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LONG BASELINE NEUTRINO OSCILLATION EXPERIMENTS

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In this article, I discuss the physics motivations for long baseline neutrino experiments and the strategies that are being used and planned at these experiments. I will also give a summary of the experiments that are running or being constructed or have been approved. Very briefly, I will discuss some of the studies done for planning experiments in far future.

Key Words: Long Baseline Neutrinos; Neutrino Survival Probability; CP Violation; K2K; MINOS; ICARUS and OPERA; Neutrino factory

1 Introduction

The deficits observed in the solar[1–5] and atmospheric[6,7,8] neutrino measurements indicate that neutrinos have properties beyond those predicted by the Standard Model. Neutrino oscillations provide the simplest explanation of both the solar[9,10] and atmospheric neutrino[11,12] deficits. If this explanation is correct, it means that

- neutrinos are massive,
- their masses are non-degenerate,
- and they mix among themselves, as the quarks do.

Recent experiments with reactor neutrinos[13] ($\bar{\nu}_e$) and accelerator neutrinos[14] (ν_μ) also show deficits and these deficits can also be explained in terms of neutrino oscillations, *with values of parameters which explain solar and atmospheric neutrino deficits* [14–17]. Hence the evidence for neutrino oscillations is very strong but so far no experiment has unambiguously observed the oscillatory behaviour predicted by neutrino oscillations.

For three active flavour neutrino oscillations, the survival and oscillation probabilities depend on mass-square differences and the elements of the neutrino mixing matrix[18] U_{MNS}. Only two of the mass-square differences are independent and usually they are chosen to be $\Delta_{21} = m_2^2 - m_1^2$ and $\Delta_{32} = m_3^2 - m_2^2$. In analogy to the CKM matrix, U_{MNS} can be parametrized by three mixing angles and a phase. The following parametrization is widely used because it leads to simplified expressions for solar and atmospheric neutrino analysis[19].

$$U_{\rm mns} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad \ldots(1)$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$. The phase, δ, causes the oscillation (but not survival) probabilities for neutrinos and anti-neutrinos to be different and leads to CP violation in lepton sector. To measure this CP violation, one needs data from both neutrino oscillations and anti-neutrino oscillations. The present experiments constrain the neutrino parameters to be in the range[14,17,20]

$$\begin{aligned} &\Delta_{21} : 4 \times 10^{-5} - 3 \times 10^{-4}\ \mathrm{eV}^2 \\ &\tan^2\theta_{12} : 0.25 - 0.85 \\ &|\Delta_{32}| : 1 - 5 \times 10^{-3}\ \mathrm{eV}^2 \\ &\sin^2 2\theta_{23} : 0.8 - 1.0 \\ &0 \leq \delta \leq 180^\circ \\ &\sin^2 2\theta_{13} \leq 0.13 \end{aligned} \qquad \ldots(2)$$

The values of these parameters indicate that the atmospheric neutrino deficit is essentially due to $\nu_\mu \to \nu_\tau$ oscillations, driven by Δ_{32}, and the solar neutrino deficit is due to $\nu_e \to (\nu_\mu + \nu_\tau)/\sqrt{2}$, driven by Δ_{21}. Note that the present experiments determine only the magnitude of Δ_{32} but not its sign. So the hierarchy in neutrino masses is not yet known. The energy dependent suppression observed in different solar neutrino experiments is expected to be generated by the MSW effect[21,22]. This can occur only if Δ_{21} is positive.

2 Physics Motivation

The goals of long baseline neutrino experiments are to

1. explicitly observe the energy dependence in the survival probability $P(\nu_\mu \to \nu_\mu)$,
2. determine $|\Delta_{32}|$ and $\sin^2 2\theta_{23}$ as accurately as possible,
3. measure the value of θ_{13} or improve the upper limit,
4. obtain evidence for the modification of $\nu_\mu \to \nu_e$ oscillation probability due to matter effect and determine the sign of Δ_{32}, and
5. search for CP violation in the lepton sector.

