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The previously published atmospheric neutrino data did not distinguish whether muon neutrinos were oscillating into tau neutrinos or sterile neutrinos, as both hypotheses fit the data. Using data recorded in 1100 live days of the Super-Kamiokande detector, we use three complementary data samples to study the difference in zenith angle distribution due to neutral currents and matter effects. We find no evidence favoring sterile neutrinos, and reject the hypothesis at the 99% confidence level. On the other hand, we find that oscillation between muon and tau neutrinos suffices to explain all the results in hand.

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I. Introduction.—In previous papers [1–3] Super-Kamiokande reported evidence for the oscillation of muon neutrinos produced in cosmic-ray induced showers in the atmosphere. This evidence rests largely upon a strong zenith angle dependent deficit in the muon data, which does not appear in the electron data, and hence limits the amount of oscillation into electron neutrinos. In fact, the results demonstrate only that muon neutrinos are disappearing, depending on the energy and flight distance. The most plausible scenario is that muon neutrinos oscillate to tau neutrinos, most of which are below the 3.4 GeV neutrino energy threshold for charged current tau production. The few charged current tau events created (we expect approximately 65 in our current sample) typically fail our cuts that identify a single electron or muon; indeed, due to the high energy of the interaction and the multiple decay modes of the tau, it is difficult to isolate any set of events that can be uniquely identified as due to charged current ν_τ interactions.

An alternative scenario that can explain muon neutrino disappearance is oscillation with a sterile neutrino (ν_s), so named because it has neither charged current (CC) nor neutral current (NC) interactions. Neutrino oscillation has also been employed to explain two other experimental anomalies: the long-standing deficit of solar neutrinos [4], and the appearance of electron antineutrinos in the LSND experiment [5]. The three oscillation signatures, LSND, atmospheric, and solar, are manifested by three widely separated values of the mass-squared difference, $\Delta m^2 = m_i^2 - m_j^2$. Because Δm_{13}^2 must equal $\Delta m_{12}^2 + \Delta m_{23}^2$, all three signatures cannot be accommodated with three neutrino states. Any additional light neutrino must be sterile to satisfy the well-known bound of three neutrino flavors that couple to the Z^0 [6].

In this Letter, we use more than 1100 days exposure of atmospheric neutrino data collected by the Super-Kamiokande detector to distinguish the behavior of $\nu_\mu \leftrightarrow \nu_\tau$ oscillation from $\nu_\mu \leftrightarrow \nu_s$ oscillation. First, for $\nu_\mu \leftrightarrow \nu_s$ oscillation, one should observe fewer neutral current events than for $\nu_\mu \leftrightarrow \nu_\tau$ oscillation. By definition a sterile neutrino does not interact with matter even through the neutral current, while a tau neutrino continues to experience the same neutral current interactions as did the original muon neutrino.

Second, the interaction of the neutrinos with matter [7] leads to a difference in the oscillation probability. The coherent forward scattering of ν_τ and ν_μ are identical; therefore the presence of matter in the neutrino path does not modify the oscillation probability for a neutrino of energy E_ν that travels a distance L in vacuum:

$$P_{\nu_\mu \to \nu_\tau} = \sin^2 2\theta_\upsilon \sin^2\left(\pi \frac{L}{l}\right), \qquad (1)$$

where $\sin^2 2\theta_\upsilon$ is the mixing angle between the two neutrino states, and l in vacuum is given by $l_\upsilon = 4\pi E_\nu / \Delta m^2$. In contrast, ν_s does not interact with matter even via the neutral current. This introduces an effective potential which modifies the mixing angle and oscillation length [7],

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta_\upsilon}{(\zeta - \cos 2\theta_\upsilon)^2 + \sin^2 2\theta_\upsilon}, \qquad (2)$$

$$l_m = \frac{l_\upsilon}{\sqrt{(\zeta - \cos 2\theta_\upsilon)^2 + \sin^2 2\theta_\upsilon}}. \qquad (3)$$

The parameter ζ is given by $\mp\sqrt{2}E_\nu G_F N_n / \Delta m^2$, where N_n is the neutron density in the matter traversed by the neutrino, the minus sign is for neutrinos, and the plus sign is for antineutrinos. By convention, Δm^2 is defined to be positive for $m_4 > m_2$, where $\nu_\mu = \cos\theta \nu_2 + \sin\theta \nu_4$ and $\nu_s = -\sin\theta \nu_2 + \cos\theta \nu_4$. For the density of matter in the earth, ζ reaches unity for E_ν of 5 GeV $\times$ $\Delta m^2/(10^{-3}\ \text{eV}^2)$. The Super-Kamiokande data indicate a likely value for Δm^2 of 3×10^{-3} eV^2, which means that neutrinos with energy greater than approximately 15 GeV will have the oscillation probability suppressed by matter effects if the oscillation is $\nu_\mu \leftrightarrow \nu_s$. Neutrinos of lower energy will have approximately the same oscillation probability in matter as in vacuum, even if the oscillation is $\nu_\mu \leftrightarrow \nu_s$.

