Measurement of Atmospheric Neutrino Composition with the IMB-3 Detector

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The atmospheric neutrino flux is measured using a 3.4-kt yr exposure of the IMB-3 detector. Single-ring events are classified as showering or nonshowering using the geometry of the Čerenkov pattern. A simulation of neutrino interactions and three models of atmospheric neutrino production are used to predict the composition of the sample. Showering-nonshowering character is strongly correlated with the flavor of the neutrino parent. In the lepton momentum range $p < 1500$ MeV/c, we find that nonshowering events comprise [41 ± 3(stat) ± 2(syst)]% of the total. The fraction expected is [51 ± 5(syst)]%.

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Cosmic-ray interactions in the atmosphere produce broad and nearly isotropic spectra of ν_e and ν_μ which may be observed by massive detectors. The flight paths of these neutrinos range from roughly 20 to 12000 km; using this long base line, atmospheric neutrino propagation may be studied over much greater distances than neutrinos produced in the laboratory. Using the ring-imaging ability of the IMB-3 detector to separate events induced by ν_e and ν_μ, the neutrino flavor content at the detector can be compared to calculated production rates in the atmosphere. Any discrepancy may point to new physics of flavor oscillation or decay in a region inaccessible to present accelerator and reactor experiments, but hinted at by our earlier data[1] and strongly suggested by a similar experiment.[2]

The IMB-3 detector,[3-7] with a 3.3-kt fiducial mass and 2048 8-in. photomultiplier tubes (PMTs) augmented with wavelength-shifting plates, has operated since May 1986. Relativistic-charged-particle tracks are detected via Čerenkov radiation, and reconstructed using timing and pulse-height information from the PMTs. A 7.5-μs time scale after the primary trigger allows detection of muon decays with 70% efficiency. The pulse-height measurements, corrected for light attenuation in water, are also used to determine the "visible energy" of each event. Visible energy is defined to be proportional to the number of Čerenkov photons radiated, and equal to the primary particle energy for $e^\pm$ and γ. Visible-energy resolution is 3% $[E_{\mathrm{vis}}(\mathrm{GeV})]^{1/2}$, with an additional systematic uncertainty of ±7%.

A live time of 376 d has been analyzed to find events originating within the fiducial volume, characteristic of either nucleon decay or neutrino interaction. Triggers resulting from prompt firing of 70–900 PMTs, corresponding to visible energies of 50 MeV to 2.5 GeV, form the initial sample for this search. Data and calibrations are independently analyzed by two groups, and the results are merged into a combined data set. The combined efficiency for extracting events starting in the fiducial volume is approximately 85% for events with over 100-MeV visible energy. A total of 422 contained events were identified. The spatial distribution of these events is roughly uniform over the fiducial volume, as expected for nucleon decays or atmospheric-neutrino-induced events. The distribution of events with identified muon decays is likewise uniform. Entering contamination from the 2.7-s^{-1} cosmic-ray muon background is estimated to be less than 5%.

Events originating in the fiducial volume are scanned by physicists to determine the number of Čerenkov rings. Of the 422 contained events, 138 (or 33%) are found to be multiple ring and are removed for separate analysis. Single-ring events are subjected to three automated and independent tests to identify the PMT hit pattern as "showering" or "nonshowering." Diffuse, showering patterns are associated with $e^\pm$ and γ, while massive charged particles ($\mu^\pm, \pi^\pm, p$) give rise to sharper, nonshowering patterns. Simulations indicate showering (nonshowering) rings are 85% (90%) correlated with parent ν_e (ν_μ).

In brief, the three tests consist of a maximum-likelihood technique using a physical model of showers and Čerenkov radiation, a composition of three linear discriminant tests using particle-independent spatial reconstruction, and an empirical technique tuned by tests on simulated data. Studies with cosmic-ray muons and simulated data show that each test correctly identifies ~80% of the events in the energy range of interest with < 5% bias toward one classification or the other. Using all three algorithms and accepting the hypothesis favored by the majority should produce a correct result for over 90% of the sample if the tests are truly independent. This is borne out by the cosmic-ray and Monte Carlo studies which find [92 ± 5(syst)]% correctly identified. Among misidentified events, net bias toward one classification or the other is negligible. For data, agreement among the three tests on an event-by-event basis conforms to that found for simulated data. Nonshowering events are uniformly distributed throughout the detector volume, indicating any entering contamination is small. Momentum spectra for showering events (assuming a massless particle) and nonshowering events (assuming a muon is observed) are plotted in Figs. 1(a) and 1(b), respectively.

