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# $L/E$ analysis of the atmospheric neutrino data from Super-Kamiokande

I. Higuchi for the Super-Kamiokande collaboration
*ICRR, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa 277-8583, Japan*
Presenter: I. Higuchi (higuchi@icrr.u-tokyo.ac.jp),jap-higuchi-I-abs1-he22-oral

Muon neutrino disappearance probability as a function of neutrino flight length L over neutrino energy E was studied. A dip in the $L/E$ distribution was observed in the data from both Super-Kamiokande-I and -II, as predicted from the sinusoidal flavor transition probability of neutrino oscillation. The observed $L/E$ distribution constrained $\nu_\mu \leftrightarrow \nu_\tau$ neutrino oscillation parameters.

## 1. Introduction

Super-Kamiokande is a 50,00 ton water Cherenkov detector located 1,000 m ( 2,700 m water equivalent) under Mt. Ikenoyama at Kamioka Observatory, Gifu Prefecture, Japan. The detector is a cylindrical tank and is optically divided into two regions. The inner detector (ID) is instrumented with 11,146 inward facing 20 inch PMTs which give a photo cathode coverage of 40 %. The outer detector (OD) completely surrounds the ID with the thickness of 2.05 m to 2.2 m water and is monitored by 1,885 outward-facing 8 inch PMTs. The OD works as a veto counter against cosmic ray muons. The charge information observed in the OD is also used to separate event sample in the $L/E$ analysis.

## 2. $L/E$ analysis

Atmospheric neutrino were observed in Super-Kamiokande-I and Super-Kamiokande-II during 1489 and 627 live-days exposure, respectively. The atmospheric neutrino events are classified into fully contained (FC) and partially contained (PC). The vertices of neutrino interactions are required to be inside the fiducial volume of the ID for FC and PC events. If the tracks of entire particles are contained inside the ID, the event is classified as FC. If one of the particles, mostly a muon, exits the ID and deposits visible energy in the OD for, the event is classified as PC. Each observed Cherenkov ring is identified as either $e$-like or $\mu$-like based on the ring pattern. The directions and the momentum of charged particles can be reconstructed from the ring image. The atmospheric neutrino events in Super-Kamiokande are predicted by a detailed Monte Carlo simulation [1].

In the $L/E$ analysis, PC events is subdivided into two categories :“OD stopping events” where the muon stops in the outer detector, and “OD through-going events” where the muon exit into the rock. The division is based on the amount of Cherenkov light detected in the OD. Since these two samples have different resolution in $L/E$, different cuts were applied for each sample, improving the overall efficiency.

The neutrino energy is estimated from the total energy of charged particles observed in the ID. The energy deposited in the OD is estimated from the potential track length in the OD and is taken into account for PC events. The relationship between the neutrino energy and the observed energy is determined based on the Monte Carlo simulation. The flight length of neutrinos, which ranges from approximately 15 km to 13,000 km depending on the zenith angle, is estimated from the direction of the total momentum of the observed particles.

The resolution of the reconstructed $L/E$ is calculated at each point of the ($cos\Theta$,$E_\nu$) plane, where $\Theta$ is the zenith angle. The $L/E$ resolution cut is set to be $\Delta L/E < 70\%$ from the Monte Carlo simulation distinguish neutrino oscillation from other hypotheses.

