Atmospheric Neutrino Oscillations in SK-I

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Abstract

The Super-Kamiokande experiment has completed an analysis of all the "SK-I" atmospheric neutrino data, spanning the period since it came on-line in April of 1996 to shutdown for maintenance in July of 2001. Improvements to both data reduction and Monte Carlo predictions have been uniformly applied to this complete set of data. The results emphatically support $\nu_\mu \leftrightarrow \nu_\tau$ oscillations, disfavor alternative ν_μ disappearance mechanisms such as oscillation to sterile neutrinos or neutrino decay, and place limits on $\nu_\mu \leftrightarrow \nu_e$ oscillations.

1. Introduction

The Super–Kamiokande (Super–K) experiment has reported evidence for the oscillation of ν_μ produced in cosmic-ray induced showers in the atmosphere via the observation of ν_μ disappearance as a function of neutrino pathlength and energy [1]. The observed ν_e signal shows no excess, so is not consistent with substantial $\nu_\mu \leftrightarrow \nu_e$ oscillation. Since a ν_τ charged-current (CC) interaction would produce a τ lepton, ν_τ below the 3.4 GeV τ production threshold do not interact via the CC channel. ν_τ above this threshold would produce τ leptons, but τ decay products would produce a multiplicity of particles. Since the data set used to observe ν_μ oscillation prefers easily reconstructed events, only the resulting disappearance of ν_μ is observed, although additional analyses targeting ν_τ appearance are consistent with such appearance within the (large) errors [2].

Several alternative scenarios have been proposed to explain the observed ν_μ disappearance. One which would simultaneously explain apparent neutrino oscillations in three widely separated regimes (atmospheric neutrinos, solar neutrinos, and the LSND experiment) is oscillation with a sterile neutrino (ν_s), which undergoes neither CC nor neutral current (NC) interactions.

A more speculative ν_μ disappearance scenario is neutrino decay [3]. If neutrinos were somehow to decay, ν_μ would still disappear independently of flavor oscillations, which could still occur. This presents two cases to be considered, a short or long neutrino lifetime τ compared to the oscillation length. Other possible causes of ν_μ disappearance are decoherence of the neutrino wave packet over time [4] and violations of Lorentz Invariance [5]. The ν_μ survival probabilities

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in these various scenarios are listed in Table 1.

Lastly, potential violations of CPT [6] can be probed. If ν_μ underwent different oscillations than $\bar{\nu}_\mu$ due to CPT violation, then the total $(\nu_\mu + \bar{\nu}_\mu)$ oscillation signal would be different, as the neutrinos producing a signal in Super–K come from the mixture of ν and $\bar{\nu}$ created in cosmic ray showers.

2. Methods and Results

Super–K is a 50 kt water Cherenkov detector employing 11,146 photomultiplier tubes (PMTs) to monitor an internal detector (ID) fiducial volume of 22.5 kilotons. Entering and exiting charged particles are identified by 1885 PMTs in an optically isolated outer volume (OD) [7]. "SK-I" refers to this configuration, which existed from April 1996 through July 2001. Fully-contained (FC) events deposit all of their Cherenkov light in the ID while partially-contained (PC) events have exiting tracks which deposit some light in the OD. The vertex position, number of Cherenkov rings, ring directions, and momenta are reconstructed and the particle types are identified as "e-like" or "μ-like" for each FC Cherenkov ring. The FC data are divided into multi- and single-ring samples. The single-ring sample provides better knowledge of the event kinematics, but multi-ring μ-like events still usefully add to our ν_μ sample. PC events in Super–K are estimated to be 97% pure ν_μ CC and result from parent neutrinos with a mean of 10 GeV. The current contained-vertex data exposure is 91.7 kiloton-years (1489 live-days).

While many single- and multiple-ring FC events result from quasi-elastic interactions and thus tag the parent neutrino flavor by the outgoing lepton, some events result from Neutral Current (NC) interactions that are insensitive to neutrino flavor. A comparatively NC rich data set is found in contained, neutrino-induced events with multiple rings, the brightest of which must be identified as an electron. To improve the angular correlation of the observed particles to their parent neutrino,the total visible energy must be greater than 400 MeV. This results in a mean angle difference between the parent neutrino and the reconstructed event direction of 33°. Checks on MC data shows this sample contains a 29% fraction of NC events, compared to the FC single ring sample's $\sim 6\%$ NC events.

Super–K also collected upward through-going muon (UTM) events produced by atmospheric neutrino interactions in the surrounding rock. Such an event requires a minimum track length of 7 m in the inner detector and an upward muon direction. A sample of upward-stopping muons (USM) are tagged by their lack of an exit signal in the OD. USM parent neutrinos are of lower energy than those of UTM, comparable to those of PC events. Downward-going neutrino induced muons cannot be distinguished from the 3 Hz of cosmic ray muons.

Separating the atmospheric neutrino data into these different classes of events provides a sensitivity over five decades of neutrino energy from 100 MeV to several TeV. Since the various mechanisms which attempt to explain ν_μ disappearance all depend upon baseline L and energy E, the data in each category are binned by arrival direction (corresponding to neutrino baseline, a range of four decades from ~ 20 to $> 10,000$ km) and (if appropriate) additional energy bins within an event class. This results in 195 different data bins.