II. Data analysis.—Super-Kamiokande is a 50 kt water Cherenkov detector employing 11 146 photomultiplier tubes (PMTs) to monitor an internal detector (ID) fiducial volume of 22.5 kt. Incoming and outgoing charged particles are identified by 1885 PMTs in an optically isolated outer volume (OD). Details of the detector, calibrations, and data reduction can be found in Refs. [1–3]. Super-Kamiokande has collected 9178 fully contained (FC) events and 665 partially contained (PC) events in a 70.5 kiloton year (1144 days) exposure. FC events deposit all of their Cherenkov light in the ID while PC events have exiting tracks which deposit some Cherenkov light in the OD. The vertex position, number of Cherenkov rings, ring directions, and momenta are reconstructed and the particle types are identified as "e-like" or "μ-like" for each Cherenkov ring. In the current FC sample, there are 3107 single-ring e-like events, 2988 single-ring μ-like events, and 3083 multiring events.

Based on 1138 live days, this detector has also collected 1269 upward through-going muon (UTM) events produced by atmospheric neutrino interactions in the surrounding rock. We required a minimum track length of 7 m in the inner detector and a zenith angle $\cos\Theta < 0$ ($\cos\Theta = -1$ means vertically upward-going events). Because of finite fitter resolution and multiple Coulomb scattering of muons in the nearby rock, some down-going cosmic-ray muons appear to be coming from $-0.1 < \cos\Theta < 0$. This background was estimated to be 9.1 ± 0.8 events [3], which was subtracted from the most horizontal bin.

A. Fully contained single-ring data: First, utilizing only the FC single-ring events, we have examined the hypotheses of two-flavor $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_s$ oscillation models using a χ^2 comparison of our data and Monte Carlo (MC), allowing all important MC parameters to vary, weighted by their expected uncertainties. For $\nu_\mu \leftrightarrow \nu_s$, the effects of matter on neutrino propagation through the earth were taken into account by a numerical evolution where the density of the earth was divided into 94 discrete steps in radius based on Ref. [8]. Furthermore, matter effects are different with positive or negative Δm^2 except for the full mixing case. Therefore, we evaluate three models of oscillation, (a) $\nu_\mu \leftrightarrow \nu_\tau$, (b) $\nu_\mu \leftrightarrow \nu_s(\Delta m^2 > 0)$, and (c) $\nu_\mu \leftrightarrow \nu_s(\Delta m^2 < 0)$. The data were binned by particle type, momentum, and $\cos\Theta$. A χ^2 is defined as

$$\chi^2_{\mathrm{FC}} \equiv \sum_{\cos\Theta,p}^{65} \left(\frac{N_{\mathrm{data}} - N_{\mathrm{MC}}(\sin^2 2\theta, \Delta m^2, \epsilon_j)}{\sigma} \right)^2 + \sum_j \left(\frac{\epsilon_j}{\sigma_j} \right)^2,$$

where the sum is over five bins equally spaced in $\cos\Theta$ and seven (six) momentum bins for e-like (μ-like) events. N_{data} is the measured number of events in each bin, σ is the statistical error, and N_{MC} is the weighted sum of MC events. The definition of χ^2, and the treatment of systematic uncertainties, ϵ_j, is identical to that in Ref. [1], except we exclude the PC events (which we employ later in this Letter).

The best-fit values of oscillation parameters are summarized in Table I. With the best-fit parameters for $\nu_\mu \leftrightarrow \nu_\tau$, we expect only 16 single-ring events from ν_τ charged current interactions in the current sample. Moreover, matter induced modifications to oscillations do not produce significant effects due to the relatively small energy (~1 GeV) of the parent neutrinos for the FC events. Therefore these three hypotheses for oscillations are essentially indistinguishable by this data sample alone.

B. Multiring sample: Next we employ a NC enriched sample of events selected from multiring (MR) data. We measure the zenith angle distribution of NC events to distinguish between $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_s$: if pure $\nu_\mu \leftrightarrow \nu_\tau$ oscillations are operating, then the up/down ratio should be nearly unity; if $\nu_\mu \leftrightarrow \nu_s$ oscillations dominate, the up/down ratio will be measurably smaller.

