A REVIEW OF LONG-BASELINE NEUTRINO OSCILLATION EXPERIMENTS*

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In this paper, I will review the status of current and planned accelerator-based long-baseline neutrino oscillation experiments which are sensitive to the oscillation parameters associated with the atmospheric neutrino mass-scale, and are designed to precisely determine the parameters of the PMNS neutrino mixing matrix.

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1. Introduction

The phenomenon of neutrino oscillations is now firmly established by a variety of experiments detecting solar and atmospheric neutrinos (see [1] and references therein). The measurements are described by mixing between the three neutrino flavour and mass eigenstates, which is conventionally described in the PMNS parameterisation as a 3×3 unitary mixing matrix with three Euler angles $(\theta_{12},\theta_{13},\theta_{23})$, and one non-trivial CP-violating phase, δ.

Simplifying to the two-flavour approximation, the probability for a neutrino of flavour α with energy E (in GeV) to oscillate to a different flavour β after travelling a distance L (in km) can be written as:

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

where $\Delta m^2 = m_i^2 - m_j^2$, is the squared-difference between the neutrino mass eigenstates i and j. The current experimental data can be explained by two independent mass-splittings associated with solar and atmospheric neutrino oscillations: $\Delta m^2_{\rm atm} = 2.4\times10^{-3}$ eV^2 and $\Delta m^2_{\rm sol} = 7.7\times10^{-5}$ eV^2. The

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mixing angles associated with solar and atmospheric oscillations are large, $\sin^2\theta_{12} = 0.304^{+0.022}_{-0.016}$ and $\sin^2\theta_{23} = 0.50^{+0.07}_{-0.06}$. The angle θ_{13} is as yet unmeasured but is known to be small ($\sin^2\theta_{13} < 0.035$, 90% C.L.) [1]. In addition, the value of the CP-violating phase, δ, and the ordering of the neutrino masses, either normal hierarchy ($m_3 \gg m_1$) or inverted hierarchy ($m_1 \gg m_3$), are unknown. Neutrino oscillation models invoking a fourth (sterile) neutrino species are strongly constrained by existing data, including the recent results from the MiniBooNE experiment [2].

Experiments using accelerator-based sources of neutrinos and long experimental baselines are important tools to address these currently unanswered questions in neutrino physics, and to precisely measure the oscillation parameters. In such experiments, the flavour content, neutrino energy spectrum and experimental baseline are chosen to maximise the size of the oscillation effect predicted by Eq. (1).

A significant advantage of long-baseline experiments lies in the use of two similar detectors. In this approach a 'Near' detector placed close to the accelerating source measures the initial neutrino energy spectrum and flavour composition, and a 'Far' detector measures the energy spectrum and flavour composition after the neutrinos have travelled a sufficient distance for flavour oscillations to occur. The large uncertainties in neutrino flux prediction and neutrino cross-sections (which are poorly known in the few-GeV energy region [3]) significantly cancel when data from the two detectors are compared.

In this paper I will focus on existing and future accelerator-based long-baseline experiments which typically employ ν_μ beams (produced chiefly from pion decays) and are sensitive to the atmospheric neutrino mass splitting ($L/E \sim 10^2$ km/GeV). The role of reactor-based experiments, which are also an important tool to measure the unknown parameter θ_{13} of the PMNS mixing matrix, are described elsewhere [4].

2. Past/current experiments

2.1. K2K

K2K [5] was the first accelerator-based long-baseline neutrino oscillation experiment. The neutrino beam was provided by 12 GeV protons at the KEK PS, which produced a 98.8% pure $\nu_\mu + \bar{\nu}_\mu$ beam peaked at approximately 1 GeV. The beam was pointed at the existing 50 kT Super-Kamiokande Water Cherenkov detector, providing an experimental baseline of 250 km. Several Near detectors were used, including a 1 kiloton Water Cherenkov device to measure the neutrino flux at the KEK site, and two fine-grained detectors to measure the rate of quasi-elastic (QE) and non-QE scattering processes, the ν_e beam content and the rate of π^0 production, which is the main background for $\nu_\mu \to \nu_e$ searches. The prediction of the neutrino flux at Super-Kamiokande was obtained by multiplying the measured flux from the Near detectors with the Far/Near flux ratio derived from particle production data measured on the K2K aluminium target. K2K collected data from June 1999 to August 2004, accumulating a total of 0.922×10^{20} protons on target (POT).

