Long Baseline Neutrino Oscillations

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Abstract

There is compelling evidence for neutrino flavor change as neutrinos propagate. The evidence for this phenomenon has been provided by several experiments observing neutrinos that traverse distances of several hundred kilometers between production and detection. This review outlines the evidence for neutrino flavor change from such experiments and describes recent results in the field.

1. Introduction

The abundant evidence for the disappearance of ν_μ and ν_e as they propagate from their production point comes from several experiments using the sun, atmosphere, nuclear reactors and accelerators as neutrino sources [1, 2, 3, 4, 5, 6]. This disappearance has been best described as oscillations between the active neutrino flavors; as neutrinos of one flavor propagate, they are able to change into neutrinos of another flavor. The oscillation is allowed because neutrinos have mass, and the flavor states are linear combinations of the neutrino mass states. The flavor states and mass states are related by a unitary 3×3 matrix known as the PMNS matrix [7]. For the case where only two neutrino flavors are involved the probability for flavor α to change into flavor β is

$$P_{\nu_\alpha \to \nu_\beta} = 1 - \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right), \qquad (1)$$

where θ is the mixing angle describing the rotation of the mass basis into the flavor basis, $\Delta m^2 \equiv m_2^2 - m_1^2$ is the difference in the squares of the masses for mass states 1 and 2 in eV^2, L is the distance, or baseline, traveled by the neutrino in kilometers, and E is the energy of the neutrino in GeV. Notice that the probability is nonzero only if neutrinos have mass and those masses are not degenerate. The maximum oscillation probability for each neutrino depends on the ratio of the distance it travels to its energy, as well as the value of Δm^2.

Experiments that detect neutrinos several hundred of kilometers from their point of production are known as long-baseline experiments. These experiments may use a near detector in addition to the far detector in order to constrain systematic uncertainties. They are either "disappearance experiments" where the experiment looks for a deficit of one flavor at the far detector, or "appearance experiments" where the experiment looks for the appearance of a flavor not produced in the beam.

The first evidence for neutrino oscillations came from atmospheric neutrino experiments such as Super-Kamiokande [1, 2]. These experiments used only one detector and observed neutrinos from baselines spanning hundreds of kilometers to more than ten thousand kilometers. The Super-Kamiokande experiment analysis looked at both ν_e and ν_μ interactions in its water Cherenkov detector. The charged-current interactions were separated based on being either electron-like or muon-like and then further divided into different energy ranges. The incoming zenith angles for the events in each flavor and energy range were then plotted. Super-Kamkiokande found that the electron neutrinos arrived at a rate consistent with the Monte Carlo simulation for all incoming zenith angles and energies, while the muon neutrinos showed a clear deficit for neutrinos coming from below the horizon. The data were fit to an oscillation model with the best fit values of $\Delta m^2_{32} = 2.2 \times 10^{-3}$ eV^2 and $\sin^2(2\theta_{23}) = 1$ [8]. The subscripts on Δm^2 and θ indicate the mass states participated in the mixing. Figure 1. shows the confidence intervals in the $\Delta m^2_{32} - \sin^2(2\theta)$ space. These results have been interpreted as $\nu_\mu \to \nu_\tau$ oscillations with maximal mixing.

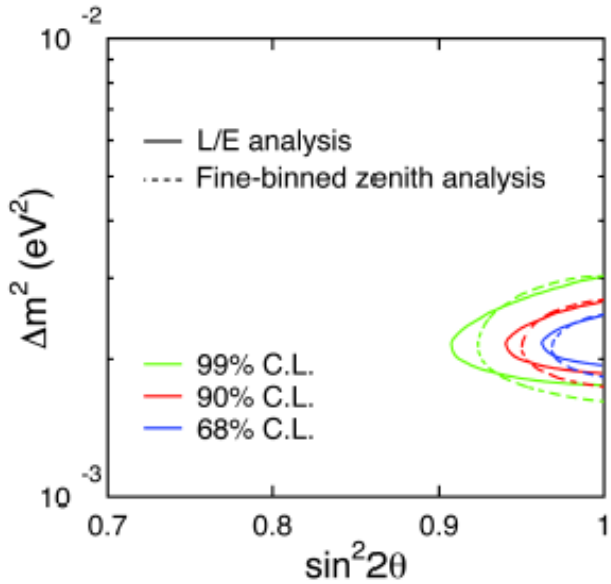

Fig. 1. Confidence intervals for the Super-Kamiokande analysis of atmospheric neutrino oscillations.

