the cone envelope. In this way, the CSLP will simulate the interaction signature of different particle types, in the extended energy range, potentially unattainable by other calibration tools, producing *a unique positive impact on particle vertex/ID reconstruction.*

  - *Simulation part*

    A related simulation study will involve simulating various physics processes required for vertex/ID reconstruction in order to build the CSLP instrument. This study will be followed by the simulation of the CSLP in the detector and how it can be used for boosting the effectiveness of pattern recognition algorithms for particle identification.

    As a result of this study, far detector π^0 NC events identification efficiency will be better understood and requirements on the near detector precision measurement of the electron neutrinos will be calculated.

  - *CSLP instrument design and construction part*

    In parallel with the simulation studies, the design of the CSLP will be developed. The CSLP design will then be optimized at the near site. The near water Cherenkov detector or, alternatively, an optional small water Cherenkov detector, will be used to tune the CSLP for different particle types using accelerator beams (i.e., 50-MeV protons, electrons, and so on).

- **Motivation for radioactive source investigation**

The final part of the proposed work is related to investigation of possible radioactive sources (gamma and neutron) for *calibration in the energy range below 20 MeV relevant for supernovae studies.* While this energy range can be successfully calibrated with a linear accelerator (at least for electrons) and a DT gun, both options incur larger expenses and more elaborate preparation with less precision. Single gamma and neutron sources are characterized by exactly defined energies and are valuable for absolute energy calibration where a low level of produced Cherenkov light makes energy measurement and vertex calibration difficult. Identification of appropriate neutron sources will be particularly important in the case of gadolinium doping of the water Cherenkov detector.

Relationship between proposed and current activities at Drexel

Previous and current related work

The proposed tasks represent a natural extension of the work currently being conducted by the Drexel neutrino group under the NSF S4 grant for LBNE WC detector:

- Prototyping Winston cone light concentrators to *improve light collection efficiency* of the LBNE far detector: LC shape optimization through simulation and building the prototype.
- Evaluation of the performance of several candidate PMT types that are under consideration for the far LBNE detector together with the Penn group and several other institutions.

In addition, the Drexel neutrino group has performed studies with LCs for the MACRO experiment. We are in the process of developing an optical position calibration device for the precision positioning to be used in the KamLAND and Double Chooz detectors and are a part of the calibration team for the Double Chooz detector.

Deliverables

The deliverables will be improved particle vertex/ID pattern recognition algorithms for the simulation, conceptual design of the CSLP, optimized configuration of PMTs with LCs and their orientation for more effective particle vertex/ID reconstruction, as well as reports on the needed precision of the electron neutrino flux and associated systematic uncertainties related to matter effects at both far and near detector sites.

Personnel and Requested Support

We request here 50% support for a post-doctoral researcher. An undergraduate student working for a full coop cycle (6 months) for the CSLP development will be funded by the project. The new post-doc will work on the simulation development, working with the current postdoc on the code developed by Duke and several other institutions (including Drexel). The PI will supervise the work of the postdoctoral researcher. We also seek travel funds for the postdoctoral researcher to attend collaboration meetings. The major part of material supplies for the CSLP and radioactive sources development will be funded by the project.

Institutional Resources

The Drexel group has an electronic shop and electronic equipment for developing the CSLP. During the course of the year Drexel will build a small-size detector that can be used for testing the conceptual design of the CSLP.

University of Hawaii Contribution to Water Cherenkov Calibrations

Note that there is another section on Hawaii studies of liquid scintillation detectors for DUSEL and LBNE.

Scope of work

The University of Hawaii High Energy Physics Group proposes to take a leading role in the in-tank optical calibrations for the large Water Cherenkov Detector option for LBNE. One system can perform several vital roles:

1) Relative time-amplitude calibrations (T-Q Cals) of all photodetectors (including electronics and water transmission). This bears directly upon the ability of the instrument to reconstruct the neutrino interaction vertex, topology and energy. Point source fitting of an isotropic calibration light source permits measurement and mapping of reconstruction biases, both over a substantial dynamic range in amplitude, and over spatial variations within the tank. This is an end-to-end calibration and needs to be carried out at multiple wavelengths as well. Ongoing calibrations may need only one wavelength for time variation recording. Note that this is not the detector energy calibration which ties response to known physics. That is best done for the few MeV range with radioactive sources, and with natural physical processes for hundred MeV to GeV range (minimum ionizing muons, muon decay, pi-zero mass reconstruction), or with an external source such as a compact particle accelerator. These latter are discussed elsewhere (BNL and LBNL proposals).

2) Water quality must be measured and monitored. Our experience in the past indicates that in-tank systems are best and several have been developed for SuperK, and are operated on-line, interwoven with normal data taking. The best method has proved to be via shooting an optical beam through the detector, and employing the direct and scattered light to deduce the optical characteristics of the water. This is not to say that other methods should not be pursued, but we know some things which will surely accomplish the task. One of the best ongoing measures of water quality in SuperK has come from the ongoing fitting of down-going cosmic ray muon trajectories. While it is true that the rate of CR muons at 4850 feet in Homestake will be down by several orders of magnitude, this still will leave on the order of a thousand muons per day which can be well fitted, and from that one can derive

the absolute optical response, including effective attenuation length for Cherenkov radiation (that is having the spectrum which matters). We do not propose to carry out this effort, but mention it as needing to be done by others, and as complimentary to the more explicit measurements which we propose (which are necessary as continuing relative measurements and diagnostics to any observed detector response drift).

This effort will be conducted by Dr. Shigenobu Matsuno (PI), with assistance from Professors Steven Dye, John Learned and Gary Varner. We request 0.5 FTE post-doc support, 0.5 FTE for a grad student (to be shared with work on SuperK, for thesis material). Plus we need 0.5 FTE engineering support from our experienced mechanical engineer Marc Rosen who has supervised the construction of 7 such systems (not only SuperK but other experiments at KEK and BES). This engineering support is for the system development studies discussed below, not project construction.

Future Efforts

1) We will start with a thorough review of our previous efforts and currently employed systems in Super-Kamiokande(some of which we have built). We will begin surveying the field for new lasers and the developments in (previously very expensive) solid state lasers. The favorite pulsed 337nm N2 laser system of recent years (LSI, now gone, had many unhappy features including unstable beam, poor reliability, and short lifetime). Aside from exploring new laser options, several problem areas are known to need study:

2) The changing availability of large core quartz fibers to deliver the light pulses to the tank from laser systems on the tank top may be a non-trivial problem. We may have to change strategy, and employ a bundle of multi-mode fibers (at least for the "Q scan" signals where substantial light must be delivered). Numerical aperture optical matching is always a nuisance and if done poorly can result in unacceptable losses at injection. Automated switching of the input laser pulse between fibers is a delicate business and needs to be done carefully if to be repeatable and stable. In the past we have found cable jackets which leaked light, and this must be checked. In any event we need to look into what is available and likely to be so for a decade and make new plans, and this will involve some test setups.

3) Another area we can tag immediately as needing work is in the re-design and implementation of the "laser balls", which serve to distribute the light from the end of the fiber

injected into the tank. While this may sound trivial, it turns out to be quite tricky (and we have seen lots of failures made by various groups over the years). One of our favorite methods in the past has been to utilize a micron scale suspension of silicon particles in water (Ludox), enclosed in a glass or quartz flask. The problem comes about from the output beam shape of the fiber being more or less conical (though can be shaped with a lens, but at any rate light all going into one hemisphere) and making a pattern which, if not sufficiently scattered, can result in a somewhat beamed image at the PMTs, when one would like isotropic illumination. On the other hand, too much scattering can cause significant attenuation and time smearing of the calibration light pulse. Various remedies have been tried over the years, involving mirrors and lenses, but in truth none were as uniform as we would like and may need to Homestake. Up/down and azimuthal variations have been on the 10% level, and we aim for the 1% level.

It must be said that this is not such a terrible problem for the "Q-T mapping" which really employs the data tube-by-tube for the time and amplitude calibrations. It is a problem if we are to use the same device for measuring water quality. For achieving maximum vertex and energy resolution, reaching the 1% level would improve matters. We do not have the data to substantiate that claim, but it is based upon our thirty years of experience in this area, and we await simulation results (as from the Iowa State group), to make the specifications more precise. We aim to focus upon the hardware conceptual design and demonstration in the laboratory. This should help us to define the laser cal construction requirements at the CD-1 level.

