Multi-ring Atmospheric Neutrino Events in Super-Kamiokande

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Abstract

We present an analysis of contained multi-ring atmospheric neutrino events from a 45 kiloton-year (735.6-day) exposure of the Super-Kamiokande detector. We look specifically at the possibilities of distinguishing between $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_{\rm sterile}$ oscillations by using neutral current induced neutral pion production. While the size of the sample is large, the current estimate of the systematic error precludes us from making a determination. We also examine other two-ring events and find they are consistent with the oscillation parameters determined from the single-ring and partially contained data samples.

1 Introduction:

When cosmic rays collide with nuclei in the upper atmosphere, they produce hadronic showers whose components decay creating atmospheric neutrinos. Neutrino production is dominated by the processes $\pi^+ \rightarrow \mu^+ + \nu_\mu$ followed by $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_{\rm e}$ (and their charge conjugates) giving an expected ratio ($\equiv \nu_\mu/\nu_{\rm e}$) of the flux of $\nu_\mu + \bar{\nu}_\mu$ to the flux of $\nu_{\rm e} + \bar{\nu}_{\rm e}$ of about two. The $\nu_\mu/\nu_{\rm e}$ ratio has been calculated in detail with an uncertainty of less than 5% over a broad range of energies from 0.1 GeV to 10 GeV (G. Barr et al., 1989) (V. Agrawal, et al., 1996) (T.K. Gaisser and T. Stanev, 1995) (M. Honda et al., 1990) (M. Honda et al., 1995).

When atmospheric neutrinos interact in water, the resultant charged particles are frequently above Cherenkov threshold. The Cherenkov light produced by these particles is observed in large underground water Cherenkov detectors and used to reconstruct the neutrino interactions.

Super-Kamiokande is a 50 kiloton water Cherenkov detector instrumented with 11,146 photomultiplier tubes (PMTs) facing an inner 22.5 kiloton fiducial volume of ultra-pure water. Interaction kinematics are reconstructed using the time and charge of each PMT signal. The inner volume is surrounded by a ~2 meter thick outer detector instrumented with 1885 outward-facing PMTs. The outer detector is used to veto entering particles and to tag exiting tracks.

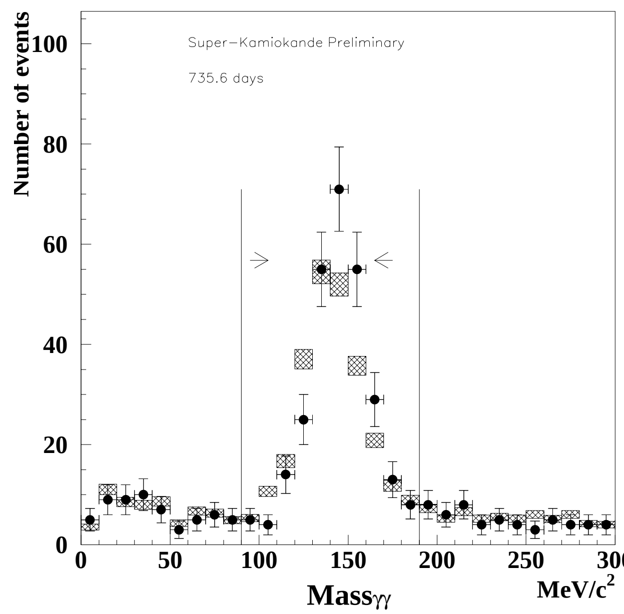

Figure 1: Invariant mass distribution for contained events with two e-like rings and no muon-decay signal. A peak of events at the pi0 mass is evident. Data points correspond to 45 kton-yrs of Super-K data; the hatched region is the Monte Carlo prediction normalized to the same livetime. The height of the hatched boxes represents the statistical uncertainty of the Monte Carlo sample.

Events are classified as entering, contained or partially contained(PC). Entering events are rejected for this analysis. The primary vertex of contained and PC events is located within the fiducial volume of the inner detector > 2 meters from the surface of the inward-facing PMTs. A contained event is one in which all visible particles come to rest or decay within the inner volume. Contained events are further divided into single- and multi-ring samples.