The neutrino beam for these experiments will be generated through a proton accelerator. The mean energy of such a beam will be 1 GeV or more[14,23]. Neutrino oscillations at such energies are insensitive to the small values of Δ_{21} given above. Present and future solar neutrino experiments and the reactor neutrino experiment KamLAND are expected to provide the strongest limits on Δ_{21} as well as $\tan^2\theta_{12}$ [24]. If Δ_{21} is near its upper limit, KamLAND is capable of observing the energy dependent suppression predicted by neutrino oscillations[25]. All long-baseline studies assume that these two neutrino parameters are provided by the above source.

As a first approximation, the small value of Δ_{21} is set equal to zero and one has

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(1.27\frac{\Delta_{32}L}{E}\right) \quad \ldots(3)$$

$$P(\nu_\mu \to \nu_\mu) = 1-\cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2\left(1.27\frac{\Delta_{32}L}{E}\right) - P(\nu_\mu \to \nu_e), \quad \ldots(4)$$

where Δ_{32} is in eV^2, the baseline length L is in km and the neutrino energy E is in GeV. A plot of $P(\nu_\mu \to \nu_\mu)$ vs E, shown in Figure 1, depends essentially on $|\Delta_{32}|$ and θ_{23}, because θ_{13} is very small. A detector capable of measuring the event spectrum can not only observe the energy dependence of $P(\nu_\mu \to \nu_\mu)$ but also determine $|\Delta_{32}|$ (by the location of the minimum of the spectrum) and $\sin^2 2\theta_{23}$ (by the number of events at the minimum) *independently of each other.* To determine these parameters accurately, one needs

$$1.27|\Delta_{32}|L/E \simeq \pi/2 \quad \ldots(5)$$

and high statistics. The next step is determining θ_{13}, which can be done by measuring $\nu_\mu \to \nu_e$ oscillations. From eq.3, we note that $P(\nu_\mu \to \nu_e)$ is maximum at the energy given by eq.5. $\nu_\mu \to \nu_e$ oscillations are also the method through which future experiments will try to observe matter effects and CP violation. To obtain the best $\nu_\mu \to \nu_e$ oscillation signal possible, the energy of the neutrino beam is to be tuned to satisfy eq.5. Hence, in all the experiments, present and future, the energy of the neutrino beam is designed such that the flux is the largest around the energy $E_{\pi/2} = 2.54|\Delta_{32}|L/\pi$.

Neutrinos in a long baseline experiment pass through earth's crust and $\nu_\mu \to \nu_e$ is modified by the forward scattering by the electrons in matter, which is parametrized by the Wolfenstein matter term[21] $A = 2\sqrt{2}G_F N_e E$. Here N_e is the number density of electrons, which is proportional to the density of matter and E is the neutrino energy. The modified oscillation probability is given by

$$P^m(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}^m\sin^2\left(1.27\frac{\Delta_{32}^m L}{E}\right). \quad \ldots(6)$$

The matter modified mass-squared difference and mixing angle in eq.6 are given by

$$\begin{aligned} \Delta_{32}^m &= \sqrt{(\Delta_{32}\cos 2\theta_{23} - A)^2 + (\Delta_{32}\sin 2\theta_{23})^2}, \\ \sin 2\theta_{13}^m &= \sin\theta_{13}\frac{\Delta_{32}}{\Delta_{32}^m}. \end{aligned} \quad \ldots(7)$$

In the case of anti-electrons A is replaced by $-A$. For Δ_{32} positive, the matter term leads to an increase of neutrino oscillation probability and a decrease in the anti-neutrino oscillation probability. For negative Δ_{32}, the situation is reversed. Hence, observing matter effects allows us to determine the sign of Δ_{32} and the hierarchy in neutrino masses. For a baseline of about 250 km, the change due to the matter effect is about