4) In Super-Kamiokande we have had multiple systems, sometimes with overlapping purposes, for both system time and amplitude relative calibrations and for water optical properties. We think an integrated light system would be appropriate for Homestake, one which includes the ability to carry out T-Q calibrations as well as some in-tank optical property monitoring. Measurements of water optical properties outside the detector have generally not been very successful in our experience (both for attenuation and more particularly for scattering). The water quality in SuperK has the further complication of varying with time (w̃eek scale) and position (over tens of meters) in the detector. Hopefully this situation will be improved for the Homestake detector, but we must be prepared. The most successful scattering measurements have been with a light beam directed through the SuperK tank with recording of the scattered light from the entire detector. This needs to be done at sev-

eral wavelengths over the range from about 337 nm to 500nm. SuperK has had variations in optical properties with depth, and this resulted in the installation of horizontal laser beams from a half dozen altitudes. Having both horizontal and vertical beams gives good ability to untangle optical inhomogeneity. Once again, however, it is very hard to model such vagaries (as they were not anticipated in SuperK, and still not entirely understood), but such will depend upon water flow, temperature stability, sources of pollution, etc. We think the best strategy is to simply iterate on the SuperK design for now, focusing our study effort on how to make substantive improvements, and update in a few years as detector simulations become more sophisticated and other systems designs (water purification for example) become more mature.

Hawaii does not propose to build all these systems (though we could), but we would like to coordinate their laboratory development, design, testing, and ultimately installation. In the course of this we propose to carry out research tasks on specific systems components (tank top laser system, switching, amplitude control and monitoring, fiber delivery cables, and light diffusers). Some other groups are interested in developing special projectors for studying vertex resolution and the like. Though these have not proved very useful in the past, we encourage their development, as we are entering a new level of sophistication and necessary control over all issues which effect the ability to carry out the LBNE mission.

Deliverables

The deliverables relating to CD0 will be:

1) Researching, testing and reporting on components involved in the in-tank T-Q and optical measurement related devices. This mostly involves lasers, fibers and optical diffusers.

2) Sketch of design for a baseline system, drawing heavily on our experience in SuperK, including rough component costing. This will also result in a baseline set of specifications for numbers and locations of devices, and more precise implications for tank top real estate and cableways.

3) Plan for further work in refining the specifications and design, and coordination with other related work.

Personnel and Resources

The University of Hawaii group has extensive experience in large Water Cherenkov detectors (beginning with being original collaborators on the IMB experiment through the present Super-Kamiokande detector. In that role we have originated many hardware and software techniques and carried them out. In particular we have along history of innovating, building and operating various calibration devices, most typically a system involving lasers, optical switching, fiber optics and special optical diffusers. The PI will dedicate 40% of his research efforts to LBNE over the next 3 years. Learned and Varner will contribute each about 10% of their research time (at no cost). Dye will contribute 25% of his research time and requests summer salary. A postdoctoral researcher will be hired with 50% of his or her time dedicated to LBNE. Two graduate students will be engaged full time to work half time on optical diffusers and new lasers. Our strategy is for getting students experience in the laboratory, along with participation in a producing experiment, which in our case is either SuperK or KamLAND, getting experience with physics data and accumulating some science publications.

Requested Support

We are seeking annual (each of three years) support for:

- Partial summer salary support (1 month) for the PI. He is otherwise state supported and thus no cost to the project.
- 6 months support for one engineer designing and helping build laser calibration system components for laboratory testing, as well as surveying available hardware (new lasers, fiber bundles, etc.).
- 6 months support for a post-doc to coordinate testing, run simulation software for studies of needed calibration sensitivity, and work with grad student on laser ball system.
- two times 6 months support for grad students (working with others) to develop new methods of constructing laser balls. Students to work on SuperK or other projects for remaining time (thesis data).

- Undergraduate laboratory assistant support at the rate of 40 hours/week (two students for 20 hours each).

- No support is needed for Prof. Learned who is 11 month State salaried. Prof. Varner has other support as well. We request summer support for Prof. Dye.

- Travel support for some collaborators to attend 3 domestic LBNE collaboration each year for a total of 6 trips. Plus, on project expense, travel for one engineer and one physicist to meet with LBNE collaborators over calibration hardware specific designs.

- Support is requested for materials and some prototype equipment. We will need some new optical measuring devices for the new test laser ball assembly and study. We will also need to purchase several new pulsed laser diodes and associated fiber optic hardware.

TABLE III: 3 years supplemental budget for Univ. Hawaii's Water Cherenkov related effort

Direct laber cost		FY11	FY12	FY13	row TOTAL
	overload S. Matsuno (1,1,1 mos)	7,794	7,794	7,794	
	overload S. Dye (1,1,1 mos)	8,063	8,338	8,338	
	graduate students (2) - 50%	24,007	24,006	24,006	
	engineering support - 50%	39,102	39,102	39,102	
	student help (2)	17,888	18,720	18,720	
	fringes	16,881	16,891	16,891	
	exempt postdoc - 50%	25,000	26,000	27,000	
	direct labor & fringes	138,735	140,851	141,851	421,437
Other direct cost					
	a. domestic travel	17,668	1,802	1,802	21,272
	b. materials and supplies	12,000	12,000	12,000	36,000
	c. research equipment				
	fast pulsed laser system	60,000	0	0	60,000
	subtotal direct costs	228,403	154,653	155,653	538,709
Indirect Cost	20.6% except for equip. & postdocs	29,541	26,503	26,503	
Total Budget		257,944	181,156	182,156	621,255

University of Hawaii Studies of a Large Liquid Scintillation Detector for DUSEL and Use with a Long Baseline Neutrino Beam

Motivation for Developing Large Liquid Scintillation Detectors

Liquid scintillation (hereafter LS) detectors in the 10-100 kiloton class may have an important role to play in future large underground detectors. Pursuing this class of detector is not necessarily competitive with water Cherenkov instruments (hereafter WC) or liquid argon drift detectors (hereafter LAr). It was only recently (Spring 2009) realized that liquid scintillation detectors may be well employed in GeV neutrino studies (that is with a beam from Fermilab in particular). Hence work has only just begun on simulations, laboratory studies and demonstrations, that this is indeed practical.

Fortunately we have several large LS detectors in operation (1 kiloton KamLAND in Japan and 200 ton Borexino in Italy) and another coming on-line in Canada soon (1 kiloton SNO+). Hence there is a great deal of community experience with large scintillation detectors (in fact more than with LAr), though none in the GeV neutrino application.

Moreover, the beam neutrino from JParc in Japan is at this writing in operation and ramping up towards design intensity, within this year. A program is started within the KamLAND Collaboration, lead by the UH group, to try and extract a few long baseline neutrino beam events to demonstrate the principal (rate expected to be only a few per month at best). Despite the fiducial volume of KamLAND being too small to make this project effective for physics results (cannot compete with SuperK with its 40x large fiducial volume), as well as the photomultiplier tubes being not at all ideal to the task, the project should yield some real world demonstration interactions.

The use of LS for these energies yields about two orders of magnitude more photoelectrons than a WC detector. This facilitates many low energy initiatives, such as those being carried out at the extant LS instruments (reactor neutrino studies, geo-neutrino measurements, supernova searches, proton decay to kaon modes, etc.) but with a 50 kiloton detector, with a sensitivity 100 times that of the present LS instruments. The LENA group, mainly based in Munich has been pushing in Europe for a 50 kiloton liquid scintillator to be built in Finland, for some years, and they have produced a long list of studies on the science which can be done with LENA.

In short, the trick for using the huge amount of light which will reach PMTs (hundreds of PE/PMT for GeV neutrino events) is the fact that Fermat's principle guarantees that the first light arriving at each PMT will be on the "Fermat surface". For a straight muon track this will be along the Cherenkov cone, with spherical cap shapes backwards and forwards, as illustrated in Figure 1. (****¿add cartoon of Fermat surface) With so many hits and timing to nanosecond levels, this cone is highly constrained, and early simulation results showed that resolutions in energy, vertex location, and angles competitive (perhaps even better than WC) could be achieved. The first calculations were done at UH, but have been followed by more complete simulations at the University of Washington and the Technical Institute of Munich (TUM). More importantly perhaps these initial studies indicate essentially complete flavor separation between (quasi-elastic) muon and (quasi-elastic) electron events in this energy range, as directly applicable to the LBNE goals in neutrino mixing studies. Indeed the TUM studies show that one can not only reconstruct the muon track, but also resolve the nuclear recoil (which cannot be done in WC).

In short this technique appears to have some strong attractions for the LBNE application, and though we are starting late compared to WC and LAr, there is indeed time to bring such a detector into the mix for DUSEL. One reason is that the kiloton scale instruments do exist already, but another is that the cavern needs are very similar to WC instruments. Hence if a first cavity were dedicated to WC, a second of similar or the same design might be used by LS. Basically, one wants a large cylinder lined with PMTs. The PMTs and DAQ will be very similar. The big difference will be in the need to be very careful with contamination by unwanted isotopes, now a well known set of protocols. Such an instrument will need its own scintillator treatment plant as well. One possible difference between WC and LS, is that due to limited optical attenuation length in LS one may prefer a cavity which is teller than in diameter. This hinges upon studies of appropriate scintillators and what kind of optical clarity can be achieved.

We at UH and others have produced a White Paper on the potential for employing a large (think scale of 50-100 kilotons) for employment at DUSEL. We direct the reader to that paper for more detail, too much to include here.

