Measurement of the Flux and Zenith-Angle Distribution of Upward Throughgoing Muons by Super-Kamiokande

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A total of 614 upward throughgoing muons of minimum energy 1.6 GeV are observed by Super-Kamiokande during 537 detector live days. The measured muon flux is $[1.74 \pm 0.07(\mathrm{stat}) \pm 0.02(\mathrm{sys})] \times 10^{-13}\ \mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$ compared to an expected flux of $[1.97 \pm 0.44(\mathrm{theor})] \times 10^{-13}\ \mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$. The absolute measured flux is in agreement with the prediction within the errors. However, the zenith-angle dependence of the observed upward throughgoing muon flux does not agree with no-oscillation predictions. The observed distortion in shape is consistent with the $\nu_\mu \leftrightarrow \nu_\tau$ oscillation hypothesis with $\sin^2 2\theta > 0.4$ and $1 \times 10^{-3} < \Delta m^2 < 1 \times 10^{-1}\ \mathrm{eV}^2$ at 90% confidence level. [S0031-9007(99)08762-1]

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Energetic atmospheric ν_μ or $\overline{\nu}_\mu$ passing through the Earth interact with the rock surrounding the Super-Kamiokande ("Super-K") detector and produce muons via weak interactions. While those neutrino-induced muons traveling downwards are impossible to differentiate from the constant rain of cosmic ray muons, upwardgoing muons are mostly ν_μ or $\overline{\nu}_\mu$ induced because upwardgoing cosmic ray muons cannot penetrate through the whole Earth, and ν_e and $\overline{\nu}_e$ induced electrons and positrons shower and die out in the rock before reaching the detector. Those muons energetic enough to cross the entire detector are defined as "upward throughgoing muons." The mean energy of their parent neutrinos is approximately 100 GeV. Neutrinos arriving vertically travel roughly 13 000 km, while those coming from near the horizon originate only $\sim$500 km away.

Previously published results on atmospheric neutrinos with average energies below $\sim$10 GeV have indicated an anomalously low ν_μ/ν_e ratio [1–4] and have also reported a strong zenith-angle dependence [2]. This has been interpreted as a possible signature of neutrino oscillations. Recent results from this experiment [5,6] have shown strong evidence for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations [7]. These results have reported on lower energy ν_μ and ν_e neutrinos which interacted in the water of the detector itself, hereafter referred to as "contained" events.

The oscillation hypothesis has also been suggested to explain the anomalous upward throughgoing muon zenith-angle distributions observed by Kamiokande [8] and MACRO [9] as well as the low absolute upwardgoing muon flux seen in MACRO. However, the absolute upwardgoing muon fluxes measured in Kamiokande, IMB [10], and Baksan [11] were consistent with the no-oscillation expectations within the large errors present in the absolute flux predictions.

We make the first report on the measurement of upward throughgoing muon flux and its zenith-angle distribution as observed by Super-K. The experimental site is located at the Kamioka Observatory, Institute for Cosmic Ray Research, the University of Tokyo, 1000 m underground in the Kamioka mine, Gifu prefecture, Japan.

The Super-K detector is a 50 kton cylindrical water Cherenkov calorimeter. The detector is divided by an optical barrier instrumented with photomultiplier tubes ("PMT"s) into a cylindrical primary detector region (the inner detector, or "ID") and a surrounding shell of water (the outer detector, or "OD") serving as a cosmic ray veto counter. Details of the detector can be found in Ref. [5].

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 $\sim$100% for all zenith angles. The nominal detector effective area for upward throughgoing muons with a track length $>$7 m in the ID is $\sim$1200 m^2.

The data used in this analysis were taken from April 1996 to January 1998, corresponding to 537 days of detector live time. Event reconstruction is made by means of the charge and timing information recorded by each hit PMT. The direction of a muon track is first reconstructed by several automated grid search methods, which find the track by minimizing the width of the residual distribution of the photon time-of-flight subtracted ID PMT times. Details of one such muon fitter are described elsewhere [12].

