Upward Coming Muons in SuperKamiokande and Muon Neutrino Oscillations

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Abstract

Upward coming cosmic ray muons, produced by neutrinos in the surrounding rock and passing through or stopping in the SuperKamiokande water Cherenkov detector tank, have been analyzed from 537 days of livetime. Their zenith angle distributions and relative fluxes can be explained consistently by neutrino oscillation between ν_μ and ν_τ, with a large mixing angle ($\sin^2 2\theta > 0.4$, $10^{-3} < \Delta m^2 < 5 \times 10^{-2}$ eV), and no oscillations are rejected at $> 99\%$ CL. Potential backgrounds, particularly due to near horizontal atmospheric muons, are shown to have negligible influence on the results.

1 Introduction:

The Super-Kamiokande ("Super-K") atmospheric neutrino analyses (Fukuda *et al.*, 1998-a) provide evidence for $\nu_\mu \leftrightarrow \nu_\tau$ (or $\nu_\mu \leftrightarrow \nu_{sterile}$) flavor oscillations. These analyses examine neutrinos whose interaction vertices are inside the water of the Super-K detector. In order to extend this analysis to higher energies, we study muons produced outside the detector in a large volume of the surrounding rock. However, since the overwhelming majority of the downward muons are the atmospheric muons, only the upward coming muons are usable for the study of the neutrino oscillation at Super-K.

Detection of upward coming muons resulting from tauons produced in ν_τ or $\bar{\nu}_\tau$ charged current interactions is suppressed by branching ratios and kinematics to $\lesssim 3\%$ of the ν_μ induced muon flux. Thus, the event rate of the upward coming muons is closely related to the flux of the muon-flavored neutrinos, allowing a test of possible ν_μ disappearance due to flavor oscillations.

The first analysis of the upward through-going muons at Super-K was published (Fukuda *et al.*, 1999) and the combined analysis of upward stopping and through-going muons is being done (Habig, Super-K, 1999). In this presentation, the contamination of the atmospheric muons in the upward muon events will be extensively studied.

2 Detection of upward coming muons:

The Super-K detector is a 50 kton cylindrical water Cherenkov calorimeter located at the Kamioka Observatory ~1000 m underground in the Kamioka mine, Japan. The detector is divided by an optical barrier instrumented with photomultiplier tubes into a cylindrical primary detector region (the Inner Detector) and a surrounding shell of water (the Outer Detector) which allows the tagging of entering and exiting particles (Fukuda it et al., 1998-b).

The cosmic ray muon rate at Super-K is 2.2 Hz. The trigger efficiency for a muon entering the detector with momentum more than 200 MeV/c is ~100% for all zenith angles. The nominal detector effective area for upward coming muons with a track length > 7m in the Inner Detector is ~1200 m^2.

The data used in this analysis were taken from Apr. 1996 to Jan. 1998, corresponding to 537 days of detector livetime for the through-going muon analysis and 516 live-days of the stopping muon analysis.

To select muon events starting outside the detector, signals from the Outer Detector at the muon's entrance point are required. A minimum track length cut of 7m (~1.6 GeV) was applied. This cut serves to eliminate non-muon showering background and the contamination of upward pions coming from hadronic interactions of atmospheric muons (Ambrosio *et al.*, 1998).

In Fig. 1, the selected muon events satisfying $\cos\theta < 0.1$ are plotted on the angular plane of (ϕ, cosθ), where ϕ and θ are the azimuthal and zenith angles of the muon track, respectively. A few clusters of events seen above the horizon in Fig. 1 are due to relatively thin rock depths, which is well reproduced by a Monte Carlo simulation now under way.