In sum, we are claiming that a possible LS detector at DUSEL will bring new capabilities in the LBNE physics, will open up new physics exploration channels at low energies and in nucleon decay searches, and indeed provides an off-ramp for permitting much world class physics even in the event that θ_{13} is found to be too small for next round studies (as will be revealed in the next few years).

Scope of work

The University of Hawaii High Energy Physics Group proposes to take a leading role in the LS studies, but we hope for substantial collaborative help from other groups in the US and abroad. We have expressions of interest from a half dozen groups in the US (U. Washington, Alabama, UC Davis, LANL, BNL, Maryland, Wichita State) but they will have to make their own proposals and commitments. (Some other groups which are presently overwhelmed with bringing detectors on line have expressed intent to join us in several years time.)

So, in the following, we outline the work we propose to undertake over the next three years relating to demonstration of the LS capability and practicality, and moving towards preliminary design. For the moment we are assuming a 50 kiloton scale as our baseline instrument. Items in need of study, in order of our assessment of importance are:

1)Simulations of a large LS detector with GeV neutrino interactions 2)Extraction of $\tilde{G}$eV sample events from KamLAND 3)Liquid Scintillator studies 4)Tests of photodetectors, with emphasis on the use of timing in event reconstruction 5)Exploration of prospects for MeV level directional neutrino measurment

Future Efforts

The goal of these efforts is to move as swiftly as possible towards realistic preliminary design (and hence reasonable performance and cost prediction) for a large LS detector. Amongst major unknowns at this time are the limitations on rejection of asymmetric pizero events in LBNE studies, limitations on detector geometry due to attenuation limitations, optimization of the number of pixels and desired time resolution, optimal and affordable (including possible neutron absorbing doping) LS choices.

Deliverables

The deliverables relating to CD0 will be:

1) Detector and physics simulations at the level of GEANT, focusing upon the LBNE application, and permitting comparison to WC and LAr techniques.

2) At least one formulation for LS to realize such a detector. Such a recipe includes choice of base liquid (most likely at the time linear-alkybenzene, which is readily available as a dishsoap base, non-toxic and not a fire hazard) along with high light output dopants and possible large neutron absorption cross section additives. An important issue here is the tradeoff between fast response and high light output scientillators.

3) Recommendations about photo-detectors and DAQ system, enabling engineering design. A possible key in this would be credible availability of new generation light detectors (LAPD) as being developed at ANL-Chicago. If these not developing fast enough then fall back would be either small and inexpensive medical PMTs or perhaps PMTs similar to those used in SNO and ICECUBE.

Personnel and Resources

The University of Hawaii group has extensive experience in large neutrino detectors (beginning with being original collaborators on the IMB experiment through the present Super-Kamiokande detector) and in the last ten years with the KamLAND liquid scintillation detector. In addition, John Learned was involved in the first long distance drifting in LAr at UCI with Herb Chen in the late 1970's and was co-author on the LANNDD proposal. Thus we have real world experience with all the three technologies which might be used in an LBNE at DUSEL. In fact, from this basis we think each has its strong and unique features, and that LS has been neglected so far, and needs to be brought along. We propose to nucleate this effort from UH, though others may take the lead (if and) as the initiative gains favor in the community.

Requested Support

We are seeking annual (each of three years) support for:

- Full time support for a post-doc to run simulation software for the large LS detector, and supervise laboratory studies of scintillators and detector components.

- Partial summer salary support (2 months) for one faculty member (Steve Dye). He has a joint UH HPU academic appointment.
- 6 months support for one engineer carrying out test equipment design and construction.
- two times 6 months support for grad students (working with others) to develop new methods of constructing laser balls. Students to work on SuperK or other projects for remaining time (thesis data).
- Undergraduate laboratory assistant support at the rate of 40 hours/week (two students for 20 hours each).
- No support is needed for Profs. Learned and Matsuno (co-PIs)who are 11 month State salaried. Prof. Varner has other support as well.
- Travel support for some collaborators to attend 3 domestic LBNE collaboration each year for a total of 6 trips. Plus travel for two physicists to meet with LS LBNE collaborators.
- Support is requested for materials and some prototype equipment.

TABLE IV: 3 years supplemental budget for Univ. Hawaii's Liquid Scintillator related effort

Direct labor costs		FY11	FY12	FY13	row TOTAL
	overload S. Dye (2,2,2 mos)	16,126	16,676	16,676	
	graduate students (2) - 50%	24,007	24,007	24,007	
	engineering support - 50%	39,102	40,449	40,449	
	student help (2)	17,888	18,720	18,720	
	fringes	16,887	17,404	17,404	
	exempt postdoc	48,000	50,000	52,000	
	direct labor & fringes	162,010	167,256	169,256	498,522
Other direct costs					
	a. domestic travel	17,668	1,802	1,802	21,272
	b. materials and supplies	20,000	20,000	20,000	60,000
	c. research equipment				
	spectrophotometer system	50,000	0	0	50,000
subtotal direct costs		249,678	189,058	191,058	629,794
Indirect Costs.	20.6% except equip,postdocs	31,246	28,646	28,646	
Direct + Indirect costs		280,924	217,704	219,704	
Total Budget		280,924	217,704	219,704	718,332

Iowa State University Contribution

Scope of work

The Iowa State University High Energy Physics group is proposing to participate and lead aspects of the calibration for the large Water Cherenkov Detector option for LBNE. The calibration system is an essential feature in a Water Cherenkov detector because the properties of the water change with time and wavelength. In fact, in Super-Kamiokande the water attenuation length was observed to vary as much as 20 m within a month and even twice that when comparing year to year. The attenuation coefficient is a function of wavelength as it is subject to Rayleigh and Mie scattering as well as absorption terms. The relative timing of PMTs is another factor that has variation as a function of pulse height. It is possible that in a larger Water Cherenkov detector the water circulation of a larger mass of water will make this a more significant issue. All these changes potentially have an impact on physics quantities such as vertex and angular resolution and consequently particle identification efficiency. While every effort will be made to measure each factor individually and eventually input it into the simulation, measuring the physics quantities for different particles types provides more direct access to the final uncertainties.

The goal of the Iowa State proposal is the development and investigation of the systems and procedures to calibrate vertex and angular resolution and particle identification efficiency. These parameters vary as a function of energy as well as time and our capability of reliably calibrating them need to be well understood. The calibration of vertex reconstruction and improvement in particle identification is key to reducing the background due to mis-identification of neutral current neutrino scattering events with single neutral pion production and charged current muon neutrino events which are major sources of background for the electron neutrino appearance in a muon neutrino beam. This calibration can be accomplished by a combination of naturally occurring events inside the detector and a series of dedicated systems to be installed inside and outside the detector; including radioactive sources which will have to be deployed inside the detector volume.

The main thrust of the Iowa State effort will be to demonstrate if naturally occurring events (such as cosmic muons, neutral pions, Michel electrons, etc) in the detector are sufficient to carry out the vertex and ID calibration at the required level to achieve the goals of the experiment. A potential concern is the low muon rate at 4850 feet depth of LBNE. This effort will require simulations as well as the development of dedicated software algorithms to reconstruct, identify, analyze and select suitable subsets of events that can verify and improve the uncertainty in the vertex reconstruction and contribute to improved, more robust particle identification. The water Cherenkov simulation developed by LBNE collaborators at Duke University, which is based on the T2K 2km water Cherenkov detector, will be used as a starting point. In addition to the naturally occurring sources, other possibilities have been proposed for the high (GeV) energy range including 1 GeV and 100 MeV accelerator options for energy calibration. The impact of these on effectively improving the particle ID efficiency for electrons will also be studied. Beyond the neutrino beam studies in the GeV range, lower energies (¡1 GeV) are also of interest for proton decay, studies of supernovae, relic supernovae and solar neutrinos. At these energies the vertex resolution degrades significantly and becomes more challenging, deployment of radioactive sources is helpful and simulations will be conducted to determine at what rates.

This effort will be conducted by Prof. Mayly Sanchez (PI) and a 0.5 FTE postdoc for which support is requested. The PI is also overseeing, in collaboration with Gus Sinnis at Los Alamos, the main Calibration WBS element as well as Management and Safety for this element.

Future Efforts

An initial review of the literature of previous Water Cherenkov efforts will define the requirements at the CD-1 level. After CD-1 is granted, we will work on simulations and algorithms to determine the level of uncertainties obtained with natural occurring events. We also plan to participate in the development of hardware for the water transparency and light scattering measurements. In particular the idea of using side-going laser beams in substitution of vertical deployment.

Deliverables

The deliverable will be calibration studies and procedures for naturally occurring events and a report on the level of uncertainties obtained with this type of events. A comparison to other proposed options will also be done.