A minimum track length cut of 7 m ($\sim$1.6 GeV) was applied. To reduce the abundant downwardgoing cosmic ray muons, events satisfying $\cos\Theta < 0.1$ are selected, where Θ is the zenith angle of the muon track, with $\cos\Theta < 0$ corresponding to upwardgoing events. Muons which leave both entrance and exit signal clusters in the OD are regarded as throughgoing. After a visual scan by two independent groups (event loss probability $<$0.01%) and a final hand-fit direction, 614 upward throughgoing muon events with $\cos\Theta < 0$ are observed. Different hand fits are consistent with each other within 1.5°. They are shown to be unbiased in blind tests using Monte Carlo (MC) simulated events, with deviations between the reconstructed track direction and the real muon direction ($\Delta\theta_{\rm rec}$) estimated to be 1.4°. Using this same MC, the directional correlation between a muon and its parent neutrino is estimated to be 4.1°, including contributions from the muon production angle and from multiple Coulomb scatterings in the rock.

Because of the finite fitter resolution and multiple Coulomb scattering in the nearby rock, some downgoing cosmic ray muons may appear to have $\cos\Theta < 0$. Figure 1 illustrates the estimation of this contamination. Assuming this background continues to fall exponentially as $\cos\Theta$ decreases, the contribution to apparent upwardgoing muons is estimated to be 4.3 ± 0.4 events, all

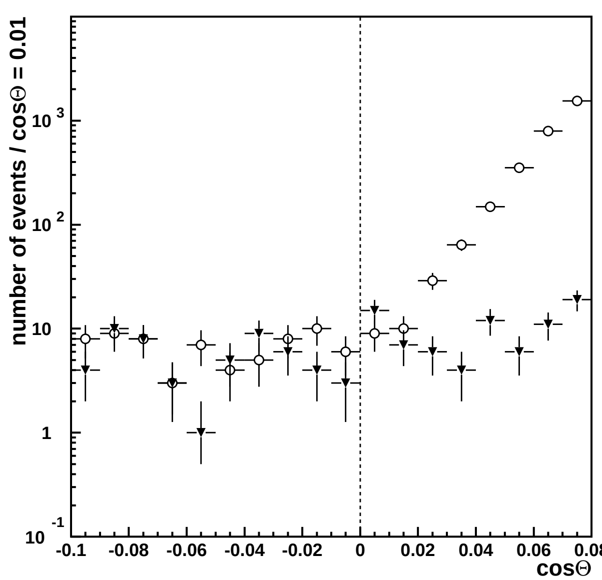

FIG. 1. Zenith-angle distribution of throughgoing muons near the horizon observed by Super-K. Filled triangles (open circles) indicate events coming from the 180° azimuthal region where the rock overburden is thick (shallow). Most of the downwardgoing ($\cos\Theta > 0$) muons denoted by filled triangles are induced by atmospheric neutrinos.

contained in the $-0.1 < \cos\Theta < 0$ zenith-angle bin. The contamination at the Kamioka site due to cosmic ray photoproduced upwardgoing pions [13] meeting the 7 m track length requirement is estimated to be <1%.

The total detection efficiency of the complete data reduction process for upward throughgoing muons is estimated by a Monte Carlo simulation to be >99%, which is almost isotropic for $-1 < \cos\Theta < 0$. Using the upward/downward symmetry of the detector configuration, the validity of this Monte Carlo program has been checked by real cosmic ray downward throughgoing muons.

