# Study of Atmospheric Neutrino Oscillations using $\pi^0$ Events in SK-I

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## Abstract

As one of the ways to distinguish whether muon neutrinos are oscillating into tau neutrinos or sterile neutrinos, we have measured a double ratio $R_{\pi^0} \equiv (\pi^0/\mu)_{\rm DATA}/(\pi^0/\mu)_{\rm MC}$ for the atmospheric neutrino sample in Super-Kamiokande. Since the single $\pi^0$ sample has a large NC fraction, the two scenarios make a difference in $R_{\pi^0}$. To test our Monte Carlo simulation and to reduce the systematic uncertainty on $R_{\pi^0}^{\rm SK}$, which is mainly due to neutrino cross sections and pion nuclear effects, we made a measurement of $R_{\pi^0}$ in the 1kt water Cherenkov detector using the K2K beam neutrinos before oscillations. The measured $R_{\pi^0}^{\rm SK}$ with the reduced uncertainty is more consistent with the $\nu_\mu \leftrightarrow \nu_\tau$ hypothesis at the Super-Kamiokande's best-fit oscillation parameters.

## 1. Introduction

With the help of matter effects on high energy muon neutrinos, the Super-Kamiokande (SK) experiment already excluded the possibility of atmospheric muon neutrino oscillations into sterile neutrinos ($\nu_s$) at the 99% confidence level [1]. Another way to distinguish between $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_s$ is made possible by measuring the neutral current (NC) to charged current (CC) interaction ratio and comparing it to the predictions for each hypothesis. Since both tau and muon neutrinos interact via the NC with the same cross sections, no attenuation in the NC signal is expected for the $\nu_\mu \leftrightarrow \nu_\tau$ hypothesis, while for the $\nu_\mu \leftrightarrow \nu_s$ hypothesis, the NC rate would be reduced. The cleanest atmospheric neutrino NC signal in Super-Kamiokande comes from single $\pi^0$ production. Thus we measure the double ratio $R_{\pi^0} \equiv (\pi^0/\mu)_{\rm DATA}/(\pi^0/\mu)_{\rm MC\,no\,osc}$ and compare this ratio with a MC prediction for various oscillation scenarios.

## 2. $\pi^0$ events and $\mu$ events

Super-Kamiokande is a 50 kt water Cherenkov detector located in Kamioka Observatory, ICRR, University of Tokyo, 2700 meters-water-equivalent below the peak of Mt. Ikenoyama in Kamioka, Japan. The cylindrical inner detector with

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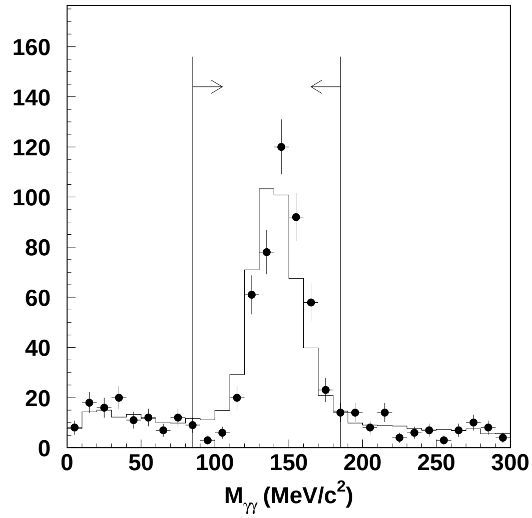


**Fig. 1.** The invariant mass distributions of 2 $e$-like rings for the events which satisfy the cuts (A)-(C) (see text). The dots represent the data with statistical errors. The boxes show the atmospheric neutrino Monte Carlo expectation for no oscillations normalized to the live time. The size of boxes shows the statistical errors. The arrows show the invariant mass cut (D).

a height of 36.2m and a diameter of 33.8m is viewed by 11146 photomultiplier tubes (PMTs) of 50cm diameter. The fiducial volume is 22.5 kt. Details of the detector are described elsewhere [2].

For this analysis, we use 11872 fully-contained (FC) events observed in 1489 live days of exposure. To extract the $\pi^0$ events from the FC events sample, the following selection criteria are used : (A) the number of rings is 2, (B) both rings have a showering ($e$-like) particle identification, (C) no decay electron, (D) the invariant mass of 2 $e$-like rings is in the range of 85 MeV/$c^2$ to 185 MeV/$c^2$. Fig. 1 shows the invariant mass distribution of the events after the cuts (A)-(C). We can see a clear $\pi^0$ mass peak.

In the full-detector Monte Carlo simulation, we use the atmospheric neutrino flux calculated by Honda *et al.*[3]. For neutrino interactions, the following types of interaction are taken into account : quasi-elastic scattering (q.e.), single $\pi$ production from $\Delta$ resonance ($1\pi$), coherent $\pi$ production (c$\pi$) and multi $\pi$ production (m$\pi$). We use Rein-Sehgal's model to simulate the single $\pi$ production [4]. According to our MC simulation for no oscillations, 86% of the $\pi^0$ sample is from NC interactions. The CC events are backgrounds to this sample and are mainly from $\nu_e$CC q.e. and CC $1\pi$ interactions.

