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Study of Neutrino Oscillations at DUNE & LBNO

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ABSTRACT:We investigate the neutrino oscillations at DUNE (Deep Underground Neutrino Experiment) in Fermilab of baseline 1300 Km and LBNO(Long Baseline Neutrino Oscillation) in Finland of baseline 2290 Km. These two long baseline neutrinooscillation experiments have the potential to address proton decay, supernova burst neutrinos, octant θ_{23} , neutrino mass hierarchy, and the existence of CP violation in the lepton sector. We attempt to study the last two by studying the oscillation and survival probabilities. The long baseline provides a unique opportunity to study neutrino flavour oscillations over their 1st and 2nd oscillation maxima exploring the L/E behaviour, and distinguishing effects arising from CPV phase and matter. We propose the required neutrino energy to get the neutrino oscillations from the simulated probability-energy curves. And found that the longer baseline is favourable to observe the unknown properties of neutrinos. In extension of this work matter effects can be considered.

KEYWORDS: Long baseline, Neutrino oscillations, three flavourmixing, mass hierarchy, CPV phase.

I. INTRODUCTION

Since the Pauli postulate in1930, neutrino has come a long way. Today neutrino physics has entered an excited phase of research with better precision and ever constantly improving the existing data. We know many properties of neutrinos now. However, the pressing unknown properties are: nature of neutrinos, absolute masses, precise value of θ_{23} , mass hierarchy and CP violating phase. Out of these unknown properties DUNE (Deep Underground Neutrino Experiment) [1] and LBNO (Long Baseline Neutrino Observatory) [2]are designed to unravel the last three unknown properties. Both these experiments deals with neutrino oscillations in the earth. Neutrino oscillate between three distinct flavours: muon, tau, and electron. Understanding details of these oscillation remains on the most intriguing puzzles in fundamental physics.

These long baseline (LBL) accelerator experiments are sensitive to both $v_{\mu} \rightarrow v_e$ (appearance) and to $v_{\mu} \rightarrow v_{\mu}$ (disappearance). In particular $v_{\mu} \rightarrow v_e$ channel canprobe CP violation in the leptonic sector [3]. LBL experiments like T2K [4] and NOvA [5] are also designed to search these two parameters. However, the major goals of future long-baseline experiments such as the proposedLBNO [6, 7], DUNE [8, 9] and HyperKamiokande [10] are the conclusive determination of themass hierarchy (MH) and the search for leptonic CP-violation (CPV) via the determination δ_{cp} .

DUNE and LBNO are the best candidates to unravel CP violating phase and mass hierarchy. DUNE will starttaking data from 2024. In the literature, recent studies related to CP violation discoverypotential of DUNE as well as other superbeam experiments can be found [11-13].

Paper is organized as follows. Section II gives an overview of the DUNE and LBNO experiments. Theory of neutrino three flavours oscillation and the subsequent plots and itsanalysis are given in Section III. Finally, Section IV presents conclusion.

II. DUNE AND LBNO EXPERIMENTS

DUNE EXPERIMENT OVERVIEW

The Deep Underground Neutrino Experiment (DUNE) is a future dual site accelerator experiment for neutrino science and proton decay studies. The experimental specifications are almost similar toLBNE [cf.3]. It is an international collaboration project from 26 countries which was officially formed in April 2015. It will start taking data from 2024 [14].For detailed timeline of DUNE may see [b]. The intense v_{μ} (\bar{v}_{μ}) neutrino beam from Fermilab will travel 1300 Km



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through the earth before striking its target the 35-40 kt Liquid Argon (LAr) far detector at the Stanford Underground Research Facility (Homestake Mine) located in Lead, South Dakota. In this journey, we study the quantum mechanical flavor transformations, called the neutrino oscillations. By precisely measuring differences between the oscillations of v_{μ} (\bar{v}_{μ}) into v_e (\bar{v}_e) respectively, i.e., $P(v_{\mu} \rightarrow v_e)$ and $P(\bar{v}_{\mu} \rightarrow \bar{v}_e)$, DUNE will determine the neutrino mass hierarchy and the explicit demonstration of leptonic CP violation, if it exists, and octant of θ_{23} . Besides these, it will also provide exciting additional research opportunities in nucleon decay, studies utilizing atmosphericneutrinos, and neutrino astrophysics, including measurements of neutrinos from a core-collapse supernova should such an event occur in our galaxy during the experiment's lifetime. The experiment plans to run for 10 years both in anti-neutrino (5 years) and neutrino (5 years) mode. A 1.2 MW - 120 GeV proton beam will deliver 10^{21} protons-on-target (POT) per year which corresponds to a total exposure of 35×10^{22} kt-POT-yr. Physics milestone of DUNE is given in Table 1.