Personnel and Resources

The Iowa State group has extensive experience in long baseline neutrino experiments such as MINOS and NOvA. In particular the PI lead the first electron neutrino appearance analysis in a long baseline neutrino experiment. Sanchez will dedicate 40% of her research efforts to LBNE over the next 3 years. A postdoctoral researcher will be hired with 50% of his or her time dedicated to LBNE. A graduate student or several graduate students will cover 0.5 FTE in assisting with LBNE activities while spending the remaining time in MINOS and NOvA which have the data necessary for their thesis.

Requested Support

We are seeking support for:

- 50% of a postdoctoral researcher for 3 years. The postdoc will work on the simulations and development of algorithms with the goal of establishing the vertex resolution and particle ID calibration. Researcher will be stationed at Fermilab and will spend the other 50% working on NOvA.

- 50% of a graduate student for 3 years. The student will assist on the simulations and development of algorithms with the goal of establishing the vertex resolution and particle ID calibration.

- Travel support for the group to attend 4 domestic LBNE collaboration each year for a total of 8 trips.

- Partial summer salary support (1 month or 50%) for the PI for 3 years.

Kansas State University Contribution

Scope of work

The Kansas State University (K-State) High Energy Physics Group is proposing to conduct simulation studies of MicroBooNE-like liquid argon (LAr) detectors in order to research the capabilities of, and develop the design of, LAr detectors in the LBNE far and near detector complexes. The MicroBooNE collaboration is currently constructing a 0.1-kton-scale detector to study neutrino interaction physics and to investigate the excess in low energy events observed by the MiniBooNE experiment. The detector consists of a 89-ton active volume read out as a time projection chamber (TPC) by three planes of wires, with photomultiplier tubes (PMTs) providing timing and additional energy deposition information. It promises high-resolution tracking capabilities, with good discrimination between photon and electron events. MicroBooNE will address neutrino interaction physics using both the Fermilab Booster Neutrino Beam, on-axis, and the Neutrino Main Injector (NuMI) beam, off-axis. MicroBooNE development is seen as a key step in developing 20-kton-scale detectors; a candidate technology for LBNE far detectors is a set of such detectors. The LAr TPC technology is therefore of interest for both near and far detector use.

There are two overall goals for the simulation studies:

- Specify the requirements for LAr TPCs in the far and near detector complexes to achieve the best achievable sensitivity for the overall LBNE oscillation program. This includes detector hardware requirements, such as wire spacing, which also directly impact budgetary considerations. This also includes consideration of what beam-characterizing data can be provided to any and all LBNE far detectors by employing the near LAr detector as a non-identical near detector, in addition to evaluating any cancellation of systematics when used with a far LAr detector.

- Help determine the scope of the far detector physics programs. In addition to measurements for the neutrino oscillation program, the studies will also explore other physics could be addressed with 20 to 100 kton of LAr, such as nucleon disappearance and relic supernova neutrinos.

There are also technical issues for LAr to be addressed: in particular, development of better reconstruction and data reduction algorithms for LAr TPC detectors. K-State will work with the Liquid Argon Software working group (LArSoft).

This effort will be conducted by Dr. David McKee and Profs. G. Horton-Smith, T. Bolton, and Y. Maravin. We will involve undergraduate research students in several ways, including resolution studies and comparison of "hand scanned" events with automated reconstruction. In 2011, we propose to add a graduate student who would split time between the final stages of this study and MicroBooNE data analysis.

Simulation Study

The effort will involve coordination with the LBNE Beamline working group and the Near and Far detector working groups. We will rely on data from the beamline group in simulating the performance of the MicroBooNE-like near detector and larger far detector to explore the sensitivity of the LAr–near-and-far scenario. In evaluating the use of a MicroBooNE-like near detector with a far detector of different technology, we will rely on simulations from the appropriate Far Detector working group. This effort should be coordinated with other near- and far-detector simulation efforts to identify benchmarks and valid ways of comparing simulation results.

The use of the LArSoft detector simulation and data processing package is key to this effort. K-State is a member of the MicroBooNE collaboration and LArSoft group and has access to this code. We have run the LArSoft simulation package as preparation for a quick study of resolving power as a function of wire spacing, to be performed using "hand scanning" of events. More advanced studies, as well as work on automatic TPC track reconstruction, will follow.

Relevant physics simulations will include:

- The hand-scanning–based "quick study" of a "zoo of events" collected from many people in the LArSoft working group, with 3-mm and 5-mm wire spacing. We will involve a K-State undergraduate in this work immediately, and involve REU students in the summer of this year.

- Reconstruction of various charged-current interactions at sub-GeV to few-GeV neutrino energies.

- Simulation of background reactions and other reactions of interest. The discrimination between photons and electrons is of particular interest.
- Simulation of options for calibration, including consideration of how test beam data might improve modeling of LArTPC response to electromagnetic and hadronic showers.

It is planned that the full set of studies described will take 3 years, with the studies most relevant for preliminary design (and CD1 input) completed rapidly, and studies relevant to more specific technology choices (and CD2 input) completed later.

Personnel and Resources

K-State has extensive experience in neutrino interaction and detector physics, including past roles in the NuTeV experiment and current roles in KamLAND, Double Chooz, and MicroBooNE. We also have extensive experience in challenging event reconstruction and data reduction for the DØ and CMS collider experiments. K-State is well positioned to complete this study and make key contributions to the LAr option for the LBNE program. In addition to physicists, we have exclusive use of a modest cluster of four recent-model computers (quad-core, 64-bit Intel(R) Xeon(R) E5520 @ 2.27 GHz, 25 GiB RAM, running Scientific Linux 5.3), with 5 TB storage, maintained by the department's Physics Computer Support Center (PCSC). This will directly support the activity proposed here.

This effort will be lead by Prof. Glenn Horton-Smith and Dr. David McKee (postdoctoral researcher), with additional contributions from Profs. Tim Bolton and Yurii Maravin. Undergraduate effort will also be utilized, and graduate student effort will begin starting in 2011.

Requested Support

We are seeking support for the following:

1. Salary support for 50% of one postdoctoral researcher in 2010-2012, one part-time undergraduate research assistant in 2010-2012, and one full-time graduate student in 2011-2012.

2. Travel support to attend LBNE meetings and work with collaborators for Dr. McKee, the graduate student, and a single "professor unit". (It is anticipated that Profs. Horton-Smith, Bolton, and Maravin will attend LBNE meetings in alternation.) This totals to 12 person-trips a year.

3. An appropriate fraction of the support fee for the department's Physics Computer Support Center, which maintains the local cluster and workstations to be used for this study.

Louisiana State University Contribution

Scope of Work

The Louisiana State University group proposes to design, prototype, and test components of a calibration source deployment system and perform simulation studies to better define the energy calibration requirements for the far water Cherenkov detector.

The proposed simulation study will focus on the sensitivity of neutrino oscillation parameters to the event energy resolution and energy scale uncertainty. The study will primarily investigate the energy region from a few hundred MeV to several GeV which is most relevant for the neutrino beam oscillation measurement. The signal events will predominantly stem from charged current quasi-elastic interactions and produce electron showers. Beam intrinsic electron neutrinos form an irreducible background and have the same event characteristics. However, due to the different energy spectra of signal and beam background, accurate knowledge of the event energy will help to minimize the beam intrinsic electron neutrino background. Another dominant background source at the far detector are π^0s from neutral current interactions that can mimic single electron events if the two showers overlap or only one of the gammas is observed. Among others, an accurate energy measurement of the electromagnetic shower energy will help to discriminate against such π^0 background events. The effects of energy resolution and scale uncertainties on the sensitivity toward neutrino oscillation parameters will be studied independently for signal and various backgrounds by smearing and shifting the corresponding true event energies. The detector response is expected to be non-uniform due to the cylindrical shape and the fiducial volume extending close to the photomultiplier region. Hence, the position dependence of the calibration requirements and correlations with other detector parameters such as coverage with photosensitive area need to be studied by varying the relevant parameters. Follow up studies will investigate correlations with additional parameters such as uncertainties on position and direction reconstruction as well as uncertainties on particle identification. Reasonable assumptions for the latter quantities will have to be derived in collaboration with the physics and simulation working groups. The proposed simulation studies will use the LBNE water Cherenkov detector simulation which is based on the Super-Kamiokande detector simulation and has previously been used to model the 2 km detector for the T2K experiment.

As a second step the above simulation studies will be adjusted and applied to lower energy regimes that are of interest for the detection of solar and diffuse SNe neutrinos as well as nucleon decays. One particular aspect for these studies in the lower energy regimes is the impact of the detector energy threshold uncertainty on the detector's capability to make precision measurements based on solar and diffuse SNe neutrinos.

