LONG BASELINE NEUTRINO EXPERIMENT*

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The selection of Homestake Mine in Lead South Dakota by the United States' National Science Foundation (NSF) as the site for Deep Underground Science and Engineering Laboratory (DUSEL) has opened new research opportunities for neutrino physics community. The proposed Long Baseline Neutrino Experiment (LBNE) will explore the interactions and transformations of a high-intensity neutrino beam by sending it from Fermi National Accelerator Laboratory (FNAL) more than 1000 kilometers through the earth to DUSEL. DUSEL would be one of the world's deepest underground laboratory and shield the LBNE neutrino detectors from cosmic particles at a depth of 4300 meters-water-equivalent (m.w.e.). Two detector technologies are considered: a 300 to 500 kTon water Cherenkov detector deployed deep underground at a DUSEL site and a 50–100 kT Liquid Argon Time-Projection Chamber (TPC). The physics sensitivities of the proposed experiments are summarized. We find that conventional horn focused wide-band neutrino beam options from FNAL aimed at a massive detector with a baseline greater than 1000 km have the best sensitivity to CP violation and the neutrino mass hierarchy for values of the mixing angle θ_{13} down to $2°$.

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1. Introduction

Particle physics has been very successful in creating the Standard Model, a theoretical framework that describes many particle physics phenomena. However, major discoveries such as the evidence for dark matter and the observation of nonzero neutrino mass as well as the apparent unification of fundamental forces at a high energy scale have shown that the Standard Model is incomplete. Neutrinos and dark matter are believed to hold some of the key answers to physics beyond the Standard Model of particle physics.

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Neutrinos could provide the explanation to many crucial questions like: Why is the Universe as we know it made of matter, with no antimatter present? What is the origin of this matter–antimatter asymmetry, also known as CP violation? Are neutrinos connected to the matter–antimatter asymmetry, and if so, how? If neutrinos exhibit CP violation, is it related to the CP violation observed in quark interactions? Are neutrinos their own antiparticles? What role did neutrinos play in the evolution of the Universe?

So what do we know about neutrinos? There are three neutrino flavor eigenstates (ν_e, ν_μ, ν_τ) made up of a superposition of three mass eigenstates (ν_1, ν_2, ν_3). Mixing between the flavor states is responsible for the phenomenon of neutrino oscillations. As there are three neutrino generations, a complex phase ($\delta_{\rm CP}$) determines the amount of violation of the charge-parity (CP) symmetry. Our current knowledge of the parameters governing neutrino oscillations is summarized in [1]. The value of the mixing angle, θ_{13} is unknown, but is limited to be less than 10° at the 90% C.L. The sign of the mass difference Δm^2_{31} which determines the ordering of the mass eigenstates is also unknown and the value of $\delta_{\rm CP}$ is unknown. The current generation of neutrino oscillation experiments [2, 3] has limited sensitivity to the value of $\delta_{\rm CP}$ and the mass hierarchy. The goal of the next generation of neutrino oscillation experiments is to extend the sensitivity to θ_{13}, determine whether CP is violated in the neutrino sector, and unambiguously determine the mass hierarchy.

Previous studies have demonstrated that excellent sensitivity to CP violation and the mass hierarchy can be achieved (for values of $\theta_{13} > 1^\circ$) by searching for $\nu_\mu \to \nu_e$ appearance using very long baseline experiments with conventional neutrino beams and massive detectors [4, 5]. In these studies, the sensitivity to CP violation and the mass hierarchy as a function of baseline was determined using a MW broad-band neutrino beam with a peak energy of around 2 GeV and a massive water Cherenkov detector (300–500 kT). We find that the sensitivity to CP violation is roughly the same for baselines between 500 and 2000 km [4]. The main advantage of the longer baseline is lower sensitivity to systematic errors and higher sensitivity to the mass hierarchy. Sensitivity to the mass hierarchy improves by almost an order of magnitude when the baseline is increased from 500 km to 1500 km and is almost constant for baseline greater than 1500 km.

The selection of former Homestake gold mine in Lead South Dakota by the United States' National Science Foundation (NSF) as the site for Deep Underground Science and Engineering Laboratory (DUSEL) opens new research opportunities for particle physics community. The emphasis on neutrino experiments is consistent with the priorities identified by a US national panel (Particle Physics Project Prioritization Panel or P5 report) as some of the most important physics projects to be pursued in the 21st century: The

Deep Underground Science and Engineering Laboratory would offer a major new facility for US particle physics. Located in the Homestake mine in Lead, South Dakota, DUSEL would be an underground laboratory housing a wide spectrum of experiments. When the first parts of the laboratory begin operation around 2013, DUSEL would be a key element in the US particle physics program. A large detector for long-baseline neutrino physics would be a key part of the initial suite of experiments, as would detectors for dark matter and double beta decay experiments.

