Measurement of the Flux and Zenith-Angle Distribution of Upward Through-Going Muons in Kamiokande II + III

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The flux of upward through-going muons of minimum (mean) threshold energy >1.6 (3.0) GeV is measured, based on a total of 372 events observed by the Kamiokande II + III detector during 2456 detector live days. The observed muon flux was $\Phi_{obs} = [1.94 \pm 0.10(\text{stat.})^{+0.07}_{-0.06}\text{sys.})] \times 10^{-13} \text{ cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$, which is compared to an expected value of $\Phi_{theo} = [2.46 \pm 0.54(\text{theo.})] \times 10^{-13} \text{ cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$. The observation is in agreement with the prediction within the errors. The zenith-angle dependence of the observed upward through-going muons supports the previous indication of neutrino oscillations made by Kamiokande using sub- and multi-GeV atmospheric neutrino events. [S0031-9007(98)06952-X]

In 1988, the Kamiokande group observed a smaller $(\nu_\mu + \overline{\nu}_\mu)/(\nu_e + \overline{\nu}_e)$ ratio than the expected value in sub-GeV fully contained atmospheric neutrino events [1]. This discrepancy was later confirmed by other experiments IMB-3 [2,3] and Soudan II [4], while some other experiments (Fréjus [5] and Nusex [6]) did not observe such discrepancy within the experimental errors.

Recently, a measurement of this ratio using multi-GeV atmospheric neutrino events was made by the Kamiokande experiment [7]. The observed $(\nu_\mu + \overline{\nu}_\mu)/(\nu_e + \overline{\nu}_e)$ ratio in this energy range was also significantly smaller than expected and depended strongly on the zenith angle.

Having observed the discrepancy in both sub- and multi-GeV atmospheric neutrino events, the next logical step [8–11] is to investigate events that are produced by neutrinos of even higher energies. Energetic atmospheric ν_μ or $\overline{\nu}_\mu$ traveling through Earth interacts with rock layers surrounding the detector and produces muons via charged-current interactions. Upward-going muons are considered neutrino induced, since upward-going cosmic-ray muons range out in Earth. Especially, those energetic enough to pass through the detector are defined as "upward through-going muons." The mean energy of the parent neutrino producing them is approximately 100 GeV.

The experimental site is located 1000 m underground in the Kamioka mine, Gifu prefecture, Japan. The Kamiokande-II detector is a cylindrical water Cherenkov calorimeter. The inner detector is 14.4 m in diameter $\times 13.1$ m in height, which contains 2142 metric tons of purified water. A total of 948 20-inch-in-diameter photomultiplier tubes (PMTs) are mounted on the tank walls and cover 20% of the inner tank surface. The detector also has an optically isolated 4π solid-angle anticounter which is also a 1500-metric-ton water Cherenkov detector with 123 20-inch-in-diameter PMTs and is divided into top, barrel, and bottom parts. The anticounter tags incoming and/or outgoing muons and shields γ rays and neutrons from the surrounding rock. Charge and relative timing information from each hit PMT is recorded for the event reconstruction. The triggering efficiency for a muon having momenta more than 200 MeV/c is ~100%. The nominal detector effective area for upward-going muons is roughly 150 m^2. The deviation between the reconstructed track direction and the real muon direction

($\Delta\theta_{rec}$) is studied by using Monte Carlo events and is estimated to be 2.1° [8]. See [8] for more details of the Kamiokande-II detector. The new phase of the experiment started in December 1990, after replacement of the entire electronics, replacement of the dead PMTs, and installation of an aluminized Mylar cone around each PMT. The description of the Kamiokande-III detector is found elsewhere [12].

The data sets used in this analysis are taken from December 1985 to April 1990 in Kamiokande-II and from December 1990 to May 1995 in Kamiokande-III corresponding to 2456-day detector live time. A total of 2.2×10^8 events were recorded during these data-taking periods.

In Kamiokande-III, when the following three requirements are satisfied, it is considered that a muon hits one of the three anticounter parts: (1) total number of photoelectrons (p.e.) in a part of the anticounter ≥ 20 p.e., (2) number of hit PMTs in the same part of the anticounter ≥ 5, and (3) maximum number of photoelectrons/PMT in an event in the same part of the anticounter ≥ 5 p.e. By requiring the two parts or the barrel part hit in the anticounter, through-going muons can be selected. A selection criterion that the total number of photoelectrons of an event should be larger than 6000 p.e. is imposed to ensure the minimum muon track length of 7 m [corresponding to minimum (mean) muon threshold energy of 1.6 (3.0) GeV]. An upper limit is also set at 40 000 p.e. (corresponding to $\simeq 30$ m track length for a relativistic muon in the detector) to remove multiple muons or muons accompanied with bremsstrahlung, pair production, and/or hadronic showers. The event reduction procedures in Kamiokande-II is described elsewhere [8].