Single-ring events have only one visible - charged and over Cherenkov threshold - particle among those produced by the interaction. Multi-ring events have more than one visible Cherenkov ring. After classification as a two-ring event, hit tubes are assigned to each ring and particle identification algorithms are run on each ring separately. The rings are then classified as being e-like or μ-like. In this paper, we will discuss the analysis of two-ring events in detail. The detector, event classification and data reduction procedures are described in detail elsewhere (Fukuda et al., 1998,1)(Fukuda et al., 1998,2).

We studied the ν_μ/ν_e ratio using single-ring and PC events and subsequently reported evidence for neutrino oscillations of type $\nu_\mu \leftrightarrow \nu_x$, where ν_x may be ν_τ or a new, non-interacting "sterile" neutrino. (Fukuda et al., 1998,3) In this paper, we report on analysis of the two-ring sample to both verify consistency with the oscillation analysis of the single-ring and PC sample, and to distinguish between the $\nu_\mu \leftrightarrow \nu_\tau$ and the $\nu_\mu \leftrightarrow \nu_{\rm sterile}$ oscillation hypotheses.

2 Two-Ring Events:

We analyzed contained events in the 22.5 kiloton fiducial volume for 735.6 days of exposure, or a total of 45 kiloton-years. In this period, we found 1398 two-ring contained events out of a total of 6085 contained events or a total of about 23% of all contained events. This is consistent with Monte Carlo predictions of about 24%.

The Monte Carlo event generator is based on (D. Rein and L.M. Seghal, 1981) for single resonance pion production, (D. Rein and L.M. Seghal, 1983) for coherent pion production, and (M. Nakahata et al., 1986) for multi-pion production and for tracking pions produced in ^{16}O nuclei.

We tried to isolate samples of events with a high purity of either neutral current (NC) or charged current (CC) interactions. There were two samples of CC interactions, ν_e-enriched and ν_μ-enriched, with which we show consistency with respect to the oscillation parameters gleaned from single-ring and PC events. Since ν_τ's interact via the NC and sterile neutrinos do not, we use the NC sample to try to distinguish between the two oscillation hypotheses favored by the single-ring and PC sample.

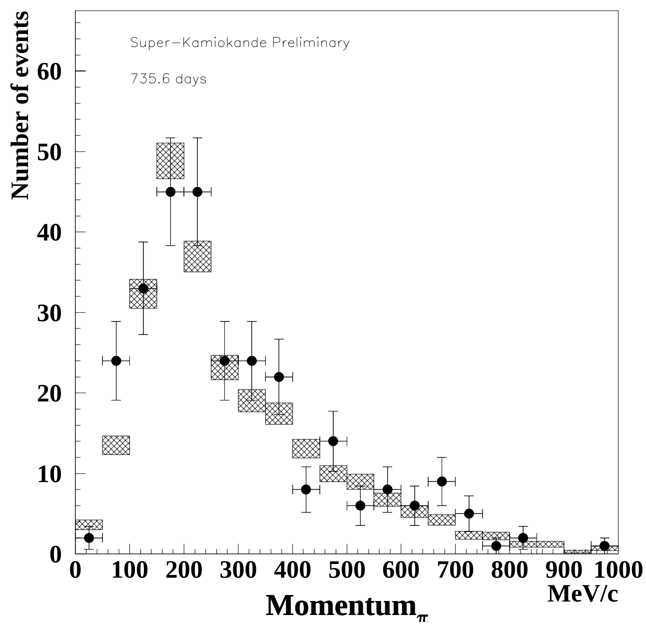

Figure 2: Momentum distribution for contained events with two e-like rings and no muon-decay signal. Data points correspond to 45 kton-yrs of Super-K data; the hatched region is the Monte Carlo prediction normalized to the same livetime. The height of the hatched boxes represents the statistical uncertainty of the Monte Carlo sample.