This analysis used a model which is a combination of the Bartol atmospheric neutrino flux model [14] and a neutrino interaction model composed of quasielastic scattering [15] + single-pion production [16] + deep inelastic scattering (DIS) multipion production. The DIS cross section is based on the parton distribution functions (PDF) of GRV94DIS [17] with the additional kinematic constraint of $W > 1.4$ GeV/c^2. Lohmann's muon energy loss formula in standard rock [18] is then employed to analytically calculate the expected muon flux at the detector. This flux is compared to three other analytic calculations to estimate the model-dependent uncertainties of the expected muon flux. The other flux calculations use the various pairs of the Bartol flux, the GRV94DIS PDF, the atmospheric neutrino flux model calculated by Honda *et al.* [19], and the CTEQ3M [20] PDF. These comparisons yield ±10% of uncertainty for the absolute flux normalization and −3.7% to +1.6% for the bin-by-bin shape difference in the zenith-angle distribution. The shape difference is due mostly to the input flux models.

The Bartol+GRV94DIS calculation results in an expected muon flux $\Phi_{\rm theor}$ of $[1.97 \pm 0.44({\rm theor})] \times 10^{-13}$ cm^{-2} s^{-1} sr^{-1} ($\cos\Theta < 0$), where the estimated theoretical uncertainties are described in Table I. The dominant error comes from the absolute normalization uncertainty in the neutrino flux, which is estimated to be approximately ±20% [14,19,21] for neutrino energies above several GeV.

Given the detector live time T, the effective area for upward throughgoing muons $S(\Theta)$, and the detection efficiency $\varepsilon(\Theta)$, the upward throughgoing muon flux is calculated by the formula

$$\Phi_{\rm obs} = \sum_{j=1}^{N} \frac{1}{\varepsilon(\Theta_j)} \frac{1}{S(\Theta_j)2\pi} \frac{1}{T},$$

where the suffix j represents each event number, 2π is the total solid angle covered by the detector for upward throughgoing muons, and N corresponds to the total number of observed muon events (614). Subsequently, we subtract the cosmic ray muon contamination (4.3 events) from the most horizontal bin ($-0.1 < \cos\Theta < 0$).

Conceivable experimental systematic errors are summarized in Table II. Including these experimental systematic errors, the observed upward throughgoing muon flux is $\Phi_{\rm obs} = [1.74 \pm 0.07({\rm stat}) \pm 0.02({\rm sys})] \times 10^{-13}$ cm^{-2} s^{-1} sr^{-1}.

Figure 2 shows the flux as a function of the zenith angle. The shape of the distribution is not well represented by the theoretical prediction without neutrino oscillation having a χ^2/degrees of freedom (d.o.f.) = 18.7/9 corresponding to 2.8% probability. This shape comparison is done after multiplying the expected flux by a free-running normalization factor $(1 + \alpha_\mu)$, whose best fit value is $\alpha_\mu = -14\%$.

A set of neutrino oscillation hypotheses are then tested using the zenith-angle distribution. The expected flux $[(d\Phi/d\Omega)_{\rm osc}]$ for a given set of Δm^2 and $\sin^2 2\theta$ is calculated and the same binning ($d\cos\Theta = 0.1$) 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

$$\sum_{i=1}^{10} \left[\frac{(\frac{d\Phi}{d\Omega})^i_{\rm obs} - (1 + \alpha_\mu)(\frac{d\Phi}{d\Omega})^i_{\rm osc}}{\sqrt{\sigma^2_{{\rm stat},i} + \sigma^2_{{\rm sys},i}}} \right]^2 + \left(\frac{\alpha_\mu}{\sigma_{\alpha_\mu}} \right)^2,$$

where $\sigma_{{\rm stat},i}$ ($\sigma_{{\rm sys},i}$) is the statistical (experimental systematic) error in the observed flux $(d\Phi/d\Omega)^i_{\rm obs}$ for the ith bin, and $(1 + \alpha_\mu)$ is an absolute normalization factor of the expected flux. The absolute flux normalization error σ_{α_μ} is estimated to be ±22% by adding in quadrature the bin-to-bin correlated experimental errors and theoretical

TABLE I. List of theoretical uncertainties in the flux calculation.

Error source	Error (%)
Chemical composition of the rock	$\ll 1$[a]
ν flux normalization	±20[a]
Theoretical model dependence	
absolute flux	±10[a]
bin by bin	−3.7 to +1.6[b]
spectral index	±1.4[a]

[a]Theoretical bin-by-bin correlated uncertainty.
[b]Theoretical uncorrelated uncertainty.