In order to obtain a sample enhanced with NC events, we applied the following selection criteria: (1) vertex within the fiducial volume and no exiting track; (2) multiple Cherenkov rings; (3) particle identification of the brightest ring is e-like; and (4) visible energy greater than 400 MeV.

The first criterion provides a contained event sample, and the second and third criteria serve to enrich the NC event fraction. The fourth criterion helps to obtain good angular correlation between the incident neutrino and the reconstructed direction, defined as the pulse height weighted sum of the ring directions. The mean angle difference between the parent neutrino and reconstructed directions is estimated to be 33°. According to our MC study, for no oscillations (and $\nu_\mu \leftrightarrow \nu_\tau$ oscillations at best-fit parameters), the resultant fraction of NC events is 29% (30%), ν_eCC is 46% (48%), and ν_μCC is 25% (19%) (and ν_τCC is 3%). In contrast, the FC single-ring sample contains only ~6% NC events. In the current exposure, 1531 events satisfy the above criteria. Figure 1(a) shows the zenith angle distribution of these events with predictions from the MC.

TABLE I. Best-fit oscillation parameters for fully contained sample.

Mode	Δm^2 (eV^2)	$\sin^2 2\theta$	χ^2_{min}/d.o.f.
$\nu_\mu \leftrightarrow \nu_\tau$	3.2×10^{-3}	1.000	61.33/62
$\nu_\mu \leftrightarrow \nu_s(\Delta m^2 > 0)$	4.0×10^{-3}	0.995	62.56/62
$\nu_\mu \leftrightarrow \nu_s(\Delta m^2 < 0)$	3.2×10^{-3}	1.000	62.62/62

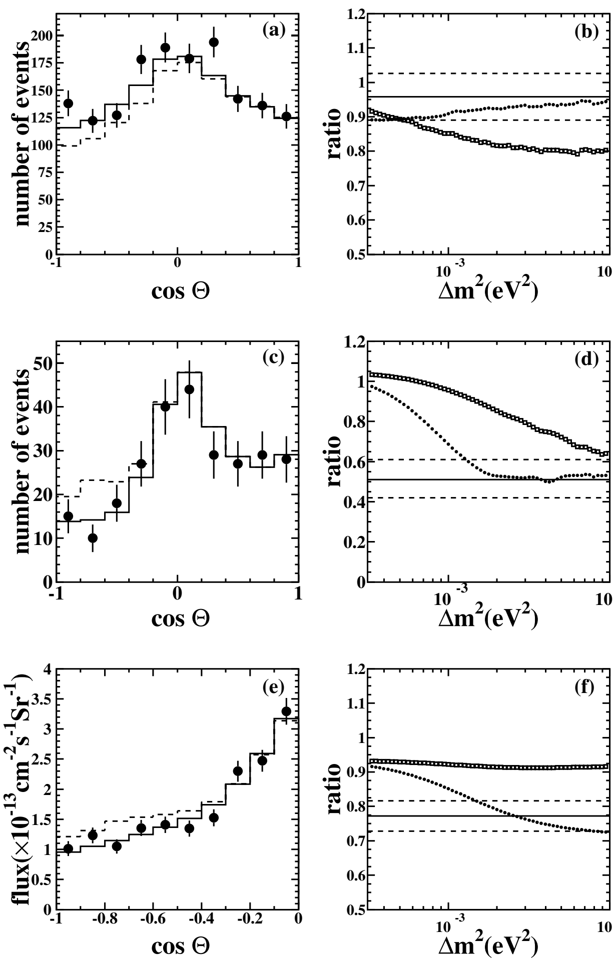

FIG. 1. (a),(c),(e) Zenith angle distributions of atmospheric neutrino events satisfying cuts described in the text: (a) multi-ring sample, (c) partially contained sample, and (e) upward through-going muon sample. The black dots indicate the data and statistical errors. The solid lines indicate the prediction for $\nu_\mu \leftrightarrow \nu_\tau$, and the dashed lines for $\nu_\mu \leftrightarrow \nu_s$, with $(\Delta m^2, \sin^2 2\theta) = (3.2 \times 10^{-3}\ \mathrm{eV}^2, 1)$. The two predictions are independently normalized to the number of downward-going events for (a) and (c) and the number of horizontal events for (e). (b),(d),(f) Expected value of the corresponding test ratio as a function of Δm^2. The solid horizontal lines indicate the measured value from the Super-Kamiokande data with statistical uncertainty indicated by dashed lines. Black dots indicate the prediction for $\nu_\mu \leftrightarrow \nu_\tau$, and empty squares for $\nu_\mu \leftrightarrow \nu_s$, in both cases for maximal mixing.