The SNO and KamLAND experiments observed solar electron neutrinos and reactor electron anti-neutrinos respectively. The SNO experiment compared rates of charged-current interactions to neutral-current interactions [9]. Only electron neutrinos can be observed through the charged-current interaction in that detector, while all flavors participate in the neutral-current interaction. The number of charged-current interactions observed was nearly a factor of 3 fewer than expected based on solar models, while the number of neutral-current interactions was in agreement with the expectation. The conclusion from these data was that electron neutrinos changed flavor as they propagated outward from the core of the sun.

The KamLAND experiment observed electron anti-neutrinos from nuclear reactors in Japan and Korea. The observed energy spectrum of these anti-neutrinos shows a clear energy dependent deficit compared to Monte

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Carlo expectation in the absence of oscillations. The combination of the results from these two experiments indicates that only two mass states are relevant for the observed mixing and $\Delta m^2_{21} = (7.59 \pm 0.21) \times 10^{-5}\text{eV}^2$ and $\tan^2(\theta_{21}) = 0.47 \pm 0.06$ [4]. Notice that the value of Δm^2_{32} is approximately a factor of 30 larger than Δm^2_{21}. Also note that while the value of $\tan^2(\theta_{21})$ is not its maximum possible value, it is still quite large.

The results from these three expirments can be combined to give an overall picture of neutrino oscillations. There are two distinct mass-squared splittings, with the first and second mass eigenstates having very similar masses and the third mass eigenstate being well separated from the other two. The third mass eigenstate interacts almost entirely as either a ν_μ or ν_τ, as indicated by the maximal mixing in the atmospheric neutrinos. The second mass eigenstate has equal probability to interact as any of the three flavors, as indicated by the SNO results. The first mass eigenstate interacts primarily as ν_e with the remaining probability evenly split between ν_μ and ν_τ.

Despite the success of these experiments, many questions about neutrinos and neutrino oscillations remain to be answered. For example, the coupling of the electron neutrino to the third mass eigenstate is described by θ_{13}, however this mixing angle has only been bounded to be less than about 12° [10] by the CHOOZ collaboration. If θ_{13} is non-zero, then experimentalists can use that mixing angle to determine the size of CP violation in the lepton sector. It is possible that CP violation in neutrinos contributed to baryogenesis in the early universe. Additionally, as seen above, the neutrino mixing angles are all quite large except for one, a situation very different from quark mixing where only the diagonal elements of the mixing matrix are large and the off diagonal elements are all small. Naively one might have expected some symmetry between the quarks and neutrinos; the fact that they are quite different is likely an indication of different physics behind neutrino mixing and quark mixing. Another interesting and unresolved question is whether the third mass eigenstate is heavier than the other two or lighter. Finally, the number of active neutrino flavors is known to be three, however there is the possibility that more neutrino species which do not couple to the electroweak current could exist. These questions can all be answered by long-baseline accelerator based neutrino oscillation experiments.

2. Accelerator Based Long-Baseline Experiments

Accelerator-based experiments offer a distinct advantage over the atmospheric, solar and reactor experiments, namely the baseline, energy spectrum, and flavor content of the beam can be controlled. Additionally, these experiments make use of two detectors to understand the neutrino beam before the neutrinos have had a chance to oscillate. These experiments have primarily focused on the atmospheric mass-squared splitting, Δm^2_{32} as that splitting most affects the neutrinos having the L/E of long-baseline experiments. The neutrino beams are created by accelerating protons to the desired energy and then having them impinge on a target. The resulting pions and kaons are then focused using magnetic horns in order to select hadrons with the appropriate energy and to point them at the detectors. The hadrons then decay into neutrinos and muons in a decay pipe. A large amount of absorbing material is at the end of the decay pipe to absorb any hadrons that did not decay, as well as the produced muons leaving a beam of neutrinos.

