Atmospheric and accelerator neutrinos

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Abstract. Results from the atmospheric neutrino measurements are presented. Evidence for the $\nu_\tau$ appearance in the atmospheric neutrino events was shown by statistical methods. The long baseline oscillation experiment using man-made neutrinos has confirmed the atmospheric neutrino oscillation. The future accelerator experiments are briefly discussed.

1. Atmospheric neutrinos[1, 2, 3]

In the frame work of the two flavor oscillation, the oscillation probability is shown by

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta_{23} \sin^2 (1.27\Delta m^2_{23} L/E).$$

The wave length of the oscillation, $\lambda = 4\pi E/\Delta m^2$, is proportional to the energy, $E$, of neutrinos. Therefore, the oscillatory behavior may be seen in the $L/E$ plot. The mixing angle behaves as a strength of the oscillation. The typical half wave length, $\lambda/2$, for the atmospheric neutrinos with the energy of 1GeV and for $\Delta m^2 = 2.5 \times 10^{-3}$ eV$^2$ is $\sim 500$ km.

The atmospheric neutrinos are produced through the interactions of the primary cosmic rays in the atmosphere. The atmospheric neutrinos consist of the mixture of $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_e$, $\bar{\nu}_e$. In the recent development, the secondary particles produced by the primary interactions are treated in three dimensional[4, 5]. The error of the absolute neutrino flux is estimated to be about 15% for the low energy neutrinos below 10 GeV and the uncertainty of 0.05 for the primary CR spectrum index above 100 GeV is assigned.

The zenith angle distribution is a key to the oscillation analysis. The uniformity of the primary cosmic rays beyond the energy above the geomagnetic cut off indicates the up-down symmetric distribution of the neutrino flux. Uncertainty of the ratio is 1~2% for the entire energy range and uncertainty of the horizontal and vertical ratio which is used for the upward going muon analysis is about 2% which mostly come from the uncertainty of the K productions in the hadronic interactions.

Super-Kamiokande-I (SK-I), took data between May-1996 and July-2001, was equipped with 11,146 photo-multiplier tubes (PMTs) of 50cm in diameter providing 40% photo-cathode coverage of the inner surface of the detector. SK-II has started in December 2002 and is running as of July 2005 with a reduced photo-cathode coverage of roughly 20% due to the tragic accident happened in Nov-12 in 2001 by which nearly 6,777 PMTs were lost in a couple of seconds. We expect to start the full restoration work in October 2005 and so called SK-III with all the PMTs back will be taking data by the summer, 2006.
1.1. L/E analysis and parameter determination[6]
Since the oscillation wave length is proportional to the neutrino energy, E, therefore you can expect to observe a sinusoidal behavior in the L/E plot. This oscillatory pattern also distinguishes other exotic hypotheses. On the other hand, this analysis gives strong constraint on the determination of $\Delta m^2$, since the position of the dip corresponds directly to $\Delta m^2 (\lambda/E = 4\pi/\Delta m^2)$. However, the L/E plot for all the data decreases monotonously and does not reveal any oscillatory patterns at all. We need to select the events with good L/E resolution in order to observe the expected pattern.

We therefore have selected those events with $\delta(E/L) < 70\%$. The selection basically has removed horizontally going events and low energy events. The rejected events poorly determine L. The 2726 events, which are about 1/5 of the total 15726 events, have remained after the cuts for the SK-I data.

The dip was observed at around 500 km/GeV, which provides strong confirmation of the neutrino oscillation. This first dip observed cannot be explained by other hypotheses, and we have rejected those hypotheses with significance of 3.4 $\sigma$ for decay and 3.8 $\sigma$ for decoherence.
Even if we have altered the resolution cut from 50% to 90% at every 10% step, the obtained $\Delta \chi^2$ for those hypotheses does not change. The results, therefore, are very robust.

The best fitted oscillation parameters of $(\Delta m^2, \sin^2 2\theta) = (2.4 \times 10^{-3} \text{ eV}^2, 1.00)$ for the physical region were obtained. The allowed parameter regions are shown in Fig. 1 as three different lines for the different confidence levels at 68%, 90% and 99% from the inner line to the outer lines. The obtained regions are consistent with that from the standard analysis and give much stronger constraint on $\Delta m^2$ even with fewer events.

The analysis including the data from SK-II is under study, but the preliminary plot for the combined data set is shown in Fig. 2.

1.2. Two flavor analysis with finer binning

The standard zenith angle analysis gives good constraint for the mixing angle, and the L/E analysis for the mass square difference. What is the best analysis by taking into account of the advantages of each analysis?