The simulation studies will serve as a basis to determine the types of energy calibration sources which will be required and to develop a strategy for source deployment locations and frequency. All of these parameters are critical to the design of an appropriate source deployment system. The baseline design of the LBNE water Cherenkov detectors foresees multiple calibration access ports at different radial positions. Multiple access ports have the advantage that simpler and hence more reliable calibration source deployment systems can be built. The LSU group proposes to design calibration source deployment systems and perform components tests to determine whether the designed systems meet all specifications. As an example, one of the simplest source deployment devices consists of a wire and a winch, which is driven by computer controlled position sensitive stepping motors. The graduate and undergraduate students will be responsible to evaluate the performance of such components, ensure that material specifications are met, and address any interface requirements. If needed, more sophisticated systems such as a a pulley system (e.g., SNO), calibration arms (e.g., KamLAND, Double CHOOZ), or even more flexible deployment systems such as a remotely controlled submarine will be considered.

Deliverables

The first deliverable will be a specifications of energy calibration requirements, specifically energy resolution and scale, for the far water Cherenkov detector of the LBNE project. The second deliverable will be an energy calibration strategy for the far water Cherenkov detector of the LBNE project along with a design of an appropriate deployment device and performance test results on components for such a calibration deployment system.

Personnel and Resources

Initially, LSU PI Thomas Kutter will spend 15% of his time on the LBNE project, which will be used to supervise the post-doc and students. Furthermore, in the first year post-doc W. Coleman will spend an increasing fraction (20%) of his time working on the outlined simulation and hardware effort while continuing data analysis on T2K. In the second and third years, Coleman will work full time on LBNE. A new graduate student will contribute to the simulation and component development tasks. An LSU undergraduate student, who would be supported by University scholarship funds, will mostly contribute to the hardware development tasks and the associated data analysis. The LSU group has much experience with large and complex detector simulations, most recently from the SNO, K2K, and T2K experiments. In the past five years the PI has led the design, R&D, construction, and installation of one of the near detector components for the T2K experiment. The gained experience and background is applicable and valuable to the proposed tasks. The LSU groups benefits also from very experienced in-house electronics and machine shops, which are critical for any design and development work of a calibration source deployment system and components thereof.

Requested Support

- We are asking for travel support for Kutter and Coleman to attend four domestic LBNE collaboration meetings and working group meetings and for a graduate student to attend two domestic LBNE collaboration meetings each year, for a total of 10 trips.
- Support for a 50% FTE post-doc in the first year who will work under the supervision of the PI. In the first year, the remaining 50% of the post-doc will be supported from existing DOE funds which will be partially redirected toward LBNE and the post-doc will continue to work on T2K data analysis. In the second and third years, full support for post-doc salary is requested as T2K DOE funds for the post-doc run out.
- Support for a 50% FTE graduate student who would work initially on LBNE simulation and hardware calibration tasks while spending the remaining time on T2K data analysis in fulfillment of PhD requirements. The remaining funds for the student salary would come from departmental and scholarship sources.

- Modest funds for professional services from the electronics and machine shops in the Department of Physics and Astronomy at LSU to support development work for components of a calibration deployment device.

- Funds in support of desktop computers and the addition of one computing node and data storage is foreseen. The computers are for the post-doc and students to perform LBNE simulations and analysis of data resulting from component tests.

- Funds are requested for materials and supplies to purchase expendable lab supplies, commercial software, PC cards, and other miscellaneous items for day-to-day operations.

New Mexico Contribution

Scope of Work

Simulations of the LBNE neutrino beam are the major tool(s) for studying the correlations between the neutrino beam characteristics at the near and far detectors with various components of the beam design itself and with various measurables (possibly before and) after the decay region. Of particular interest to our group is to quantify the precision needed (from the beam related measurements) to limit systematic errors in the neutrino oscillations measurements. Once the measurement precision is known we will focus on possible instrumentation options.

As the NUMI beamline is a prototype for LBNE, we hold open the possibility for installation of prototype beam monitoring instrumentation in (or adjacent to) the NUMI beam.

In addition to LANL the other LBNE group working in this area is U of Colorado. Given the number of issues sharing responsibilities should not be a problem.

Personnel and Resources

The LBNE group at the University of New Mexico (UNM) includes Professor John Matthews and Dr. Bernard Becker (post-doctoral scientist). William Miller, instrumentation specialist in the department of Physics and Astronomy, typically contributes 10% of his time to instrumentation projects in our group.

The group has a history of innovative instrumentation design in particle physics and particle astrophysics experiments. Our current experiments include the Pierre Auger Observatory and the HAWC TeV γ-ray experiment. Additionally Matthews has been active in both fixed target and collider experiments at Fermilab. Becker's doctoral thesis was on the MINOS experiment.

Perhaps our most valuable asset is the physical closeness of the LANL and UNM groups. Thus our goal is to work closely with the LBNE team at LANL on issues of common interest and responsibility in LBNE beamline and near detector instrumentation.

The NuMI-MINOS experiment has shown the value of different configurations of the NuMI beam/target to produce neutrino beams with different properties to aid the study of systematic uncertainities associated with the neutrino oscillation measurement. Since the final goal is to measure the oscillation parameters at the far detector, the neutrino beam profile must be understood at the near detector. This involves actual measurements of neutrino's in the near detector, measurements from beam monitoring of associated charged particles, and detailed simulations.

A similar exercise can be considered for LBNE. Although the LBNE beamline is a different beamline then NuMI, similar measurements must be simulated and ultimately implemented. As currently envisioned, LBNE will have a near detector which is closer to the target, a bigger diameter decay tunnel and is optimized for lower energies and higher total power when compared to the NuMI beamline. This (new) beamline design must be studied in order to understand what type of beam monitoring is required to make the optimal measurements of the charged particles which when combined with the near detector neutrino measurements result in the best possible prediction (ie minimum systematics) for the far detector.

We propose, as a good first step in this process, to examine how the charged particle flux (that can be observed by beam monitoring) is related to the observed neutrino flux at the near detector and how this changes with some possible variations (horn and target configuration, for example) in the beam design. This can be carried out using a preliminary beamline design which could be improved as a more final beam design is produced. For example, it could turn out that certain types of beam monitors are more optimally placed at a certain place in the beamline to reduce uncertainites in the far detector spectrum.

Requested Support

To be effective we request the following:

- travel support for bi-weekly meetings and collaborative work at LANL
- travel support for Becker and Matthews to attend LBNE collaboration meetings

University of Pennsylvania Contribution

Proposed Work

The University of Pennsylania (Penn) group proposes to make measurements of PMT optical and eletrical properties and perform related simulation studies focused on two main areas:

- The sensitivity of oscillation measurements to the uncertainties on neutrino beam spectra and neutrino interaction cross sections.
- The influence of photomultiplier tube (PMT) parameters on the rejection of π^0 backgrounds, and the associated need for a water Cherenkov detector located at a near-detector site.

For both of these studies, the water Cherenkov simulation developed by LBNE collaborators at Duke University will be used. The Duke simulation was based on the simulation used for the Super-Kamiokande 2 km water Cherenkov detector.

The first study is critical for determining how well the near detector must perform in order for LBNE to achieve its goals of measuring the neutrino mixing parameters. For example, the plan for a relatively broad-band beam lends itself to the possibility that at the far detector the neutrino oscillation pattern can be used to constrain Δm^2_{23} and to help unravel degeneracies associated with the matter effect. Using the oscillation pattern—which depends on L/E_ν—to determine the mixing parameters implicitly assumes that the energy energy dependence of the neutrino interaction cross sections is well understood. The relevant question is how sensitive the measurement is to these uncertainties and, hence, how well will the measurements of such interaction cross sections have to be at the near detector site. Similarly, the estimates of the intrinsic ν_e backgrounds at the far detector will depend on an extrapolation of the near-detector spectra and angular distributions. A deterimination is needed for how precise such spectra need to be in order to accurately predict the background.

The second study is aimed both at helping to identify backgrounds at the far site as well as whether a water Cherenkov detector will be needed at the near site. The Penn group has responsibilty for the coordination of measurements of candidate photomultiplier tubes for the water Cherenkov option for the far detector. Part of the difficulty in identifying

π^0 events that look like single electrons occurs when the Cherenkov rings from the two individual decay γs overlap. Such events can be better separated with higher granularity of the PMT array, but this comes at a large cost. Instead, it may be possible to improve identification of these events by looking for multiple hits on individual PMTs, using either charge, or timing, or both. The charge response of last-generation PMTs (such as those used in SNO and Super-Kamiokande) is not good enough to reliably distinguish two hits from a single hit on a PMT. The newer generation of PMTs, such as the 10-inch Hamamatsu R7081 that are candidates for LBNE, have much better charge response and therefore may be able to resolve multiple hits. Timing may be helpful as well (though likely less so because the arrival time differences between multiple Cherenkov photons are likely to be short), but a study using realistic PMTs needs to be done. If this is possible, it argues more strongly for a water Cherenkov option at the near site, as a way of calibrating the separation algorithm.

