Neutrino Oscillation Experiments

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Abstract. Accelerator- and reactor-based experiments operating at the first maximum for atmospheric oscillation have been an important driver in our understanding of neutrino properties in recent years. The current generation of reactor-based experiments have measured the mixing angle $\theta_{13}$ with great precision, while accelerator-based experiments have taken significant exposures with both $\nu_\mu$ and $\bar{\nu}_\mu$ beams to study their disappearance into other flavors, primarily sensitive to the mixing angle $\theta_{23}$, and electron neutrinos appearing via $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations which are sensitive to the ordering of the neutrino mass eigenvalues and the $CP$-violating phase $\delta_{CP}$. Both reactor- and accelerator-based experiments have measured the mass-splitting $\Delta m^2_{atm}$ to great precision.

This presentation covers the latest developments in neutrino oscillation experiments in the context of the standard three flavor paradigm. Other presentations in the session provided a theoretical overview [1] and covered short baseline experiments exploring large neutrino mass splittings and other phenomenon driven by physics beyond the three flavor paradigm [2], solar neutrinos [3], geoneutrinos, and supernova neutrinos [4].

1. Introduction
1.1. Neutrino Oscillations

Neutrino oscillations, the precession of neutrino flavor as they propagate in space-time, results from the misalignment of neutrino flavor and mass (and therefore energy) eigenstates [9]. The amplitudes of the oscillations are determined by the elements of the unitary transformation $U$ (“mixing matrix”) relating the flavor and mass eigenstates, while the frequency in proper time (equivalently the “baseline” of propagation $L$ divided by the neutrino energy $E$) is set by the differences of the squares of the mass eigenvalues $\Delta m^2_{ij} = m_i^2 - m_j^2$ where $i,j = \{1,2,3\}$ label the mass eigenstates. For three flavor mixing, $U$ can be parameterized by three real mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$ and an irreducible $CP$-odd phase $\delta_{CP}$, while the mass eigenvalues define three mass-squared splittings $\Delta m^2_{21}, \Delta m^2_{31}, \Delta m^2_{32}$. Further details can be found in other presentations presented at this conference [1], including important connections to how these neutrino properties impact our understanding of the baryon asymmetry of the universe [5].

1.2. Current Program

The discovery of neutrino oscillations via $\nu_\mu$ disappearance in atmospheric neutrinos [6] established the “atmospheric” mass splitting $|\Delta m^2_{32}| \sim 2.5 \times 10^{-3}$ eV$^2$ and that $\theta_{23}$ is large, while solar and reactor-based measurements [7] established the smaller “solar” mass splitting $\Delta m^2_{21} \sim 7.6 \times 10^{-5}$ eV$^2$ and $\theta_{12}$ to be large. Subsequently, the first accelerator-based long-baseline...
experiment [8] confirmed the $\nu_\mu$ disappearance observed in the atmospheric data, and the field turned to a new generation of accelerator-based experiments to search for $\nu_\mu \rightarrow \nu_e$ oscillations and reactor-based experiments to search for $\bar{\nu}_e$ disappearance driven by the atmospheric splitting to determine whether $\theta_{13}$, the remaining mixing angle, is non-zero. The positive outcome of both endeavors established that all three mixing angles are non-zero, setting the scene for the possibility of CP violation in neutrino mixing through $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations and observing enhancements/suppressions in the oscillation probability resulting from matter effects that depend on the mass ordering, i.e., whether $\Delta m^2_{31} > 0$ or $< 0$. As we shall see, this oscillation probability depends on all the mixing parameters, and thus increased precision on all parameters is desired. Precision is interesting in its own right as the theoretical community explores the possibility of patterns in the mixing parameters that may be driven by physics beyond the Standard Model, such as the possible “maximality” of the $\theta_{23}$ mixing angle.