2.1. K2K

The first experiment to make use of such an experimental setup was K2K, having a baseline of 250 km [5]. K2K made use of the Super-Kamiokande detector for its far detector, and a set of near detectors to measure the flux of neutrinos in the beam before they could oscillate. K2K observed a deficit of muon neutrino events at the far detector compared to the prediction based on the near detector data and measured a value of Δm^2_{32} that was consistent with the Super-Kamiokande results [5].

2.2. MINOS

The next accelerator based experiment to take data was MINOS,with a baseline of 750 km [6]. The MINOS experiment makes use of two detectors as well, a near detector having a mass of 0.98 kt and a far detector with a mass of 5.4 kt. The goals of this experiment include: i) making the most precise measurement of Δm^2_{32}; ii) searching for electron neutrino appearance in the beam of muon neutrinos; iii) searching for alternate oscillation scenarios such as sterile neutrinos; and iv) searching for evidence of CPT violation using muon anti-neutrinos. The analyses described below represent and exposure of 3.2×10^{20} protons incident on the target in the NuMI neutrino beam.

ν_μ *Disappearance*

MINOS measured the value of $|\Delta m^2_{32}| = (2.43 \pm 0.13) \times 10^{-3}$ eV^2 by comparing the rate of charged-current muon neutrino interactions in the far detector with the prediction based on the near detector data. The data showed a clear energy dependent deficit as seen in Figure 2. The 90% confidence interval for the best fit in $\Delta m^2_{32} - \sin^2(2\theta_{23})$ space is shown in Figure 3. As seen by the comparisons to other experiments in this figure, MINOS has made the most precise measurement of Δm^2_{32} to date [6].

ν_e *Appearance*

The NuMI neutrino beam in which the MINOS detectors operate is composed of 99% muon neutrinos and anti-neutrinos. The remaining 1% are electron neutrinos and anti-neutrinos. MINOS has made an initial search for electron neutrino appearance in the beam. This analysis requires knowledge of the electron neutrino content of the beam as well as the ability to distinguish electromagnetic showers associated with electron neutrino charged-current interactions from hadronic showers. The charged-current electron neutrino interactions in both detectors are identified through the use of an artificial neural net that makes use of variables based on event topologies designed to differentiate hadronic and electromagnetic showers. The analysis is based on the total number of observed electron neutrino events at the far detector. The Monte Carlo simulation predicts a total of $27 \pm 5(stat.) \pm 2(syst.)$ events in the absence of electron neutrino appearance, while 35 events are observed at the far detector. These data are fit to determine the values of the CP violating phase, δ and $\sin^2(2\theta_{13})$ that best describe the observed appearance. The best fit value for $\sin^2(2\theta_{13})$ is very close to the CHOOZ limit [11]. The next analysis of MINOS data will involve twice the current exposure and may be able to exclude $\sin^2(2\theta_{13}) = 0$ at greater than the 90% confidence level.

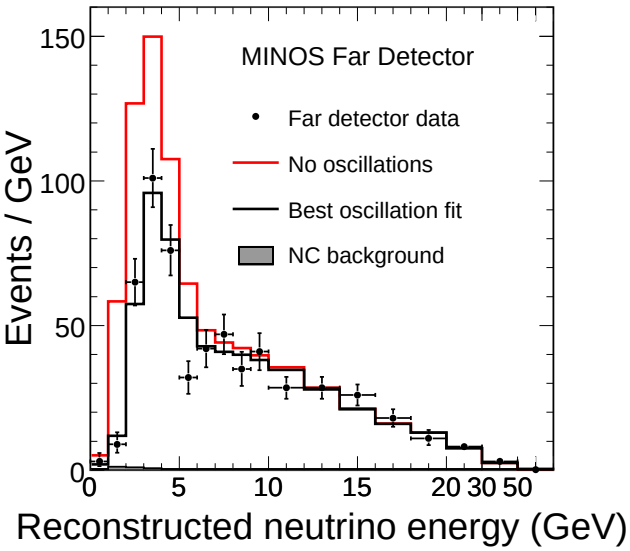

Fig. 2. MINOS charged-current spectrum at the far detector. There is a clear energy dependent deficit of observed events compared to the Monte Carlo prediction.