The ν_μ disappearance results from K2K are summarised in Fig. 1. In total, 112 ν_μ charged-current candidates were observed in Super-Kamiokande, with an expectation of 158.1 (assuming no oscillations). In addition, a distortion of the Far detector energy spectrum was measured in 58 single Cherenkov ring events (mainly ν_μ QE interactions) consistent with neutrino oscillations. The allowed range of the mixing parameters, assuming $\nu_\mu \to \nu_\tau$ oscillations, are $\sin^2 2\theta_{23} > 0.6$ and $1.9 < \Delta m^2_{\rm atm} < 3.1 \times 10^{-3}$ eV^2, with a best-fit of $\Delta m^2_{\rm atm} < 2.8 \times 10^{-3}$ eV$^2, \sin^2 2\theta_{23} = 1.0$ [5]. The allowed region (90% C.L., 2 d.o.f.) shown in Fig. 1 is in good agreement with the Super-Kamiokande atmospheric neutrino analysis [6].

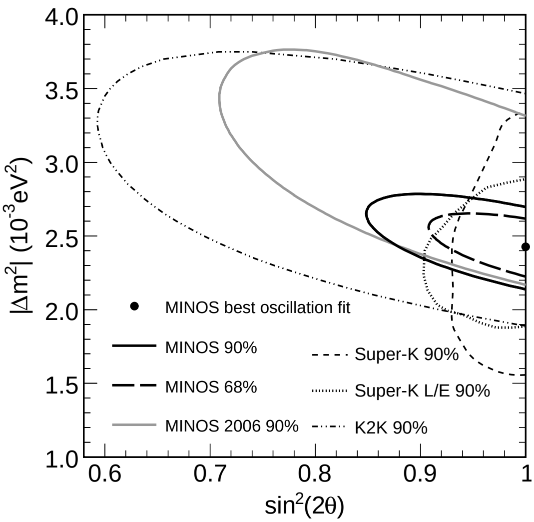

Fig. 1. Allowed regions for the mixing parameters $\Delta m^2_{\rm atm}$ and $\sin^2 2\theta_{23}$ for MINOS and K2K, compared to results from the Super-Kamiokande atmospheric experiment.

A search for sub-dominant $\nu_\mu \to \nu_e$ oscillations at the atmospheric neutrino mass-scale was also carried out by K2K, by looking for an excess of neutrino candidates with electron-like Cherenkov rings in Super-Kamiokande. A single candidate event was observed, consistent with the background estimate from single π^0 production and the intrinsic ν_e component of the beam. From this data, a limit on the mixing angle θ_{13} was derived. At the best-fit value of $\Delta m^2_{\rm atm}$, a limit of $\sin^2 2\theta_{13} < 0.26$ was obtained at 90% C.L. [7]. This compares to the current best experimental limit of $\sin^2 2\theta_{13} < 0.1$ from the CHOOZ reactor experiment [8].

2.2. MINOS

The MINOS experiment utilises a 250 kW neutrino beam provided by 120 GeV protons from the Fermilab Main Injector, and two similar iron/scintillator sampling calorimeters: a 980 T Near detector located at the Fermilab site, and a 5.4 kT Far detector situated in the Soudan Underground Mine, MN, at a distance of 735 km from the neutrino source. The neutrino beam (98.5% $\nu_\mu + \bar{\nu}_\mu$) is produced from decays of pions and kaons created by the protons impinging on a graphite target. The position of the target can be adjusted relative to the first focussing horn, producing a continuously variable neutrino energy spectrum. The most recent results published by MINOS were derived from 3.36×10^{20} POT recorded between May 2005 and July 2007 [9], which consisted of 3.2×10^{20} POT recorded in the low energy beam configuration (peak energy ~ 3 GeV) and 0.15×10^{20} POT in the high energy configuration (peak energy ~ 10 GeV).

