The Future of the Short-Baseline Neutrino Oscillation Experiments in the US: MiniBooNE and ORLaND

Ion Stancu [a]

[a]Department of Physics, University of California, Riverside, CA 92521, USA
E-mail: ion.stancu@ucr.edu

Following the potential oscillation signals from LSND, several short-baseline neutrino oscillation experiments are currently in different development stages in the US. They are targeted at unambiguously confirming or dismissing these observations. The MiniBooNE experiment at FermiLab will focus on the $\nu_\mu \to \nu_e$ appearance channel using a decay-in-flight ν_μ beam. The ORLaND experiment at the Oak Ridge National Laboratory will focus on the $\bar{\nu}_\mu \to \bar{\nu}_e$ decay-at-rest channel, while being able to perform a wide variety of neutrino physics in parallel to the oscillation searches.

1. INTRODUCTION

Currently, the Liquid Scintillator Neutrino Detector (LSND) at the Los Alamos National Laboratory is the only accelerator-based experiment to have evidence for neutrino oscillations [1]. In light of the rather strong evidence for neutrino oscillations coming from both atmospheric and solar neutrino experiments – as reported by Superkamiokande and other experiments (see e.g. Ref. [2]) – the LSND observation appears to be quite controversial. It suggests a third mass squared difference, $\Delta m^2 = \mathcal{O}(1)$ eV^2, quite different from the much smaller mass squared differences implied by the atmospheric ($\Delta m^2 = \mathcal{O}(10^{-3})$ eV^2) and by the solar ($\Delta m^2 = \mathcal{O}(10^{-5})$ or $\mathcal{O}(10^{-10})$ eV^2) neutrino experiments. Moreover, the disappearance of both the atmospheric ν_μ and the solar ν_e has been consistently observed in a series of independent experiments, whereas the LSND result has not been confirmed by another measurement. Therefore, it is necessary to perform a series of independent appearance experiments, in both the $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ channels, in order to unambiguously confirm or dismiss the LSND observation. In parallel to the efforts to perform such an experiment at CERN [3], two US proposals for short baseline neutrino oscillation experiments are now well underway to perform this task. These efforts are reviewed in the following.

2. THE MINIBOONE EXPERIMENT AT FERMILAB

The Booster Neutrino Experiment (BooNE) at FermiLab consists of a two-detector setup, using a new neutrino beam-line coming off of the FNAL 8 GeV proton booster. The booster is expected to provide 2×10^7 s of running per year, while delivering 5×10^{12} protons per 1 μs pulse at a rate of 5 Hz to the BooNE detectors, in parallel to supplying protons for the TeVatron and NuMI programs. The secondary pions beam will emerge from a two-horn focusing system into a 50 m decay region. The pion decay length will be either 25 m or 50 m, depending on the position of a movable steel beam stop. This variation in the decay length will provide an important check on the systematics errors for neutrino oscillations.

The first phase of BooNE – MiniBooNE – consists of a single detector positioned at 500 m downstream from the decay region. The detector itself is a spherical tank of 6 m radius, filled with 807 tons of pure mineral oil. An internal structure at 5.75 m will support the photo-multiplier tubes (PMTs) and form an optical barrier that separates the tank into a main volume and an outer (active) veto shield. Čerenkov and scintillation light from neutrino interactions in the main volume are detected by 1220 8-inch PMTs, providing 10% photocatode coverage of the 445 tons fiducial volume. The veto shield is viewed by 290

PMTs mounted on the outer region of the optical barrier.

Typical ν_μ energies will be from 0.5 to 1.0 GeV, as illustrated in Fig. 1. In one year of running,

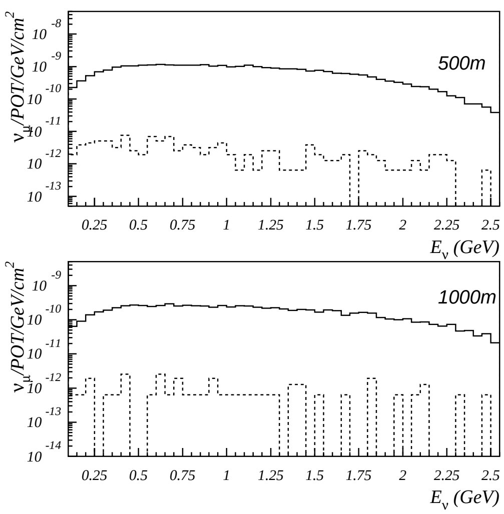

Figure 1. Calculated ν_μ fluxes at the center of the two BooNE detectors along with the intrinsic ν_e beam contamination (dashed histograms).

the experiment will collect approximately 500000 reconstructed $\nu_\mu C \rightarrow \mu^- X$ events. The intrinsic ν_e contamination in the beam will be approximately 0.3%, or approximately 1500 reconstructed $\nu_e C \rightarrow e^- X$ background events.