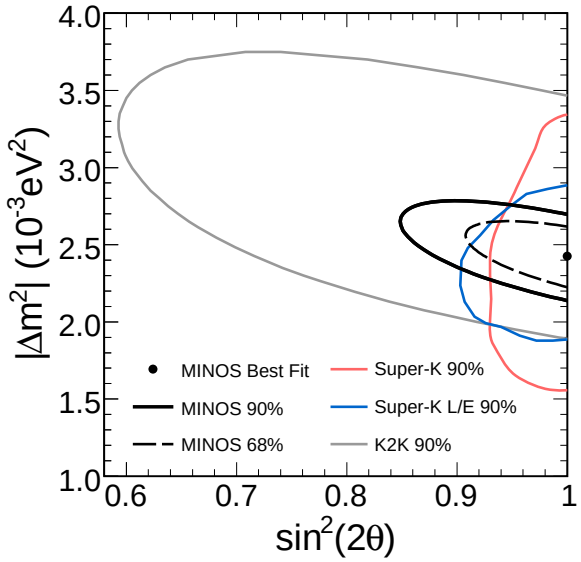

Fig. 3. MINOS 90% confidence level contour compared to other long-baseline experiments. MINOS has the most precise measurement of Δm^2_{32} to date.

Sterile Neutrino Search

As mentioned above, there may be more neutrino species than the three active flavors. If so, then the new species must not couple to the electroweak current as measurements of the Z boson decay width indicate there are only three light active neutrinos [12]. These potential new species are referred to as sterile neutrinos and offer a possible resolution to several outstanding problems in particle physics and astrophysics. For example, sterile neutrinos with masses at the eV energy scale can participate in the seesaw mechanism to introduce neutrino masses [13] and can also aid in heavy element nucleosynthesis in supernovae [14]. MINOS has searched for evidence of sterile neutrinos using neutral-current interactions in its detectors as all light active species participate in such interactions. The far detector spectrum for these interactions along with the Monte Carlo predictions assuming oscillations among the active flavors with and without nonzero θ_{13} is shown in Figure 4. These data were fit to two models that each allow for the inclusion of one sterile species in the neutrino oscillations. One model assumes that the corresponding fourth mass eigenstate is degenerate with the first, and the other assumes that the fourth mass eigenstate is much heavier than the others, with $\Delta m^2_{41} \sim 1$ eV^2. The best fits to the data are used to limit the fraction of disappearing muon neutrinos that could have converted to the sterile species. That fraction is limited to be less than 52% for the case without electron neutrino appearance in the beam and 55% with electron neutrino appearance.

CPT Violation Search

The NuMI beam has a contamination of 5% muon anti-neutrinos when operated in the mode to produce muon neutrinos. These anti-neutrinos were used to search for CPT violation in the first observation of muon anti- neutrinos from an accelerator beam. The data were selected using the magnetized steel in both detectors in order to determine the charge sign of the muons produced in charged-current interactions. As with the electron neutrino appearance analysis, this analysis is based on the total number of muon anti-neutrinos observed at the far detector. The Monte Carlo prediction for the far detector is $58.3 \pm 7.6(stat.) \pm 3.6(syst.)$ for the CPT conserving case while 42 events were observed, a 1.9σ discrepancy. The energy spectrum represented by these data was fit for the oscillation parameters governing anti-neutrinos, $\Delta\overline{m}^2_{32}$ and $\sin^2(2\overline{\theta}_{23})$. As seen in Figure 5., the 90% confidence region for this fit overlaps with the 90% confidence region from the MINOS muon neutrino disappearance analysis. Also seen in the figure is the region of CPT-violating parameter space previously allowed by global fits to various neutrino experiments that has been excluded by the MINOS analysis. MINOS is currently taking data from the NuMI beam in anti-neutrino mode and will be able to significantly narrow the allowed region with as small of an exposure as 1×10^{20} protons on target.

2.3. *Opera*

Opera is an experiment operating in the CNGS neutrino beam. It has a similar baseline to MINOS, 730 km, and has been taking data since 2008. The experiment is looking for the appearance of tau neutrinos in a beam of muon neutrinos in order to verify that oscillations occurring with the atmospheric mass-squared splitting are best described by $\nu_\mu \rightarrow \nu_\tau$ oscillations. The experiment had an exposure of 1.8×10^{19} protons on target in 2008. The Monte Carlo simulation predicted a total of 0.7 tau neutrino interactions in the detector for that exposure. Opera began taking data again in June, 2009 and expects to have a total exposure of 3.2×10^{19} protons on target by the end of the 2009 data taking. The possibility of observing a tau neutrino in the total data set is quite good.

