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LONG BASELINE NEUTRINO EXPERIMENTS: ADVANCING THE PRECISION ERA

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Abstract: Long-baseline neutrino experiments have played a central role in advancing the understanding of neutrino oscillations, evolving from the first experimental confirmation of neutrino flavor transformation to the present search for leptonic CP violation. This review presents a comprehensive overview of the development of long-baseline accelerator experiments, organized by their major scientific eras: the foundational era of oscillation discovery; the precision oscillation era; the current era focused on electron-neutrino appearance and the search for CP violation; and the next-generation experimental era. The search for CP violation in the neutrino sector remains one of the most important objectives of contemporary particle physics, as a non-zero leptonic CP-violating phase $\boldsymbol{\delta_{CP}}$would imply different oscillation behaviors for neutrinos and antineutrinos and could provide important insights into the origin of the matter-antimatter asymmetry of the Universe. This review summarizes the experimental framework for investigating leptonic CP violation and discusses the capabilities, major achievements, and current status of long-baseline experiments, including K2K, MINOS, T2K, and NOvA, together with the physics goals and expected sensitivities of next-generation facilities such as DUNE and Hyper-Kamiokande. The experimental challenges associated with precision measurements of the CP-violating phase are also discussed, highlighting the expected role of future long-baseline experiments in establishing CP violation in the neutrino sector.

***Index Terms*–CP Violation, Long-baseline experiments, CP-violating phases, mass squared differences.**

I. INTRODUCTION

The discovery of neutrino oscillations established that neutrinos are massive particles and that different neutrino flavors can transform into one another during propagation [1]. This phenomenon cannot be explained within the original Standard Model of particle physics and therefore provides clear evidence for physics beyond the Standard Model. Neutrino oscillations are described by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix, which contains three mixing angles, two independent mass-squared differences, and a Dirac CP-violating phase, δ_{CP} [2].While significant progress has been made in measuring the neutrino mixing angles and mass-squared differences, the value of the CP-violating phase remains largely unknown. Determining these unknown parameters has become one of the major goals of modern neutrino physics.

A nonzero value of the CP-violating phase, δ_{CP}, would imply that neutrinos and antineutrinos oscillate differently. Several experimental approaches, including short-baseline such as MicroBooNE [3] and the Short-Baseline Neutrino (SBN) program[4], reactor experiments such as Daya Bay[5], RENO[6] and Double Chooz[7] atmospheric experiments such as Super-Kamiokande[8] and IceCube [9], and long-baseline neutrino experiments such as T2K [10], NOνA[11], and DUNE[12], have been developed to investigate CP violation in the neutrino sector. Among these, long-baseline accelerator experiments are particularly well suited for this search because they can directly compare the appearance probabilities of neutrinos and antineutrinos, $P(\nu_\mu \rightarrow \nu_e)$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$over large propagation distances, thereby providing enhanced sensitivity to the leptonic CP-violating phase δ_{CP}.
The oscillation probabilities in vacuum are given as

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \ \sin^2 1.27\frac{\Delta m^2 L}{E_\nu} \qquad (1)$$

which depend on the neutrino mixing angles, mass-squared differences, CP-violating phase, and the ratio (E/L), where (E) is the energy of the neutrino or antineutrino and (L) is the distance travelled from the source to the detector. Therefore, under CP conservation, the probabilities for neutrinos and antineutrinos remain the same while propagating in vacuum. If the two probabilities are found to be different, it indicates the presence of CP violation in the neutrino sector.

The observation of leptonic CP violation would not only improve our understanding of neutrino mixing but could also provide important clues about the origin of the matter-antimatter asymmetry of the Universe through mechanisms such as leptogenesis. For neutrinos traveling through dense matter over very long distances, the neutrino and antineutrino probabilities can also become different because of the Mikheyev-Smirnov-Wolfenstein (MSW) effect. This effect depends on the neutrino energy, the travelled distance, and the matter density. The MSW effect can be understood as an effective modification of the mixing angles and the

neutrino mass-squared differences, which results in different oscillation probabilities for neutrinos and antineutrinos. The probability of transition of a neutrino to an antineutrino state or vice versa in a two-flavor neutrino state is given by[13]

$$P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = \sin^2 2\ \theta_m \sin^2 \frac{m_m^2\, \Delta L}{4E} \qquad (2)$$

where, θ_m and Δm_m^2 corresponds to the effective mixing angle and effective mass squared difference, respectively. Here, the various parameters get modified due to the presence of effective matter potential A. The influence of these matter effects becomes increasingly significant in long-baseline neutrino experiments, where neutrinos propagate through the Earth's crust over hundreds of kilometers before reaching the detector. Such experiments are therefore ideally suited to investigate neutrino oscillations, leptonic CP violation, and the neutrino mass ordering.