1.3. Neutrino Oscillation Probabilities
The relevant oscillation probabilities follow, where the baseline $L$ and neutrino energy $E$ are assumed to be in km and GeV, respectively. For reactor-based experiments, the “survival” probability of $\bar{\nu}_e$ to remain as such is given by:

$$P(\nu_e \rightarrow \nu_e) \sim 1 - \sin^2 2\theta_{13} \sin^2 \left(1.27 \Delta m^2_{31} L / E\right) - \sin^2 2\theta_{12} \sin^2 \left(1.27 \Delta m^2_{21} L / E\right).$$

(1)

where two modes of oscillation driven by the atmospheric and solar mass splittings are manifest, with the former studied by experiments operating at $L \sim 2$ km. For such “disappearance” measurements probing the survival probability of the initial flavor, CP T symmetry requires that the survival probability is the same for neutrinos and antineutrinos, e.g., $P(\nu_e \rightarrow \nu_e) = P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$.

For accelerator-based experiments employing $\nu_\mu$ and $\bar{\nu}_\mu$ beams and detecting neutrinos at the atmospheric oscillation maximum, the corresponding survival probability for these neutrinos is given by:

$$P(\nu_\mu \rightarrow \nu_\mu) \sim 1 - \left[\cos^4 \theta_{13} \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^2 \theta_{23} \right] \sin^2 \left(\Delta m^2_{31} L / 4E\right).$$

(2)

We note that with $\theta_{13} \neq 0$, the amplitude for this oscillation is maximum at $\theta_{23} \neq \pi/4$.

The probability of $\nu_\mu \rightarrow \nu_e$ transitions is given as follows [11]:

$$P(\nu_\mu \rightarrow \nu_e) \sim \sin^2 2\theta_{13} \times \sin^2 \theta_{23} \times \frac{\sin^2((1-x)\Delta)}{(1-x)^2} \times \frac{\sin \Delta \sin[x\Delta] \sin[(1-x)\Delta]}{x(1-x)},$$

$$+ \times \frac{\sin \Delta \sin[x\Delta] \sin[(1-x)\Delta]}{(1-x)} \times \cos \Delta \sin[x\Delta] \sin[(1-x)\Delta]$$

(3)

where $\alpha = |\Delta m^2_{21} / \Delta m^2_{31}| \sim 1/30$ is the ratio of the solar and atmospheric mass splittings, $x = \pm \sqrt{2 G_F N_e E} / \Delta m^2_{31}$ parameterizes matter effects in the oscillation [10] effected by the electron density $N_e$ through which the neutrino travel and depend on the sign of the mass splitting $\Delta m^2_{31}$, with the “+/-” corresponding to $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations, respectively. The second line is a CP-odd term that will change sign if we consider $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations, and thus provides an opportunity to observe CP-violating asymmetries in $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$. Given the dependence of this oscillation on all three mixing parameters, accelerator-based experiments typically perform a combined analysis of their $\nu_\mu \rightarrow \nu_\mu / \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ data with $\nu_\mu \rightarrow \nu_e / \bar{\nu}_\mu \rightarrow \bar{\nu}_e$ data in order to consistently constrain $\theta_{23}$ and $\Delta m^2_{31}$, with the parameters $\theta_{12}$ and $\Delta m^2_{21}$ set by the “solar” measurements, and the further option of constraining $\theta_{13}$ based on the precise measurement in reactor-based experiments.
NOVA'S PHYSICS GOALS

Is CP violated in the lepton sector? What is the mass hierarchy or ordering for atmospheric neutrinos? Are there other neutrinos beyond the three known active flavors?

First NOVA antineutrino data at this conference

Neutrino and antineutrino data are required – ν̄μ → ν̄e events vs. νμ → ν̄e events at NOvA versus mass ordering (red vs. blue oval), δCP (points within each red/blue oval), and sin2θ23 (top right red/blue ovals vs. bottom left red/blue oval) [18]. Note that the νμ → ν̄e events which are jointly analyzed play an important role in determining sin2θ23 in addition to the νμ → νe events.