The Penn group has extensive experience with precision simulation of water Cherenkov experiments such as the Sudbury Neutrino Observatory (SNO), and, in particular, with the simulation of PMT charge and timing response. It also has long experience with developing and modeling the readout electronics for PMT-based experiments. At other institutions, measurements of the complex index of refraction will be made of candidate PMTs, and from these a simulation model like that used by SNO will be developed. At Penn, we will then test this model using a Cherenkov source, possibly with the PMT photocathode face immersed in water. Then various alternatives can be explored, including waveform digitization of the PMT pulses, the effects of cable length on multi-hit separation and through simulation the consequent effects on π^0 identification. The same study can be done for a water Cherenkov detector at a near-detector site.

Deliverables

The deliverables will be the results of Cherenkov-source tests of candidate PMTs, and improved PMT and data acquisition models for the simulation. We will also provide reports on the needed precision of the systematic uncertainties and the possibility of π^0 identification at both far and near-detector sites using the multi-hit response of candidate PMTs.

Personnel and Requested Support

The simulation work will be done by a post-doctoral researcher, who will be supported 50% out of funds from the NSF. The post-doc will help develop the simulation, working with the code provided by Duke. The post-doc would be working under the supervision of the PI, and the remaining half of his or her effort will be on either the MiniCLEAN dark matter experiment, or the SNO+ neutrinoless double-beta decay experiment. The tests of the PMTs will be done by undergraduates, with support for the development of the test set-up and electronics coming from the Penn instrumentation group. Support for the PI will come from re-direction of the existing Penn base grant, as will partial support for engineering and technical personnel. We request here new funds for the support of undergraduates, and for additional technical and engineering support.

Institutional Resources

The Penn group has a small computing farm and that can be used for developing the simulation. We have a working dark box, oscilloscope and data acquisition system for the needed measurements. In addition, the LBNE collaboration has access to much larger computing farms that could be used for production simulation running.

Pittsburgh Contribution

Scope of Work

The University of Pittsburgh High Energy Physics Group proposes to contribute to LBNE near detector design through Monte Carlo simulation and technology feasibility studies. Our group also worked on both the MINERνA and the T2K ND280 P0D detectors, both of which are fine-grained scintillator based tracking detectors that encountered similar design issues as an LBNE near detector will have. Together with the Rochester group we have been involved in proposing a scintillator-based tracking detector design that is optimized for the LBNE beam needs.

In addition the Pitt group will study the possibility of using the expected MINERνA results in combination with directly measuring the hadronic spectra (species, angle and momenta) off the proposed LBNE target from a dedicated experiment. This study will determine if the proposed combination will be sufficient to meet the LBNE oscillation measurement requirements.

The LBNE near hall facility will require one or several spectrometer magnets to perform near detector and beam production monitor measurements. Any near detector design will require a magnetic field to measure sign and momenta of muons in charged-current interactions. It may also prove useful to separate electron and positron candidates produced in charged-current electron neutrino interactions. A proposed in-situ production experiment will also require a well understood analyzing magnet to precisely measure particles produced in the LBNE target. Naples has been asked to be L3 manager for the near hall magnets. This will require studies to access the needs of the various detector designs including required field coverage and strength.

The specific goals of our proposed contribution to these studies include:

- Incorporation of passive water target material into the detector target volume. The existing MINERνA detector has several nuclear targets in the upstream region. We propose incorporating water targets throughout the active volume similar in granularity to the T2K P0D detector.

- In addition to simulations optimizing the granularity and mass of water, an off-the-shelf water "bag" technology would be investigated and later prototyped. We propose using the same water target technology employed by the FGD/ND280 detector of the T2K experiment. The "bags" consist of polycarbonate multi-walled sheets used in the construction of green houses.

- Studies of γ-electron ID would also be performed. The aim would be to determine the efficiency and purity of π^0 Id needed to measure the Neutral-current π^0 and beam ν_e background components.

- Simulate and optimize the design of added magnetized iron toroid sections to the active target volumes for the purposes of measuring the beam flux through charged-current interactions at the near location. One relatively inexpensive option for incorporating a magnetic field would be to use a segmented iron tracking spectrometer downstream of the target region. We have put forward a design that includes an active target section followed by a graded-thickness iron-based magnetized toroid detector, with this unit repeating several times to make a hybrid detector capable of low energy (down to about 300 MeV) muon momentum measurement. A GEANT-based simulation of the muon spectrometer would be performed and used to optimize this design.

- Study if the MINERνA results in combination with a dedicated LBNE target hadroproduction measurement (*alla* MIPP) would be sufficient to satisfy the LBNE oscillation measurement requirements.

Future Efforts

After CD-1 is granted, our group will contribute to finalizing the design of and eventually construction of the Near detector and/or beam monitoring detectors.

Personnel and Resources

In addition to leading roles on MINERνA and T2K P0D detector electronics systems, our group has also been working on the MINOS experiment for the past 10 years. On MINOS our group was responsible for design and prototyping of the NuMI muon monitor Pad ionization chamber detectors. We can take advantage of our university electronics shop and machine shop both of which contributed to our past design, testing, and construction projects.

The work will be carried out by PIs Naples and Paolone. A postdoc research assiociate is requested to work half time on LBNE with Naples and half time on Minerva. Half of the effort of the Pitt group's current postdoc Danko will be redirected to work on LBNE studies. One advanced undergraduate student will work with Paolone during the summer on water target prototyping.

Requested Support

We are requesting support for :

1. One month of summer salary for Naples

2. 6 months of salary for postdoc to work on LBNE simulation studies and support for 6 months of existing postdoc (Danko).

3. Hourly salary or one undergraduate student to work on water target prototyping.

4. Travel support to attend LBNE meetings and work with collaborators for Naples, Paolone, and postdoc for a total of eight trips per year.

5. A laptop for LBNE postdoc.

6. Parts needed for water bag prototyping: Commercial polycarbonate sheets, water pumps, and water pipe/sealing hardware.

Princeton Contribution

Scope of work

The Princeton University High Energy Physics Group of Prof. K. McDonald is proposing to conduct simulation studies of a magnetized liquid argon TPC near detector, and of the solenoid horn neutrino beam option. The liquid Ar TPC studies will be an extension of Princeton U. involvement in the μBooNE experiment at Fermilab, while the solenoid horn beam concept is an outgrowth of our work on a closely related concept for future Neutrino Factories and/or Muon Colliders.

Future Efforts

As the LBNE project develops we plan to participate in the design of both near and far liquid argon TPCs, and in software development for these detectors (as an extension of Princeton involvement in the μBooNE Experiment.

Personnel and Resources

This effort will be conducted by Prof. K. McDonald, a graduate student and a postdoctoral physicist who will work on this study as well as on the μBooNE experiment.

This group will benefit from close contact with Prof. P. Meyers, formerly of the mini-BooNE experiment, and from Drs. Q. He and C. Lu who work with Prof. McDonald on the Daya Bay Reactor Neutrino Experiment.

Software studies will be conducter on the Princeton High Energy Physics linux cluster "Feynman".

Requested Support

We are seeking support for:

1. 50% support for one graduate student and for one postdoctoral physicist.

2. 1/6 of Prof. McDonald's summer salary.

3. Travel support to attend LBNE meetings and work with collaborators for Prof. McDonald, the graduate student and the postdoctoral physicist for a total of twelve trips per year.

4. A computing node (to be added to the "Feynman" cluster) for code maintenance and data storage for these studies.

Rochester Contribution

Scope of work

The University of Rochester High Energy Physics Group proposes to contribute simulation studies and hardware R&D to the LBNE near detector design effort. The near detector group is currently considering construction of a fine-grained solid scintillator near detector based on technology similar to that used in the MINERνA detector. MINERνA, which is currently being installed in the MINOS near-detector hall at Fermilab, is a new detector optimized for the study neutrino interaction physics. The detector consists of a substantial tracking volume filled with fine-grained scintillator extrusions surrounded by electro-magnetic and hardonic calorimetry. It boasts fine resolution, excellent tracking capabilities, and full event reconstruction. MINERνA will address near-detector type physics and operate in a high-intensity wideband-neutrino beam (the NUMI beamline), similar to what has been proposed for LBNE. The University of Rochester has taken a leading role in the development of the MINERνA detector and is uniquely positioned to lead investigations of this technology for use in LBNE. In the near term, we propose to conduct simulation studies evaluating the appropriateness of a MINERνA-like detector as a potential near detector candidate for LBNE. The purpose of the simulation studies are two fold:

- Specify the requirements for a near detector complex which does not limit the sensitivity of the overall LBNE oscillation program. This includes detector hardware requirements, as well as explorations of various target materials and configurations. Simulation and budget constraints will be key pieces of information used to formulate the final detector design.

- Help determine the scope of the near detector physics program. In addition to measurements required to support the oscillation program, the studies will also explore what neutrino interaction physics are possible to address with a MINERνA-like detector, running in the LBNE beamline.

We will also take a leading role in the associated hardware R&D effort. R&D funds are expected to become available in the second half of FY2011. The University has already proposed several R&D initiatives investigating both scintillator technologies and photosensors that will build upon and further the technology of fine-grained solid scintillator near detectors. This effort will be conducted by Dr. Robert Bradford, Prof. Kevin McFarland, and a graduate student who will split time between these efforts and MINERνA data analysis.

