Prospects of Measuring Lepton CP-violation with LBNE at DUSEL

Jelena Maricic for LBNE Collaboration
Department of Physics, Drexel University, 3141 Chestnut St, Philadelphia, PA, USA
E-mail: jelena@physics.drexel.edu

Abstract. Excellent measurement of the neutrino oscillation parameters achieved in recent years has set the scene for probing the size of the leptonic CP-violation angle. The Long Baseline Neutrino Experiment (LBNE) will have an unprecedented sensitivity to CP-violation angle and a range of other physics questions. LBNE will be a massive neutrino detector located at the Deep Underground Science and Engineering Laboratory (DUSEL) in the Homestake mine in the town of Lead, South Dakota, USA. Two independent detector technologies have been utilized for detector design: water Cherenkov and liquid argon time projection chamber (LArTPC) type of detector and both technologies have similar sensitivity to the main physics questions to be answered. The experiment will measure the value of CP-violation phase $\delta$ in lepton sector, ordering of neutrino masses and value of the angle $\theta_{13}$. In addition, the 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 measure the relic supernovae neutrino flux. In order to address most of the aforementioned physics questions, the detector will be placed at large depth of 1480 m (WC). The scientific goals require a minimal size of $2 \times 100$ kton equivalent water Cherenkov fiducial volume or $2 \times 17$ kton LArTPC, or the combination of the both. The LBNE will obtain $3\sigma$ C.L. measurement of $\theta_{13}$ at the 0.001 level, for any value of CP-$\delta$ phase. In addition LBNE will resolve the neutrino mass hierarchy at $3\sigma$ C.L. measurement of the neutrino mass hierarchy if $\sin^2 2\theta_{13} \geq 0.01$ for any value of CP-$\delta$ phase and measure about 50% of all CP-$\delta$ phases with $3\sigma$ C.L. for $\sin^2 2\theta_{13} \geq 0.01$. The experiment will make these measurements using an electron neutrino appearance signal in the muon neutrino beam sent to LBNE from Fermilab, 1300 km away. The beam will be 700 kW and then 2 MW. The experiment will run in both neutrino and anti-neutrino mode. In addition to detectors at DUSEL, a near detector complex at Fermilab is foreseen for beam normalization measurement. The report on the physics reach, design status and current undergoing research and development toward construction of the LBNE.

1. Introduction
There are several important open questions in the neutrino physics today: the value of charge parity (CP) violation phase $\delta$ in lepton sector; the ordering of the three neutrino masses (normal mass hierarchy ($m_1 \leq m_2 \leq m_3$) or inverted mass hierarchy $m_3 \leq m_1 \leq m_2$); and the value of the last non-measured neutrino mixing angle $\theta_{13}$. The Long Baseline Neutrino Experiment (LBNE) 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 detectors will be located at the Deep Underground Science and Engineering Laboratory (DUSEL) in the Homestake mine in the town of Lead,
South Dakota, USA. Figure 1 shows the overview of the water Cherenkov detector. Strong neutrino beam will be sent from Fermi National Laboratory, 1300 km away (see Fig. 2). The experiment will measure the flux of electron (anti-)neutrino appearance signal in the muon (anti-)neutrino beam in order to search for CP-$\delta$ phase, $\theta_{13}$ and mass hierarchy.

**Figure 1.** Outline of a 100 kton water Cherenkov detector module. Up to three modules are planned to be installed at DUSEL.

**Figure 2.** Muon neutrino beam will be sent to LBNE from Fermi National Laboratory, 1300 km away.

### 2. Scientific potential

#### 2.1. Beam neutrino physics

Using a strong muon neutrino beam from Fermi National Laboratory, 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 a wide band beam with initial proton beam energy 60 to 120 GeV (with 700 kW and 2 MW power) that produces neutrinos in 1-10 GeV range. Wide band beam, at the 1300 km baseline allows observation of two oscillation maxima at 0.8 GeV and 2.4 GeV as shown in Fig. . The physics studies have been conducted by the LBNE physics working group [1] for 700 kW and 2 MW beam. Fig. 4 shows muon neutrino charged current signal in the case of normal and inverted hierarchy. Weaker signal in the case of inverted hierarchy drives the beam intensity requirements. The studies of the sensitivity to $\delta$-CP, mass hierarchy and $\theta_{13}$ have been performed for two different
Figure 3. LBNE will utilize a wide band beam from Fermilab. A long baseline allows observation of two distinct oscillation maxima in comparison to the shorter baselines (signal at a distance of NO\(\nu\)A experiment shown).

