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The Long Baseline Neutrino Oscillation Experiment at DUSEL

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Abstract. Rapid progress in neutrino physics in recent years has brought us closer to realization of a massive neutrino detector at the Deep Underground Science and Engineering Laboratory (DUSEL) in the Homestake mine in the town of Lead, South Dakota, USA. The detector is being designed with the following scientific goals in mind: value of CP-violation phase $\delta$ in lepton sector, neutrino mass hierarchy and value of the angle $\theta_{13}$. In addition, the Long Baseline Neutrino Experiment (LBNE) will be able to search for proton decay, get a detailed energy spectrum in the case of galactic supernovae, detect solar and atmospheric neutrinos, possibly geoneutrinos and even relic supernovae neutrinos that have never been successfully detected before. The physics goals dictate the minimal size of 300 kton fiducial volume, and the plan is to realize it with three 100 kton fiducial volume modules that will be placed at the depth of 1480 m. LBNE will be able to obtain 3$\sigma$ C.L. measurement of $\theta_{13}$ if the value of $\sin^2 2\theta_{13} \geq 0.005$ for any value of CP-$\delta$ phase; 3$\sigma$ C.L. measurement of the neutrino mass hierarchy if $\sin^2 2\theta_{13} \geq 0.012$ for any value of CP-$\delta$ phase and measure 50% of all CP-$\delta$ phases with 3$\sigma$ C.L. for $\sin^2 2\theta_{13} \geq 0.012$. This is all under the assumption that an upgraded neutrino beam is sent to LBNE from Fermilab, 1300 km away and experiment is run for 6 years. This paper describes physics reach, status and current undergoing research and development effort toward construction of the LBNE.

1. Introduction
Recent discoveries in neutrino physics, including oscillations and precision measurements of majority of neutrino mixing parameters, have paved the path for even greater open physics questions: the value of charge parity (CP) violation phase $\delta$ in leptons; the ordering of the three neutrino masses; and the value of the last non-measured neutrino mixing angle $\theta_{13}$. The plans are underway for the Long Baseline Neutrino Experiment (LBNE) that will have the potential to address these questions and maintain a broad physics program at the same time - search for the proton decay, galactic supernovae detailed neutrino spectrum measurement, relic supernovae neutrinos, solar and atmospheric neutrinos and possibly geoneutrinos. The LBNE will be located at the Deep Underground Science and Engineering Laboratory (DUSEL) in the Homestake mine in the town of Lead, South Dakota, USA. Strong neutrino beam will be sent from Fermi National Laboratory, 1300 km away, in order to search for CP-$\delta$ phase, $\theta_{13}$ and mass hierarchy.
Figure 1. Location of the LBNE in Lead, South Dakota, with respect to Fermi national Laboratory that will send a strong neutrino beam 1300 km away.

Figure 2. The layout of water Cherenkov modules.

Table 1. The sensitivity of the experiment with a water Cherenkov detector for different integrated luminosity and detector size. For $\sin^2 2\theta_{13}$ and the mass hierarchy, the sensitivity is given as the minimum value of $\sin^2 2\theta_{13}$ at which the experiment achieves a $3\sigma$ reach for all $\delta_{CP}$. For CP violation, the sensitivity is given as the minimum value of $\sin^2 2\theta_{13}$ at which the experiment achieves $3\sigma$ reach for 50% of $\delta_{CP}$. This assumes a 5% systematic uncertainty on the background.

| Detector Size (kTons) | POT($\times 10^{20}$)@120GeV | Years | $\sin^2 2\theta_{13} \neq 0$ | Mass Hierarchy | CP Violation |
|-----------------------|-------------------------------|-------|-----------------------------|----------------|-------------|
| 100                   | 30 + 30                       | 3 + 3 | 0.014                      | 0.031          | 0.1         |
| 300                   | 30 + 30                       | 3 + 3 | 0.008                      | 0.017          | 0.025       |
| 600                   | 30 + 30                       | 3 + 3 | 0.005                      | 0.012          | 0.012       |
| 300                   | 60 + 60                       | 3 + 3 | 0.005                      | 0.012          | 0.012       |