To eliminate abundant downward-going cosmic-ray muons (0.37 Hz), the events satisfying $\cos\Theta > -0.04$ are cut, where Θ is the zenith angle with $\cos\Theta = 1$ corresponding to downward-going events. The detection efficiency for upward through-going muons is estimated by a Monte Carlo simulation. Using the upward/downward symmetry of the detector configuration, the validity of the Monte Carlo program is checked by real cosmic-ray downward through-going muons. The average detection efficiency is estimated to be $\sim 97\%$. The details of the selection criteria are described in [12]. Finally, 184 and 188 upward through-going muon events are observed during Kamiokande-II [8,13] (1124 days) and Kamiokande-III [12] (1332 days) experimental periods, respectively.

In this analysis, the combination of the Bartol atmospheric neutrino flux model [14], the parton distribution functions of GRV94DIS [15], and the Lohmann's muon energy loss formula in the standard rock [16] are employed, when one analytically calculates the standard expected muon flux. Also, a Monte Carlo technique is introduced in order to estimate the directionality between a muon and the parent neutrino and it is found that $\sqrt{\Delta\theta_{\nu\mu}^2 + \Delta\theta_{mul}^2}$ is 4.1° for the atmospheric neutrino energy spectrum, where $\Delta\theta_{\nu\mu}$ stands for μ production angle relative to ν direction in the neutrino-nucleon interaction and $\Delta\theta_{mul}$ for deflec-

tion by multiple Coulomb scatterings in the rock. To estimate the model-dependent uncertainties ($\pm 10\%$ for the absolute flux normalization and -3.6% to $+1.5\%$ for the bin-by-bin shape difference in zenith-angle distribution) of the expected muon flux, the combination of another atmospheric neutrino flux model calculated by Honda et al. [17] and another parton distribution function of CTEQ3M [18] are also considered.

As a result, the expected muon flux Φ_{theo} is calculated to be $[2.46 \pm 0.54(theo.)] \times 10^{-13}$ cm^{-2} s^{-1} sr^{-1} ($\cos\Theta < -0.04$), where the estimated theoretical uncertainties are described in Table I. The dominant one originates from the absolute normalization uncertainty in the neutrino flux which is estimated to be approximately $\pm 20\%$ [14,17,19] above several GeV.

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

$$\Phi_{obs} = \sum_{j=1}^{N} \left(\frac{1}{\varepsilon_2(\Theta_j)T_2 + \varepsilon_3(\Theta_j)T_3} \right) \times \frac{1}{S(\Theta_j)2(1 - 0.04)\pi},$$

where suffix 2 (3) represents Kamiokande-II (-III), the suffix j stands for each event number, $2(1 - 0.04)\pi$ is the total solid angle covered by the detector for upward through-going muons, and N corresponds to the total number of observed muon events (372 events). The angular dependence of the detection efficiency for each experimental period is found in [8] and [12], respectively. Conceivable experimental systematic errors are summarized in Table I.

TABLE I. List of experimental systematic errors and theoretical uncertainties in the flux measurement.

Error source	Error (%)
Uncertainty in $\Delta\theta_{rec}$	± 1 [a]
$\cos\Theta = -0.04$ cut dependence	$+18.2, -4.4$ [a]
Cosmic ray μ contamination	-10 [a]
Detection efficiency	$+2.8, -8.3$ [a]
	$+0.6, -1.2$ [b]
7 m track length cut	± 0.5 [c]
Live time	± 0.4 [c]
Effective area	± 0.3 [c]
PMT gain	$\ll 1$ [c]
Water transparency	$\ll 1$ [c]
Chemical component in the rock	$\ll 1$ [d]
ν flux normalization % [14,17,19]	± 20 [d]
Theoretical model dependence	± 10 [d]
	-3.6 to $+1.5$ [e]

[a]Experimental uncorrelated systematic error specific in the most horizontal bin $-0.1 < \cos\Theta < -0.04$.
[b]Experimental uncorrelated systematic error specific in the bins $-1 \leq \cos\Theta \leq -0.1$.
[c]Experimental correlated systematic error.
[d]Theoretical correlated uncertainty.
[e]Theoretical uncorrelated uncertainty.

TABLE II.   Summary of upward-going muon flux measurement. E_μ represents the muon energy. Kamiokande, Baksan, and MACRO employ the Bartol neutrino flux [14], while IMB adopts the Lee and Koh neutrino flux [20] (the Volkova flux [21]) for neutrino energies lower (higher) than 15 GeV.