The baseline from FNAL to Homestake is 1297 km and is within the optimal range for sensitivity to both CP violation and the mass hierarchy. The proposed Long Baseline Neutrino Experiment (LBNE) will explore the interactions and transformations of the world's highest-intensity neutrino beam by sending it from Fermilab straight through the earth to one of the largest particle detectors ever built. DUSEL would be one of the world's deepest underground laboratory and shield the LBNE neutrino detectors from cosmic particles at a depth of 4300 m.w.e.

2. Long Baseline Neutrino Experiment — overview

The goal of the Long Baseline Neutrino Experiment is to measure with high precision the mixing angles that describe the propagation and interference of the neutrino oscillations. LBNE will use the Main Injector accelerator at Fermilab to produce a pure beam of muon neutrinos. As the neutrinos travel through the earth, they will oscillate meaning that a muon neutrino created at Fermilab will be a mixture of all three types of neutrinos by the time it arrives at a neutrino detector located at DUSEL. The recorded data will allowed for the most precise measurements of the mixing angles, possible CP-violating effects, and their comparison to CP violation observed in quarks and antiquarks. The large scale neutrino detectors will also be used to search for proton decay and to study the oscillation of neutrinos produced in Earth's atmosphere and in the Sun. In addition, the neutrinos from a supernova in our galaxy could be detected. Astronomers predict that a supernova occurs in our Milky Way about every 40 years. The neutrino detectors can be used to look for diffuse supernova neutrinos, left over from early supernovae that have occurred since the beginning of time. Collectively, those capabilities would make a 300-kiloton neutrino detector a world class research facility.

2.1. Neutrino beam

A new neutrino beamline pointed towards DUSEL will serve as a source of conventional horn-focused neutrino beams. The modest upgrades to the existing FNAL complex can increase the Main Injector beam power from the current 300 kW (NuMI) to 1.2 MW at 120 GeV [6]. The Main Injector upgrades to 700 kW are already planned as part of the NOνA project.

Project X at FNAL [7] is a more ambitious upgrade plan which proposes replacing the 8 GeV booster with a super-conducting linac. Project X could raise the Main Injector beam power to 2.3 MW in the energy range of 60–120 GeV.

A survey of the FNAL site has determined that a new neutrino beamline directed towards the Homestake-DUSEL site in South Dakota can be accommodated on site. A wide-band low-energy (WBLE) target and horn design [8] was selected for the design of a new FNAL-DUSEL neutrino beamline. A decay pipe is selected with a diameter of 4 m and a length of approximately 300 m which fits within the FNAL site. The spectra of neutrino events from the WBLE 120 GeV beam at 0.5° off-axis are shown in Fig. 1 with the oscillation probability at a 1300 km baseline overlaid. The WBLE spectrum is a wide-band spectrum peaked near the 1st oscillation maxima and with significant flux at the 2nd maxima.

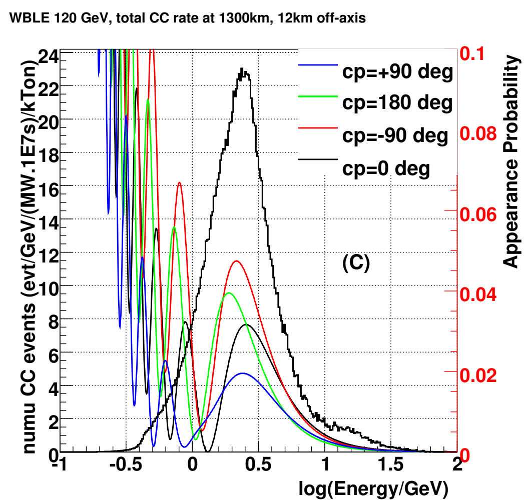

Fig. 1. The WBLE 120 GeV beam at 0.5° off-axis. Overlaid are the oscillation probabilities for different values of $\delta_{\rm CP}$ at 1300 km (WBLE) for normal mass hierarchy with $\sin^2 2\theta_{13} = 0.04$ and $\Delta m^2_{31} = 2.5 \times 10^{-3}$ eV^2.

Table I summarizes the ν_e appearance charged-current interaction rates expected using the FNAL neutrino beam designs described above. The rates are given for $\sin^2 2\theta_{13} = 0.02$, different values of $\delta_{\rm CP}$, and the mass hierarchy. The table shows the rates for $\nu_\mu \to \nu_e$ oscillations as well as the $\bar{\nu}_\mu \to \bar{\nu}_e$ rates produced by reversing the horn currents. The event rates are given in units of 100 kT$\times$MW$\times 10^7$ and do not include any detector effects such as efficiency, resolution, or detector backgrounds. The irreducible electron neutrino contamination in the beam is also shown.