The fluxes of cosmic-ray neutrinos produced in the atmosphere have been calculated by several authors.[8-13] The effect of muon polarization on the flavor abundances are included in the later calculations,[10-13] which all predict the same ratio ν_e/ν_μ. We adopt the fluxes of Lee and Koh[11] as our base line, because they incorporate a full three-dimensional treatment of air-shower development. The fluxes of Barr, Gaisser, and Stanev[10] have essentially the same spectra at all but the lowest neutrino energies, with a 20% higher total flux. The fluxes of Honda *et al.*[13] lie in between. Several models of neutrino interactions with water have been developed.[5,7,14] Uncertainties at the level of 10% in the axial-vector form factor and perhaps 10%–20% due to nuclear effects are present in the description of even relatively well-understood quasielastic interactions. Because these quantities enter the cross sections in conjunction with the kinematic variable q^2, which is in turn related to the lepton mass, their effects are *a priori* flavor sensitive. For many channels involving pion production, the cross-section uncertainties are as large as a factor of 2. Agreement among the various models in the rate, spectrum, and composition of interactions should therefore be no better than the ~15% observed.

A simulated exposure to ten years of atmospheric neutrinos has been analyzed. The simulated data are passed through both analysis chains, although the labor-intensive final spatial reconstruction by visual scanning has been replaced by an automated method (tuned to reproduce the manual results). Single-ring events are extracted by inspection, using the known Monte Carlo parameters to assist the scanner.

The visible-energy spectrum for all events (single and multiple ring) predicted by Monte Carlo simulation is in good agreement with the data (see Fig. 2). The absolute fluxes of Ref. 10 have been used; no normalization to the data has been performed. There is a 12% excess in the total number of contained events, but given the uncertainties in calculation of absolute neutrino fluxes and cross sections, this is an acceptable agreement. The spectrum of events with identified muon decays is likewise in good agreement with expectations. Figure 3 shows the visible energy spectra of single-ring events, which exhibit similar compatibility with predictions.

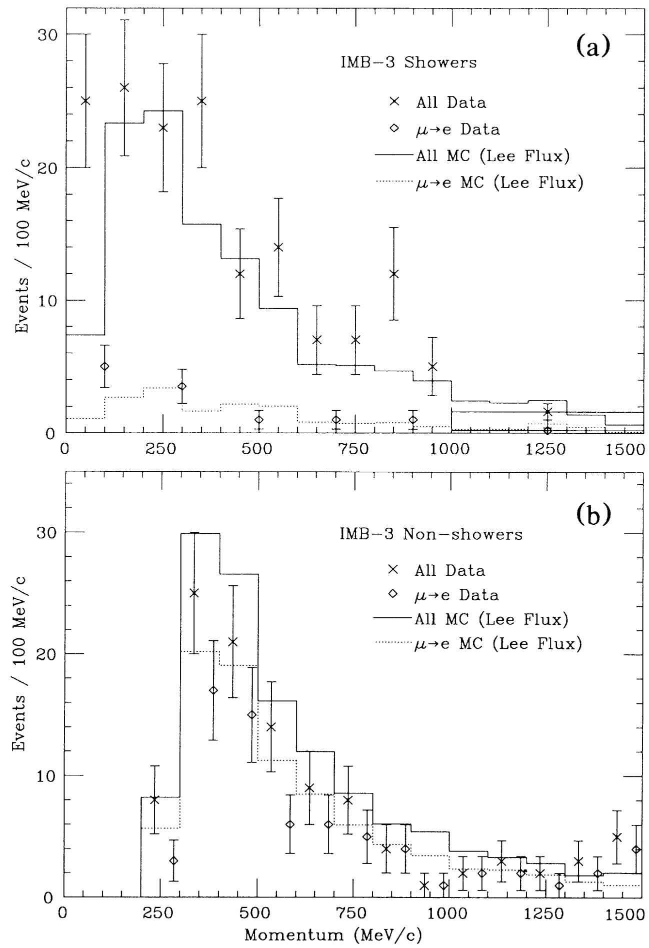

FIG. 1. (a) Momentum spectra for showering single-ring events. (b) Momentum spectra for nonshowering single-ring events.