Simulation Study

Because the near detectors must work in concert with the beamline and far detectors to observe an oscillation result, the effort will involve close coordination with the LBNE Beamline and Far Detector working groups. We will use appropriate input from the Beamline group (beam flux files, for example) to simulate the performance of a MINERνA-like detector, which will then be combined with simulations from the Far Detector working group to explore the experimental sensitivity under a given overall detector scenario. Contacts and procedures must be established for communication of results between the various working groups. We will also coordinate our effort with other near-detector simulation efforts (at University of South Carolina) to identify benchmark reactions and valid means for comparison of simulation results. The heart of our effort will involve the use of the MINERνA detector simulation package. MINERνA has developed a Geant 4 simulation that works with a larger Gaudi-based software framework. The software and a realistic geometrical description are working and available. The University of Rochester is a member institution of the MINERνA collaboration and has access to this code. We have already secured and compiled a version of the code for the purposes of developing the study. We will implement the LBNE beam flux information and alter the detector configuration as required for exploration of various detector options (addition of a magnetic field, for example). We plan to work with the GENIE event generator.

Relevant physics simulations will include:

- Reconstruction of charged-current quasi-elastics at few-GeV neutrino energies. Quasi elastic scattering is the proposed oscillation signal for the LBNE program., and will be the hallmark signal for measurement of the neutrino flux in the near detector.

- Simulation of appropriate background reactions. This will address topics such as various neutral current background reactions and electron/photon discrimination. Given the timeline set out by DOE for the LBNE approval process, it is planned that this study will last 2-3 years. The initial goal is to help the collaboration conduct simulations required for the CD1 and CD2 approval stages. If a MINERνA-like detector is chosen for the LBNE near-detector suite, we will continue to develop an official LBNE near detector simulation by porting an appropriately configured version of the MINERνA simulation to the LBNE software framework.

Hardware R&D

The University has proposed several hardware initiatives that have been included in the LBNE Near Detector Group's FY2011 hardware R&D request. The proposed initiatives include:

- Investigation of scintillator with embedded wavelength shifting fiber: For MINERνA optical epoxy was used to glue a wavelength shifting fiber into a hole running the length of the scintillator extrusions. The process of gluing the fiber was expensive, and often produced channels that were optically non-uniform if the epoxy failed to completely wet the fiber. A proposed alternative technique is to embed a WLS fiber in the scintillator at the time of extrusion (running the fiber through the extruder). This technique should produce a more uniform scintillator at a substantial cost savings. We would investigate the optical properties (overall light yield, attenuation lengths) of scintillator samples produced at the Fermilab extrusion facility and evaluate its appropriateness for use in LBNE near detectors.
- Small cosmic ray prototype: We propose to construct and operate a small prototype scintillator array. We would produce several small planes of scintillator (with embedded wavelength shifter). The scintillator would be instrumented with SIPM photosensors using prototype electronics from Fermilab. The setup would allow us to address some of the early integration issues, study options for mounting SIPMs, verify the performance of the entire system, and take some cosmic ray data.

Future efforts

After CD-1 is granted, we plan to participate in the development of hardware for the near detectors or post-target hadron flux detectors.

Personnel and Resources

The University of Rochester has extensive experience in ν interaction and near detector physics, including leading roles within the MINERνA experiment and the T2K 280 m near detector, and is well position to complete this study and make key contributions to the LBNE near detector program. In addition to physicists, we maintain support an inhouse mechanical engineer (with particle detector design experience), machine shops, and a team of experienced technicians.

This effort will be lead by Professor Kevin McFarland and Dr. Robert Bradford (post-doctoral researcher), and will require the effort of graduate students within our group.

Requested Support

We are seeking support for:

1. Stipend support for one full-time graduate student to work on the study. In practice, this is likely to be more than one student over the period of the study as students complete a simulation project and move to analysis of MINERvA data

2. Travel support to attend LBNE meetings and work with collaborators for Prof. McFarland, Dr. Bradford and the graduate student for a total of twelve trips per year

3. A computing node to code maintenance and data storage for these simulations. Computing support for the study beyond this build/storage node, which will reside at Rochester, will come from the Fermilab Intensity Frontier cluster and the University of Rochester BlueHive cluster.

South Carolina Contribution

Synopsis of the proposal

We propose to conduct simulation studies aimed at the design of the near detector complex for the Long-Baseline Neutrino oscillation Experiment(s) (LBNE) at the Deep Underground Science and Engineering Lab (DUSEL). In particular we propose to study the HiResMν [**?** **?**] concept, which embeds a high-resolution tracking detector in a magnetic field and augments it with downstream muon identification and downstream and transverse calorimetry. The concept has evolved from the NOMAD detector. The integrated neutrino flux produced at the Fermilab main injector for LBNE will be perhaps 100 times higher than in predecessor experiments. At the far detector (FD), twice as far from the neutrino source as the MINOS and NOvA detectors, we expect to accumulate roughly 10^6 ν_μ charged current events. The fine granularity, high resolution, and hermeticity of the HiResMν will bring to the immense samples of neutrino events a commensurate suppression of systematic error. In the LBNE era optimization of the measurement of the elements of the neutrino mixing matrix depends on this careful attention to systematic error. Indeed since LBNE may be the first experiment to detect some processes, discovery will depend on an empirical control of systematic errors.

Broadly speaking, the HiResMν has two goals:

Constraining the systematic uncertainties in the LBNE oscillation measurements and searches: First we want to quantify the precision of ND measurements that will benefit neutrino oscillation studies (νOSCL) in LBNE. Regardless of the process under study the systematic error should be less than the corresponding statistical error. Once we understand the precision needed in the ND, the focus will turn to the detector parameters that will ensure this precision. To this end we will pay particular attention to simulations of **(a)** the *in situ* determination of the relative flux, as a function of E_ν, of all four neutrino species, ν_μ, $\overline{\nu}_\mu$, ν_e and $\overline{\nu}_e$; **(b)** π^0, photon, and electron measurement in ν-induced charge-current (CC) and neutral-current (NC) interactions; **(c)** $\pi^\pm$ detection in CC and NC interactions; **(d)** differential cross-section measurements for various exclusive, semi-exclusive, and inclusive channels relevant for the νOSCL studies; and **(e)** investigation of nuclear-target material which might effect the ν-nucleus interactions.

Precision standard model neutrino physics: We will determine the consistency of detector parameters optimized for LBNE with a generational advance in the precision of standard model measurements. As a case study, we propose to investigate the feasibility of two measurements of the weak-mixing angle, $\sin^2\theta_W$: first, in the $\nu(\overline{\nu})$-q (DIS) channel at a momentum transfer in the neighborhood of 4 GeV with a precision approaching 0.2%, and second, in the $\nu(\overline{\nu})$-e^- channel at a momentum transfer in the neighborhood of 0.06 GeV. The sought precision on $\sin^2\theta_W$ in this experiment is comparable to that attained by the collider experiments.

Carolina faculty members Sanjib R. Mishra, Roberto Petti, and Carl Rosenfeld will lead these studies with the assistance of a post-doc and a graduate student.

The Proposed Simulation Studies

The detection of events in the FD incurs its own statistical and systematic errors. In the first part of our study we aim to quantitate these errors and to determine their implications for the design goals for the ND. In this task we will be considering the following νOSCL measurements: **(1):** ν_e ($\overline{\nu}_e$) appearance; **(2):** the CP-violating parameter δ and the mass hierarchy; **(3):** ν_μ ($\overline{\nu}_\mu$) disappearance; and **(4):** NC/CC(E_{Had}) in FD versus ND. This task depends on the beam and the FD simulations, and we intend to coordinate closely with the corresponding working groups. Indeed we plan to invest a portion of our effort in development of the LBNE beam simulation.

The second part of our study is the core of this proposal. In this part we will determine the parameters of ND designs required to achieve the systematic errors determined in the preceding part. The HiResMν concept calls for a large volume of straw tube tracker embedded in a dipole magnetic field of $\boldsymbol{B \approx 0.4}$ T. Most features of this tracker design derive from the extant ATLAS-TRT and COMPASS sub-detectors. A key feature of the tracker is its low density, $\boldsymbol{\rho \approx 0.1}$ gm/cm$^{\mathbf{3}}$, i.e. roughly the density of liquid hydrogen. In regard to the muon identification and the calorimetry the concept is at this point less detailed. The benchmark objectives that we will use to characterize the errors attendant on a specific ND design are as follows.