| Physics milestone | Exposure kt · MW · year (reference beam) | Exposure kt · MW · year (optimized beam) |
|---|---|---|
| $1^{\circ} \theta_{23}$ resolution $(\theta_{23} = 42^{\circ})$ | 70 | 45 |
| CPV at 3σ ($\delta_{\rm CP} = +\pi/2$) | 70 | 60 |
| CPV at 3σ ($\delta_{\rm CP}=-\pi/2$) | 160 | 100 |
| CPV at 5σ ($\delta_{ m CP}=+\pi/2$) | 280 | 210 |
| MH at 5σ (worst point) | 400 | 230 |
| 10° resolution ($\delta_{ m CP}=0$) | 450 | 290 |
| CPV at 5σ ($\delta_{ m CP}=-\pi/2$) | 525 | 320 |
| CPV at 5σ 50% of $\delta_{ m CP}$ | 810 | 550 |
| Reactor θ_{13} resolution | 1200 | 850 |
| $(\sin^2 2\theta_{13} = 0.084 \pm 0.003)$ | | |
| CPV at 3σ 75% of $\delta_{ m CP}$ | 1320 | 850 |

Table 1 DUNE physics milestones. Best case MH: 5σ w/ 20-30 kt-MW-yr; Best case CPV (+ π /2): 3σ w/ 60-70 kt-MW-yr.

LBNO EXPERIMENT OVERVIEW

In 2013, the next generation long baseline neutrino oscillation experiment (LBNO) has been proposed by the LAGUNA-LBNO consortium [15], with the objectives to address fundamental question in particle and astroparticle physics. The deep underground neutrino observatory located at Pyhäsalmi mine, Finland at a depth of 1400 m and at a distance 2300km from CERN (SPS & HPPS) offered an essential to explore neutrino astrophysics and look for proton decay; in particular the neutrino mass hierarchy and CP violating phase δ_{cp} . The proposed experiment foresees in the phase I a 20 kton underground liquid Argon detector located at the Pyhäsalmi mine, to be incremented to a 70 kton detector in the phase II. The design of the liquid argon detector at Pyh" as almiis based on the GLACIER (Giant Liquid Argon ChargeImaging ExepeRiment) concept [16, 17]. It relies on technical expertise of the LNG industry in constructing largecryogenic vessels to house a large scale liquid argonTPC and a novel double-phase charge readout. Large matter effects due to the length of the CERN-to-Pyhäsalmi baseline give rise to a significant asymmetry between $v_{\mu} \rightarrow v_e$ and $\bar{v}_{\mu} \rightarrow \bar{v}_e$ oscillation probabilities that depends on the sign of Δm_{31} (if MH is -1 (+1) (anti)neutrino oscillation are suppressed). Additionally, at this baseline onehas the possibility to access both 1st and 2nd maxima of the v_e appearance probability. This gives an opportunity to measure δ_{cp} from the L/E behaviour of the oscillationprobability over a wide energy range. The accessto the 2nd oscillation maximum is also important. Sincethe dependence of the oscillation probability on the δ_{cp} is much stronger there, the sensitivity to CPV is significantlyimproved if one can access that part of the L/Eregion.