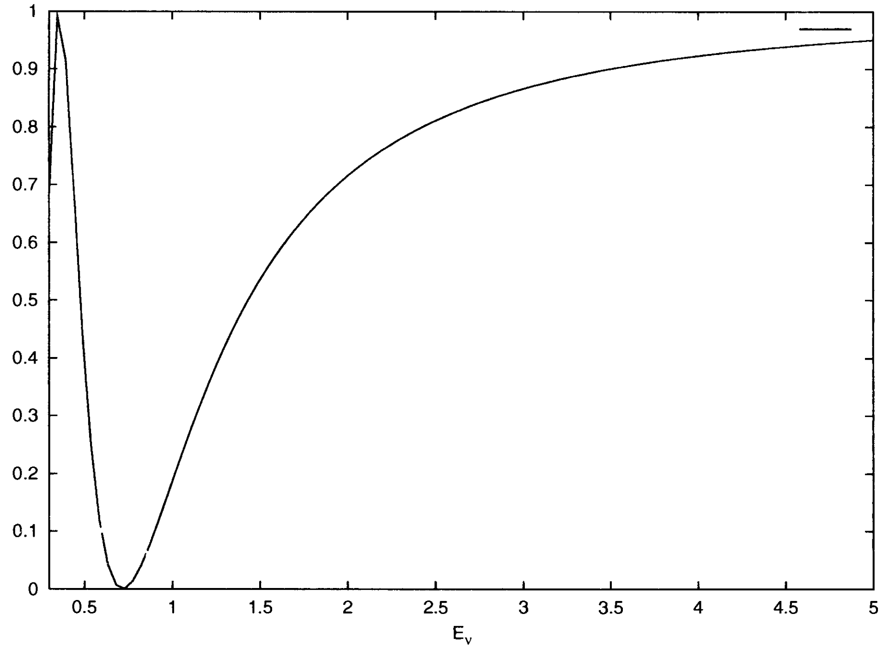

Fig. 1 Plot of $P(\nu_\mu \to \nu_\mu)$ vs E for $|\Delta_{32}| = 3 \times 10^{-3}$ eV^2 and $L = 295$ km.

10%. This change increases to 25% if the baseline is 730 km[26, 27]. Both the phase δ (CP violation) and the term A (matter effects) lead to asymmetries between neutrino and anti-neutrino oscillation probabilities. In general they can be disentangled because the energy dependence of these two effects is different[28]. However, it is possible to design experiments where, in one configuration CP violation asymmetry is dominant and, in another configuration matter term asymmetry dominates.

The longer the baseline, the higher should be the energy of the neutrino beam to satisfy the constraint of eq.5. The neutrino beam is expected to be generated by conventional means: That is by trapping and focussing positively charged mesons in proton-nucleus interactions and letting them decay in a long decay pipe. The resultant beam consists of mostly ν_μs with very small admixture of ν_e ($\leq 1\%$) and even smaller admixtures of $\bar{\nu}_\mu$ and $\bar{\nu}_e$[23, 30]. These experiments use ν_μ beams rather than $\bar{\nu}_\mu$ beams for two reasons. Charge conservation dictates that more positively charged mesons should be produced in proton-nucleus collisions. Also the cross section for ν–N interactions is much larger than that for $\bar{\nu}$–N interactions. Hence a much larger event sample can be obtained by using a neutrino beam. In the cases where CP violation in the neutrino sector is proposed to be studied, there must, of course, be a $\bar{\nu}_\mu$ beam also, which can be obtained by trapping negatively charged mesons produced in proton-nucleus collisions. Data from ν_μ and $\bar{\nu}_\mu$ beams can also provide evidence for matter effects and determine the sign of Δ_{32}, provided the baseline is long enough[27]. However, these physics objectives can also be realized using ν_μ data alone if we have data from one moderate baseline experiment and one long baseline experiment[26] or from only one long baseline experiment with wide band neutrino beam[29].

As mentioned earlier, for an accurate determination of neutrino parameters, we need very large event rates. The event rate, of course, is a product of the neutrino flux and its interaction cross section with the detector material. The ν_μ–N interaction cross section increases with energy. Also it is easier to collect mesons of higher energy and collimate them to produce beams of very high fluxes[23, 31]. So it would seem that high energy beams are more advantageous compared to low energy beams. That, however, is not true because an experiment with higher energy must have a longer baseline to satisfy eq.5. The advantage gained by higher energy is nullified because the neutrino flux falls off as $1/L^2$ and hence, roughly, as $1/E^2$ at the detector location. In the long baseline experiments running or being constructed, the length is determined by locations of existing facilities and the energies of the beams are correspondingly tuned so that eq.5 is satisfied.