The primary physics goal of MINOS is a precision measurement of the oscillation parameters $\Delta m^2_{\rm atm}$ and $\sin^2 2\theta_{23}$ via ν_μ disappearance. The ν_μ charged-current energy spectrum at the Far detector location is predicted using the measured energy spectrum in the Near detector. A beam transfer matrix is used to translate the true energy spectrum from Near to Far, after correcting for energy smearing and event selection efficiencies. A total of 730 muon-like events recorded in the low energy beam configuration was observed in the Far detector, with a no-oscillation expectation of 936. In the high energy configuration, 118 events were observed with an expectation of 129. A strong energy-dependent suppression of the event rate is seen, and the best fit oscillation parameters are $\Delta m^2_{\rm atm} = 2.43 \pm 0.13 \times 10^{-3}$ eV^2 and $\sin^2 2\theta_{23} = 1.0_{-0.1}$ (90% C.L., 1 d.o.f.) [9]. The allowed region shown in Fig. 1 is in good agreement with K2K and Super-Kamiokande, and represents the most precise measurement of $\Delta m^2_{\rm atm}$ to date.

MINOS has also presented a measurement of the neutral current energy spectrum in the Far detector, for 2.45×10^{20} POT, in order to search for $\nu_\mu \to \nu_s$ oscillations, where ν_s is a sterile neutrino. Such a transition would produce a deficit in the number of observed neutral current interactions. No significant depletion is observed, which provides additional support to the $\nu_\mu \to \nu_\tau$ oscillation hypothesis, and sets a limit on the fraction, f_s, of ν_μ oscillating to ν_s at the atmospheric mass-scale of $f_s < 0.68$ (90% C.L.) [10]. MINOS also has sensitivity to sub-dominant $\nu_\mu \to \nu_e$ oscillations via the search for an excess of events in the Far detector with energy depositions consistent with electromagnetic showers. The sensitivity of this analysis, with the existing data sample, is expected to be competitive with the CHOOZ limit[1].

2.3. OPERA

The OPERA experiment [12] is designed to search for ν_τ appearance via the observation of tau decay kinks in a high-resolution nuclear emulsion based detector. The experiment uses a high energy ($\langle E_\nu \rangle = 17\,\mathrm{GeV}$) wide band ν_μ beam (LNGS) produced by the CERN SPS and a hybrid emulsion/tracking detector situated in the Gran Sasso Laboratory and has an experimental baseline of 732 km. The active detector mass of 1.35 kT is composed of 77,000 emulsion bricks, which consist of alternate layers of lead absorber (1 mm thickness) and nuclear emulsion (44 μm thickness). The location of interaction vertices within a particular brick is determined from extrapolation of measured tracks in scintillator tracking planes which are located between the 58 brick 'walls'. The bricks containing the candidate interaction vertices are then removed for scanning and event reconstruction.

A total of 1.782×10^{19} POT were recorded during the 2008 LNGS run. Two candidate charm events were observed, consistent with expectations. Analysis of the exposed emulsion bricks is ongoing. Assuming maximal $\nu_\mu \to \nu_\tau$ oscillations with $\Delta m^2_{\mathrm{atm}} = 2.5 \times 10^{-3}$ eV^2, this dataset should contain 1–2 ν_τ candidates. A five-year exposure of the LNGS beam is planned. The expected ν_τ signal, assuming 4.5×10^{19} POT/year is 10.4 events, with a background of less than one event. Due to its fine granularity, the OPERA detector also has good sensitivity to sub-dominant $\nu_\mu \to \nu_e$ oscillations, with a projected limit from a five-year exposure of $\sin^2 2\theta_{13} < 0.06$ at 90% C.L. assuming $\Delta m^2_{\mathrm{atm}} = 2.5 \times 10^{-3}$ eV^2.