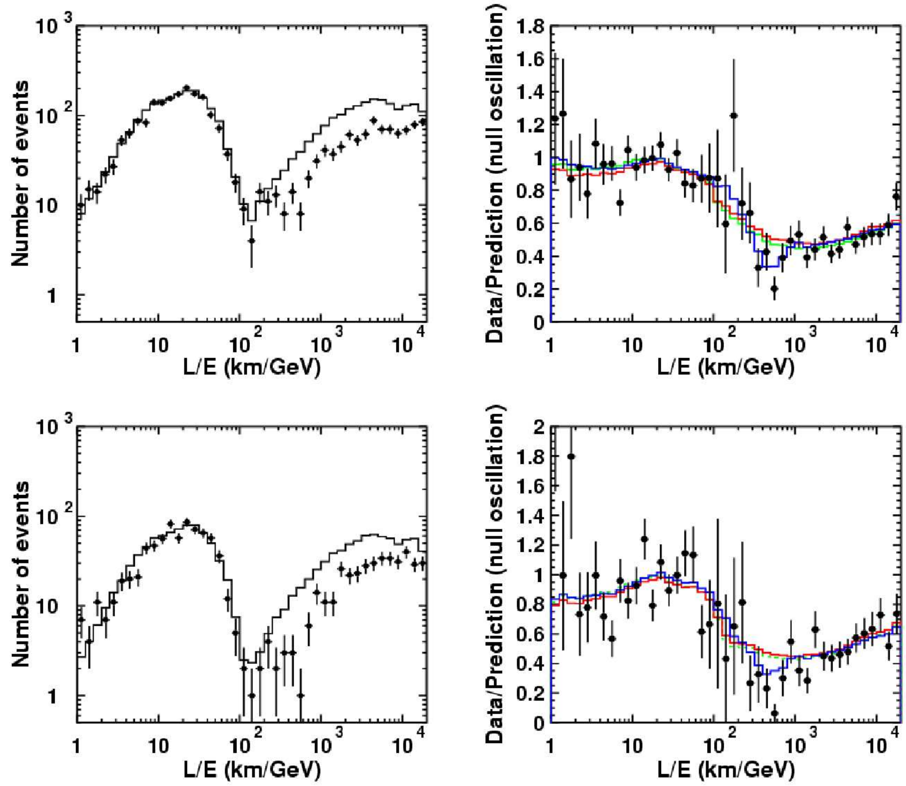


**Figure 1.** Upper and lower plots are for Super-Kamiokande-I and -II(preliminary), respectively. Left: Number of events as a function of the reconstructed $L/E$ for the data (point) and the atmospheric neutrino Monte Carlo events without neutrino oscillation(histogram). Right: Ratio of the data to the non-oscillated Monte Carlo events (points) with the best-fit expectation for 2-flavor $\nu_\mu \leftrightarrow \nu_\tau$ oscillations (blue line). Also shwon are the best-fit expectaion for neutrino decay (red line) and neutrino decoherence (green line).

The left plots in Figure 1 shows the number of events as a function of $L/E$ for the data and Monte Carlo predictions whithout oscillation, and the right plot shows the data over non-oscillated Monte Carlo ratio with the best-fit expectation for 2-flavor $\nu_\mu \leftrightarrow \nu_\tau$ oscillations in which systematic errors are considerd. A dip, which should correspond to the first oscillation minimum, was observed around $L/E = 50km/GeV$ for both Super-Kamiokande-I and -II.

A fit to the observed $L/E$ distributions was carried out assuming neutrino oscillations. In the analysis, the $L/E$ distribution is divided into 43 bins between $log(L/E) = 0.0$ and 4.3. the likelihood of the fit and the $\chi^2$ are difined as :

$$\mathcal{L}(N^{\rm prd}, N^{\rm obs}) = \prod_{i=1}^{43} \frac{\exp\left(-N_i^{\rm prd}\right)(N_i^{\rm prd})^{N_i^{\rm obs}}}{N_i^{\rm obs}!} \times \prod_{j=1}^{24} \exp\left(-\frac{\epsilon_j^2}{2\sigma_j^2}\right), \tag{1}$$

$$\chi^2 \equiv -2\ln\left(\frac{\mathcal{L}(N^{\rm prd}, N^{\rm obs})}{\mathcal{L}(N^{\rm obs}, N^{\rm obs})}\right), \tag{2}$$

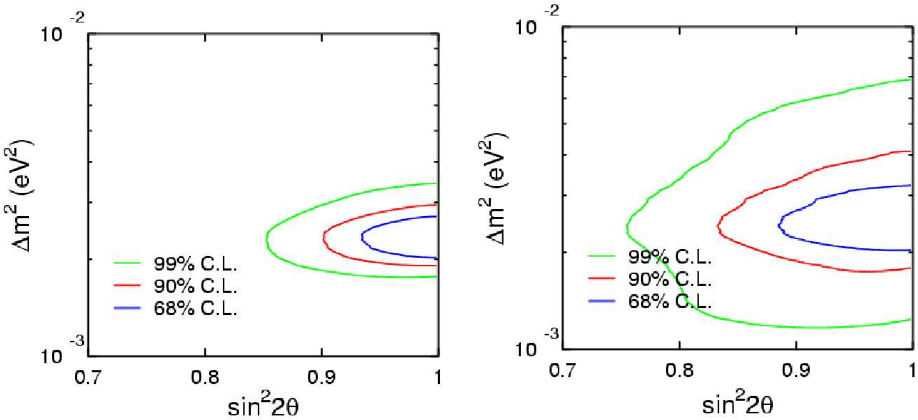


**Figure 2.** 68,90 and 99 % C.L. allowed oscillation parameter regions for 2-flavor $\nu_\mu \leftrightarrow \nu_\tau$ oscillations obtained by the $L/E$ analysis. Left and right plots show the SK-I and SK-II(prelliminary) allowed oscillation parameter region, respectively.