The dectectors in long baseline experiments must satisfy certain basic requirements. They should be capable identifying both electrons and muons with high efficiency. They also should be capable of measuring the energies of all final state particles so that the energy of the initial neutrino energy can be determined accurately. Good background separation capability and low cost are other considerations. Water Cerenkov detectors are particularly suitable for these experiments because they have nearly 100% efficiency in identifying muons and electrons[8]. If these experiments have baselines of about 250 – 300 km, there are additional advantanges. For $|\Delta_{32}|$ in the range given by atmospheric neutrino problem, $E_{\pi/2}$ for such baselines is about 0.5 – 1.5 GeV. At these energies, charged current (CC) quasi-elastic scattering is the dominant ν–N interaction and the incident neutrino energy can be measured very accurately by measuring the charged lepton energy and the scattering angle. The neutral current (NC) process $\nu_{\mu,e}N \to \nu_{\mu,e}N\pi^0$, which gives rise to a significant background to ν_e interaction signal, is quite small and can be vetoed, because the energy of the π^0 is small and both the photons from its decay can be reconstructed[30]. Hence these experiments have the best sensitivity to $\nu_\mu \to \nu_e$ oscillations and they have the additional advantage in observing CP violation. As mentioned earlier, matter effects can mimic CP violation but they are small (about 12%) if the baseline is about 300 km. Hence, such experiments are more suitable for measuring CP violation than experiments with longer baselines. I will discuss other types of detectors in conjuction with the corresponding experiments.

3 Long Baseline Experiments

In this section, I discuss the various long baseline experiments that are running or being constructed, their detector capabilities and physics reach.

K2K

K2K is the only long baseline experiment presently running. The neutrino beam from KEK is directed to the Super-Kamiokande water Cerenkov detector 250 km away. The fiducial volume of the detector is about 22.5 ktons. The neutrino beam is produced by a 12 GeV proton beam and and consists of 98% ν_μs with a mean energy of 1.3 GeV. The experiment also contains a near detector 300 meters from the neutrino beam source which measures the flux of neutrinos at very short distance and hence the flux of neutrinos without oscillation. The near detector is designed such that its systematics are very similar to those of Super-Kamiokande. The main motivation of this experiment is to observe neutrino oscillations in ν_μ disappearance mode, that is, to measure $P(\nu_\mu \to \nu_\mu)$ as a function of energy. They expect to take data for an integrated flux which corresponds to 10^{20} protons on target (POT). So far, data with half of this flux has been collected and the results are presented in ref.[14].The expected number of events in the case of no oscillations can be calculated by scaling the flux measured by the near detector. They expected to observe 80 ± 6 muon events but have observed only 44. For 29 of the 44 events they were able to reconstruct the energy of the neutrino. The shape of the energy distribution is in agreement with neutrino oscillation hypothesis with the best fit point at $|\Delta_{32}| = 2.8 \times 10^{-3}$ eV^2 and $\sin^2 2\theta_{23} = 1$. Since the statistics are small, it is not possible to constrain the neutrino parameters strongly. At 90% C.L., the constraints are $|\Delta_{32}|$: 0.001 eV^2 - 0.1 eV^2 and $\sin^2 2\theta_{23} \geq 0.4$. The probability that no oscillation hypothesis can explain the shape of the energy distribution is about 1%. In principle, K2K is also sensitive to $\nu_\mu \to \nu_e$ oscillations. However, due to low statistics, it cannot improve the CHOOZ limit on $\sin^2 2\theta_{13}$.