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| | v_{μ} unosc. CC | v_{μ} osc. CC | ve beam CC | $v_{\mu} \rightarrow v_{\tau}$ CC | $v_{\mu} \rightarrow v_e \text{ CC}$ $\delta_{cp} = -\pi/2 0 \pi/2$ |
|---|---------------------------|-------------------------|------------------|-----------------------------------|--|
| SPSbeam,24kton,NH | | | | | |
| 11.25×10^{20} POT for v | 12492 | 3392 | 77 | 733 | 883 693 57 |
| 3.75×10^{20} POT for $\overline{\upsilon}$ | 1907 | 504 | 10 | 112 | 232 40 41 |
| SPSbeam,24kton, IH | | | | | |
| 11.25×10^{20} POT for v | 12497 | 3337 | 77 | 860 | 229 138 97 |
| 3.75×10^{20} POT for $\bar{\upsilon}$ | 1907 | 502 | 10 | 110 | 80 102 114 |
| SPSbeam,24kton, IH | | | | | |
| 11.25×10^{20} POT for v | 19440 | 7791 | 162 | 458 | 1355 922 815 |
| 3.75×10^{20} POT for $\overline{\upsilon}$ | 2073 | 789 | 15 | 47 | 32 48 48 |
| SPSbeam,24kton, IH | | | | | |
| 22.25x10 ²¹ POT for v | 19440 | 7901 | 162 | 499 | 445 216 166 |
| 7.5×10^{21} POT for $\bar{\upsilon}$ | 2073 | 801 | 15 | 46 | 84 122 127 |

Table 2 Expected event rates in the energy range from 0 to 10 GeV for SPS and HPPS proton beam options and NH and IH. A total exposure of $15 \times 10^{20} (30 \times 10^{21})$ POT is assumed for SPS (HPPS) with 75% of running time dedicated to beam operation in the neutrino mode.

Mass Hierarchy determination

Quick and conclusive determination of mass hierarchy (MH) during the first few years of operation is one of the main objectives of the LBNO physics program. For a given exposure equal sharing of the running time between v and \overline{v} is assumed. LBNO has close to 100% statistical power to select a correct MH hypothesis independent of the value of δ_{CP} at 3σ level after accumulating 2 × 10²⁰ POT or about two years of SPS beam operation. With this exposure one also achieves more than 60% probability of determining MH at 5 σ level. The discovery (at 5 σ level) can essentially be guaranteed with an exposure of 4 × 10²⁰POT or about four years of running.

CPV determination

In Phase I (LBNO20: SPS based neutrino beam and24 kton LAr detector), LBNO has a median sensitivity to CPV at or above 3σ level for about 45% of possible values of δCP . With addition of the 50 kton detector, the experiment has the sensitivity to cover 63% and 35% of the parameter space at 3σ and 5σ level, respectively. The ultimate combination of HPPS and 70 kton detector would give a sensitivity at 3σ (5σ) level for 80% (65%) of the δCP parameter space.

III. NEUTRINO THREE FLAVOUROSCILLATIONS

$$|v_{\alpha}\rangle = U_{\alpha 1}|v_{1}\rangle + U_{\alpha 2}|v_{2}\rangle + U_{\alpha 3}|v_{3}\rangle$$
 (1)

Where $\alpha = e, \mu, \tau$

If we generate $|v_{\alpha}\rangle$ neutrino at the source and we can calculate the probability of finding $|v_{\beta}\rangle$ neutrino at the detector

as follows. $P(v_{\alpha} \rightarrow v_{\beta}) = |\langle v_{\beta}(x,t) | v_{\alpha}(0,0) \rangle|^{2}$

For three flavours neutrino oscillations, the transitionand the survival probabilities are given in equations (3) and (4).

(2)



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$$P(v_{\mu} \rightarrow v_{e}) = 4U^{2} \mu_{2} U e^{2} \sin^{2} \Delta \frac{m^{2}_{21}}{4E} + 4U^{2} \mu_{3} U^{2} e_{2} \sin^{2} \Delta \frac{m^{2}_{31}}{4E} + 2U_{\mu 3} U_{e_{3}} U_{e_{3}} U_{e_{2}} (\sin \Delta \frac{m^{2}_{21}}{2E} \sin \Delta \frac{m^{2}_{31}}{2E})^{(3)}$$

$$P(v_{\mu} \to v_{\mu}) = 1 - 4U_{\mu 2}(1 - U^{2}_{\mu 2})\sin^{2}\Delta\frac{m^{2}_{21}L}{4E} - 4U^{2}_{\mu 3}(1 - U^{2}_{\mu 3})\sin^{2}\Delta\frac{m^{2}_{31}L}{4E} + 2U^{2}_{\mu 2}U^{2}_{\mu 3}$$

$$(4)$$

$$(4\sin^{2}\Delta\frac{m^{2}_{21}L}{4E}\sin^{2}\Delta\frac{m^{2}_{31}L}{4E}) + 2U^{2}_{\mu 2}U^{2}_{\mu 3}(\sin^{2}\Delta\frac{m^{2}_{21}L}{2E}\sin^{2}\Delta\frac{m^{2}_{31}L}{2E})$$