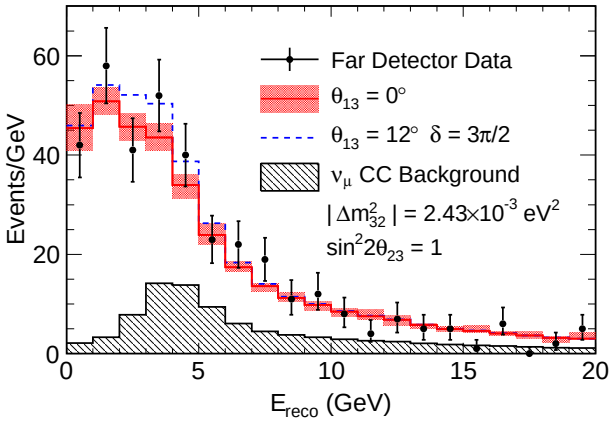

Fig. 4. MINOS neutral-current spectrum at the far detector. The data are well described by the Monte Carlo prediction for oscillations among the three active flavors, either with no electron neutrino appearance or with the appearance allowed by the CHOOZ limit for θ_{13}.

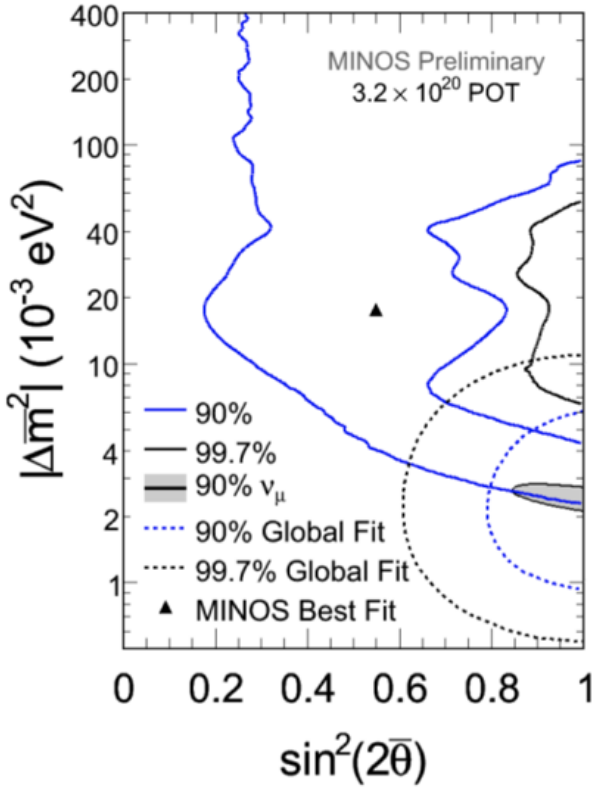

Fig. 5. Allowed 90% confidence interval for $\Delta\overline{m}^2_{32}$ and $\sin^2(2\overline{\theta}_{23})$ for the MINOS muon anti-neutrino analysis.

3. Future Experiments

The current generation of neutrino experiments has made precision measurements of the majority of the parameters describing neutrino mixing and masses. The next generation of experiments will focus on the following key parameters, θ_{13}, the CP violating phase δ, and the location of the third mass eigenstate relative to the other two, also known as the mass hierarchy. To make the required measurements, the future experiments will need far detectors with substantial fiducial mass in order to observe as many interactions as possible. These experiments will also need to have good efficiency for identifying the signal ν_e charged-current interactions in order to observe ν_e appearance in the beam. The use of a narrow band beam will also enable the experiments to maximize the oscillations of the beam neutrinos as those neutrinos will all have the correct energy given the size of the mass-squared splitting.