3. Near-future experiments

The primary goal of the next generation of long-baseline experiments is to search for evidence of a non-zero value of θ_{13}. In order to achieve this, large and fine-grained detectors are required to separate ν_e charged-current events from background (chiefy single π^0 events); and increased beam power, in order to probe oscillation probabilities that may be of the order of 1%. Two projects are planned: the T2K experiment, which uses a newly-constructed neutrino beamline at the J-PARC facility in Tokai, Japan and the existing Super-Kamiokande detector ($L = 295\,\mathrm{km}$) [13]; and the NOvA experiment,

[1] Following this conference, the MINOS experiment released the first results of this analysis for an exposure of 3.2×10^{20} POT. No significant excess of electron-like events is observed in the Far detector and a limit of $\sin^2 2\theta_{13} < 0.29$ (90% C.L.) is obtained for $\Delta m^2_{\mathrm{atm}} = 2.43 \times 10^{-3}$ eV^2, assuming the normal hierarchy and $\delta = 0$ [11].

which will use an upgraded neutrino beam provided by the existing NuMI facility at Fermilab, and a newly-constructed 15 kT segmented liquid scintillator detector located at Ash River, MN ($L = 810$ km) [14]. Both experiments use the 'off-axis beam' concept, in which the low-energy neutrino flux is enhanced (and the high-energy tail is suppressed) by placing the Far detector one to three degrees off-axis from the neutrino beamline.

The T2K experiment will begin to take data in 2009. The current schedule for NOvA, which is presently awaiting final approval, is for data taking to start in 2012 with a 2.5 kT Far detector, and for the full 15 kT to be completed in 2014. The experiments are expected to be sensitive to $\sin^2 2\theta_{13} \sim 0.01$ after five years of running at the nominal beam powers of 0.77(0.7) kW for T2K and NOvA, respectively. The sensitivity of the two experiments to θ_{13} also depends on the value of the CP-violating phase, δ and the sign of Δm^2_{31} [15].

It is possible to determine the sign of Δm^2_{31} in NOvA by comparing the oscillation probabilities measured in neutrino and anti-neutrino runs. Differences between oscillation probabilities are enhanced in a region of parameter space corresponding to one half of δ by matter effects, which are much larger in NOvA than T2K due to the factor of three longer baseline (see the left-hand plot of Fig. 2 which shows the potential of NOvA to resolve the sign of

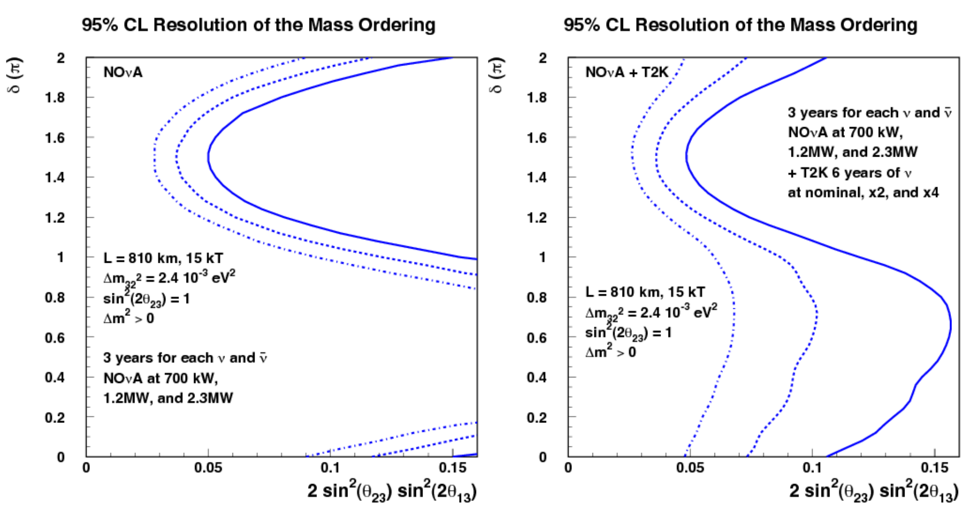

Fig. 2. NOvA/T2K sensitivitity to the mass hierarchy. Left: 95% C.L. resolution of the mass hierarchy (sign(Δm^2_{31})) as a function of δ from NOvA neutrino and anti-neutrino running (normal hierarchy assumed). Right: the same plot for the combination of NOvA and T2K measurements. The lines denote three different assumptions for NOvA and T2K beam power. Plots courtesy [16].