Using these two equations, we simulate different graphs using the following data from Table 3 for DUNE and LBNO experiments. As of now we really don't know with cent percent accuracy of neutrino data. Therefore, we consider the current accepted data for three different values best-fit, 2σ , and 3σ to compare and analysis the graphs and finally draw a conclusion from it about the neutrino oscillations and infer the unknown properties of neutrinos for these two different basslines 1300 Km and 2290 Km.

| Parameter | Best-fit | 2σ | 3σ |
|--|----------|-------|-------|
| $\sin^2\theta_{12}$ | 0.304 | 0.28 | 0.26 |
| $\sin^2 \theta_{13}$ | 0.0218 | 0.033 | 0.050 |
| $\sin^2\theta_{23}$ | 0.452 | 0.38 | 0.34 |
| Δm^2_{21} | 7.5 | 7.3 | 7.1 |
| $\frac{10^{-5} eV^{2}}{\Delta m_{31}^{2}}$ | 2.45 | 2.1 | 2.0 |

Table 3 Neutrino oscillations data from different experiments

We begin with the study of transition or oscillation probability $P(v_{\mu} \rightarrow v_{e})$ and survival probability $P(v_{\mu} \rightarrow v_{\mu})$ for DUNE and LBNO with a baseline of 1300 Km and 2290 Km respectively for three different values of neutrino parameters as given in Table 3. For the best-fit data, the simulation graphs are given in Figures 1&2; while for 2σ values in Figures 3 and 4; and for 3σ data, the graphs are shown in Figures 5 and 6.



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Fig.1 For DUNE 1300Km (left), the Transition Probability(Red) and Survival Probability(Blue)asafunctionofneutrinoenergyEinGeV. Fig.2 For LBNO 2290 Km (right), the Transition Probability(Red) and Survival Probability(Blue)asafunctionofneutrinoenergyEinGeV.



Fig.3 The TransitionProbability (Red) and Survival probability (Blue)asafunctionofneutrinoenergyEinGeVfor1300Km. Fig.4 The TransitionProbability (Red)and Survival probability (Blue)asafunctionofneutrinoenergyEinGeVfor2290Km.



Fig.5The transition probability (Red)and survival probability (Blue)asafunctionofneutrinoenergyEinGeVfor1300Km. Fig.6The transition probability (Red)and survival probability(Blue)asafunctionofneutrinoenergyEinGeVfor2290Km.



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The plots from figures 1 to 6, for the same baselines 1300 for DUNE, 2290 Km for LBNO, for best-fit, 2 sigma, 3 sigma values of neutrino parameters, these plot showed the oscillation and survival probabilities are similar in nature. Implicating that a small variation in best-fit, 2 sigma, and 3 sigma really do not change the shape of the plots. However for all the plots the oscillation probability is very distinct compared to survival probability. This implies one need to study for oscillation probability rather than a survival probability while attempting to determine the unknown neutrino parameters. Again if we compare the two baselines 1300 km and 2290 km, all plots showed that the oscillation of the neutrinos for the later baseline are very good. This is expected of longer baselines.



Fig.7Thesurvivalprobability (left-best-fit) as a function of neutrino energy EinGeVfor1300Km(Red) and 2290Km(Blue). Fig.8Thesurvivalprobability (right-3 σ) as a function of neutrino energy EinGeVfor1300Km (Red) and 2290Km (Blue).

These two plots also show that the blue (LBNO) curves oscillation are more prominent than the red (DUNE) ones. Implying that the disappearance or survival probabilities also favour a longer baseline to determine the various unknown parameter. Next we take into account of the CP violating phase in particular of DUNE experiment. The oscillation probability is given below.