In a typical long-baseline neutrino experiment, a proton beam strikes a target and produces positive and negative mesons. These mesons are selectively focused into a long decay pipe, where they decay and produce beams that are mainly composed of ν_μ and $\bar{\nu}_\mu$. These beams are first measured in a near detector and then travel a long distance to a far detector. During their propagation, a fraction of the ν_μ and $\bar{\nu}_\mu$beams can oscillate into ν_e and $\bar{\nu}_e$, respectively, which are then detected in the far detector.The neutrino and antineutrino event rates are determined from the following inclusive charged-current interactions:

$$\nu_\mu + N \to \mu^- + X, \bar{\nu}_\mu + N \to \mu^+ + X, \nu_e + N \to e^- + X, \bar{\nu}_e + N \to e^+ + X.$$

Over the past two decades, the long-baseline experiments have played a crucial role in establishing the three-flavor neutrino oscillation framework and in improving the precision of neutrino oscillation parameters. Experiments such as T2K and NOνA have provided increasingly stringent constraints on δ_{CP} and have also contributed significantly to the determination of the neutrino mass ordering and the atmospheric mixing angle, θ_{23}. Motivated by these achievements, next-generation facilities, including DUNE and Hyper-Kamiokande, have been designed with enhanced beam intensities, larger detector volumes, and improved detector technologies to achieve high-precision measurements of neutrino oscillation parameters and to establish leptonic CP violation with high statistical significance.

In this review, an overview of the development and progress of long-baseline neutrino experiments is presented, with the discussion organized according to the major eras of their evolution. Section II describes the foundational era, during which accelerator-based experiments established the phenomenon of neutrino oscillations. Section III discusses the precision oscillation era, focusing on the improved measurement of neutrino oscillation parameters. Section IV describes the discovery of electron-neutrino appearance and the beginning of the search for leptonic CP violation. Finally, Section V discusses the upcoming generation of long-baseline neutrino experiments and their prospects for precision measurements of neutrino oscillations and CP violation.

II. The Foundational Era: Establishing Long-Baseline Neutrino Oscillations (1990s--2000)

The development of accelerator-based long-baseline neutrino experiments began with the need to test the atmospheric neutrino oscillation picture using a controlled artificial neutrino beam. Before this period, the evidence for neutrino oscillations mainly came from natural sources, particularly atmospheric neutrinos, for which the neutrino energy and propagation distance were not directly controlled. Long-baseline accelerator experiments therefore provided a direct and controlled method to study neutrino flavor transformation.

K2K: The First Direct Accelerator-Based Long-Baseline Experiment

The KEK to Kamioka (K2K) experiment was constructed as the first long-baseline accelerator neutrino experiment to directly test neutrino oscillations. Its main aim was to study the disappearance of a predominantly muon-neutrino beam over a baseline of approximately 250km and to test the oscillation parameters suggested by atmospheric neutrino observations. K2K observed a deficit of muon-neutrino events and a distortion in the neutrino energy spectrum, providing direct accelerator-based evidence for neutrino oscillations. Its results were consistent with the atmospheric oscillation picture and gave an oscillation parameter value of approximately$\Delta m_{23}^2 = 2.8 \times 10^{-3} eV^2$ with large mixing, $\sin^2 2\theta_{23}$~1 [14].

However, K2K had limited statistics, moderate beam intensity, and insufficient sensitivity to electron-neutrino appearance. Therefore, it could not provide a precise measurement of θ_{13}, instead, it provided an approximate limit of $\sin^2 2\theta_{13} > 0.15$[15]. Its successful completion established the feasibility of the long-baseline technique and motivated the development of experiments with higher beam intensities, larger data samples, and improved sensitivity to the subdominant oscillation channels.

III. The Precision Oscillation Era: Measuring the Atmospheric Sector (2000--2010)

Following K2K, the focus shifted from establishing the existence of neutrino oscillations to measuring the oscillation parameters with greater precision. The next generation of experiments aimed to improve the determination of the atmospheric parameters, study $\nu_\mu \to \nu_e$ appearance, and search for effects related to matter and neutrino--antineutrino differences. These studies were important because electron-neutrino appearance depends on θ_{13}, whose value determines the possibility of observing leptonic CP violation.

MINOS: From Oscillation Discovery to Precision Measurements

The MINOS experiment was constructed to improve the precision of neutrino oscillation measurements using the NuMI beam from Fermilab and a far detector located approximately 735km away. Its primary aim was to study ν_μ disappearance and determine the atmospheric oscillation parameters more accurately. MINOS measured an atmospheric mass-squared difference of approximately $|\Delta m_{32}^2| = 2.4 \times 10^{-3}\ eV^2$. For a CP-conserving phase of $\delta_{CP} = 0$, the MINOS experiment obtained the upper limits$\sin^2 2\theta_{13} < 0.12$. for the normal mass hierarchy (NH) and $\sin^2 2\theta_{13} < 0.20$for the inverted mass hierarchy (IH) at the 90% confidence level. The corresponding best-fit values were $\sin^2 2\theta_{13}$=0.041for NH and $\sin^2 2\theta_{13}$.=0.079 for IH [16]. It also searched for $\nu_\mu \to \nu_e$ appearance and contributed to the study of θ_{13}.