Δm^2_{31} assuming the normal mass hierarchy). Measurements of $P(\nu_\mu \to \nu_e)$ by NOvA and T2K are complementary due to their different sensitivity to matter effects. Additional sensitivity to the mass ordering in the region $0 < \delta < \pi$ is provided by the combination of NOvA and T2K measurements as shown in Fig. 2 (right).

4. Far-future experiments

The third generation of long-baseline experiments (envisaged for the latter part of the next decade and beyond) are currently in the initial planning stages in the USA, Japan and Europe. These experiments call for an order of magnitude increase in detector mass (100–300 kT) and beam power greater than 1 MW. The physics goals of these experiments are to provide sensitivity to non-zero θ_{13}, the sign of Δm^2_{31}, and search for non-zero values of the CP-violating phase δ, for values of θ_{13} well below 10^{-2}. Several detector technologies are being studied, with particular emphasis on Water Cherenkov and Liquid Argon devices. Longer baselines (1000–1300 km) are being considered in order to enhance the matter effect (which is proportional to L) at the first oscillation maximum. Measurements at the first and second oscillation maxima (either by measuring the energy spectrum in a single detector, or placing two detectors at different distances from the neutrino source) are envisaged. Since the matter effect at the second oscillation minimum is much reduced, comparison of measurements at the first and second maximum can help to distinguish between matter and CP-violating effects.

The current proposals are: in the US for a new beamline from an upgraded accelerator complex at Fermilab (2.3 MW beam power) to a large 100–300 kT detector situated in the DUSEL Underground Laboratory ($L =$ 1300 km) [17, 18]; in Japan and Korea for massive 270 kT Water Cherenkov detectors situated at the first (Kamioka, $L = 290$ km) and second (Korea, $L \sim 1000$ km) oscillation maximum from an upgraded (1.66 MW) neutrino beam from J-PARC [19]. In Europe, feasibility studies are underway to assess the possibility of directing high intensity conventional beams or beta ν_e beams from CERN to large ($\sim$ 100 kT) detectors situated in existing European underground laboratories [20].

5. Summary

Since 1998, there has been a paradigm shift in neutrino oscillation studies. With the seminal solar and atmospheric neutrino measurements of Super-Kamiokande and SNO, and their confirmation by a series of experiments using terrestrial neutrino beams, the phenomenon of neutrino oscillations is now well-established. We are now entering into the (precision) measurement phase of the PMNS matrix elements. In this regard, the role of long-baseline accelerator based neutrino oscillation parameters will be crucial. The current generation of experiments (K2K, MINOS and OPERA) are providing precision measurements of the 2–3 sector of the PMNS matrix and are testing the $\nu_\mu \to \nu_\tau$ interpretation of the atmospheric neutrino data. Although these experiments have some sensitivity to θ_{13} beyond current experimental limits, the next generation of long-baseline experiments (T2K and NOvA) will greatly expand the reach of $\nu_\mu \to \nu_e$ oscillation searches. By the middle of the next decade, they will provide sensitivity down to $\sin^2 2\theta_{13} \sim 10^{-2}$ and, in combination, may provide a resolution of the mass hierarchy (sign of Δm^2_{31}) if $\sin^2 2\theta_{13} > 0.05$. In order to extend the sensitivity to lower values of $\sin^2 2\theta_{13}$ and to provide an opportunity of observing CP violation in the lepton sector, a third generation of experiments are planned. These require an order of magnitude improvement in detector size and beam power over existing experiments.

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