The detector will reconstruct quasi-elastic $\nu_e C \rightarrow e^- X$ interactions by identifying the electrons via their characteristic Čerenkov and scintillation light signatures. The primary background sources will be due to the intrinsic ν_e contamination of the beam – due to decays of pions and kaons – as well as from the misidentification of muons and neutral pions in the tank. Monte Carlo simulations constrained by production data will be used to limit the systematic uncertainty in the ν_e background to better than 10%. In addition, it will be possible to measure the pion energy spectrum using the observed ν_μ events, virtually all of which will come from pion decay. The technique exploits the classic energy-angle correlation in neutrino beams, which will be enhanced here by the relatively low beam energy and the small solid angle subtended by the detector. By measuring the pion spectrum, MiniBooNE expects to reduce the uncertainty in the pion component of the ν_e background to less than 5%.

Approximately 92% of the muons contained in the detector will decay, and thus they will be relatively easily identified by the presence of the second track (correlated in space and time). However, the remaining 8% of the muons that get captured have a greater chance to be misidentified as electrons. This misidentification will be estimated by studying the large sample of muons that do decay and determining the particle identification algorithm performance while ignoring the second track. Using this technique, which does not necessarily rely on the Monte Carlo simulation, the muon misidentification uncertainty is expected to be below 5%.

Most neutral pions will be identified by their two electro-magnetic decay tracks. The small fraction (1%) of asymmetric π^0 decays will not yield two resolvable tracks, and will therefore be more likely to be misidentified. The misidentification contribution of these decays will be studied with Monte Carlo simulations, which will be constrained by the large sample of measured π^0's in the experiment. The pion misidentification uncertainty is expected to be approximately 5%.

If neutrino oscillations occur indeed as indicated by LSND, MiniBooNE will be able to observe an excess of approximately 1000 events in one year of running. Fig. 2 shows the number of excess events and their significance for two points in the LSND favoured region. The significance is calculated using the systematic uncertainties for the various background sources discussed above.

MiniBooNE will gain additional sensitivity by measuring the energy dependence of the ν_e events. The oscillation signal has a different energy distribution than the background events. Therefore, an underestimate of the background should not necessarily lead to a fictitious oscillation signal. Fig. 3 shows the sensitivity of the

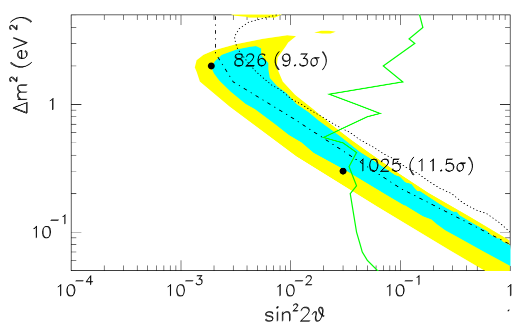

Figure 2. The expected number of excess events in MiniBooNE and their significance for two points in the LSND decay-at-rest allowed region, after one year of data collection.

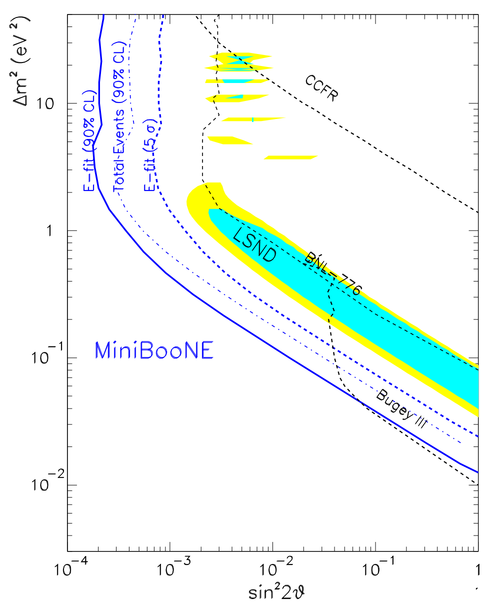

Figure 3. MiniBooNE 90% confidence level limits using energy-dependent fit (solid), and total event counting (dot-dashed). Also shown is the 5σ sensitivity contour of the energy-dependent fit (dashed).

experiment for the energy-dependent fit, as well as the limit based on using the total number of observed events above background.

The MiniBooNE detector and the new 8 GeV neutrino beam line are being designed at FermiLab, and the experiment is scheduled to start data taking early 2002. Should there be an unambiguous oscillation signal, the second phase of the experiment would proceed placing a second identical detector at about 1000 m from the decay region. The full BooNE setup will then be able to make high precision measurements of the neutrino oscillation parameters that govern the $\nu_\mu \to \nu_e$ transitions.