TABLE II. List of experimental systematic errors in the flux measurement.

Error source	Error (%)
Uncertainty in $\Delta\theta_{\rm rec}$	<±1[a]
Detection efficiency	<±1.2[b]
7 m track length cut	±0.5[c]
Live time	±0.1[c]
Effective area	±0.3[c]
PMT gain	$\ll 1$[c]
Water transparency	$\ll 1$[c]

[a]Experimental uncorrelated systematic error specific in the most horizontal bin $-0.1 < \cos\Theta < 0$.
[b]Experimental uncorrelated systematic error.
[c]Bin-by-bin correlated experimental systematic errors.

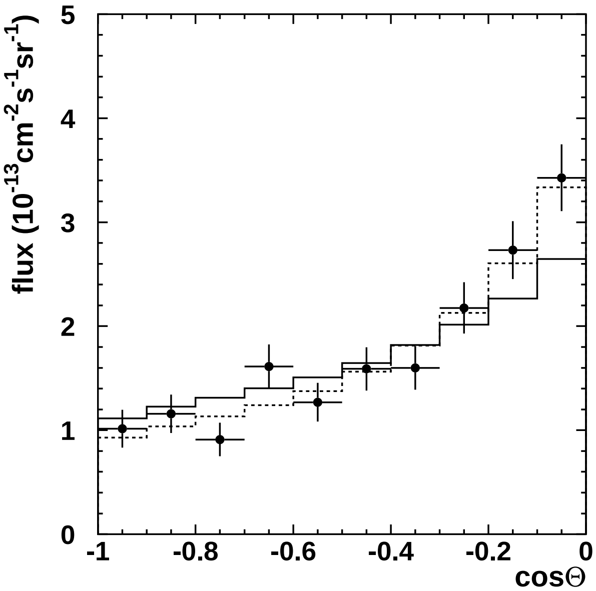

FIG. 2. Upward throughgoing muon flux observed in Super-K as a function of the zenith angle. The error bars indicate uncorrelated experimental systematic plus statistical errors added in quadrature. The solid histogram shows the expected upward throughgoing muon flux with normalization ($\alpha_\mu = -14\%$) based on the Bartol neutrino flux for the null neutrino oscillation case. Also shown as a dotted line is the expected flux assuming the best fit parameters at $(\sin^2 2\theta, \Delta m^2) = (0.95, 5.9 \times 10^{-3}\ \mathrm{eV}^2)$, $\alpha_\mu = +12\%$ for the $\nu_\mu \leftrightarrow \nu_\tau$ oscillation case.