2. Physics Potential

Neutrino Physics Program Using a strong muon neutrino beam from Fermi National Laboratory (Fig. 1), appearance search for electron neutrinos will be conducted at the neutrino detector in Homestake mine, to search for the value of CP violation phase, ordering of neutrino masses and value of the the neutrino oscillation angle $\theta_{13}$. Evaluation of the physics prospects has been conducted for two possible wide band beam power levels 1 MW and 2 MW, and initial proton beam energy 60 to 120 GeV that produces neutrinos in 1-10 GeV range. Preliminary studies have been conducted for various detector sizes, assuming 3 years of running in the neutrino mode and additional 3 years of running in the anti-neutrino mode. The summary of results is shown in the Table 1. The conclusion is that reaching science goals requires beam power of at least 2 MW, 300 kton fiducial volume for a water Cherenkov detector (50 kton for the Liquid Argonne detector) and six years of neutrino, anti-neutrino combined running. Under these conditions LBNE will be able to obtain $3\sigma$ C.L. measurement of $\theta_{13}$ if the value of $\sin^2 2\theta_{13} \geq 0.005$ for any value of CP-\delta phase; $3\sigma$ C.L. measurement of the neutrino mass hierarchy if $\sin^2 2\theta_{13} \geq 0.012$ for any value of CP-\delta phase and measure 50% of all CP-\delta phases with $3\sigma$ C.L. for $\sin^2 2\theta_{13} \geq 0.012$. Thus, meeting these requirements will ensure strong neutrino physics potential of LBNE.

Nucleon Decay Proton decay is one of the most important predictions of Grand
Unification, but has not been observed yet. A number of theoretical models predict proton decay with a lifetime in the range of 10\(^{35-36}\) years. There are a lot of possible branches for the proton decay with the modes \(p \rightarrow e^+ + \pi^0\) and \(p \rightarrow K^+ + \nu\) being common benchmarks.

Based on the experience from SuperKamiokande detector, 20 years of running with 300 kton water Cherenkov detector will result in 10\(^{35}\) years lifetime limit at 90\% C.L. for \(p \rightarrow e^+ + \pi^0\) decay mode.

Mode \(p \rightarrow K^+ + \nu\), \(K^+\) is affected by atmospheric neutrino background concurrent to kaon decay at rest. As a result, for a 20 year long run, expected sensitivity is in the range 1 – 2 \(\times 10^{34}\) years long proton lifetime in this decay mode.

**Cosmological Supernovae** Neutrino remnants from all previous supernovae stream throughout the universe and can be detected on Earth with neutrino detectors. Learning more about this flux and spectrum of relic supernovae neutrinos will provide insight in the star formation mechanism and era when they were formed. Supernovae relic neutrinos are detected in water Cherenkov via inverse beta decay interaction on protons, resulting in positron and neutron capture on proton in the energy range between 10 MeV (above reactor neutrino energy) and below 100 MeV (atmospheric anti-neutrino background). Above 20 MeV, the dominant background is due to atmospheric neutrino interactions. Water Cherenkov detector has no means of tagging \(\gamma\) photons from the neutron capture due to its low energy of 2.2 MeV. However, if the the detector is loaded with Gd, then the \(\gamma\)'s emitted in neutron capture are at the level of 8 MeVs and can be tagged successfully. A 300 kton Gd loaded water Cherenkov detector should be able to unambiguously detect relic supernovae neutrino flux.

**Galactic Supernovae and Solar neutrinos** Galactic supernova will produce a strong signal in the LBNE neutrino detector and provide a detailed temporal and spectral profile of detected neutrinos. This information will lead to better understanding of core collapse, accretion, neutron star cooling and possible transition to quark matter or black hole, tests of exotic physics and measurement of neutrino oscillation parameters including mass hierarchy and \(\theta_{13}\). Such a large neutrino detector will collect the largest number of solar and atmospheric neutrinos in the energy range from 5 MeV to 1 TeV.

### 3. Experimental design

The LBNE consists of several integral components that are required to reach the physics goals and these are: neutrino detector at DUSEL inside the Homestake mine, neutrino beam that will be built at Fermi lab and near detector that will be built adjacent to the neutrino beam to measure detailed beam profile, normalize neutrino flux and monitor neutrino beam stability. Two complementary technologies are planned for neutrino detector in South Dakota. The first one is well understood and proven to work, water Cherenkov detector technology and the second one is Liquid Argonne detector technology that is promising, but requires a lot of research and development before a large scale detector (of the order of 50 kton) can be built.

Water Cherenkov detector (Fig. 2) will consist of three 100 kton fiducial volume modules and they are envisioned as right cylinders 54 m high and 53 m in diameter. Approximately 50,000 ten inch PMTs are needed per module to get more than 20% photocoverage.

### 4. Status and Prospects

Work is underway to prepare the cavern at 1479 m depth for the water Cherenkov and liquid Argonne detectors. There is a vigorous research and development effort in the USA to produce conceptual design for LBNE, followed by the full technical design. The plan is to start building the detector by 2013 fiscal year. LBNE has a strong discovery potential and will seek answers to a number of open questions in particle and astroparticle physics.