Oscillations between ν_μ and ν_τ are one of the hypotheses favored by the single-ring and PC event sample. Since the flux of atmospheric ν_τ's is essentially unobservable, the observation of ν_τ's in Super-Kamiokande would imply $\nu_\mu \leftrightarrow \nu_\tau$ oscillations. However, since the threshold for a CC ν_τ interaction is ~3.5 GeV and since the atmospheric neutrino flux above this energy is small, distinguishing between ν_τ or $\nu_{\rm sterile}$ oscillations by searching for τ lepton production is not the most promising.

NC neutrino cross sections are flavor-independent, so if the $\nu_\mu \leftrightarrow \nu_\tau$ oscillation hypothesis is correct, the number of NC events observed should not differ from our expectations. However, sterile neutrinos, by definition, do not interact via the electroweak force, so if the $\nu_\mu \leftrightarrow \nu_{\rm sterile}$ oscillation hypothesis is correct, we should observe fewer NC events than we expect.

NC induced single π^0 production provides the cleanest signal available in Super-Kamiokande to study NC events.

2.1 Neutral Current Two-Ring Sample: Neutral pions decay into two gamma rays 98.8 percent of the time. The gamma rays induce electromagnetic showers which are identified as e-like by our reconstruction algorithms. We therefore see two e-like rings. In addition to requiring two e-like rings, no μ decay signature was permitted for the event. Figure 1 shows the invariant mass distribution for events passing these criteria.

The invariant mass was required to be between 90 and 190 MeV$/c^2$. From Monte Carlo studies, we determined the CC contamination of the π^0 data sample to be about 16%. The following shows the relative contributions to the π^0 sample: CC ν_e 11%, CC ν_μ 5%, NC Δ production 43%, NC coherent π production 20%, NC multi π production 13%, NC others 7%.

We observed 279 π^0 events compared with 253.6 expected from simulated data. Results with a background subtraction are consistent. The momentum distribution (Figure 2) of the π^0 sample shows no significant deviation from the simulated data. Though the number of observed events exceeds the expectations by ten percent, the absolute neutrino flux is only known to about twenty percent. In order to reduce the importance of this uncertainty, we assume $\nu_\mu \leftrightarrow \nu_x$ oscillations and assume ν_e's do not participate in oscillations. We then use the single-ring e-like event sample to normalize the expected π^0 rate. We form the following ratio $R_{\pi^0} \equiv (\pi^0/e)_{data}/(\pi^0/e)_{MC}$. For oscillations to ν_τ, this ratio should be close to unity. For $\nu_{\rm sterile}$ oscillations, the ratio will depend on the oscillation parameters. For the best fit values from (Fukuda et al., 3) of $\sin^2 2\theta = 1.0, \Delta m^2 = 2.2 \times 10^{-3}$ eV^2, the expected value of R_{π^0} is about 0.8.

We observe $R_{\pi^0} = 1.03 \pm 0.06 \pm 0.02 \pm 0.24$, where the first term in the uncertainty is from data statistics, the second is from Monte Carlo statistics and the third is the systematic error. The systematic error prevents us from distinguishing ν_τ and $\nu_{\rm sterile}$ oscillations.

The primary sources of systematic error for R_{π^0} are as follows: cross section 20%, event reconstruction 7%, nuclear interaction 7%, effect of the flux uncertainty 3%.

The dominant source of systematic error is from uncertainties in the neutrino cross sections for π^0 production. If this uncertainty could be substantially reduced, we might be able to distinguish between ν_τ and $\nu_{\rm sterile}$ oscillations.

2.2 Charged Current Two-Ring Samples: The two CC event samples were the ν_e-enriched and the ν_μ-enriched samples. Both samples required two rings, each with momentum higher than 300 MeV$/c$.

For the ν_e-enriched sample, we required either two e-like rings which did not correspond to the π^0 event sample (invariant mass outside the 90-190 MeV$/c^2$ range), or one e-like and one μ-like ring where the momentum of the e-like ring was greater than that of the μ-like ring. Also, no μ decay signature was permitted. According to Monte Carlo estimates, the sample is: 60% CC ν_e, 8% charged current ν_μ, and 32% NC interactions.

For the ν_μ-enriched sample, we required either two μ-like rings, or one μ-like and one e-like ring where the momentum of the μ-like ring was greater than that of the e-like ring. Also, at least one $\mu \to e$ decay was required. According to Monte Carlo estimates, the sample is: 89% CC ν_μ, 2% CC ν_e, and 8% NC interactions.