Although MINOS improved the precision of the atmospheric oscillation parameters, itsstatistics and systematic uncertainties were not sufficient for a definitive study of CP violation. The experiment therefore completed its primary physics program as the field moved toward experiments with greater sensitivity to electron-neutrino appearance, the neutrino mass

ordering, and CP violation. The limitations of MINOS consequently motivated the development of more powerful and specialized long-baseline experiments.

IV The Discovery Era of Electron-Neutrino Appearance and CP Violation (2010--2020)

The discovery of a non-zero value of θ_{13} changed the direction of long-baseline neutrino physics. The observation of electron-neutrino appearance became experimentally accessible, making the comparison of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ probabilities possible. Consequently, the main goals shifted towards the measurement of θ_{13}, θ_{23}, the neutrino mass ordering, and the Dirac CP-violating phase δ_{CP}.

T2K: The Beginning of the Direct Search for Leptonic CP Violation

The Tokai to Kamioka (T2K) experiment was constructed to observe $\nu_\mu \rightarrow \nu_e$ appearance and investigate possible differences between neutrino and antineutrino oscillations. The experiment uses a beam produced at J-PARC and sends it over a baseline of approximately 295km to the Super-Kamiokande detector. Its design was optimized for the first oscillation maximum, where the probability of electron-neutrino appearance is enhanced.

T2K observed electron-neutrino appearance and provided important constraints on the leptonic CP phase. The results are consistent with earlier T2K analyses and with the results of other neutrino oscillation experiments. The CP-conserving values of δ_{CP} are disfavored at more than the 90% confidence level. The data show a slight preference for $\theta_{23} > 45°$ and for the normal mass ordering [17]. However, the limited number of appearance events, correlations among δ_{CP}, the mass ordering, and θ_{23}, together with uncertainties in neutrino interaction models, limited the precision of the measurements. These limitations motivated complementary experiments with longer baselines, stronger matter effects, and higher statistics.

NOνA : Enhancing Sensitivity to Matter Effects and the Mass Ordering

The NOνA experiment was constructed to complement T2K by using a longer baseline of approximately 810km. Its main objectives were to study $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$appearance, determine the neutrino mass ordering, measure θ_{23}, and search for CP violation. The longer baseline increases the influence of matter effects, which modify neutrino and antineutrino oscillation probabilities differently depending on the mass ordering.

NOνA observed electron-neutrino appearance and improved the measurement of the atmospheric oscillation parameters. Its results provided important constraints on θ_{23} and δ_{CP} and contributed to the study of the mass ordering. However, the experiment faced the difficulty of separating genuine CP-violating effects from matter-induced differences between neutrinos and antineutrinos. The limited number of appearance events and correlations among the mass ordering, δ_{CP} , and the θ_{23} octant also restricted the precision of the measurements. These limitations demonstrated the need for next-generation experiments with much larger data samples and improved control of systematic uncertainties.

V The Precision Era: Toward Definitive Measurements of CP Violation (2020—Present)

The period beginning around 2020 represents a transition from the discovery phase to precision measurements of neutrino oscillations and CP violation. T2K and NOνA have shown that the comparison of neutrino and antineutrino oscillations can provide information about δ_{CP}. However, a precise determination of CP violation requires larger event samples and better control of uncertainties related to neutrino interaction cross sections, nuclear effects, beam fluxes, detector response, the mass ordering, and θ_{23}. The next generation of experiments has therefore been designed with higher beam power, larger detectors, improved detector technologies, and longer baselines.

NOνA + T2K

The combined analysis of T2K and NOνA data has significantly improved the precision of neutrino oscillation parameters by exploiting the complementary baselines, beam energies, and detector capabilities of the two experiments. While T2K provides enhanced sensitivity to the leptonic CP-violating phase through measurements near the first oscillation maximum, NOνA offers greater sensitivity to the neutrino mass ordering due to stronger matter effects. Their combined analysis reduces parameter degeneracies and provides more stringent constraints on the atmospheric mass-squared difference and the CP-violating phase.