3. THE ORLAND EXPERIMENT AT OAK RIDGE

The Oak Ridge Large Neutrino Detector (ORLaND) facility at the Oak Ridge National Laboratory (ORNL) is designed to take advantage of the tremendous neutrino fluxes that will be available at the upcoming Spallation Neutron Source (SNS). The existing spallation neutron sources, namely LANSCE at the Los Alamos National Laboratory, and ISIS at the Rutherford-Appleton Laboratory in the UK, have been successfully used as intermediate energy neutrino sources. The ISIS facility is powered by 200 μA of 0.8 GeV protons on a lead target. The accelerator is a rapid cycling synchrotron with a pulsed beam. The LANSCE facility is driven by an 800 μA 0.8 GeV proton linear accelerator, but with a long beam spill. The lack of a good pulse structure like that of ISIS prevents one from discriminating against the majority of the cosmic-ray background.

The SNS at ORNL will combine the advantages of a large beam current and short pulse duration. This provides an excellent opportunity to build an intermediate energy neutrino facility that would be superior to any other one for the foreseeable future. The SNS will consist of a 1 GeV proton linear accelerator feeding an accumulator ring. A proton beam of 2 mA will impinge on a water-cooled mercury target producing copious quantities of pions as well as neutrons. The neutrino flux from the decay of the emerging pions and their daughter muons is calculated to be 2×10^{16} s^{-1} in the full solid angle. This is 5 times the intensity of that at LANSCE, and more than 10 times that of ISIS.

Spallation neutron sources, optimized to produce neutrons by spallation of nucleons by high energy protons, are also prolific sources of π^+ and π^- mesons. These mesons decay as follows: $\pi^+ \to \mu^+\nu_\mu$ and $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$, and similarly for the negative chain. In heavy (high Z) targets however, most of the π^- and μ^- are rapidly absorbed by the nuclei of the target and shielding prior to decaying, and thus the neutrino population is vastly dominated by the positive decay chain species. It is exactly this feature that makes spallation sources ideal setups for $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance experiments. The sensitivity of such an oscillation search is limited by the intrinsic $\bar{\nu}_e$ contamination of the beam, coming primarily from the decays of the μ^- that are not captured, i.e., $\mu^- \to e^-\bar{\nu}_e\nu_\mu$. At SNS, the ratio of $\bar{\nu}_e/\bar{\nu}_\mu$ has been calculated to be 2.4×10^{-4}, which is a factor of three lower than the calculated ratio for LSND, namely 7.5×10^{-4}.

The ORLaND experiment will take full advantage of the much higher neutrino fluxes, excellent beam timing structure, and lower $\bar{\nu}_e$ beam contamination, to perform $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation searches with a sensitivity 100 times higher than that of LSND, and 10 times higher than those reached by MiniBooNE or I-216, as shown in Fig. 4. The proposed liquid scintillator/vCerenkov detector is a vertical cylindrical tank of 7 m radius and 14 m height. It is viewed by 6730 20-inch photo-multiplier tubes (PMTs), providing a 25% photo-cathode coverage of the 1540 metric tons fiducial volume. The active medium is mineral oil doped with 0.054 g/l of butyl-PBD. This scintillator concentration has been determined to be the optimal concentration which allows a very efficient 2.2 MeV gamma detection and reconstruction (from the neutron capture following the $\bar{\nu}_e p \to e^+ n$ oscillations signature), while still maintaining a very good direction reconstruction accuracy for electrons.

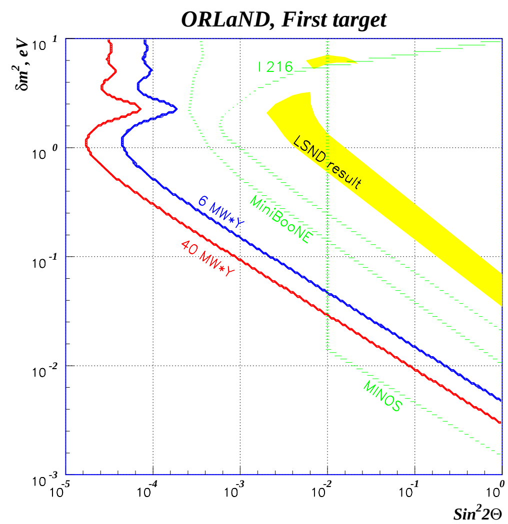

Figure 4. ORLaND sensitivity compared to those of the MiniBooNE and I-216 short-baseline experiments, and with the MINOS long-baseline experiment.

