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OSCILLATORY SIGNATURE IN ATMOSPHERIC NEUTRINOS.

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Interactions of atmospheric neutrinos in Super-Kamiokande detector (SK-I) have been recently reanalysed. We report here results of standard oscillation analysis based on zenith angle distributions as well as the new analysis based on a subsample of higher precision data. The latter show a dip in the plot of the muon neutrino survival probability as a function of the ratio of the distance over neutrino energy. As a result the parameters of the transitions $\nu_\mu \leftrightarrow \nu_\tau$ are better constrained: $1.9 \times 10^{-3} < \Delta m^2 < 3.0 \times 10^{-3}$ eV^2 and $\sin^2 2\theta > 0.90$ at 90% C.L.

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1. Introduction

Since the discovery of neutrino oscillations [1] the parameters of the ν_μ disappearance have been determined by the analysis of zenith angle distributions in subsamples of atmospheric neutrinos corresponding to various energy ranges and neutrino flavors. The consistency of the parameters fitting the different data samples provided an important support to the data interpretation by $\nu_\mu \leftrightarrow \nu_\tau$ transitions.

In a two flavor mixing approximation the survival probability is given by:

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

for a neutrino flight distance L(km) and energy E(GeV), where $\Delta(m)^2 = m_1^2 - m_2^2$ in (eV^2) and θ is the mixing angle. With much increased statistics a closer look at the sinusoidal dependence on L/E became possible. We thus first report here new results of standard oscillation analysis and then results of a search for oscillatory signature in the functional dependence of the ν_μ survival probability on L/E.

The Super-Kamiokande detector (SK) measures the energy, direction and time of the charged products of neutrino interactions by recording the emitted Cherenkov light [2]. The data have been collected since April 1996. During the detector upgrade in the summer of 2001 an accident destroyed half of the photo-multipliers. The detector was then rebuilt and since January 2003 it has been collecting data with about half of the original photocathode coverage. In this report only the SK-I data, recorded during 1489 days until Jul 2001, are presented. Details about the data analyses can be found in Refs. 3 and in the forthcoming paper [4].

The data are compared with the updated Monte Carlo simulations. They include new three-dimensional neutrino flux calculations and are based on recent primary cosmic ray measurements [5]. Some modifications are introduced to neutrino interaction model thanks to measurements in the near detectors of the K2K experiment [6]. Also improved data reduction and reconstruction algorithms were used, as well as new treatment of sytematic uncertainties.

2. Standard analysis.

About 13000 contained events were reconstructed in 22.5 kton fiducial volume. Out of this sample about 9500 events were used for standard oscillation analysis. Those were contained single and multi-ring $\mu - like$ and single-ring $e - like$ events with visible energy above 100 MeV as well as about 2200 upward-going muons.

In the standard oscillation analysis formula (1) was fitted to the zenith angle, Θ, distributions in several energy intervals. The data divided in 180 bins of energy and angle were used in the χ^2 minimum analysis. The oscillation parameters, $\sin^2 2\theta$ and Δm^2, as well as the absolute flux normalization were treated as free parameters. In order to take into account 38 systematic effects their fractional change normalized by corresponding systematic errors was parametrized. The best fit point was searched by scanning a $(\sin^2 2\theta, \log \Delta m^2)$ grid and finding χ^2_{min} by optimizing the systematic error parameters at each point. The χ^2_{min} value of $175/177$ d.o.f. was obtained for the parameter set: $(\sin^2 2\theta,\, \Delta m^2) = (1.02,\, 2.1 \times 10^{-3}\,\mathrm{eV}^2)$. At 90% c.l. the acceptable values are $\sin^2 2\theta > 0.92$ and Δm^2 between $1.5 \times 10^{-3}\,\mathrm{eV}^2$ and $3.4 \times 10^{-3}\,\mathrm{eV}^2$ for maximum mixing.

However this analysis does not make evident the sinusoidal L/E dependence of the survival probability and alternative hypotheses with an exponential term can be fitted to the zenith angle distributions. These hypotheses are neutrino decay [7] and neutrino decoherence [8]. The former allows for the eigenmass state not participating in solar oscillations to decay to a sterile state, while the latter assumes that quantum gravitation effects destroy coherence of two oscillating states. With the large SK samples an analysis was undertaken to select a sample of events with good resolution in L/E.

3. Analysis of the high precision sample.

We present here briefly results described in greater details in Ref. 9. Only the contained $\mu - like$ events were considered for this analysis. In order to increase the statistics the fiducial volume was expanded to 26.4 ktons. Also a special procedure was devised to use the photoelectrons recorded in outer detector to improve energy resolution.