Returning to the momentum spectra of showering and nonshowering events (Fig. 1), the shapes of the Monte Carlo spectra give good fits to the data. The lowest bin of momentum in each plot should be viewed with some caution, since it contains events with visible energies less than 100 MeV. Below 100 MeV, reconstruction and identification are less efficient, and many events are eliminated by the 70-PMT cut. Also, the Fermi-gas model of the oxygen nucleus is invalid at the lowest energies. For these reasons, we remove showering events with $p < 100$

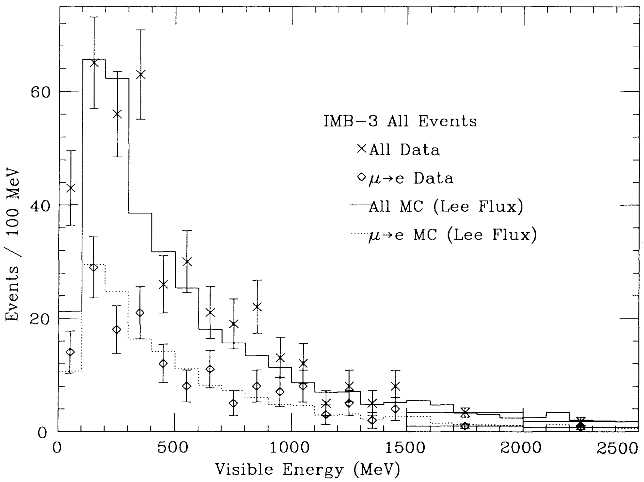

FIG. 2. Visible-energy spectra for all contained events.

MeV/c, and nonshowering events with $p < 300$ MeV/c, from further discussion.

The data with $p < 1500$ MeV/c and $E_{\rm vis} > 100$ MeV consist of 139 showering and 97 nonshowering events. The ratio of nonshowering events to the total is 0.41 ± 0.03(stat) ± 0.02(syst), while 0.51 ± 0.05 is expected. In Fig. 1 the difference between the observed and expected nonshowering fractions is about evenly split between a slight excess of showers and a slight deficit of nonshowers; if the 12% difference in normalization between data and Monte Carlo simulation were removed, the effect would be more clearly manifest as a deficit of nonshowers. Within the momentum cuts $300 < p < 700$ MeV/c for nonshowers and $100 < p < 700$ MeV/c for showers, we find 107 showers and 69 nonshowers. The nonshowering fraction in this low-momentum range is $0.39 \pm 0.04 \pm 0.02$, while the expected value is 0.48 ± 0.05. The systematic error in the expected fraction is determined by varying the axial-vector form factor and Pauli-suppression parameters in the neutrino cross sections over a $\pm 20\%$ range of uncertainty and also using several flux models. Figure 4 shows the nonshowering fraction as a function of z-direction cosine. Within statistics the nonshowering fraction is uniform over direction, as expected for atmospheric neutrino interactions in this energy range.

Events with delayed coincidences attributable to muon decay provide a check on particle identification. Employing only events with $p < 1500$ MeV/c to select against exiting tracks, $(67.0 \pm 4.8)\%$ of nonshowering events have identified muon decays, compared to $(68.9 \pm 1.4)\%$ for the Monte Carlo simulation. Both results agree with our measured 70% efficiency for finding the decays of cosmic-ray muons which stop in the detector. Muon decays accompany $(14.4 \pm 3.0)\%$ of the showering events and $(14.5 \pm 1.0)\%$ of the simulated showering events. Even without misidentification, muon decays would be expected to accompany approximately 8% of the showering sample due to weakly or nonradiating massive particles which are not resolved from the primary ring. Table I summarizes the 376-d IMB-3 data set and the results of three atmospheric neutrino simulations.

Events with muon decays also allow a measurement of the atmospheric neutrino composition which is independent of the Čerenkov pattern identification. The fraction of single-ring events with muon decay is 0.36 ± 0.03, while the simulation predicts 0.42 ± 0.01. The uncertainties quoted are statistical only. We note that a similar deficit of events with muon decays was found in data from the 417-live-day exposure of the IMB-1 detector.[1] With somewhat lower efficiency for identifying muon decays, the fraction of all events with muon decays was 0.26 ± 0.03, to be compared with an expected fraction of

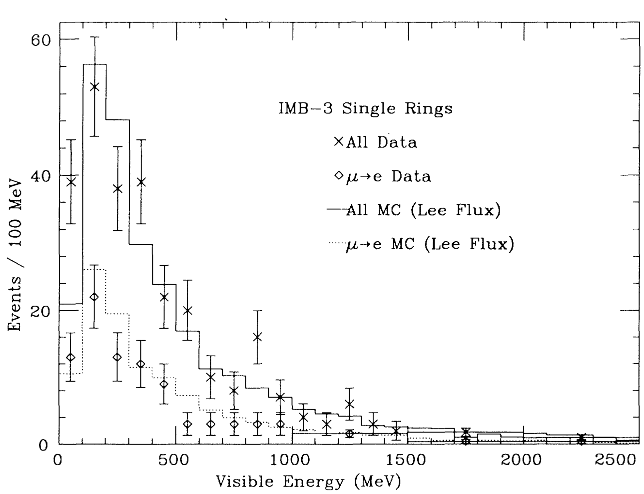

FIG. 3. Visible-energy spectra for single-ring events.