The detector is located at approximately 46 m from the target, in a bunker designed to provide shielding from cosmic rays and from beam neutrons. The bunker is an underground, reinforced concrete structure adjacent to the SNS target building. It is a cylindrical structure, with an internal diameter of 24 m and a height of 22 meters (from floor to ceiling), with 0.9 m thick walls and a base floor 2.5 m thick. It would have four mezzanine levels, each with bearing strength to accommodate several 200 ton detectors. The three upper levels would have large, circular openings to accommodate the large steel tank of the main 2000 ton scintillating Čerenkov detector. The inner wall of the tank will have an active/passive veto shield, composed of liquid scintillator and lead. The bunker will be covered by precast concrete beams 0.3 m wide and 2.1 m high, supporting two layers of steel blocks, approximately 1.3 m thick. The entire structure will be covered by a concrete cap, level with the ground. Details of the bunker with a schematic view of several detector inside are shown in Fig. 5.

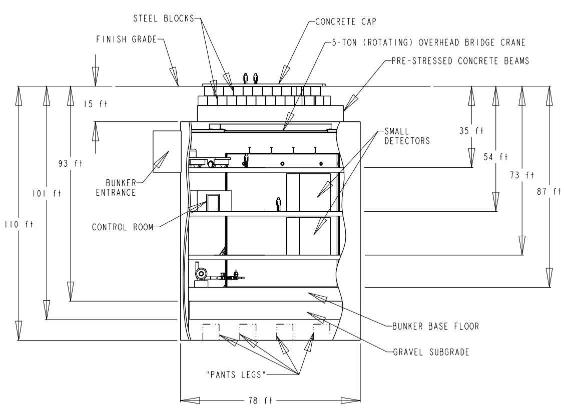

Figure 5. Detail view of the ORLaND detector bunker.

In addition to establishing the presence (or absence) of a significant excess of $\bar{\nu}_\mu \to \bar{\nu}_e$ events, ORLaND will be able to make precision measurements of the oscillation parameters – should the LSND signal prove to be present. This is illustrated in Fig. 6, as achieved with the main detector after three years of running. The accuracy of this measurement would be significantly increased with the construction of a second target station at the SNS, with a baseline of approximately 140 m from the planned ORLaND bunker.

In parallel to the $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation search, a search for the $\nu_\mu \to \nu_e$ appearance using the mono-energetic (30 MeV) ν_μ from the π^+ decay-at-rest can also be performed, by exploiting the very short time structure of the beam. Moreover, the experiment will be capable of easily observing the signal from the KARMEN time anomaly [4,5], attributed to a new and exotic decay branch

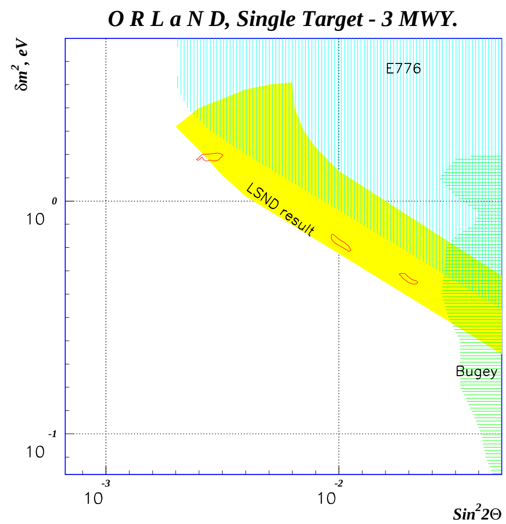

Figure 6. ORLaND accuracy of the oscillation parameters measurement for three different points in the LSND favoured region for a 2 kton detector and three years of operation.

$\pi^+ \to \mu^+ X$. It will also perform high accuracy measurements of neutrino-electron elastic scattering and $\nu_e C$ reactions, such as $\nu_e C \to e^- \, ^{12}N^*$, $\nu_e C \to e^- \, ^{12}N_{gs}$, $\nu_e C \to C^* \gamma$ (15.11 MeV). The high statistics neutrino-electron elastic scattering measurement will allow the determination of the Weinberg angle, $\sin^2 \theta_W$, to approximately 1%.

Complementing the main Čerenkov detector, a series of smaller (several hundred tons), segmented detector will be used to measure a wide variety of neutrino-nuclear cross sections, of crucial importance in astrophysics, e.g. in supernovae collapse models, etc. The intensity and pulse structure at the SNS make the proposed ORLaND facility ideal for making measurements that directly support theoretical nuclear physics and astrophysics.

4. CONCLUSIONS

The approved MiniBooNE experiment at FermiLab and the proposed ORLaND experiment at

Oak Ridge will be able to unambiguously confirm or dismiss the LSND signal and also make precision measurements of the oscillation parameters, should a positive signal emerge. Therefore, if the atmospheric and solar neutrino deficits continue to support the mass squared differences of $\mathcal{O}(10^{-3})$ and $\mathcal{O}(10^{-5}/10^{-10})$ eV^2, respectively, a definite positive signal in the LSND region will not only prove the existence of neutrino oscillations, but it will also point towards rather exciting new Physics. Either way, these complementary experiments will certainly produce some very interesting results starting in 2003 and beyond.

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