2. Current status of θ13 with reactor-based ν̄e disappearance

Following the observation of ν̄e disappearance in Daya Bay and RENO, reactor-based experiments operating at the first atmospheric oscillation maximum (~2 km for ~4 MeV antineutrinos) have made steady progress in improving the measurement of θ13 as given by Equation 1.3, which now results in the world average sin2θ13 = 0.0218 ± 0.0007 [12], the most precisely measured mixing angle. The mass-splitting driving this oscillation, Δm2ee = (2.52 ± 0.07) × 10−3 eV2, is also measured with precision comparable to those obtained in νμ oscillations in Equation 1.3. The high statistics of these experiments has allowed the oscillatory behavior to be measured in detail over the first full cycle of oscillation, and also has allowed other tests of the three flavor mixing model against potential non-standard effects.

3. Accelerator-based Neutrino Beams

Two accelerator facilities, J-PARC and FNAL, are currently providing accelerator-based neutrino beams for long-baseline experiments with steadily increasing intensities. While the details of the beam lines (the T2K beam line at J-PARC and NuMI at FNAL) differ, they operate on the same basic principles. In each case, high energy protons are fast-extracted from the accelerator complex and impinge upon a target, inducing pion production. A set of pulsed electromagnets (“horns”) focus positive or negative pions depending on their polarity, giving rise to a beam of νμ or ν̄μ after the π → μ + νμ process in a decay region following the target and horns. A beam absorber at the end of the decay region stops the remaining particles, apart from the neutrinos, which continue on their way to the experiments, and high energy muons, which may penetrate past the beam dump and provide a means to monitor the beam line. Beam delivery is measured in terms of the protons delivered to the target (“POT”), though due to the
G. S. Davies (Indiana U.): NOvA

3-flavor oscillation results

\( \nu_\mu \) and \( \bar{\nu}_\mu \) at FD

Total Observed 102

Best fit prediction 96

Cosmic bkgd 0.8

Beam bkgd 1.4

Unoscillated pred.

78% more data

-flavor oscillations describe data well (goodness-of-fit \( p = 0.91 \))

August 6th, 2019

**Figure 2.** Top: \( \nu_\mu \to \nu_\mu \) (left) and \( \bar{\nu}_\mu \to \bar{\nu}_\mu \) (right events) observed at NOvA. Bottom: same for T2K.

different primary proton energies and other differences in the designs of the two beam lines and the experiments operating on them, their POT figures are not comparable in any direct way.

The long-baseline experiments currently operating on these beam lines (T2K at J-PARC and NOvA at FNAL) employ the “off-axis” configuration wherein the beams are directed slightly away (2.5\(^\circ\) in the case of T2K, 14.6 mrad in the case of NOvA) from the far detectors, which gives rise to a neutrino flux that is peaked at lower energy and suppresses the tail at higher energy [14]. The angles are tuned to maximize the flux at the energy corresponding to the oscillation maximum for the baseline of the experiment (\( E \sim 0.6 \) GeV for 295 km at T2K, and \( E \sim 2 \) GeV for 810 km at NOvA), while the diminished flux at higher energies reduces backgrounds from neutral current interactions of these neutrinos that “feed down” into the signal energy region. Both experiments have accumulated substantial exposures with both \( \nu_\mu \) and \( \bar{\nu}_\mu \) beams with NOvA collecting \( 8.85 \times 10^{20} \) POT in neutrino mode and \( 6.91 \times 10^{20} \) POT antineutrino mode, while for T2K the corresponding numbers are \( 15.1 \times 10^{20} \) and \( 16.5 \times 10^{20} \) POT at the time of the conference. We provide further details on the two experiments in the following sections.
3.1. T2K
The T2K experiment [15] uses the neutrino beam line at J-PARC to send an off-axis 0.6 GeV $\nu_\mu/\bar{\nu}_\mu$ beam to the Super-Kamiokande detector which functions as the “far” detector for the experiment 295 km away. At 280 meters from the production target are two near detector systems, one on the axis of the neutrino beam (INGRID), and the other (ND280) positioned 2.5° off-axis in the direction of the Super-Kamiokande. ND280 is a magnetized detector system which allows for detailed sign and momentum analysis of charged particles emitted from the neutrino interactions, and the detection of photons using its calorimeter system [16], while INGRID allows a precise monitor of the beam direction and event rate directly from neutrino events. At 0.6 GeV, where the neutrino spectrum peaks, charged current neutrino interactions give rise primarily to pionless final states, which are readily identified in Super-Kamiokande as a single Cherenkov ring produced from the primary lepton, which can be classified to tag the flavor of the interacting neutrino. Under the assumption that the underlying reaction is “quasi-elastic” (i.e. $\nu_\ell + (n/p) \rightarrow \ell + (p/n)$), the energy of the incoming neutrino can be inferred so that the spectrum of the oscillated events can be studied. However, the presence of several mechanisms that can give rise to pionless final states result in significant uncertainties in determining the expected rate and reconstructed energy spectrum for these interactions. Recently, $\nu_e$ interactions giving rise to a single charged pion, detected via the decay electron produced from the $\pi \rightarrow \mu \rightarrow e$ chain, have been added to the analysis.