The neutrino energy was calculated for every event from a functional relationship between the neutrino and the observed energy found from MC simulation. The worst neutrino energy reconstruction occurs for events of energies above 5 GeV with some energy leakage outside of the detector. However they are advantageous for flight distance determination because of a very good correlation between neutrino and muon direction and a good angle reconstruction. Interactions of low energy neutrinos result in the worst angular resolution because of large transverse momenta of invisible recoil nucleons. The flight path is poorly reconstructed for all horizontal-going neutrinos due to large $dL/d\Theta$.

Using MC event samples contiguous regions of the reconstructed ($\cos\Theta$, E_ν) value sets were selected for which the resolution of $\Delta(L/E)$ was better than 70 %. In total 2726 events were thus selected. Their L/E distribution is compared with the MC simulated sample in Fig. 1. In order to get the ν_μ survival probability the data were divided by the MC histogram; the ratio is also shown in the figure. The plot displays a dip around $L/E = 500$ km/GeV, i.e. just where the first oscillation maximum is expected. Note that according to formula (1) the best fit value obtained from the standard analysis implies a maximum at L/E =588 km/GeV.

The observed L/E distribution was fitted assuming $\nu_\mu \leftrightarrow \nu_\tau$ oscillations, taking into account 25 systematic uncertainties. The systematic terms are allowed to vary within the estimated errors which account for uncertainties in flux calculation, detector calibration, data reduction, event reconstruction, and neutrino interaction models. The minimum χ^2 was found at $(\sin^2 2\theta,\, \Delta m^2) = (1.00,\, 2.4 \times 10^{-3}\,\mathrm{eV}^2)$. At 90 % C.L. the parameters are constrained by: $\sin^2 2\theta\ > 0.90$ and $1.9 \times 10^{-3}\,\mathrm{eV}^2 < \Delta m^2 < 3.0 \times 10^{-3}\,\mathrm{eV}^2$ for maximum mixing. The L/E analysis gives thus a more precise determination of Δm^2 than the standard analysis.

The expected L/E dependence for best fit oscillation parameters is shown by solid line in Fig. 1. Alternative hypothesis were also fitted and are displayed in the figure. A slight rise at large L/E seen both for the data and the fitted histogram originates from energy-dependent systematic errors on neutrino cross sections.

4. Conclusions

The SK-I atmospheric neutrino sample is now large enough to look at a subsample of $\mu - like$ events, which makes possible a determination of the L/E variable with better precision. The ν_μ survival probability as a function of L/E displays a dip just where the first oscillation maximum is expected for the parameters deduced from the standard oscillation analysis. The oscillation analysis based on this higher precision subsample better constrains Δm^2. At 90 % C.L. the parameters are constrained by: $\sin^2 2\theta\ > 0.90$ and $1.9 \times 10^{-3}\,\mathrm{eV}^2 < \Delta m^2 < 3.0 \times 10^{-3}\,\mathrm{eV}^2$ for maximum mixing. This implies that at least one of the neutrino masses is larger than 44 meV.

After the explanation of the solar neutrino deficit by SNO and KamLAND and

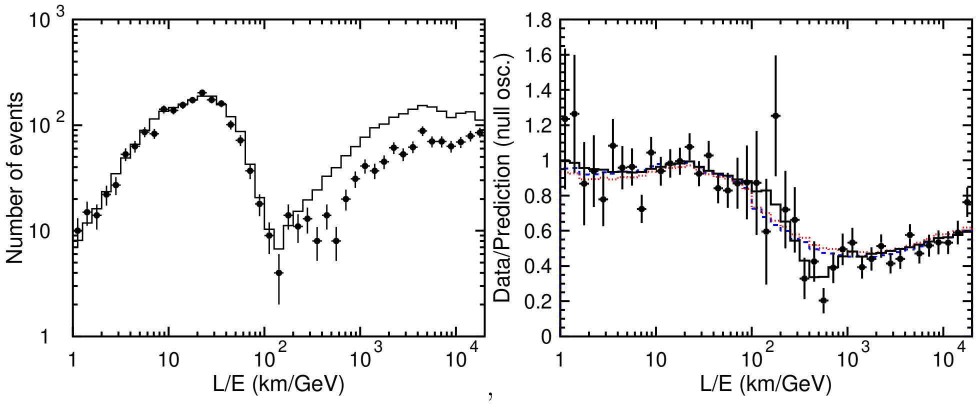

Fig. 1. Left: Number of events as a function of reconstructed L/E for the data (points) and MC events without oscillations (histogram). The MC histogram is normalized by the detector live-time. Right: Ratio of the data to MC event rates. Solid line histogram shows the best-fit expectation for 2-flavor $\nu_\mu \leftrightarrow \nu_\tau$ oscillations. The error bars are statistical only. Also shown are the best-fit expectations for neutrino decay (dashed line) and neutrino decoherence (dotted line).

confirmation of the atmospheric neutrino oscillation parameters by K2K the exciting search for solutions of the neutrino puzzles has thus been completed. With the firm evidence for neutrino oscillations we have now started the phase of precision measurements of neutrino properties in many future projects.

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