We utilize an up-to-down ratio as the discriminant, which cancels some systematic uncertainties (otherwise dominated by the large uncertainty in absolute rates). In this context we define "upward" as a cosine of zenith angle less than -0.4, and "downward" as greater than $+0.4$. There are 387 upward events and 404 downward events. Figure 1(b) shows the Δm^2 dependence of the expected up/down ratio in the case of full mixing ($\sin^2 2\theta = 1$). For Δm^2 of 3.2×10^{-3} eV^2, the data are consistent with $\nu_\mu \leftrightarrow \nu_\tau$, while the data differ from the prediction for $\nu_\mu \leftrightarrow \nu_s$ oscillation by 2.4 standard deviations.

We estimated the total uncertainty in the up/down ratio of the data and MC to be ± 2.9 %, dominated by the 2.6% uncertainty in the neutrino flux caused by the absorption of muons in the mountain above the detector. All other sources of systematic uncertainty such as background contamination, the up/down response of the detector, the uncertainty of the NC cross sections, and the difference between the up/down ratio of two independent flux calculations [9,10] are less than 1%.

C. Partially contained sample: Next we report on the search for matter effects by using high energy partially contained events. As discussed above, matter effects impact only $\nu_\mu \leftrightarrow \nu_s$ oscillations, where at high energies the matter effect suppresses oscillations. Partially contained events in Super-Kamiokande are estimated to be 97% pure ν_μ charged current, with a mean neutrino energy of 10 GeV. In order to select higher energy ν_μ events, which are more sensitive to matter effects, we additionally require visible energy greater than 5 GeV. We estimate the typical energy of the parent atmospheric neutrino is 20 GeV. After cuts are made upon the current data sample we find 267 events. Figure 1(c) shows the zenith angle distribution of these events with predictions from MC, as before. Again we employ an up/down ratio to cancel systematic uncertainties, with the same angular definition as used for the multiring sample. There are 43 upward events and 84 downward events. Figure 1(d) shows the Δm^2 dependence of the expected up/down ratio in the case of full mixing. For Δm^2 of 3.2×10^{-3} eV^2, the data are consistent with $\nu_\mu \leftrightarrow \nu_\tau$ oscillation, whereas they differ from $\nu_\mu \leftrightarrow \nu_s$ oscillation by 2.3 standard deviations.

We estimated the total systematic uncertainty in the up/down ratio to be $\pm 4.1\%$, dominated by the 3.4% uncertainty caused by the mountain above the detector and the 2.0% uncertainty caused by possible background contamination by cosmic-ray muons. All other sources of uncertainty were less than 1%.

D. Upward through-going muon sample: Next we report on the search for possible matter effects by using upward through-going muon events. The approach of this analysis is similar to that for the PC events. Because the typical energy of the UTM parent neutrino is approximately 100 GeV, matter effect suppression should appear most prominently in this data set. Figure 1(e) shows the zenith angle distribution of these events with predictions. Again we utilize a ratio as the test parameter, dividing "vertical" and "horizontal" at cosine of zenith angle $= -0.4$. Figure 1(f) shows the Δm^2 dependence of the expected vertical/horizontal ratio in the case of full mixing. At the point of 3.2×10^{-3} eV^2, the data are consistent with $\nu_\mu \leftrightarrow \nu_\tau$ oscillation, while $\nu_\mu \leftrightarrow \nu_s$ oscillation differs from the data by 2.9 standard deviations.

We estimated the total systematic uncertainty in the horizontal/vertical flux ratio to be $\pm 3.3\%$, dominated by the 3% uncertainty in the π/K production ratio in the cosmic-ray interaction in the atmosphere [11]. All other sources of systematic uncertainty, including the background contamination in the most horizontal bin [3], the spectral index of the neutrino flux, and the difference between two independent flux calculations [9,10] were 1% or less.