MINOS

In MINOS experiment, a neutrino beam from Fermilab will be directed at a detector in Soudan mine 735 km away. The neutrino beam is generated by impinging 120 GeV protons on a graphite target. The horn focussing system has been designed such that the mean energy of the beam can be varied between 3–18 GeV[32]. During the first run, MINOS is expected to run in the low energy configuration (with energies in the range 1–6 GeV) so as to satisfy the condition of eq.5. The beam intensity is 3.8×10^{20} POT. The ν_e component of the beam is expected to be less than 1%. The MINOS experiment also has a near detector to measure the neutrino flux without oscillations and it is designed to have the same systematics as the far detector. The detectors consist of magnetized steel layers interspersed with scintillator strips. The mass of the far detector is 5.4 kton. This detector has both good muon detection efficiency and good calorimetry.

It detects ν_μ CC events by looking for high energy muons. It also measures the total energy of both CC and NC events. The main physics goals are to observe the oscillatory behaviour in the energy distribution of muon events and an accurate determination of $|\Delta_{32}|$ and $\sin^2 2\theta_{23}$. Since it can observe NC events also, it is capable of measuring the total active flavour neutrino flux at the far detector and obtain limits on ν_μ oscillations into sterile flavours, much as SNO has determined limits on ν_e oscillations into sterile flavours[5]. Data taking is expected to start in December 2004 and with 10 kton-year of data, MINOS expects to determine $|\Delta_{23}|$ and $\sin^2 2\theta_{23}$ to 10% accuracy.

MINOS can also search for $\nu_\mu \to \nu_e$ oscillations which occur due to non-zero value of θ_{13}. The background due to ν_e component of the beam is known from the near detector data. However, NC events from high energy neutrinos form a substantial background to the electron signal in the detector and severely limit the sensitivity. With 10 kton-year of data, they expect to improve the CHOOZ limit on $\sin^2 2\theta_{13}$ by a factor of 2. It is found that the intensity of the neutrino beam is sharply peaked at low energies at locations which are a few degrees off the beam axis. There are efforts to construct an experiment at an off-axis site to improve the sensitivity to $\nu_\mu \to \nu_e$ oscillations[33].

ICARUS and OPERA

ICARUS and OPERA are two neutrino experiments being planned in the Gran Sasso Underground Laboratory. The neutrino beam will be produced by the interactions of 400 GeV protons extracted from SPS at CERN, 735 km away. These neutrinos have very high energy with a mean of 18 GeV which makes them suitable for the detection of ν_τs produced by the oscillations of ν_μs[34]. An intensity of about 4.5×10^{19} POT is envisaged. With the oscillation parameters given in eq.2, the number of ν_μ CC interactions at Gran Sasso is about 2600/kton/year and the number of τs produced will be 15/kton/year. The experiments are expected to start in 2006. The great challenge for these experiments is to isolate and efficiently identify the τs from the huge number of ν_μ CC events. The OPERA experiment will use a detector made of nuclear emulsions and will detect the τ by reconstructing the primary neutrino interaction vertex and the kink produced by τ decay. The decay channels investigated are τ decaying into an electron or a muon or one charged hadron. The background in these channels is small enough that OPERA expects to discover unambiguous evidence for $\nu_\mu \to \nu_\tau$ oscillations in 5 years of data taking.

ICARUS detector is based on the principles of very good particle identification and of reconstructing event kinematics with enough precision to select interesting events. It relies on the possibility to do 3 dimensional imaging of events in a time projection chamber filled with liquid argon. The whole detector consists of multiple modules of 300 tons, with typical size 4 m × 4 m × 20 m. The final detector is expected to have a size of 3000 tons. ICARUS will search for ν_τ production by looking for $\tau \to \nu_\tau e \bar{\nu}_e$. The ν_e component of the neutrino beam gives rise to a large background for this process via the deep inelastic scattering $\nu_e N \to eX$. But the signal events have a large missing energy due to final state neutrinos whereas the background events have much less missing energy. Hence a cut on missing energy provides a clean sample of $\nu_\tau \to \nu_\tau e \bar{\nu}_e$ events and can confirm $\nu_\mu \to \nu_\tau$ oscillations in 5 years of data taking. Because of its excellent electron identification capability and energy measurement ICARUS is sensitive to $\nu_\mu \to \nu_e$ oscillations also. The main background here comes from the ν_e component of the beam. With 5 years of data, ICARUS can improve the limit on $\sin^2 2\theta_{13}$ by a factor of 2 compared to the CHOOZ limit.