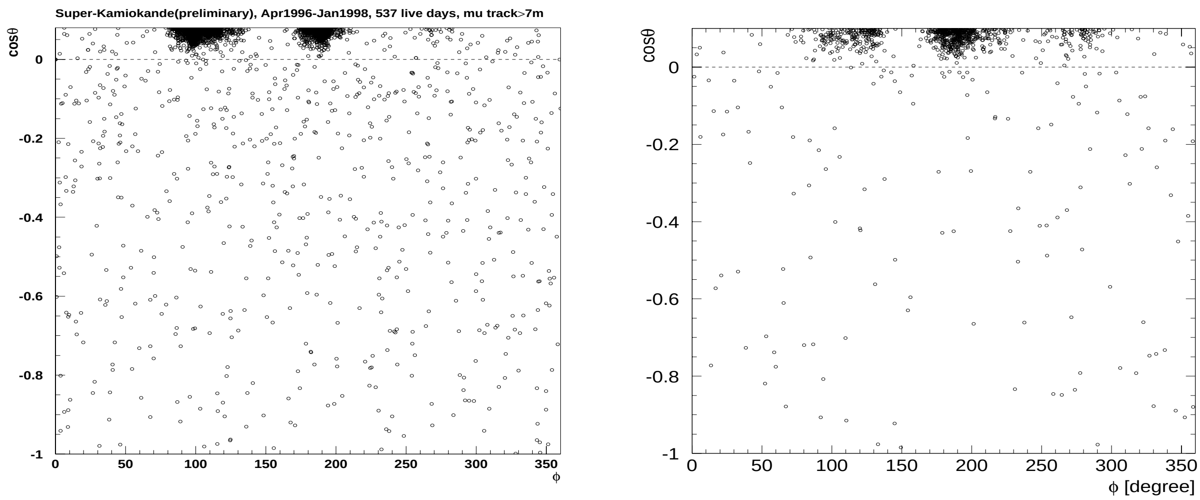

Figure 1: The observed throughgoing (left) and stopping (right) muon events on the angular plane (ϕ,cosθ) for 537 and 516 live days respectively, with track length $>$ 7m.

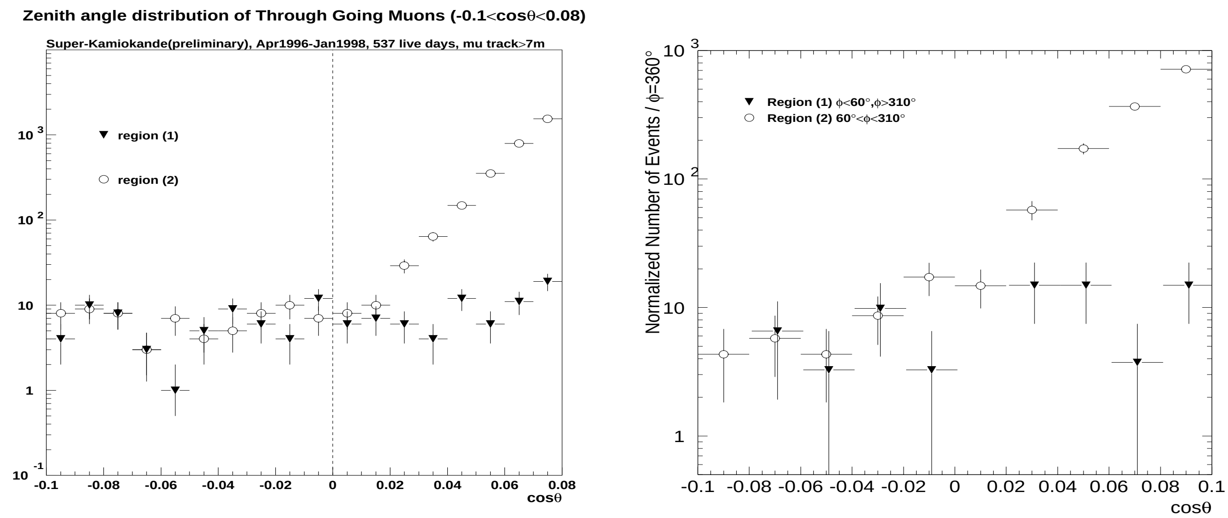

Figure 2: Zenith angle distributions of through-going (left) and stopping (right) muons near the horizon. Filled triangles (open circles) indicate events coming from azimuthal region where the rock overburden is thick (thin). The azimuthal regions with the thin rock are defined as $60° < \phi < 240°$ for the through-going muons, and $60° < \phi < 310°$ for stopping muons. Most of the downward-going ($\cos\Theta > 0$) muons denoted by filled triangles are induced by atmospheric neutrinos.

Due to the finite angular resolution (1.5°) and multiple Coulomb scattering in the nearby rock, some down-going cosmic ray muons may appear to have $\cos\Theta < 0$. The estimation of this background in the nearly horizontal zenith angle bin is done by fitting the nearly horizontal down-going muon zenith angle shape in the azimuthal region of thin rock defined in Fig. 2 and projecting its assumed exponential tail below the horizon.