The finner binning data enable us to follow the oscillation behavior much better. Especially, high energy data are sensitive to the oscillation dip where we use a single combined energy bin for the standard zenith angle analysis.

A new analysis aiming to get the best parameters is done by using the finner binning data. The energy of the multi-GeV data are divided into 3 to 5 energy bins and the PC data are sub-divided into the PC-stop and PC-through data like one adopted in the L/E analysis. Furthermore, we have added the multi-Ring e-like data sample. Total 370 bins, 37 momentum bins $\times$ 10 zenith bins, are used.

The best fit parameters obtained in the physical region are

$$(\Delta m^2, \sin^2 2\theta) = (2.5 \times 10^{-3} \text{ eV}^2, 1.00).$$

The $\chi^2$ distribution sliced at $\sin^2 2\theta=1.0$ for the three different analysis, the standard (180 bins) analysis, the L/E analysis and the finner binned (370 bins) analysis have been compared in Fig. 3. The new analysis gives a sharp minimum value at $2.5 \times 10^{-3} \text{eV}^2$ while the 180 bin analysis has a broad minimum covering from 2.0 to $2.5 \times 10^{-3} \text{eV}^2$.

1.3. Evidence for tau appearance

The tau events cannot be identified by the event-by-event basis since many hadrons are produced and the incident neutrino directions are not known. By making use of the characteristic of the
tau production and by using the fact that tau events can only be seen as upward going events, we can apply a statistical analysis to enhance the tau events.

However, it is not an easy task, because the energy threshold of the tau production is 3.5 GeV and the expected rate for the tau production—1 FC charged current $\nu_\tau$ events per kton per year—is very small comparing the event rate of the usual $\nu_\mu, \nu_e$ interactions, which is about 130 events per kton per year.

Figure 4. The zenith angle distribution of the event sample enhanced for the tau events. The excess consistent with the expected tau production is seen for the upward going events. The number of events corresponding to the difference between two lines seen in the upward direction are the calculated tau production in the detector.

We have selected multi-GeV and multi-Ring events and constrained the event vertices within the fiducial volume, 2m from the ID PMT surface. Those events, whose the most energetic ring is e-like, are selected as initial data. The six distributions, for example, the visible energy, the distance of the event vertex to the $\mu$-e decay electron vertex, number of rings and so on, were used to statistically differentiate tau events from other BG events. Two independent methods, a likelihood analysis and a neural network program, were applied for those distributions.

For the likelihood analysis, the events with higher tau likelihood are selected. The efficiency to select tau events are estimated to be 42% and the contamination from the $\nu_\mu, \nu_e$ interaction events are 3.4%. The zenith angle distribution for the finally selected events is shown in Fig. 4. The clear enhancement due to the tau production is seen for the upward going events.

The number of the fitted tau events is $145\pm48$ (stat.) $^{+9}_{-36}$ (syst.) while the expected number of tau events is $79\pm31$ (syst.). Another method, the neural network, gives similar results: The number of the fitted tau events is $152\pm47$ (stat.) $^{+12}_{-27}$ (syst.) while the expected number of tau events is $79\pm31$ (syst.). Those numbers are consistent with the expected excess from the oscillated $\nu_\tau$ events.

2. Long baseline accelerator oscillation experiments

2.1. K2K experiment

The first long baseline neutrino oscillation experiment using man-made neutrinos is the K2K (KEK to Kamioka) experiment[7] which has started in 1999, one year after the announcement of the discovery of the atmospheric neutrino oscillation.

For $\Delta m^2=2.5\times10^{-3}$ eV$^2$ and full mixing, by putting the distance of 250km between the neutrino source and the detector and the averaged energy of 1.3 GeV, the expected survival probability is expected to be about 70%.

The total number of protons delivered on the production target (POT) is $0.561\times10^{20}$ for SK-I and $0.488\times10^{20}$ for SK-II. The total POT used for the analysis is $0.992\times10^{20}$ POT. The
direction of the beam is controlled well within 1 mrad and monitored by the muon distributions measured by the counters placed downstream of the end plug of the decay volume.

The neutrino beam at KEK-PS is produced every 2.2 seconds with the duration of 1.2 μs. The clocks at KEK and Kamioka have been synchronized to the accuracy less than 100 ns by using the GPS. The events produced by interactions of the man-made neutrinos were selected by using the expected beam arrival time at Super-Kamiokande.