JHF-Kamioka

This experiment is a high statistics version of the K2K experiment. A very high intensity narrow band neutrino beam, produced by the High Intensity Proton Accelerator (HIPA) at the Japanese Hadron Facility (JHF), will be directed towards the Super-Kamiokande detector 295 km away[30]. In the first phase, the intensity of the beam is about 10^{21} POT per year. To achieve the best results, the direction of the beam will be designed such that the Super-Kamiokande detector will be 2° off-axis. Such a beam will have a sharp peak in neutrino spectrum at 0.7 GeV, which is $E_{\pi/2}$ for this baseline length. The ν_e contamination is expected to be about 1%. This experiment also has a near detector to measure the neutrino flux and neutrino spectrum without oscillation. With 5 years of data taking, the experiment expects to measure $|\Delta_{32}|$ to an accuracy of 10^{-4} eV^2 and $\sin^2 2\theta_{23}$ to an accuracy of 1%. For the same period of running, it can discover $\nu_\mu \to \nu_e$ oscillations if $\sin^2 2\theta_{13} \geq 0.02$ or, in the case of no signal, set an upper limit of 0.006. By measuring the rate of the NC reaction $\nu N \to \pi^0 \nu N$, the experiment also expects to constrain the probability of ν_μ oscillating into a sterile neutrino.

In the second phase of the experiment, a 5-fold increase in the flux is envisaged. In addition, a 1 megaton fiducial volume Hyper-Kamiokande water Cerenkov detector is also being planned. With these increases in the flux and detector size, the event rates will go up by a factor of 200 and the experiment will observe $\nu_\mu \to \nu_e$ oscillations for values of $\sin^2 2\theta_{13} \geq 0.002$ or will set an upper limit $\sin^2 2\theta_{13} \leq 4 \times 10^{-4}$ in two years of data taking. With six years of additional data using $\bar{\nu}_\mu$ beam, the experiment can measure CP violation in the neutrino sector if $\delta \geq 20°$. In addition, this experiment can also improve the limit on proton lifetime to 3×10^{34} year with 20 mton-years of exposure.

Very Long Baseline Experiments

Recently two studies were conducted to explore the possibility of measuring very small values of θ_{13} and observe evidence for matter effects using very long baselines. The first proposal is an extension of the JHF-Kamioka and is mainly directed towards determining the sign of Δ_{32}. In this proposal the neutrino beam from JHF, with 10^{21} POT per year, will be directed to a 100 kton water Cerenkov detector 2100 km away. Five years each of data will be taken at two energies $E = E_{\pi/2} = 6$ GeV and at $E = 4$ GeV with only ν_μ beam. With such data, the sign of Δ_{32} can be established at the 3σ level if $\sin^2 2\theta_{13} \geq 0.04$[35]. In the second proposal a wide band neutrino beam, with energy in the range 0.5 – 7 GeV, from Brookhaven laboratory will be aimed at a 500 kton water Cerenkov detector at Homestake 2540 km away. The intensity of the beam again is 10^{21} POT per year. With 5 years of data, this experiment has a sensitivity reach of 0.004 for $\sin^2 2\theta_{13}$ and it can also determine the sign of Δ_{32} if $\sin^2 2\theta_{13} \geq 0.02$. This experiment will also be capable of searching for $\nu_\mu \to \nu_e$ oscillations driven by Δ_{21} in the appearance mode if $\Delta_{21} \geq 6 \times 10^{-5}$ eV^2[36].

In addition, neutrino factories, with very intense ν_e and ν_μ beams coming from muon storage rings, are being discussed. Because the energy of the muon in a muon storage ring will be very large (about 50 GeV), the energy of the neutrino beam also will be quite large (greater than 10 GeV). Hence these experiments necessarily will have very long baselines (3,000–7,000 km). For a discussion of the physics potential of these experiments, see ref.[37,38], and also the article by D. Indumathi in this volume.

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