There are currently two long-baseline experiments under construction to determine these parameters, NOνA and T2K. NOνA is a liquid scintillator detector where the scintillator is housed in extrusions of PVC. The far detector will have a total mass of 14 kt and will be located 813 km from the neutrino source. T2K will use Super-Kamiokande as its far detector and the neutrino source is 295 km from the far detector. Both experiments will make measurements of $\sin^2(2\theta_{13})$, however only NOνA has sensitivity to δ and the mass hierarchy. The reason that NOνA has sensitivity to the mass hierarchy and CP violating phase is its longer baseline. That baseline allows the electron neutrino component of the beam to have a significant forward scattering off the electrons in the matter between the source and the far detector. This forward scattering will either enhance or suppress the electron neutrino appearance in the beam depending on the size of the phase and whether the beam is composed of neutrinos or anti-neutrinos. The shorter baseline of T2K does not intersect enough material between the source and detector to observe a significant matter effect.

Thus, NOνA and T2K are complimentary experiments; both experiments can measure electron neutrino appearance in a beam of muon neutrinos, while NOνA will also have sensitivity to processes that T2K cannot observe. NOνA will take data with the NuMI beam in both neutrino and anti-neutrino mode in order to measure the mass hierarchy and δ. The combination of the NOνA data with the T2K data will allow an improved sensitivity to certain regions of phase space for the mass hierarchy determination, with the combined sensitivity shown in Figure 6.. Despite NOνA's longer baseline, it will still be unable to measure δ to the desired 3σ level; such a measurement will have to wait for the next generation of experiments.

The JPARC proton beam which will produce the neutrino beam for T2K was commissioned in April, 2009. T2K will begin data taking in the winter of 209-2010 with an initial beam power less than the designed power and then increase the beam power to the design value. NOνA broke ground for its far detector in May, 2009. The first 2.5 kt of the far detector will be built in the spring of 2012, and the full detector will be completed in summer of 2013.

The experiments built after NOνA and T2K must be even larger and at longer baselines in order to make the desired 3σ sensitivity measurement of δ. Both the United States and Japan are looking into building such experiments. Those experiments will also allow for the first observation of both the first and second neutrino oscillation maxima. Current and new detector technologies are being explored for these experiments. The primary options appear to be water Cherenkov and liquid argon detectors.

4. Summary

Long-baseline experiments have provided a wealth of information about neutrino oscillations. The current generation of experiments have illuminated the general hierarchy of the neutrino masses by making precision

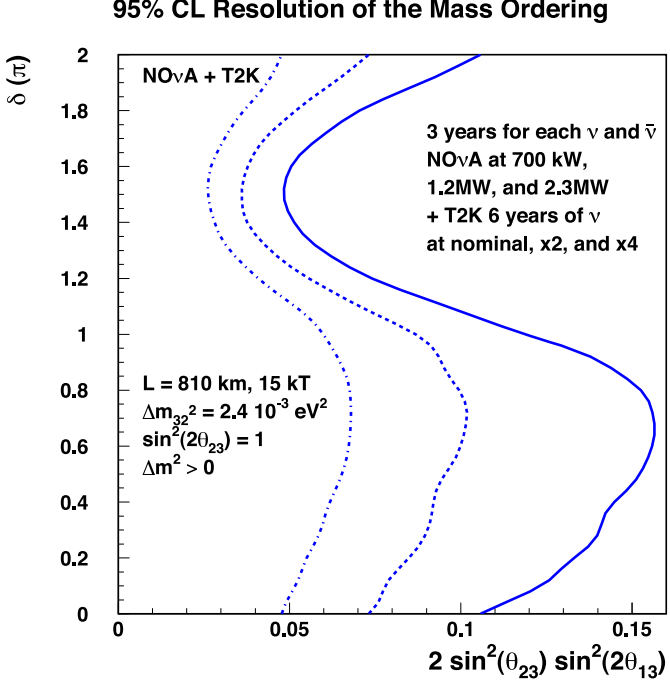

Fig. 6. 95% confidence level sensitivity to the mass hierarchy for the combination of NOνA and T2K data.

measurements of the mass-squared splittings as well as making precision measurements of several of the mixing angles. These experiments have also tested more exotic physics such as the existence of sterile neutrinos and possible CPT violation. The next generation of experiments will provide precision measurements of the remaining mixing angle, resolve the mass hierarchy, and point to the value of the CP violating phase δ. It will be up to experiments that are currently in the conceptual design phase to make a precision measurement of δ as well as illuminating the surprises in neutrino physics that are sure to surface in the next several years.

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