Figure 3 shows the ν_e-enriched sample and the ν_μ-enriched sample with oscillated and un-oscillated simulated data. The oscillated data is for $\nu_\mu \leftrightarrow \nu_x$ with $\sin^2 2\theta = 1.0, \Delta m^2 = 3.5 \times 10^{-3}$ eV^2 (Kaneyuki, these proceedings). The data is in clear agreement with the oscillated Monte Carlo.

3 Conclusions:

We have presented an analysis of the contained multi-ring atmospheric neutrino data set collected at Super-Kamiokande for 736 days. The sets composed predominantly of CC interactions are much better explained by oscillation parameters favored by the single-ring event sample. The π^0 event sample, composed predominantly of neutral current events is consistent with both the $\nu_\mu \leftrightarrow \nu_\tau$ or the $\nu_\mu \leftrightarrow \nu_{\rm sterile}$ oscillation hypothesis. The systematic error, especially the uncertainty in the neutrino induced π^0-production cross sections, must be

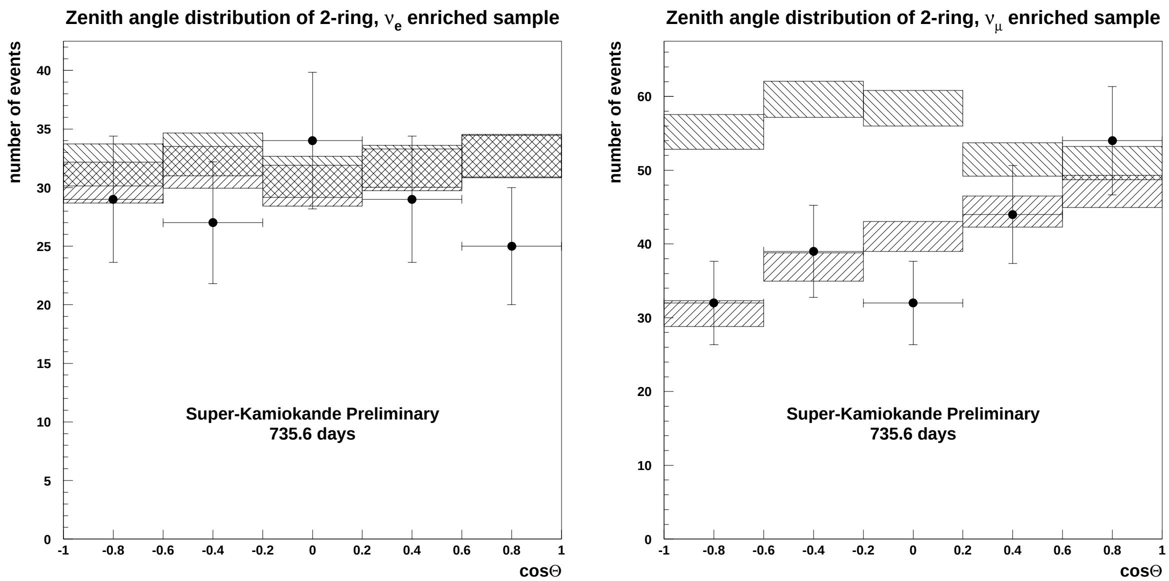

Figure 3: CC Enhanced Two-Ring Samples. Left: $\nu_{\rm e}$-enriched sample. Right: ν_μ-enriched sample. Data points correspond to 45 kton-yrs of Super-K data; the hatched regions are the Monte Carlo predictions normalized to the same livetime. The height of the hatched boxes represents the statistical uncertainty of the Monte Carlo samples. Upper-left to lower-right hatches are un-oscillated Monte Carlo. The other is oscillated.

reduced in order for this analysis to be effective at distinguishing between the two hypotheses favored by the single-ring analysis. High flux long baseline neutrino oscillation experiments, such as K2K taking place at KEK and the Kamioka site, can use near detector components to reduce this systematic uncertainty.

4 Acknowledgements

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