•**[1]:** Determination of the relative abundance and the energy spectrum of the four species of neutrinos in the NuMI beam, $\boldsymbol{\nu_\mu}$, $\boldsymbol{\overline{\nu}_\mu}$, $\boldsymbol{\nu_e}$ and $\boldsymbol{\overline{\nu}_e}$. The CC interactions in the ND will yield an $\boldsymbol{in\ situ}$ empirical parametrization of $d^2\sigma/dx_F dP_T^2$ of the parent meson species, $\pi^\pm$, $K^\pm$ and K_L^0. From the empirical parametrization follows an absolute prediction of the energy-dependent rates of all ν species at the FD absent any modification by oscillation physics.

•[2]: Determination of the myriad features of the hadronic components of CC and NC events, e.g. the multiplicities of secondary $\pi^\pm$, $K^\pm$, π^0 and p.

•[3]: Characterization of e^-, e^+, γ, and proton production in exclusive and semi-exclusive processes.

•[4]: Classification as NC or CC for events with no muon ID and measurement of NC/CC as a function of hadronic energy, $0.2 \leq E_{Had} \leq 50 GeV$.

•[5]: Reconstruction efficiency for ν_μ quasi-elastic scattering in single-track and two-track topologies. This objective probes proton ID and momentum resolution.

•[6]: Calibration of the energy scale of CC interactions — a major consideration for the error in Δm^2.

•[7]: Determination of the species of target nucleus with which a neutrino has interacted.

To the above objectives related to νOSCL we will add two more that will illuminate the relative merits of alternative ND designs for a next-generation standard model neutrino physics.

•[1]: Measurement of $\sin^2\theta_w$ in $\nu(\overline{\nu})$-q (DIS).

•[2]: Measurement of $\sin^2\theta_w$ in $\nu(\overline{\nu})$-e^-.

In addition to the insights related to the ND design these studies have the potential to produce important insights for LBNE beam design.

Methodology

Thus far we have studied some of the above objectives using a fast simulation based on parametrizations of physics and of the ND detector response. In the studies that we propose we will implement a GENIE-based simulation of the physics and a full GEANT-based simulation of the ND. At the upstream end of the simulations we will use the LBNE ν-flux files adopted by the ND working group. We plan to validate our simulations by comparing various outputs with data from the NOMAD experiment to which we have immediate access.

It will not be our ambition to optimize the ND design irrespective of cost. Neither will it be our ambition to pursue any design for the sake of reducing cost. Rather our ambition will be to converge to a design that is uncompromising in its support of LBNE physics and nonetheless commensurate with the overall cost of this project.

Future Effort

The studies described above will be ongoing for about three years. The petition for CD-1 approval in 12 to 18 months will constitute an intermediate milestone. We project that the ND working group will recommend in the CD-1 petition that a detector conforming to the HiResM$\boldsymbol{\nu}$ concept becomes the anchor of a constellation of instruments in the target hall and the near detector hall. Simulation work subsequent to CD-1 approval will help to inform the petition for CD-2. Post CD-1 approval we plan to launch a hardware R&D project to test the STT design. We will seek support for this effort in an independent proposal to build 3-modules of STT and expose them in a test beam at FNAL or CERN.

Requested Support

Professors Mishra, Petti, and Rosenfeld will be the leaders of this project. Collectively they have a long history of participation in of $\boldsymbol{\nu}$-physics projects including CCFR, NOMAD, DONUT, MINOS, and NO$\boldsymbol{\nu}$A. At present commitments to the ongoing MINOS experiment and fabrication of the NO$\boldsymbol{\nu}$A apparatus between them saturate the effort of our post-docs and students. For the proposed LBNE simulation studies we need at a minimum an additional FTE of post-doctoral effort and one FTE of graduate student effort starting in 2010. In practice two post-docs will each spend 50% of their time on the LBNE-simulation and the other 50% on the NO$\boldsymbol{\nu}$A and MINOS experiments. We anticipate that the student will spend her first year or two on the simulation task and then migrate to a NuMI experiment to complete her thesis. To itemize the support we seek:

- Support for one FTE post-doc and one full-time graduate student.
- Travel support for five physicists to attend LBNE collaboration meetings and to travel to collaborating institutions for a total of twenty trips

- Two computing nodes and associated disk storage for these simulations. We will augment our computing with the existing facilities at Carolina.

Tufts University LBNE Proposal

(Profs. Gallagher, Mann, and Schneps)

Physics Sensitivity Studies: The Tufts group has been investigating the capabilities of a long baseline neutrino experiment to DUSEL using a liquid argon (LArTPC) detector in the 20-100 kiloton range for several years now. The goal is to explore the sensitivity to the neutrino mass hierarchy and δ, the CP violating parameter, as a function of the value of θ_{13} below presently established limits. Studies conducted by Prof. Schneps have taken into account ν_e identification efficiency, backgrounds from beam ν_e and from CC and NC interactions, as well as overall systematic errors. We plan to also examine sensitivities to possible non-standard phenomena , e.g., CPT violation, Lorentz violation. The student supported by this proposal would work with Prof. Schneps over the coming years to continue these sensitivity studies, in particular for new physics scenarios, and specific detector configurations and capabilities are being proposed.

Physics Simulations: The other focus of the work supported by this proposal will be on Monte Carlo development, in particular physics simulations. This work will encompass several aspects. The first will be to assist in supporting the overall simulations effort of the collaboration. Detailed, highly accurate simulations will be crucial to the success of the LBNE effort as the physics reach of competing designs are evaluated and specific design decisions are made. This poses a particular challenge for this project, since our understanding of few-GeV neutrino interactions is still evolving, with the recent results from the K2K, miniBoone, sciBoone, MINOS, and NOMAD experiments shedding new light but introducing many new questions, in particular regarding the important role of nuclear physics at these energies [**?**]. It is likely that during the next few years, with the renewed attention of the theoretical community, and a new generation of large / finely segmented detectors like the Minerva detector at Fermilab and the T2K Near Detectors, that a significant amount of new information will be gained. Members of the GENIE collaboration are involved in several of these experiments, with a strong motivation towards continually improving the set of models in GENIE to reflect new experimental and theoretical insights. Historically, these efforts have always been understaffed, and priority in model development has gone to ongoing experiments and their stated priorities. The manpower provided by this proposal would help to ensure that simulations improvements most likely to benefit the LBNE effort will also receive adequate attention. This will be crucial for the experiment since its extended sensitivity exposes it to background processes that are negligble for other experiments, and hence have yet to be carefully included in event generators. Some examples include $\Delta S = 1$ production, which can produce important backgrounds from atmsopheric antineutrino scattering to supersymmetric proton decay modes with kaon production. Theoretical work in recent years has pointed out processes that can simulate ν_e appearance, but not all of these calculations have been carried out in a way suitable for inclusion in event generators. More work, particular in collaboration with theorists, will be required to incorporate these rare channels and define the necessary parameters and switches to control the model behavior. Some examples of such processes include internal muon bremmstrahlung [**?**], axial-anomaly mediated photon production [**?**], and diffractive vector and axial vector production.

The student supported by this proposal would also devote effort to the development and maintainance of the overall simulations framework, including the interface between the detector simulation, output of the beam simulation and the event generator. This person would also be responsible for ensuring that related analysis tools, such as those required to do event-by-event reweighting of existing Monte Carlo samples to simulate physics model or parameter changes, are available within the groups software framework. Since the LBNE collaboration's software and simulations tools, as well as the GENIE software, are likely to evolve rapidly over the next several years, dedicated attention to these crucial interfaces between software packages will be needed. This person will also assist in the preparation and validation of new Monte Carlo samples for use by the collaboration.

Previous Contributions: In 2005 the Tufts group carried out a scan study of realistic Monte Carlo simulations of neutrino-event samples prepared by Adam Para of FNAL. This work showed that final-state electron identification in ν_e charged-current interactions (of E_ν range appropriate for $\nu_\mu \rightarrow \nu_e$ at a NuMI off-axis site) can be maintained at an efficiency of $\geq$ 80%. Background rates from neutral-current events which produce π^0's can be reduced to below the rate ($\sim$ 1%) arising from intrinsic ν_e contamination in the ν_μ beam.

The question of optimal location for deployment of a five kiloton prototype detector was studied by Prof. Schneps in September 2007. Such a device, though the primary purpose would be R&D for a more massive detector, would have physics capabilities comparable to or exceeding that of NOνA in a similar time frame. He compared Ash River off-axis siting to Soudan on-axis siting in the medium energy NuMI beam. His study favored the Soudan site and this point of view was adopted in the P982 LAr5 proposal. This choice also provides the opportunity for dealing with underground construction questions, important for deployment of a future massive detector at DUSEL.

Prof. Gallagher led the development of the `neugen3` [?] neutrino event generator, which has been used by numerous experiments over the past decade, in particular the Soudan 2, MINOS, and NoVA experiments. He is part of the GENIE collaboration [?], the C++ replacement for `neugen3` , which simulates neutrino simulations over the 100 MeV - 1 TeV energy range. Over the past five years the GENIE package has been adopted for use, either as the primary or secondary event generator, by the MINOS, Minerva, T2K, and NoVA experiments.

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