3.2. NOvA
NOvA uses the NuMI beam line to send a $\sim 2$ GeV $\nu_\mu/\bar{\nu}_\mu$ 810 km to a 14 kt far detector [17]. The far detector consists of arrays of $5.6 \times 3.5 \times 1550$ cm$^3$ extruded PVC cells filled with liquid scintillator and a looped wavelength shifting fiber coupled to an avalanche photodiode to detect ionizing particles passing through the cell. The cells are stacked perpendicularly to the incident neutrino beam with alternating vertical and horizontal orientations to provide separate two dimensional views of an interaction which can be combined to form a full three dimensional representation of the event. The sampling also allows the NOvA detector to readily distinguish between the minimum ionizing behavior resulting from the primary muon in a $\nu_\mu$ charged-current interaction from an electromagnetic shower induced by the primary electron resulting from a $\nu_e$ interaction, while calorimetry can be performed on the hadronic recoil system to infer the total energy of the event and the incident neutrino. A functionally identical but scaled-down near detector operates close to the NuMI beamline to study neutrino interactions in the absence of neutrino oscillations using the same detection and reconstruction principles as the far detector.

4. Results
The energy spectrum of $\nu_\mu$ (left) and $\bar{\nu}_\mu$ (right) events observed at NOvA (top) [18] and T2K (bottom) [19] are shown in Figure 2. In each case, the large disappearance of $\nu_\mu/\bar{\nu}_\mu$ events expected from near-maximal mixing in Equation 1.3 is observed. More quantitatively, however, the T2K data prefer maximal disappearance of $\nu_\mu/\bar{\nu}_\mu$ while for NOvA, the events present at the oscillation maximum lead to preferred values of $\theta_{23}$ somewhat away from maximal disappearance.

Likewise, the energy spectrum of $\nu_e/\bar{\nu}_e$ events at the two experiments are shown in Figure 3. For T2K, there is an additional aforementioned $\nu_e$ sample comprised of events with charged pion production identified via a decay electron that is not shown. While $\nu_\mu \rightarrow \nu_e$ oscillation events expected according to Equation 1.3 are conclusively observed in both experiments, quantitatively, the results prefer somewhat different oscillation parameters. For T2K, the sample of observed $\nu_\mu \rightarrow \nu_e$ events is relatively large, whereas the corresponding $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ sample is relatively small, so much so that the latter process is not conclusively observed. As a result, the data prefer a maximal asymmetry between the CP-conjugate modes favoring the neutrino oscillation process over antineutrino process. This is achieved with normal mass
ordering (i.e. $\Delta m^2_{32} > 0$) and $\delta_{CP} \sim -\pi/2$. NOvA, however, has clear indications of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ events, so that rather than favoring a large $CP$ asymmetry, the data suggest large oscillation probabilities for both neutrino and antineutrino modes, which can be achieved with larger $\sin^2 \theta_{23}$ in the $\theta_{23} > \pi/2$ octant. The large $\nu_\mu \rightarrow \nu_e$ oscillation probability also disfavors the inverted ordering for most values of $\delta_{CP}$ apart from $-\pi/2$, while for assumed normal ordering, nearly all values of $\delta_{CP}$ are consistent with observation.