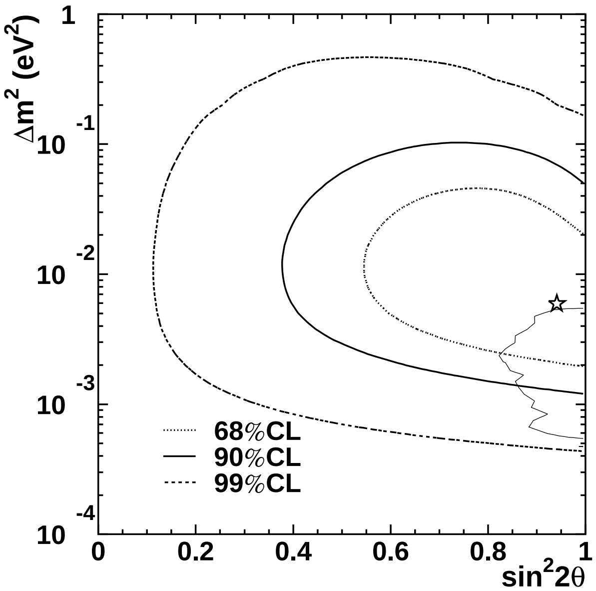

FIG. 3. Allowed region contours at 68% (dotted contour), 90% (thick solid), and 99% (dashed) C.L. obtained by the Super-K upward throughgoing muon analysis on the $(\sin^2 2\theta, \Delta m^2)$ plane for the $\nu_\mu \leftrightarrow \nu_\tau$ oscillation hypothesis. The star indicates the best fit point at $(\sin^2 2\theta, \Delta m^2) = (0.95, 5.9 \times 10^{-3}\ \mathrm{eV}^2)$. Also shown is the allowed region contour (thin solid) at 90% C.L. by the Super-K contained event analysis. The allowed regions are to the right of the contours.

uncertainties in Table I. Based on the bin-by-bin correlated systematic errors in Table II added in quadrature, we estimate $\sigma_{\mathrm{sys},i}$ to range from $\pm(0.3$–$3.8)\%$. Then, the minimum $\chi^2(\chi^2_{\min})$ is searched for on the $\Delta m^2 - \sin^2 2\theta$ plane.

Assuming $\nu_\mu \leftrightarrow \nu_\tau$ oscillations, $\chi^2_{\min}(= 7.5/8$ d.o.f.) occurs at $(\sin^2 2\theta, \Delta m^2) = (0.95, 5.9 \times 10^{-3}\ \mathrm{eV}^2)$ and $\alpha_\mu = +12\%$, in good agreement with the overall normalization found in the contained event analysis [7], although the α_μ of this analysis refers to the flux normalization of neutrino energies predominantly around 100 GeV. For the null oscillation case ($\sin^2 2\theta = 0$), we obtain χ^2 of 19.2 at a best fit $\alpha_\mu = -14\%$ using the same χ^2 definition. The zenith-angle distribution of $(1 + \alpha_\mu)(d\Phi/d\Omega)^i_{\mathrm{osc}}$ for the best fit parameters is shown in Fig. 2 together with the data. Figure 3 shows the confidence intevals on the $(\sin^2 2\theta, \Delta m^2)$ plane for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations. The 90% C.L. contour marks the line of $\chi^2_{\min} + 4.6$. If we replace the Bartol neutrino flux [14] by Honda's [19] and/or the GRV94DIS parton distribution functions [17] by CTEQ3M [20], the allowed region contours are similar to those presented in Fig. 3. Consequently, we find that the zenith-angle dependence is in favor of the $\nu_\mu \leftrightarrow \nu_\tau$ oscillation hypothesis and supports the Super-K contained event analysis [5–7]. It is also consistent with the data presented in the Kamiokande [8] and MACRO [9] upwardgoing muon analyses. Interactions of ν_τ in the rock below are estimated at less than a few percent and neglected in this analysis. Oscillation of ν_μ to ν_e in this range of parameter space has been ruled out by the CHOOZ experiment [22].

In conclusion, based on 614 upward throughgoing muon events during 537 detector live days, the flux of the upward throughgoing muons (>1.6 GeV) is measured with the Super-K detector: $\Phi_{\mathrm{obs}} = [1.74 \pm 0.07(\mathrm{stat}) \pm 0.02(\mathrm{sys})] \times 10^{-13}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$. This is compared with the expected flux of $\Phi_{\mathrm{theor}} = [1.97 \pm 0.44(\mathrm{theor})] \times 10^{-13}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$. The absolute observed upward throughgoing muon flux is in agreement with the expected flux within the relatively large uncertainties in the theoretical calculations. We find that the zenith-angle dependence does not agree with the theoretical expectation without neutrino oscillations at the 97% C.L. However, the $\nu_\mu \leftrightarrow \nu_\tau$ oscillation hypothesis with $\sin^2 2\theta > 0.4$ and $1 \times 10^{-3} < \Delta m^2 < 1 \times 10^{-1}\ \mathrm{eV}^2$ is consistent with the observed zenith-angle shape at 90% C.L. This result supports the evidence for neutrino oscillations given by the analysis of the contained atmospheric neutrino events by Super-K.

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