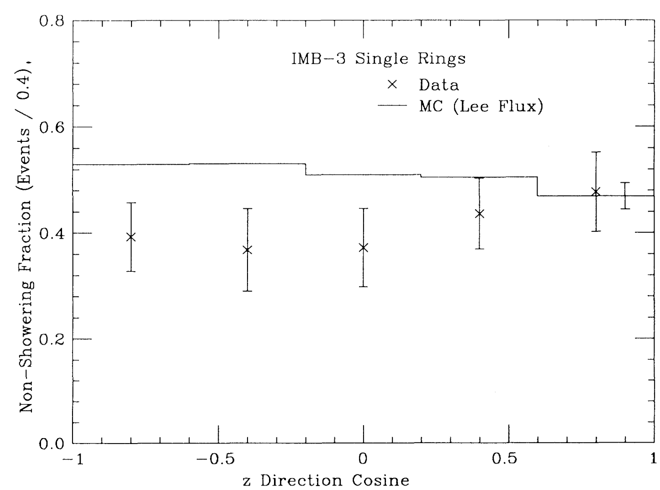

FIG. 4. Nonshowering event fraction vs z-direction cosine. Tracks with $\cos\theta = 1$ are traveling straight up. The statistical error on one Monte Carlo bin is also plotted.

TABLE I. Summary of the 376-d IMB-3 contained data, and simulated atmospheric neutrino data for three fluxes.

	Data		Lee flux		Gaisser flux		Honda flux	
	All	Muon decay	All	Muon decay	All	Muon decay	All	Muon decay
Single ring in p cuts	236	85	232.1	98.1	302.3	127.3	262.0	111.0
Showering	139	20	113.7	16.5	150.0	22.2	128.7	19.3
Nonshowering	97	65	118.4	81.6	152.2	105.1	133.4	91.7
All single ring	284	96	270.6	113.4	351.1	147.3	308.8	129.0
Showering	166	24	128.9	18.9	168.4	25.2	147.1	22.1
Nonshowering	118	72	141.7	94.5	182.7	122.2	161.7	107.0
Multiple ring	138	68	106.0	50.1	140.8	66.9	130.3	62.3
Total	422	164	376.6	163.5	491.3	229.1	439.1	191.3

0.34 ± 0.01. The quoted result includes both single-ring and multiple-ring configurations; however, the same effect was also present in the subset of high-anisotropy events, which closely correspond to the IMB-3 single-ring sample of the present analysis.

The Kamiokande group has reported a $(39 \pm 10)\%$ deficit of nonshowering single-ring events.[2,15,16] For all momenta with $E_{\text{vis}} > 100$ MeV, their measured nonshowering fraction is 0.43 ± 0.04(stat), and their expected fraction is ~ 0.53. The nonshowering fraction in the low momentum range defined above is 0.37 ± 0.05(stat), with an expected value of ~ 0.50. Although geomagnetic effects approximately double the flux of neutrinos with $E_\nu < 500$ MeV at IMB, the *fraction* of ν_μ is not affected.[11] Since both experiments are water Čerenkov detectors and their analyses are similar, the measurements of the two experiments may be directly compared and are in agreement. Their expected values differ by only 5%.

The Fréjus Collaboration has analyzed charge-current interactions in their detector and find a fraction of 0.64 ± 0.04(stat)± 0.02(syst) in which the final-state lepton is a muon.[17] Their expected fraction is 0.63 ± 0.03(syst). The NUSEX Collaboration has studied the contained interactions (charged- and neutral-current interactions cannot be separated) in their apparatus and also find a 0.64 ± 0.07(stat) fraction of muonlike events.[18] Their expected fraction is 0.64, with a systematic error quoted as negligible. Because Fréjus and NUSEX are fine-grain iron calorimeters, and because all lepton momenta and multiprong topologies have been included in their analyses, quantitative comparison with the results of IMB and Kamioka is difficult. It is clear, however, that neither experiment finds evidence for a deficit of ν_μ-induced events.

When the statistical and systematic uncertainties are combined, our measured fraction of nonshowering single-ring events is less than 2σ below expectation. The fraction of events with muon decays, independent of the particle identification algorithm, exhibits a similar discrepancy. If this discrepancy represents a real deficit, the vast majority of missing events would be ν_μ induced. However, the magnitude of the deviation is not sufficient to require neutrino oscillations to explain our data. The overall spectra and total number of interactions are in reasonable agreement with predictions. Furthermore, there is no correlation of deficit with energy or angle, as might be expected of an oscillation effect.

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