$$\begin{split} P(\nu_{\mu} \to \nu_{e}) &= s_{23}^{2} \sin^{2} 2\theta_{13} \sin^{2} \frac{\Delta m_{31}^{2} L}{4E} + c_{13}^{2} c_{23}^{2} \sin^{2} 2\theta_{12} \sin^{2} \frac{\Delta m_{21}^{2} L}{4E} \\ &+ 8 c_{13}^{2} s_{13} c_{12} s_{12} s_{23} c_{23} \sin \frac{\Delta m_{21}^{2} L}{4E} \sin \frac{\Delta m_{31}^{2} L}{4E} \cos \left(\frac{\Delta m_{32}^{2} L}{4E} + \delta\right) \\ &- 2 s_{12}^{2} s_{23}^{2} \sin^{2} 2\theta_{13} \sin \frac{\Delta m_{21}^{2} L}{4E} \sin \frac{\Delta m_{31}^{2} L}{4E} \cos \frac{\Delta m_{32}^{2} L}{4E} \\ &+ 4 c_{13}^{2} s_{12}^{3} s_{13} s_{23} \left(s_{23} s_{13} s_{12} - 2 c_{12} c_{23} \cos \delta\right) \sin^{2} \frac{\Delta m_{21}^{2} L}{4E} \end{split}$$



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Fig.9 Left (right): $P(v_{\mu} \rightarrow v_{e})$ ($P(\bar{v}_{\mu} \rightarrow \bar{v}_{e})$) oscillation probability at the Pyhäsalmi site for a selection of true values of δ_{cp} . In the plots $\delta_{cp} = 0$ (red), 90 (green), 180 (blue), 270 (pink). These plots assume a normal mass hierarchy. Looking at the probabilities, one can infer that spectral regions of interest are around the 1st and the 2nd maximum, and the regions in-between. For CERN to Pyhäsalmi due to its longer baseline, the second maximum occurs between 1-2 GeV. The technical limitations of conventional neutrino beams are well understood and with current technological limits on magnetic field strengths and volumes, they are not efficient at focusing hadrons with energies below ~1 GeV [18]. Access to the 2nd oscillation maximum is therefore more easily achieved with longer baselines. Taking into account vanishing neutrino cross-sections at low energies (in particular for antineutrinos), the measurement of the 2nd oscillation maximum requires in practice a baseline greater than 1500 km [cf.7]. The $_v_{\mu} \rightarrow v_{\tau}$ CC events where $\tau \rightarrow evv$, which become more important at longer baselines due to the higher energy tails of the neutrino flux, act a priori as a background to electron appearance. In conclusion, the longer baseline C2P option is more favorable for the observation of events in the second maximum.

IV. CONCLUSION

We have studied the oscillation probability $P(v_{\mu} \rightarrow v_{e})$ and survival probability $P(v_{\mu} \rightarrow v_{\mu})$ for DUNE and LBNO with a baseline of 1300 Km and 2290 Km respectively for three different values of neutrino parameters as given in Table 1. All the simulation graphs irrespective of the data fitted (best-fit, 2σ , and 3σ), longer baseline is favourable to study the unknown neutrino parameters. Again irrespective of the baseline the oscillation probability $P(v_{\mu} \rightarrow v_{e})$ is better than the survival probability $P(v_{\mu} \rightarrow v_{\mu})$.DUNE has an advanced design for a world-leading experiment focused on fundamental open questions in particle physics and astroparticle physics: long-baseline oscillation physicsto determine CPV and MH, make precision measurements of oscillation parameters, test thethree-neutrino paradigm, and look for physics beyond the standard model; search for nucleon decay in modes to which current detectors are comparatively insensitive; and neutrinoastrophysics, especially measurements of supernova neutrinos.For DUNE we have shown that the $P(v_{\mu} \rightarrow v_{e})$ and $(P(\bar{v}_{\mu} \rightarrow \bar{v}_{e}))$ oscillation probability at the Pyhäsalmi site for a selection of true values of δ_{cp} . In the plots $\delta_{cp} = 0$ (red), 90 (green), 180 (blue), 270 (pink). These plots assume a normal mass hierarchy.

We have shown that a 20 kton double-phase liquid argondetector in Pyhäsalmi and a convectional neutrinobeam based on modestly upgraded CERN SPS, couldquickly solve the question of the neutrino mass hierarchy. In this first



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phase, LBNO will also have sensitivity measure CPV at least 3σ level for 45% of the possible values of δ_{CP} . With addition of a 50kton DLAr the experimental sensitivity would increase to allow measuring δ_{CP} at the level of 3σ for 63% of the parameter phase-space. The sensitivity to discover δ_{CP} at least 5σ level for 35% of δ_{CP} values would be expected at thatstage. Ultimately, with the high intensity neutrino beamdelivered by 2MW HPPS, LBNO would reach a sensitivity at 5σ (3σ) level for 65% (80%) of the δ_{CP} phasespace.

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