The criteria like ones used for the atmospheric neutrino analysis, for example, requirement of fully contained, $E_{\text{vis}}>30$ MeV, fiducial volume of 22.5 kt, and so on, were also applied. Total 112 events have found in the time cluster of 1.2 μs. Outside of the cluster, within $\pm 5$ μs, none of the neutrino events were found. Those observed events are classified into 1-ring (67 events) and multi-ring (45 events). In 1-ring event sample, there are 58 $\mu$-like events and 9 e-like events. The systematic uncertainty for the total number of events is 3%, and among them the fiducial volume error of 2% is largest.

2.2. $\nu_\mu \rightarrow \nu_x$

The number of expected events at Super-K and the spectrum shape before the oscillation were obtained by using the measured neutrino events in the front detectors located at KEK and the MC simulations. The total number of observed neutrino events in 1 kt water Cherenkov detector with a detection efficiency of 74.9% was used to obtain the overall normalization factor. The combined spectrum fit for all the front detectors, 1 kt water Cherenkov detector, Muon Range Detector, SciFi and SciBar, was used to obtain the neutrino beam spectrum at KEK site. Then the MC calculation was used to estimate the spectrum at SK site (Far/Near ratio). Finally the expected number of events at SK, $N_{SK}^{\text{pred}}=155.9 \pm 0.3 ^{+13.6}_{-15.6}$, was obtained. The 4.1% and $^{+5.6\%}_{-7.3\%}$ uncertainties come from the 1 kt fiducial volume error and the Far/Near ratio, respectively.

The maximum likelihood method using a convolution of the number of events, the spectrum and the systematic error parameters, are adopted to obtain the oscillation parameters.

The best fit value for the physical region is $(\Delta m^2, \sin^2 2\theta) = (2.76 \times 10^{-3} \text{eV}^2, 1.0)$, shown in Fig. 5, which is consistent with the atmospheric neutrino oscillation. The confirmation of the neutrino oscillation was made by the man-made neutrinos.

![Figure 5. The allowed parameter region for the final data from K2K. The three lines corresponding to 68, 90 and 99% C.L.](image-url)
2.3. Electron appearance

In the final sample, we have 9 electron like events. The cuts applied for those selections were optimized to choose $\mu$-like events, not e-like events. Therefore we have many electron-like candidates in the final sample. In order to look for the electron appearance we need to apply further selection criteria on those 9 candidates to increase the purity of the electron final sample. The tight electron identification algorithm taking into account the opening angle information, the visible energy cut of 100 MeV and rejection of events with $\mu \rightarrow e$ decay electron were applied. Then 5 events remained.

We further applied so called $\pi^0$ cut which aims to remove $\pi^0$ contamination. This cut is effective to remove those events that the energy of one of the $\gamma$-rays from $\pi^0$ decay is dim, or escaped detection. The cut forced to look for a second ring and $\pi^0$ mass are reconstructed. Those events with the reconstructed mass consistent with $\pi^0$ mass was removed. After applying this cut, 1 electron candidate remained. The total efficiency for accepting electrons is 35.7% and 40.9% for K2K-I and K2K-II, respectively. The estimated remaining backgrounds are 1.63 events, 1.25 events from $\nu_\mu$ interactions and 0.38 events from the beam $\nu_e$ interactions, which is consistent with one observed candidate.

The excluded parameter region $\sin^2 2\theta_{\mu e} < 0.18$ at $2.8 \times 10^{-3}eV^2$ at the 90% C.L. limit, was obtained.

3. Future long baseline experiments

The purpose of first generation experiments is to confirm the neutrino oscillation observed in the atmospheric neutrinos. The future accelerator oscillation experiment will explore the region where the atmospheric neutrino study can hardly reach. A search for a definitive $\theta_{13}$ value through the electron appearance experiment can reach to the sensitivity of $\sin^2 2\theta_{13} \leq 0.01$ with the combination of a Mega watt neutrino beam and a SK-scale neutrino detector and could be realized around 2010. If the definitive $\theta_{13}$ has been determined and if the value is relatively large, then experiments with the conventional technology making use of multi-Mega watt neutrino beams and Mega-ton neutrino detectors will be able to make detailed studies on the neutrino sector like CP violation, mass hierarchy and so on.