The combined results determine the atmospheric mass-squared difference to be $\Delta m^2_{32} = 2.43^{+0.04}_{-0.03} \times 10^{-3}\ eV^2$ for the normal ordering and be $\Delta m^2_{32} = -2.48^{+0.03}_{-0.04} \times 10^{-3}\ eV^2$for the inverted ordering. Furthermore, the analysis constrains the leptonic CP-violating phase to the 3σ intervals $\delta_{CP}\epsilon$ [-1.38π, 0.30 π] for the normal ordering and$\delta_{CP}\,\epsilon[-0.92\,\pi, 0.04\pi]$for the inverted ordering. Although no strong preference for either neutrino mass ordering is observed, the analysis indicates that, if the inverted ordering were assumed to be correct within the three-flavor oscillation framework, the data would provide evidence for CP symmetry violation in the lepton sector[18].

DUNE: A Next-Generation Experiment for Precision CP Violation

The Deep Underground Neutrino Experiment (DUNE) has been developed to perform precision measurements of neutrino oscillations using a high-intensity accelerator beam and a large liquid-argon far detector located approximately 1300~km from Fermilab. Its main objectives are to determine the neutrino mass ordering, measure the oscillation parameters, and search for and precisely measure leptonic CP violation. The long baseline provides strong sensitivity to matter effects, while the broad energy spectrum allows the oscillation pattern to be studied over a wide energy range.

DUNE is a next-generation long-baseline neutrino experiment designed to determine the neutrino mass ordering and measure the CP-violating phase δ_{CP}. It will also study neutrinos from astrophysical sources and search for physics beyond the Standard Model, including rare processes such as nucleon decay. The experiment will use a high-power, wide-band neutrino beam produced by the Long-Baseline Neutrino Facility (LBNF) at Fermilab and directed towards the Sanford Underground Research Facility (SURF) [19]. The beam can operate in both neutrino and antineutrino modes, allowing the study of oscillations for both particles and antiparticles. The DUNE far detector will use Liquid Argon Time Projection Chamber (LArTPC) technology,while the near detector will measure the unoscillated neutrino spectrum and provide important information on neutrino interactions and systematic uncertainties. DUNE will be constructed in two phases. Phase I will include a partially completed far detector, a reduced near-detector system, and a 1.2MW proton beam, while Phase II will provide the complete four-

module far detector, an upgraded near detector, and a beam power greater than 2MW. The Phase II programme will further improve the sensitivity of DUNE to neutrino oscillations and CP violation through advanced detector technologies, including the Vertical Drift (VD) far-detector design and the proposed magnetized high-pressure gaseous argon time projection chamber (HPgTPC) ND-GAr near detector. These upgrades will increase the event statistics, improve particle identification and momentum measurements, and reduce systematic uncertainties. The complete DUNE configuration will therefore provide improved sensitivity to the neutrino mass ordering and δ_{CP}, while also expanding the physics programme to solar and supernova neutrinos, neutrinoless double beta decay, dark matter, and other rare decay processes [20-23].

Hyper-Kamiokande: High-Statistics Measurement of CP Violation

This The Hyper-Kamiokande (Hyper-K) detector is a next-generation underground water-Cherenkov detector that will serve as the far detector for the upgraded J-PARC [24,25] long-baseline neutrino experiment, with a primary focus on studying leptonic CP violation and additional searches for proton decay, atmospheric neutrinos, and neutrinos of astrophysical origin. The Hyper-Kamiokande experiment will use an upgraded J-PARC neutrino beam, produced by directing 30GeV protons onto a graphite target, with the beam power planned to increase to approximately 1.3MW[26]. Its near-detector complex, including INGRID and the upgraded off-axis ND280 detector with the SuperFGD, high-angle TPCs, and time-of-flight detectors, will characterize the neutrino beam and measure interaction cross sections before oscillation. These upgrades will improve particle reconstruction and help reduce systematic uncertainties in neutrino oscillation measurements.

Hyper-K will use improved 20-inch PMTs with higher photo detection efficiency, better timing and charge resolution, along with multi-PMTs that enhance light collection, vertex reconstruction, and particle identification [27,28].The Hyper-K electronics will be installed in watertight underwater vessels close to the PMTs, reducing cable length and signal loss while requiring extensive testing for long-term reliability and safe operation. These units will provide high voltage, digitize PMT signals, and transmit the data to the external data-acquisition system, while a precise GPS- and atomic-clock-based timing system will synchronize the entire detector with sub-nanosecond precision.

Hyper-Kamiokande will study leptonic CP violation by directly comparing neutrino and antineutrino oscillation probabilities. Its high-intensity beam, massive far detector, and improved near and intermediate detectors will increase event statistics and reduce systematic uncertainties, allowing δ_{CP} to be measured with a resolution better than 23°. The experiment may exclude CP conservation at the 5σ (3σ) level for approximately 60% (80%) of the possible δ_{CP} values and can potentially discover CP violation within a few years for favorable values of δ_{CP}. In addition, Hyper-K will provide strong sensitivity to the neutrino mass ordering, proton decay, and astrophysical neutrinos, including solar and supernova neutrinos[29].

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