TABLE I

Signal and background interaction rates for the indicated FNAL conventional neutrino beam configuration and baseline. Rates are given per 100 kT×MW×10^7s. The irreducible background rates from beam ν_e are shown integrated over the signal region 0–5 GeV. No detector model is used.

		$\nu_\mu \to \nu_e$ rate				$\bar{\nu}_\mu \to \bar{\nu}_e$ rates			
$(\mathrm{sgn}(\Delta m^2_{31}))$	$\sin^2 2\theta_{13}$	δ_{CP} deg.							
		0°	−90°	180°	+90°	0°	−90°	180°	+90°
WBLE 120 GeV beam at 1300 km, per 100 kT×MW×10^7s									
0.5° off-axis		Beam ν_e = 47				Beam $\bar{\nu}_e$ = 17			
(+)	0.02	87	134	95	48	20	7.2	15	27
(−)	0.02	39	72	51	19	38	19	33	52

2.2. Neutrino detector

The two detector technologies are proposed (1) a fully active finely grained liquid argon time-projection-chamber (LAr-TPC) with a mass of $\sim$ 50–100 kT, and (2) a massive deep underground water Cherenkov detector with a mass of 300–500 kT.

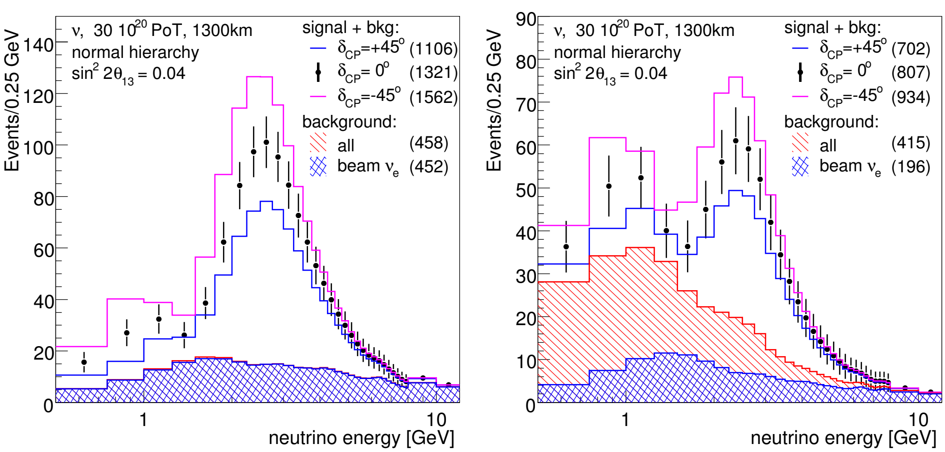

Fig. 2. The simulated ν_e appearance spectra from a WBLE 120 GeV beam 0.5° off-axis at 1300 km as seen in a 100 kT LAr TPC (left), and in a 300 kT water Cherenkov detector (right). The spectra shown are for normal mass hierarchy with $\sin^2 2\theta_{13} = 0.04$ and an exposure of 3.4 MW×yr. The numbers in brackets are the integrated event rates.

2.2.1. Liquid argon TPC

Preliminary simulation studies have indicated that a finely-segmented LAr-TPC could achieve a very high efficiency for selecting neutrino interactions with the excellent π^0 identification needed to reject neutral current backgrounds. The ν_e appearance smeared signal and background spectra obtained from a parameterized simulation of a 100 kT LAr-TPC as described in [9] is shown in Fig. 2. The points with error bars are the observed signal plus background events from the WBLE DUSEL beam at 1300 km (left plot) with $\delta_{\rm CP} = 0$, $\sin^2(2\theta_{13}) = 0.04$, and an exposure of 30×10^{20} protons. The solid histograms are signal and background with different values of $\delta_{\rm CP}$. The shaded histogram is the total background which for LAr-TPC is predominantly the irreducible background from ν_e originating in the beam. The construction of a massive 50 to 100 kT LAr-TPC is extremely challenging given that the largest LAr-TPC currently in existence has a mass of only 0.3 kT [10].