E. Combined analysis: Finally, we performed a combined statistical analysis of the multiring, high energy partially contained, and upward-going muon data sets. For each sample ($i =$ MR, PC, UTM) we construct a 1 degree of freedom χ_i^2 defined by

$$\chi_i^2 = \frac{[N_{\rm data}^A - \alpha_i N_{\rm MC}^A (1 + \frac{\epsilon_i}{2})]^2}{(\sigma_{\rm stat}^A)^2} + \frac{[N_{\rm data}^B - \alpha_i N_{\rm MC}^B (1 - \frac{\epsilon_i}{2})]^2}{(\sigma_{\rm stat}^B)^2} + \frac{\epsilon_i^2}{\sigma_{i,\rm sys}^2}, \quad (4)$$

where A is, respectively, either up-going or vertical and B is down-going or horizontal. For the UTM sample, the calculated flux is used in place of the number of events. The parameter denoting normalization is α_i, and for each ratio we introduce a systematic uncertainty parameter ϵ_i, weighted by the estimated size of the uncertainty, $\sigma_{i,\rm sys}$.

The three χ_i^2 are summed to form a total $\chi_{\rm tot}^2$ with 3 degrees of freedom. The value of $\chi_{\rm tot}^2$ is used as a hypothesis test for the cases of $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_s$ oscillation. We exclude regions in the $\sin^2 2\theta - \Delta m^2$ plane at the 90(99)% C.L. if the value of χ^2 is greater than 6.3(11.3) for χ^2 of 3 degrees of freedom. Figure 2 shows separately the excluded regions for these three alternative oscillation modes, along with the allowed region from FC single-ring event analysis. (The two cases of $\Delta m^2 > 0$ and $\Delta m^2 < 0$ are treated continuously [12], using the minimum χ^2 for the ν_s fit which was slightly lower for the case of $\Delta m^2 > 0$, and this was used to draw the contours for both cases.) One sees that the parameters allowed by the FC data in the $\sin^2 2\theta - \Delta m^2$ plane are excluded at the 99% confidence level by the independent tests for both positive and negative Δm^2 sterile neutrino oscillations.

III. Summary and conclusion.—In summary, we have presented three independent data samples that discriminate between the oscillations to either tau neutrinos or sterile neutrinos in the region of mixing angle and Δm^2 preferred by the majority of the Super-Kamiokande data. Two-flavor oscillation between muon neutrinos and sterile neutrinos fit the low energy charged current data, but do not fit the

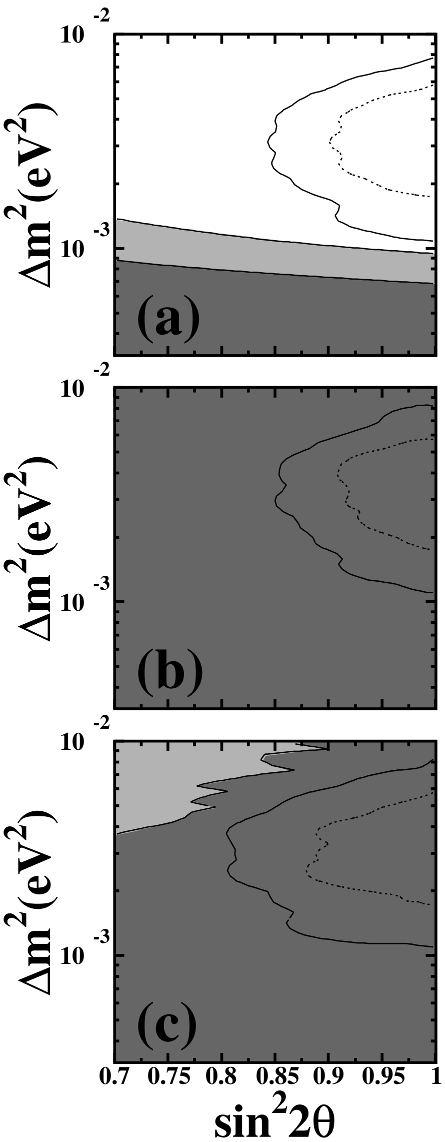

FIG. 2. Excluded regions for three oscillation modes: (a) $\nu_\mu \leftrightarrow \nu_\tau$; (b) $\nu_\mu \leftrightarrow \nu_s$ with $\Delta m^2 > 0$; (c) $\nu_\mu \leftrightarrow \nu_s$ with $\Delta m^2 < 0$. The light (dark) gray regions are excluded at 90(99)% C.L. The thin dotted (solid) lines indicate the 90(99)% C.L. allowed regions from the analysis of FC single-ring events.

neutral current or high energy data. We cannot exclude more complicated scenarios in which both $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_s$ oscillations coexist with small mixing to sterile neutrinos, or with much smaller mass difference for sterile neutrinos; yet there is nothing in these data to encourage one about the existence of sterile neutrinos. Pure $\nu_\mu \leftrightarrow \nu_\tau$ neutrino oscillations fit all of the data samples presented, without any inconsistency.

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