The criteria to select $\mu$-like events are : (a) the number of rings is 1, (b) the ring has a non-showering ($\mu$-like) particle identification, (c) the momentum of $\mu$ is greater than 200 MeV/$c$. According to the simulation for no oscillations,

**Table 1.** The numbers of observed $\pi^0$ events and $\mu$-like events compared with the unoscillated Monte Carlo predictions normalized to the live time.

| | Data | Monte Carlo | | | |
|---|---|---|---|---|---|
| | | total | $\nu_e$CC (q.e.) | $\nu_\mu$CC (q.e.) | NC ($1\pi$, c$\pi$, m$\pi$) |
| $\pi^0$ | 471 | 472.3 | 47.8 (19.3) | 19.2 (0.9) | 405.3 (224.6, 100.1, 68.2) |
| $\mu$ | 3845 | 5672.1 | 21.7 (12.9) | 5446.4 (3848.1) | 204.0 (107.4, 1.3, 69.2) |

96% (68%) of this $\mu$-like sample is from $\nu_\mu$CC ($\nu_\mu$CC q.e.) interactions.

## 3. Results

In Table 1, the numbers of observed events are shown with the corresponding Monte Carlo predictions. From the real data and the MC with no oscillations, we obtain:

$$R_{\pi^0} \equiv (\pi^0/\mu)_{\mathrm{DATA}}/(\pi^0/\mu)_{\mathrm{MC\,no\,osc}} = 1.47 \pm 0.07(\text{data stat.}) \pm 0.21(\text{sys.}) \qquad (1)$$

The result is significantly away from unity, indicating neutrino oscillations.

To test $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_s$ oscillation scenarios, we calculate $R_{\pi^0}^{\mathrm{MC}} \equiv (\pi^0/\mu)_{\mathrm{MC\,osc}}/(\pi^0/\mu)_{\mathrm{MC\,no\,osc}}$ for both hypotheses. Fig. 2 shows the expected $R_{\pi^0}^{\mathrm{MC}}$ as a function of $\Delta m^2$ assuming the maximal mixing ($\sin^2 2\theta = 1$), along with our measurement result $R_{\pi^0}$.

The largest systematic error on $R_{\pi^0}$ comes from uncertainties on neutrino cross sections and pion nuclear reinteractions. For neutrinos with energies between 500 to 2500 MeV, we have a good understanding of neutrino interactions and nuclear effects from the $R_{\pi^0}$ measurement in K2K [5]. In this energy range, we use the K2K measurement error on $R_{\pi^0}^{\mathrm{K2K}}$, 9%, as the systematic error on $R_{\pi^0}^{\mathrm{SK}}$. The differences in spectrum shape and neutrino composition between the K2K beam and the atmospheric neutrino cause additional systematic error of 4.5 %. For neutrinos with energies less than 500 MeV or greater than 2500 MeV, the error due to cross section uncertainties is estimated to be 21 %. Thus, the flux-weighted average is 12 %. Systematic errors due to the reconstruction are about 7 %. Uncertainties in the atmospheric neutrino flux contribute 2.5 % . MC statistics contribute 1 %.

## 4. Conclusion

By applying the recent measurement of $R_{\pi^0}$ in the 1kt detector at K2K, we have determined the Super-Kamiokande measurement of this double ratio to be more consistent with $\nu_\mu \leftrightarrow \nu_\tau$ oscillations at the Super-Kamiokande best-fit

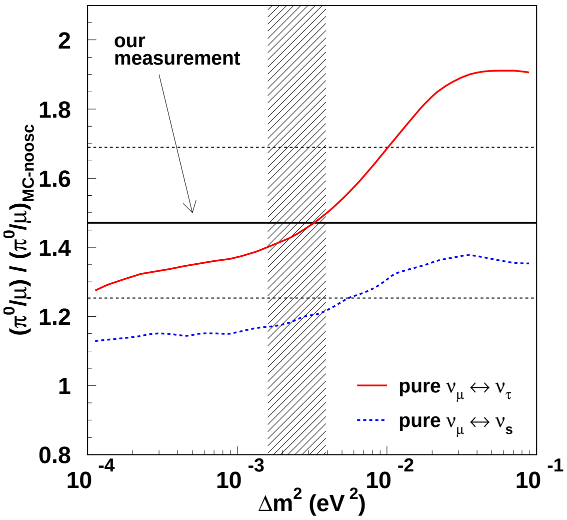


**Fig. 2.** $R_{\pi^0}^{\mathrm{MC}}$ as a function of $\Delta m^2$ for the $\nu_\mu \leftrightarrow \nu_\tau$ case (solid curve) and the $\nu_\mu \leftrightarrow \nu_s$ oscillation case (dashed curve). The maximal mixing ($\sin^2 2\theta = 1$) is assumed. The result of our measurement (solid straight line) is also shown with the estimated error (dashed straight line). A hatched area represents the Super-Kamiokande 90 % confidence level allowed range of $\Delta m^2$ in case of the maximal mixing.

point of $\Delta m^2 = 2.5 \times 10^{-3}$ and $\sin^2 2\theta = 1.0$ [6], while the $\nu_\mu \leftrightarrow \nu_s$ hypothesis is 1.5 $\sigma$ away. $R_{\pi^0} = 1.47 \pm 0.22$ while for $\nu_\mu \leftrightarrow \nu_s$, the prediction is 1.17 and for $\nu_\mu \leftrightarrow \nu_\tau$, the prediction is 1.41. The difference in the prediction for the two oscillation hypotheses is almost entirely from the NC/CC ratio as it does not rely on the matter effect for high energy neutrinos. In addition to the excellent agreement with the $\nu_\mu \leftrightarrow \nu_\tau$ hypothesis, the predicted absolute $\pi^0$ rate agrees well with the data.

## 5. References

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