**Table 1.** Results from the oscillation analysis based on the SK-I and SK-II $L/E$ distributions. Results from SK-II are preliminary.

| | $\chi^2_{min}$ at $(\sin^2 2\theta,\, \Delta m^2)$ | $\chi^2_{min}$ include unphysical region | 90% C.L. allowed region |
|---|---|---|---|
| SK-I | $37.9/40$ d.o.f<br>$(1.00,\ 2.4\times10^{-3}\,\mathrm{eV}^2)$ | $37.7/40$ d.o.f<br>$(1.02,\ 2.4\times10^{-3}\,\mathrm{eV}^2)$ | $\sin^2 2\theta\ > 0.9$<br>$1.9\times10^{-3}\,\mathrm{eV}^2 < \Delta m^2 < 3.0\times10^{-3}\,\mathrm{eV}^2$ |
| SK-II | $54.8/40$ d.o.f<br>$(1.00,\ 2.6\times10^{-3}\,\mathrm{eV}^2)$ | $54.7/40$ d.o.f<br>$(1.02,\ 2.6\times10^{-3}\,\mathrm{eV}^2)$ | $\sin^2 2\theta\ > 0.83$<br>$1.8\times10^{-3}\,\mathrm{eV}^2 < \Delta m^2 < 4.0\times10^{-3}\,\mathrm{eV}^2$ |

where $N_i^{\mathrm{obs}}$ is the number of the observed events in the $i$-th bin and $N_i^{\mathrm{prd}}$ is the number of predicted events, in which neutrino oscillation and systematic uncertainties are considered. 25 systematic uncertainties are considered in the $L/E$ analysis, which include uncertainty parameters from the neutrino flux calculation, neutrino interaction models and detector performance. Among these, only 24 constrain the likelihood as the absolute normalization is allowed to be free. The second term in the likelihood definition represents the contributions from the systematic errors, where $\sigma_j$ is the estimated uncertainty in the parameter $\epsilon_j$.

A scan was carried out on a $(\sin^2 2\theta, \log\Delta m^2)$ grid, minimizing $\chi^2$ by optimizing the systematic error parameters at each grid point. Figure 2 shows the contour plot of the 68, 90 and 99 % C.L. allowed oscillation parameter regions for both the Super-Kamiokande-I and -II data. The observed $L/E$ distributions, especially the first dip, give the direct evidence that the neutrino flavor transition probability obeys the sinusoidal function as predicted by neutrino flavor oscillations. Table 1 shows the results from $L/E$ analysis results for SK-I and SK-II.

The observed $L/E$ distribution was also fit assuming neutrino decay [3, 4] and neutrino decoherence [5, 6]. The right-hand plot in Figure 1 includes the best-fit expectation for neutrino decay and decoherence. The detail analysis is writen in [2]

Table 2 shows the $\chi^2$ values and $\Delta\chi^2$ values for neutrino decay and neutrino decoherence models.

**Table 2.** Minimum $\chi^2$ values for neutrino decay and decoherence models based on the SK-I and SK-II $L/E$ distributions. Also shown are the difference in the minimum $\chi^2$ between the oscillation and the other models. Results from SK-II are preliminary.

| | neutrino decay $\chi^2_{min}$,$\Delta\chi^2$ | neutrino decoherence $\chi^2_{min}$,$\Delta\chi^2$ |
|---|---|---|
| SK-I | $49.1/40$ d.o.f<br>$11.3/40$ d.o.f(3.4 standard deviations) | $52.4/40$ d.o.f<br>$14.5/40$ d.o.f(3.8 standard deviations) |
| SK-II | $62.8/40$ d.o.f<br>$7.9/40$ d.o.f(2.8 standard deviations) | $63.5/40$ d.o.f<br>$8.7/40$ d.o.f(2.9 standard deviations) |

## 3. Conclusions

$L/E$ analyses were carried out using atmospheric neutrino data. A dip in the $L/E$ distribution was observed, as predicted from the sinusoidal flavor transition probability of neutrino oscillation. The results from Super-Kamiokande-I and -II agree well. The allowed neutrino oscillation parameter retion, epsecially the $\Delta m^2$ regions, was tightly constrained.

## References

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