These qualitative observations are more formally expressed through statistical analyses which result in the contours shown in Figure 4 based on the $\nu_\mu/\bar{\nu}_\mu$ and $\nu_e/\bar{\nu}_e$ events observed in each experiment. The left figure shows that T2K prefers $\sin^2 \theta_{23} \sim 0.5$ which results in maximal disappearance of $\nu_\mu/\bar{\nu}_\mu$, while NOvA prefers values which depart somewhat from this configuration, with the best fit in the “second” octant with $\theta_{23} > \pi/4$, though there is a large overlap in the contours. The middle figures shows the significance as a function of $\delta_{CP}$ for the NOvA data with different assumptions of mass ordering and $\theta_{23}$ octant. Generally, inverted mass ordering is disfavored by the large $\nu_\mu \rightarrow \nu_e$ yields apart from $\delta_{CP} \sim -\pi/2$ (equivalently $\delta_{CP} \sim 3\pi/2$) where the enhancements/suppressions from the matter effect and $\delta_{CP}$ go in opposite directions. The right figure shows the posterior probability distribution for the T2K data as a function of $\delta_{CP}$ after all other parameters are marginalized, which shows that
these data prefer $\delta_{CP} \sim -\pi/2$.

5. Outlook and Future Experiments

While the results from T2K and NOvA, whether taken individually or in combination, are intriguing, it is clear that additional data and statistical precision is needed to make conclusive statements about the mass ordering, $\theta_{23}$, or $\delta_{CP}$. Fortunately, both T2K and NOvA will continue to accumulate data for the next several years in advance of next generation experiments. For both experiments, upgrades to the accelerators and beam lines will also allow more intense neutrino beams to be produced, accelerating the accumulation of statistics. If parameters are favorable, particularly in cases where the $CP$-violating effects from $\delta_{CP}$ and mass ordering act “constructively” to enhance the oscillation probability in $\nu_\mu \rightarrow \nu_e$ and suppress it in $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (or vice versa), significant evidence ($\sim 3 - 4 \sigma$) for either effect may be established.

A combined analysis with the data from the two experiments and with atmospheric neutrino measurements may strengthen any such indications from the individual experiments and also test the consistency of the results within the three flavor mixing framework.

Looking beyond the current generation of experiments, two major initiatives, Hyper-Kamiokande [20] and DUNE/LBNF, [21] are expected to start operations in the second half of the next decade. Hyper-Kamiokande envisages a water Cherenkov detector with a fiducial volume approximately eight times larger than the Super-Kamiokande detector operating at the same baseline in the J-PARC neutrino beam currently used by T2K. DUNE will employ a set of four liquid argon time projection chambers [22] with a total fiducial mass of 40 kilotons in a new 1.2 MW neutrino beamline over a baseline of 1285 km which will have strong sensitivity to matter effects. The broad band beam, with considerable neutrino flux at energies below $\sim 1$ GeV will also allow DUNE to study events at the second oscillation maximum, where both $CP$ and matter effects are significantly enhanced, providing an independent view of the oscillations that will offer important checks for the standard three flavor mixing paradigm. For Hyper-Kamiokande, there is a proposal to place a second module in South Korea at a baseline of 1100 km [23] which will similarly allow the second oscillation maximum to be studied. An important component for both experiments will be a capable near detector system that will advance the state-of-the-art in neutrino flux and interaction modelling in order to reduce the systematic errors to a level where they do not impact the high statistics measurements expected at these experiments.

On a shorter time scale, a new reactor-based experiment, JUNO [24], will operate a 20 kiloton liquid scintillator detector at a sixty kilometer baseline. Together with the large statistics, the very high energy resolution for the detector will observe the “beating” of the solar and
atmospheric oscillations in the observed $\bar{\nu}_e$ energy spectrum, which is sensitive to the mass ordering. JUNO will also offer the opportunity to improve the precision on $\theta_{12}$.