beam configuration in which the latter has a slightly narrower peak shifted to higher energy and both beam options give similar sensitivity. Results are shown in Fig. 6, Fig. 5 and Fig. 7.

Figure 4. Muon neutrino spectrum at LBNE baseline for different neutrino mixing parameter values. The left figure corresponds to normal hierarchy and \(\Delta m_{32} = 2.5 \times 10^{-3} \text{ eV}^2\), while the right figure corresponds to inverted hierarchy case and \(\Delta m_{32} = -2.5 \times 10^{-3} \text{ eV}^2\). The original muon neutrino spectrum sent from Fermilab is shown as black histogram.

2.2. Nucleon decay
Grand Unified theory predicts proton decay, but this process 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. The atmospheric neutrinos represent concurrent background to kaon decay at rest, important in the mode \(p \rightarrow K^+ + \nu\). 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.

2.3. Cosmological supernovae
Universe is permeated by the diffuse neutrino flux from all previous supernovae 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
Figure 5. $3\sigma$ (red) and $5\sigma$ (blue) sensitivity of LBNE to $\sin\theta_{13}$ as a function of $\delta$-CP for 200 kt of WC (left) and 34 kt of LAr (right). This assumes 5+5 years of and running in a 700 kW beam. Curves are shown for both normal (solid) and inverted (dashed) mass hierarchies.

Figure 6. Resolution of the mass hierarchy for 200 kt of WC (left) and 34 kt of LAr (right). This assumes 5+5 years of $\nu$ and $\bar{\nu}$ running in a 700 kW beam. To the right of the curves, the normal (solid) or inverted (dashed) mass hierarchy can be excluded at the $3\sigma$ (red) or $5\sigma$ (blue) level for the indicated values of true $\sin^2 2\theta_{13}$ and $\delta$-CP.

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 detector is loaded with Gd, then the $\gamma$'s emitted in neutron capture are at the level of 8 MeV and can be tagged successfully. A 200 kton Gd loaded water Cherenkov detector should be able to unambiguously detect relic supernovae neutrino flux.
Figure 7. 3σ (red) and 5σ (blue) sensitivity of LBNE to CP violation for 200 kt of WC (left) and 34 kt of LAr (right). This assumes 5+5 years of $\nu$ and $\bar{\nu}$ running in a 700 kW beam. Curves are shown for both normal (solid) and inverted (dashed) mass hierarchies.

2.4. 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 M eV to 1 T eV.

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 Fermilab 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. In addition, near detector will perform a whole plethora of short baseline neutrino studies and accurately measure neutrino interaction cross-sections for various channels. 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 (as used in SuperKamiokande and SNO experiments) 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 20 kton) can be built. Water Cherenkov detector (Fig. 1) will consist of two 100 kton fiducial volume modules and they are envisioned as right cylinders 54 m high and 53 m in diameter. Approximately 50,000 high quantum ten inch PMTs are needed per module to get 30% photocoverage and achieve high sensitivity to the wide LBNE physics program.

4. Status and Prospects
Cavern excavation studies and cost estimates have been performed to prepare a cavern at 1479 m depth for the water Cherenkov and liquid Argonne detectors. A vigorous research and
development effort in the USA is underway to produce conceptual design for LBNE by the end of 2010, followed by the full technical design. The plan is to start building the detector by 2013-2014 fiscal year. Construction time is foreseen to last 5 years for data taking to start in 2018-2019. LBNE has a strong discovery potential and will provide answers to a number of open questions in particle and astroparticle physics.

5. References
[1] A. Beck et al (LBNE Physics Working Group), presented at INT workshop, Seattle, USA, August 9-11, 2010