The liquid argon TPC detector will be located at or near the surface with minimal overburden. For a 100 kT LAr-TPC surface module, we estimate the rejection required is $\sim 10^8$ for cosmic muons and 10^3–10^4 for photons from cosmics. Achieving such rejection factors has not yet been demonstrated in simulations or practice. At DUSEL it would be possible to operate a LAr-TPC underground which would ameliorate the challenges posed by backgrounds from cosmics and would allow the detector to be used for proton decay experiments. Two of the primary cost drivers for a LAr-TPC are the cost of the liquid argon and the containment tank. A minimum cost for a 100 kT TPC on the surface was established to be $\sim \$\,200\,$M for the material and the containment tank. Determination of additional costs for items such as the wire planes, electronics, an argon purification system, safety infrastructure, and installation labor needs substantial design effort. Aggressive R&D is required to understand the cost and feasibility of such a detector. The LBNE project is not engaged in making a preliminary design and cost estimate for such a liquid argon detector facility.

2.2.2. Water Cherenkov detector

Conceptual designs for a 300 kT modular detector design at DUSEL-Homestake have been proposed. The modular detector design at DUSEL-Homestake involves 3–5 detector modules, each 100 kT in fiducial mass (53 m height and 53 m diameter) in separate caverns at the 4850 ft underground level [11]. Each module is thus a modest scale-up of the existing SuperKamioka detector [12] and cavern. Using the Super-Kamiokande full detector simulation and reconstruction, improvements to the π^0 reconstruction techniques were used to suppress the π^0 backgrounds in the WBLE beam [13, 14]. We find that for the WBLE beam the total signal efficiency in water Cherenkov is $\sim 14\%$ of all ν_e charged current and $\sim 0.4\%$ of all neutral current. The ν_e appearance spectrum and background in the simulated water Cherenkov detector from the WBLE 120 GeV beam is shown in Fig. 1, assuming a detector fiducial mass of 300 kT and the same beam exposure as the 100 kT LAr-TPC shown in the same figure. The LBNE project is engaged in creating a preliminary design for the cavern excavation, photomultiplier assemblies, and installation. This design will result in a detailed cost estimate and schedule by December 2010.

3. Summary

The survey of future long baseline neutrino oscillation experiments in the USA using conventional neutrino beams concluded that even with substantially increased beam intensities (1–2 MW of proton power), a very massive detector is needed for the next generation neutrino oscillation experiment. In the case of a water Cherenkov detector, the mass needs to be in the range of 300–500 kTon. In the case of the liquid argon TPC, the mass needs to be in the range of 50 to 100 kTon.

A summary of the sensitivity reach for non-zero θ_{13}, CP violation, and the sign of Δm^2_{31} for 3 different combinations of detector technologies and exposure for WBLE with 1300 km baseline is presented in Table II. The sensitivity reach is defined as the lowest $\sin^2 2\theta_{13}$ value at which at least 50% of δ_{CP} values will have $\geq 3\sigma$ reach for the mass hierarchy with the worst sensitivity.

TABLE II

Comparison of the sensitivity reach of different experiments for 1300 km baseline. The sensitivity is given as the minimal value of $\sin^2 2\theta_{13}$ at which 50% of δ_{cp} values will have $\geq 3\sigma$ reach for the choice of mass hierarchy with worst sensitivity. We assume equal amounts of ν and $\bar{\nu}$ running in the total exposure. For this table 1 yr corresponds to 1.7×10^7 seconds of running.

Beam	Detector	(MW.yr)	$\theta_{13} \neq 0$	CPV	$\mathrm{sgn}(\Delta m^2_{31})$
WBLE 120GeV, 0.5°	LAr 100 kT	6.8	0.0025	0.005	0.006
WBLE 120GeV, 0.5°	WCe 300 kT	6.8	0.006	0.03	0.011
WBLE 120GeV, 0.5°	WCe 300 kT	13.6	0.004	0.012	0.008

The best sensitivity to CP violation and the mass hierarchy is achieved using the wide-band FNAL to DUSEL approach with a 100 kT LAr-TPC (row (1) in Table II). When a 300 kT water Cherenkov detector is used in the wide-band FNAL-DUSEL beam, we find that the sensitivity worsens due to the lower signal statistics and higher neutral-current backgrounds. We can recover most of the lost sensitivity by doubling the exposure of the water Cherenkov detector as shown in Table II row (3).

Although the FNAL-DUSEL approach has the best physics sensitivities (for either a LAr-TPC or a water Cherenkov detector), it requires a new neutrino beamline. Such a beamline can be accommodated on the FNAL site using part of the existing NuMI infrastructure. The modular water Cherenkov detector proposed is a modest scale up from the existing Super-Kamiokande detector and the technical feasibility is considered low-risk. A preliminary cost estimate and schedule for such a detector is in preparation as part of the LBNE project at FNAL. There are severe technical challenges for building a massive LAr-TPC. Currently, the feasibility and cost of building a 100 kTon LAr-TPC, particularly one that can operate on the surface, has not been demonstrated and requires aggressive research and development. This development has also started at FNAL and a preliminary design and cost estimates are expected soon.

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