The MINOS [8] 5.4 kt far detector, interleaved planes of 2.54 cm thick steel plane and 1 cm thick scintillator planes, with 1.5 T toroidal magnet, is placed in the underground Soudan mine, 735 km from the neutrino source at Fermilab. Protons accelerated to 120 GeV with an intensity of $1.5 - 2.5 \times 10^{13}$ppp will produce three different neutrino beams, LE(low energy), ME, HE according to the different configurations of the beam line. The LE beam with the peak energy around 3 GeV with relatively large high energy tail will produce $1300 \nu_\mu$ charged current events in the far detector for $2.5 \times 10^{20}$POT/yr. For about 5 years of data taking with $16 \times 10^{20}$POT, MINOS will reach the accuracy of $\Delta m^2 < 10\%$. If $\theta_{13}$ is close to the CHOOZ limit, then MINOS will see $> 3\sigma$ effect in $\sim 3$ years of running. MINOS has started running at the end of 2004. The experiment has already observed beam neutrino interaction in the far detector and also numbers of atmospheric neutrino interactions have been observed. The results from the experiment will be expected soon.

The high energy $\nu_\mu$ beams from CERN is optimized for the $\nu_\tau$ appearance ($< E_\nu >= 17 GeV$) in the detectors at the Gran Sasso Laboratory, 732 km away (CNGS[9]). OPERA is a emulsion-counter hybrid experiment with the total mass of 1700 tons. For 5 years running with the yearly accumulation of the beam of $4.5 \times 10^{19}$POT/yr, OPERA expected to observe $12.4 \nu_\tau$ appearance (with 0.8 BG) for $2.4 \times 10^{-3} eV^2$. Preparation of the emulsion films is going on and the first delivery to Gran Sasso was done in January, 2005. The experiment is expected to start in June 2006 with 850 tons of emulsion films. ICARUS is a liquid Ar detector. The 476.5ton LAr detector (T600) has been sent to Hall C of Gran Sasso and being installed. By summer 2006, T600 will be ready. There is a plan to increase the volume to T1800. With this plan for 5 years
of operation, ICARUS expected to observe 6.5 $\nu_\tau$ appearance with 0.3 BG for $2.5 \times 10^{-3} eV^2$.

The long baseline neutrino oscillation experiment from Tokai to Kamioka (T2K) will be expected to start taking data in 2009 with 100 times higher power than K2K [10]. Neutrinos are produced at 40 GeV proton accelerator at J-PARC in Tokai Village, Japan. The construction of the machine has started in 2001 and will be completed in 2007. The construction of the neutrino beam line has started in 2004 and will be completed in 2008. The baseline to Kamioka is 295km and off-axis beams will be used for the experiment. The accelerator power for phase I is 0.75 MW and Super-Kamiokande will be used. The experiment aims to look for the finite $\theta_{13}$ effect through the appearance of electron neutrinos. For a future option, Phase-II to study CP violation, matter effect, mass hierarchy and so on, can be done by increasing the machine power to 4 MW and building a Mega ton detector. The off-axis beam is quasi-monochromatic and 2~3 times intense than narrow band neutrino beams. The beam energy can be tuned for the oscillation maximum by selecting the off-axis angle. By choosing the off-axis angle at 2.5 degree, we can make the peak neutrino energy to match the oscillation maximum. T2K expected to see 11,000 total $\nu_\mu$ and 8,000 charged current interactions for 5 years of running. The beam $\nu_e$ contamination is 0.4% at $\nu_\mu$ peak energy. After 5 yrs of running T2K reaches to the sensitivity of $\delta(\Delta m^2_{23}) < 1 \times 10^{-4} eV^2$, $\delta(\sin^22\theta_{23}) \sim 0.01$ and $\sin^22\theta_{13} \sim 0.008$, about 1/20 of CHOOZ limit.

The ~1 degree off-axis neutrino beam with the peak energy about 1~2 GeV will be used for NOvA [11]. The 30kt scintillator detector is placed 819km from Fermilab. The experimental sensitivity is $\delta(\Delta m^2_{23}) < 5 \times 10^{-5} eV^2$, $\delta(\sin^22\theta_{23}) \sim 0.004$ and $\sin^22\theta_{13} \sim 0.0044 \sim 0.005$. The experiment is expected to start at around 2010.

4. Summary

New finner binning analysis with total 370 bins gives the most stringent constraint on the oscillation parameters. The best fit parameters in the physical region are $\Delta m^2 = 2.5 \times 10^{-3} eV^2$ and $\sin^22\theta_{23}=1.0$, and the 90\% C.L. regions are $2.0 < \Delta m^2 < 3.0 \times 10^{-3} eV^2$, $\sin^22\theta_{13} > 0.93$.

The evidence for the $\nu_\tau$ appearance in atmospheric neutrinos was obtained.

K2K has confirmed the atmospheric neutrino oscillation and the observed energy distortion is consistent with the neutrino oscillation.

The accelerator experiments in future will be expected to bring fruitful outcomes.

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