6. Conclusions and Acknowledgements

Over the past two decades, the study of neutrino oscillations has advanced with steadily improving parameter measurements, observation of additional oscillation modes, and the first glimpse in the search for $CP$-violating asymmetries and matter effects. The current generation of accelerator-based experiments will continue to operate for the next several years with enhanced neutrino beams with the hope of strengthening indication so $CP$-violation and matter effects, while a new generation of experiments is under construction.

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References

[1] Lisi E, in these proceedings.
[2] Caratelli D, in these proceedings.
[3] Zuber K, in these proceedings and references therein.
[4] O’Connor E, in these proceedings.
[5] Petcov S, Giri A, in these proceedings, Fukugita M and Yanagida T, Phys. Lett. B 174, 45 (1986).
[6] Fukuda Y et al. [Super-Kamiokande Collaboration], Phys. Rev. Lett. 81, 1562 (1998)
[7] Fukuda S et al. [Super-Kamiokande Collaboration], Phys. Rev. Lett. 86, 5651 (2001). Ahmad Q R et al. [SNO Collaboration], Phys. Rev. Lett. 89, 011301 (2002). Hampel W et al. [GALLEX Collaboration], Phys. Lett. B 447, 127 (1999). Abdurashitov J N et al. [SAGE Collaboration], Phys. Rev. C 60, 055801 (1999) doi:10.1103/PhysRevC.60.055801, Fukuda Y et al. [Kamiokande Collaboration], Phys. Rev. Lett. 77, 1683 (1996). Eguchi K et al. [KamLAND Collaboration], Phys. Rev. Lett. 90, 021802 (2003)
[8] Ahn M H et al. [K2K Collaboration], Phys. Rev. Lett. 90, 041801 (2003)
[9] Maki Z, Nakagawa M, and Sakata S, Prog. Theor. Phys. 28, 870 (1962). Pontecorvo B, Sov. Phys. JETP 26, 984 (1968) [Zh. Eksp. Teor. Fiz. 53, 1717 (1967)].
[10] Mikheyev S P and Smirnov A Y, Sov. J. Nucl. Phys. 42, 913 (1985) [Yad. Fiz. 42, 1441 (1985)].
[11] Freund M, Phys. Rev. D 64, 053003 (2001) [hep-ph/0103300].
[12] Tanabashi M et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018) and 2019 update, Adey D et al. [Daya Bay Collaboration], Phys. Rev. Lett. 121, no. 24, 241805 (2018). Bak G et al. [RENO Collaboration], Phys. Rev. Lett. 121, no. 20, 201801 (2018), Abe Y et al. [Double Chooz Collaboration], JHEP 1601, 163 (2016). An F P et al. [Daya Bay Collaboration], Phys. Rev. D 93, no. 7, 072011 (2016)
[13] Mahn K, Marshall C, and Wilkinson C, Ann. Rev. Nucl. Part. Sci. 68, 105 (2018)
[14] Beavis D et al. [E899 Collaboration], doi:10.2172/52878
[15] Abe K et al. [T2K Collaboration], Nucl. Instrum. Meth. A 659, 106 (2011)
[16] Wilkinson C, in these proceedings.
[17] Ayres D S et al. [NOvA Collaboration], doi:10.2172/935497
[18] Psihas F, in these proceedings, Acero M A et al. [NOvA Collaboration], Phys. Rev. Lett. 123, no. 15, 151803 (2019)
[19] Sztab A, in these proceedings, Abe K et al. [T2K Collaboration], Phys. Rev. Lett. 121, no. 17, 171802 (2018)
[20] Abe K et al. [Hyper-Kamiokande Collaboration], Preprint arXiv:1805.04163 [physics.ins-det].
[21] Acquarri R et al. [DUNE Collaboration], Preprint arXiv:1601.05471 [physics.ins-det].
[22] Rubbia C, CERN-EP-INT-77-08, CERN-EP-77-08.
[23] Abe K et al. [Hyper-Kamiokande Collaboration], PTEP 2018, no. 6, 063C01 (2018)
[24] Xu B, in these proceedings, Djurcic Z et al. [JUNO Collaboration], Preprint arXiv:1508.07166 [physics.ins-det].