To calculate an expected signal, 70 live-years equivalent of Monte-Carlo (MC) data were used. To create these data, atmospheric neutrino fluxes are convoluted with the full suite of neutrino/nucleon cross sections, then particles are drawn from the resulting kinematic distributions. These particles are propagated through a GEANT-based detector simulation to properly account for detector response, making "events" in the same format as the live data. These simulated events are processed through the same data reduction procedures as the actual data and put into the same 195 bins. However, for MC-generated data the true parent neutrino parameters are known on an event-by-event basis. This allows the application of different ν_μ disappearance hypotheses to the MC data, generating the data distributions one would expect from the different hypotheses by weighting each MC event by the appropriate survival probability. Systematic errors have also been estimated, and given a chance to change the expected distribution.

Comparison of these expected distributions with the observed data allows the testing of the various ν_μ disappearance hypotheses and the estimation of their parameters in an unbiased, statistical fashion. A χ^2 difference is calculated between data and expectation for each set of model parameters and possible systematic errors. The best-fit parameters for each model are given in Table 1. Two free model parameters and three free systematic error terms result in 190 degrees of freedom. The model which best fits the data is $\nu_\mu \leftrightarrow \nu_\tau$ oscillations. Allowed regions in parameter space can be drawn, and parameters of $0.92 > \sin^2 2\theta > 1.0$ and $1.6 < \Delta m^2 < 3.9 \times 10^{-3}\text{eV}^2$ are allowed at 90% c.l. [2].

Given any two models attempting to describe the same data, the likelihood that the model which does not have the lowest χ^2 is actually the true one can be found in the difference in χ^2 between the models. The chance that the false model has produced data that has fluctuated to the lower χ^2, simultaneously with the true model producing unexpectedly poorly fitting data, is the Gaussian probability associated with a deviation of $\sqrt{\Delta\chi^2}\ \sigma$.

3. Discussion and Conclusions

Super–K's ability to discriminate between different models comes from the wide range of L, E and neutrino interactions represented in the data. A model must get many things right to earn a low χ^2. For example, $\nu_\mu \leftrightarrow \nu_s$ predicts too low a NC signal and an unobserved suppression of oscillations at high energies [8]. ν_e appearance is not seen in the e-like events (consistent with the direct CHOOZ results [9]). Likewise, if neutrino decay contributes to ν_μ disappearance, then the decayed neutrinos will not contribute to a neutral current signal, but this NC

Model	Best Fit	χ^2	$\Delta\chi^2$	σ
$\nu_\mu \leftrightarrow \nu_\tau$ $\sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$	$\sin^2 2\theta = 1.00$ $\Delta m^2 = 2.5 \times 10^{-3}$	173.8	0.0	$0\,\sigma$
$\nu_\mu \leftrightarrow \nu_e$ $\sim \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$	$\sin^2 2\theta = 0.97$ $\Delta m^2 = 5.1 \times 10^{-3}$	284.3	110.5	$10.5\,\sigma$
$\nu_\mu \leftrightarrow \nu_s$ $\sim \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$	$\sin^2 2\theta = 0.98$ $\Delta m^2 = 2.9 \times 10^{-3}$	222.7	48.9	$7.0\,\sigma$
L.I. violation $\sin^2 2\theta \sin^2(\alpha L \times E)$	$\sin^2 2\theta = 0.90$ $\alpha = 5.6 \times 10^{-4}$	281.6	107.8	$10.4\,\sigma$
ν_μ decay (short τ) $\sin^4\theta + \cos^4\theta(1 - e^{-\alpha L/E})$	$\cos^2\theta = 0.50$ $\alpha = 3.7 \times 10^{-3}$	279.4	105.6	$10.3\,\sigma$
ν_μ decay (long τ) $(\sin^2\theta + \cos^2\theta e^{-\alpha L/2E})^2$	$\cos^2\theta = 0.33$ $\alpha = 1.2 \times 10^{-2}$	194.0	20.2	$4.5\,\sigma$
ν_μ decoherence $0.5\sin^2 2\theta(1 - e^{-\gamma L/E})$	$\sin^2 2\theta = 0.98$ $\gamma = 7.3 \times 10^{-3}$	184.3	10.5	$3.2\,\sigma$
Null Hypothesis		427.4	252.4	$15.9\,\sigma$

Table 1. Various models attempting to explain the observed atmospheric neutrino flux in Super–K, their associated ν_μ survival probability, best fit parameters, the χ^2 of that fit, and its difference from the best fitting case of $\nu_\mu \leftrightarrow \nu_\tau$ oscillations.

suppression is not seen. The more convoluted ν_μ disappearance probabilities of the other models are also not well supported by the data, although decoherence is disfavored by only $3.2\,\sigma$ and long–τ neutrino decay by $4.5\,\sigma$. Likewise, ν_μ oscillating differently than $\bar{\nu}_\mu$ due to CPT violation is not seen [2].

Thus, using all the atmospheric neutrino data observed by the Super–K detector, $\nu_\mu \leftrightarrow \nu_\tau$ two-flavor oscillations appear to be the best explanation for the observed data. The data analysis and MC generation processes are being further refined to help clarify the situation more fully, and SK-II has been taking data again since December of 2002 to provide more neutrinos to study.

4. References

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