This background is estimated to be 4.3±0.4 out of the total 614 through-going events and 13.2±3.5 out of the total 137 stopping events. A Monte Carlo study to confirm the validity of this method is being performed.

The resulting flux plotted as a function of zenith angle can be seen in Fig. 3.

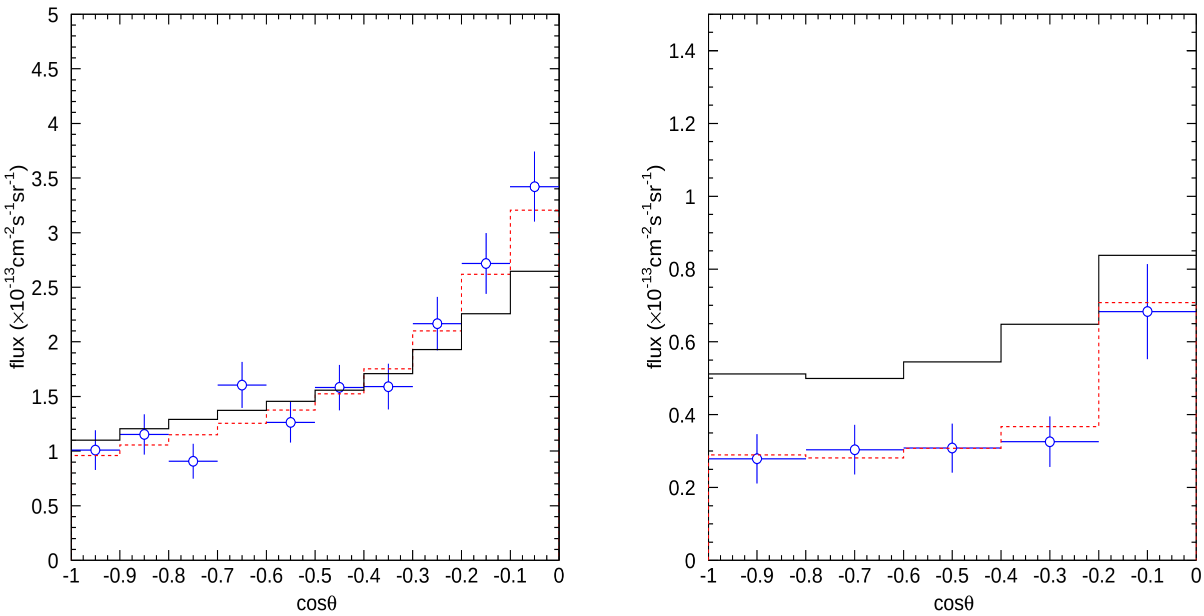

Figure 3: Upward through-going (left) and stopping (right) muon fluxes as a function of zenith angle. The error bars indicate uncorrelated experimental systematic plus statistical errors added in quadrature. The solid histogram shows the expected fluxes based on the Honda/GRV94 model (see text) for the null neutrino oscillation case, normalized by $\alpha = -10\%$ from the best-fit no-oscillation through-going muon case. The dashed lines are the expected flux in the presence of $\nu_\mu \leftrightarrow \nu_\tau$ oscillations at maximal mixing and $\Delta m^2 = 3.2 \times 10^{-3}\mathrm{eV}^2$, the best-fitting oscillation hypothesis.

3 Analysis of neutrino oscillations:

Here the combined analysis of the upward through-going and stopping muon events is presented. Since the mean energies of their parent neutrinos are much different between the two types of events ($\sim$ 100 GeV for the former and $\sim$ 10 GeV for the latter), it is meaningful to compare all of their relative fluxes and their zenith angle dependences with the theoretical expectations.

To predict the expected upward coming muon flux, this analysis uses a model which is a combination of the atmospheric neutrino flux from (Honda *et al.*,1995/1996), and a neutrino interaction model composed of quasi-elastic scattering (Llewellyn Smith, 1972) + single-pion production (Rein & Seghal, 1981) + deep inelastic scattering (DIS) multi-pion production. The DIS cross-section is based on the parton distribution functions (PDF) of GRV94DIS (Glűck, Reya, & Vogt, 1995) with the kinematic constraint of $W > 1.4$ GeV/c^2. Other models are also considered to estimate theoretical uncertainties.