Experiment	Minimum E_μ (GeV)	Observed	Expected
Kamiokande	1.6	$[1.94 \pm 0.10(\text{stat.})^{+0.07}_{-0.06}(\text{sys.})]$ $\times 10^{-13}$ cm^{-2} s^{-1} sr^{-1}	$[2.46 \pm 0.54(\text{theo.})]$ $\times 10^{-13}$ cm^{-2} s^{-1} sr^{-1}
IMB [9]	~1.4	$532 \pm 23(\text{stat.})$ events	$516 \pm 103(\text{theo.})$ events
Baksan [10]	1.0	559 events	580 events
MACRO [11]	1.0	$277 \pm 17(\text{stat.}) \pm 22(\text{sys.})$ events	$371 \pm 63(\text{theo.})$ events

Taking these experimental systematic errors into account, the observed upward through-going muon flux is

$$\Phi_{\text{obs}} = [1.94 \pm 0.10(\text{stat.})^{+0.07}_{-0.06}(\text{sys.})]$$
$$\times 10^{-13} \text{ cm}^{-2}\text{ s}^{-1}\text{ sr}^{-1}.$$

At present, three experiments other than Kamiokande reported the measurement of the upward through-going muon flux and their results are summarized in Table II, together with this measurement. The observed flux by each experiment is in agreement with the expectation within the errors.

The zenith-angle distribution of the observed flux $(d\Phi/d\Omega)^i_{\text{obs}}$ is shown in Fig. 1. The shape of the distribution is not well represented by the theory (χ^2/degrees of freedom = 21.3/9).

A neutrino oscillation hypothesis is then tested using the zenith-angle distribution. The expected flux for a given set of Δm^2 and $\sin^2 2\theta$ is calculated and the same binning is applied as data.

To test the validity of the oscillation hypothesis, a χ^2 is calculated as

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

where $\sigma_{\text{stat},i}$ ($\sigma_{\text{sys},i}$) is the statistical (experimental systematic) error in $(d\Phi/d\Omega)^i_{\text{obs}}$ in the ith bin and α is an absolute normalization factor of the expected flux. Based on uncorrelated systematic errors in Table I added in quadrature, we estimate $\sigma_{\text{sys},i}$ to be $\pm 18.5\%$ for $-0.1 < \cos\Theta < -0.04$ and ± 1.2 to $\pm 3.8\%$ for $-1 \leq \cos\Theta \leq -0.1$, respectively. The absolute flux normalization error σ_α is estimated to be $\pm 22\%$ by adding in quadrature the correlated experimental errors and theoretical uncertainties in Table I. Then, the minimum $\chi^2(\chi^2_{\text{min}})$ on the $\Delta m^2 - \sin^2 2\theta$ plane is searched for.

We note here that the allowed region given by Kamiokande sub- and multi-GeV contained event analysis [7] for $\nu_e \leftrightarrow \nu_\mu$ oscillations has been already excluded by the CHOOZ experiment [22], suggesting $\nu_\mu \leftrightarrow \nu_\tau$ oscillations for the contained and upward-going muon events. Assuming $\nu_\mu \leftrightarrow \nu_\tau$ oscillations, χ^2_{min} ($= 12.2$) occurs in the unphysical region at $(\sin^2 2\theta, \Delta m^2) = (1.35, 2.0 \times 10^{-3} \text{ eV}^2)$ and $\alpha = 1.02$. On the other hand, if we bound the oscillation parameters in the physical region, χ^2_{min} ($= 12.8$) takes place at $(\sin^2 2\theta, \Delta m^2) = (1.00, 3.2 \times 10^{-3} \text{ eV}^2)$ and $\alpha = 1.00$. For the null oscillation case, we obtain χ^2_{min} of 21.3 at $\alpha = 0.77$

(probability of statistical fluctuation: 1%). The zenith-angle distribution of $\alpha(d\Phi/d\Omega)^i_{\text{osc}}$ for the best fit parameters in the physical region is shown in Fig. 1 together with the data. Figure 2 shows the allowed region contours on the $(\sin^2 2\theta, \Delta m^2)$ plane for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations. As χ^2_{min} for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations falls down in the unphysical region, the contours are drawn according to the prescription for bounded physical regions given in Ref. [23]. If we replace the Bartol neutrino flux [14] by the Honda's [17] and/or the GRV94DIS parton distribution functions [15] by the CTEQ3M's [18], the allowed region contours are similar to those presented in Fig. 2. Consequently, we find that the zenith-angle dependence is in favor of the $\nu_\mu \leftrightarrow \nu_\tau$ oscillation hypothesis and supports the Kamiokande sub- and multi-GeV contained event analysis [7].