We estimated the most likely values of $\sin^2 2\theta$ and Δm^2 using both the 10 zenith angle bins of upward through-going muon flux and the 5 stopping muon zenith angle flux bins. The expected flux $(d\Phi/d\Omega)_{os}$ for a given set of Δm^2 and $\sin^2 2\theta$ is calculated and the same binning is applied to this flux as to the data. To test the validity of a given oscillation hypothesis, we minimize a χ^2 which is defined as:

$$\sum_{i=1}^{10}\left(\frac{\left(\frac{d\Phi_t}{d\Omega}\right)^i_{ob}-(1+\alpha_\mu)\left(\frac{d\Phi_t}{d\Omega}\right)^i_{os}}{\sqrt{\sigma^2_{stat,i}+\sigma^2_{sys,i}}}\right)^2+\sum_{j=1}^{5}\left(\frac{\left(\frac{d\Phi_s}{d\Omega}\right)^j_{ob}-(1+\alpha_\mu)(1+\eta)\left(\frac{d\Phi_s}{d\Omega}\right)^j_{os}}{\sqrt{\sigma^2_{stat,j}+\sigma^2_{sys,j}}}\right)^2+\left(\frac{\alpha_\mu}{\sigma_{\alpha_\mu}}\right)^2+\left(\frac{\eta}{\sigma_\eta}\right)^2$$

where $\sigma_{stat,i}$ ($\sigma_{sys,i}$) is the statistical (experimental systematic) error in the observed flux $(d\Phi/d\Omega)^i_{ob}$ for the ith bin, $(1+\alpha_\mu)$ is an absolute normalization factor of the expected flux, and $(1+\eta)$ is a comparative normalization between stopping and through-going fluxes. The absolute flux normalization error σ_{α_μ} is estimated to be ± 22 %. σ_η is estimated to be $^{+13}_{-12}$ %. $\sigma_{sys,i}$ ranges from $\pm(0.3-3.8)$%. The no-oscillation case results in a $\chi^2/dof = 41/15$, a poor probability (3.2×10^{-4}) of the null hypothesis. However, the best fit point of maximal mixing and $\Delta m^2 = 3.2\times10^{-3}\mathrm{eV}^2$ matches the data well with $\chi^2/dof = 8.0/13$, as can be seen in Fig. 3.

Fig. 4 shows the confidence intervals in oscillation parameter space, taking into account that the overall best fit is slightly outside the physical region at $\sin^2 2\theta = 1.1, \Delta m^2 = 3.7\times10^{-3}\mathrm{eV}^2$. These results are consistent with those obtained in the analysis of Super-K's contained atmospheric neutrino events (Fukuda, *et al*, 1998-a).

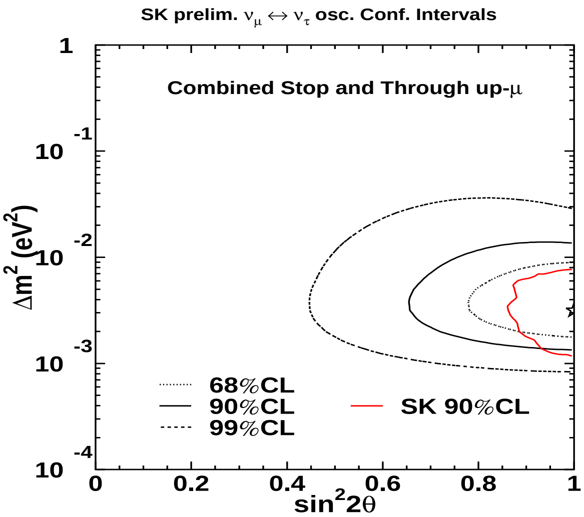

Figure 4: The allowed region contours at 68% (dotted contour), 90% (thick solid), and 99% (dashed) C.L. obtained by combining the Super-K upward through-going and stopping muon data in a fit on the $(\sin^2 2\theta, \Delta m^2)$ plane for the $\nu_\mu \leftrightarrow \nu_\tau$ oscillation hypothesis. The star indicates the best fit point at $(\sin^2 2\theta, \Delta m^2) = (1.0, 3.2\times10^{-3}\mathrm{eV}^2)$. Also shown is the allowed region contour (thin solid) at 90% C.L. by the Super-K contained event analysis.

Making use of the higher energy ν_μ interactions in the rock surrounding Super-Kamiokande provides an independent and complementary test of the $\nu_\mu \leftrightarrow \nu_\tau$ disappearance oscillations proposed to explain the atmospheric neutrino anomaly.

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