Combining this work with the previous analysis [7] of the Kamiokande sub- and multi-GeV contained events, we draw an allowed region contour on the $(\sin^2 2\theta, \Delta m^2)$ plane, as is shown in Fig. 2. The best
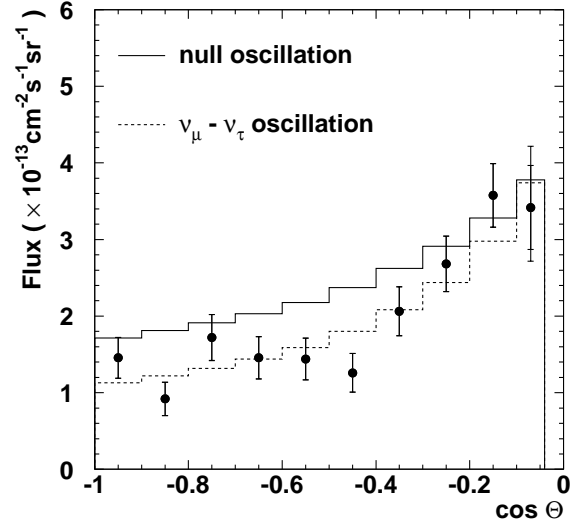

FIG. 1.   Zenith-angle distribution of upward through-going muon flux observed in Kamiokande II + III. Inner (outer) error bars indicate statistical (uncorrelated experimental systematic + statistical added in quadrature) errors. The solid histograms show the expected upward through-going muon flux for the null neutrino oscillation case. Also shown is the expected flux (dashed) assuming the best fit parameters at $(\sin^2 2\theta, \Delta m^2) = (1.00, 3.2 \times 10^{-3} \text{ eV}^2)$, $\alpha = 1.00$ in the physical region for the $\nu_\mu \leftrightarrow \nu_\tau$ oscillation case.
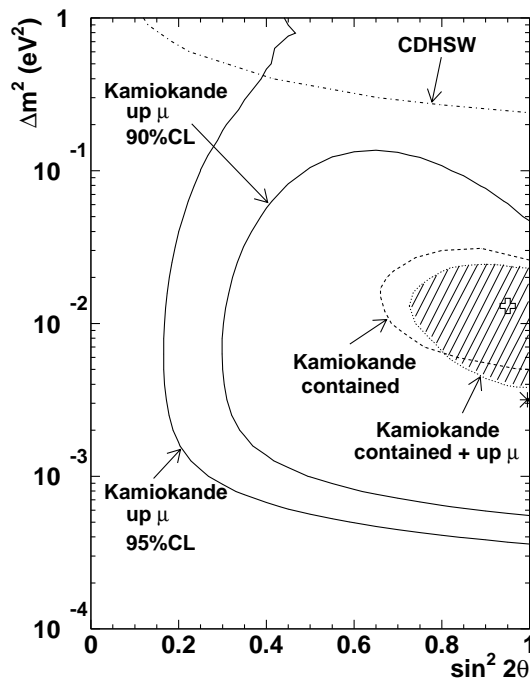
FIG. 2. The allowed regions at 90% confidence level (C.L.), obtained from the Kamiokande II + III upward through-going muon analysis (up μ) and from the combined analysis (Kamiokande contained [7] + up μ), drawn on the $(\sin^2 2\theta, \Delta m^2)$ plane for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations. Also shown are the excluded region by CERN-Dortmund-Heidelberg-Saclay-Warsaw (CDHSW) [24] and the allowed region by the Kamiokande contained event analysis [7]. The right-hand side of the contours is allowed (excluded) regions by Kamiokande (CDHSW). The asterisk (cross) indicates the best fit point for up μ (for Kamiokande contained + up μ) at $(\sin^2 2\theta, \Delta m^2) = (1.00, 3.2 \times 10^{-3} \text{ eV}^2)$ [at $(\sin^2 2\theta, \Delta m^2) = (0.95, 1.3 \times 10^{-2} \text{ eV}^2)$]. The 95% C.L. contour (up μ) is presented as well.

fit point $(\sin^2 2\theta, \Delta m^2) = (0.95, 1.3 \times 10^{-2} \text{ eV}^2)$ is obtained for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations.

In conclusion, based on 372 upward through-going muon events during 2456 detector live days, the flux of the upward through-going muons (>1.6 GeV) is measured with the Kamiokande II + III detector: $\Phi_{\text{obs}} = [1.94 \pm 0.10(\text{stat.})^{+0.07}_{-0.06}(\text{sys.})] \times 10^{-13} \text{ cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$. This is compared with the expected flux calculation of $\Phi_{\text{theo}} = [2.46 \pm 0.54(\text{theo.})] \times 10^{-13} \text{ cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$. The observed upward through-going 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 of the upward through-going muons does not agree with the theoretical expectation (probability of statistical fluctuation: 1%), yet is favored by the $\nu_\mu \leftrightarrow \nu_\tau$ oscillation assumption. This result supports the indication of neutrino oscillations given by the analysis of the sub- and multi-GeV atmospheric neutrino events by Kamiokande.

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