Search for Muon Neutrino Oscillations with the Irvine-Michigan-Brookhaven Detector

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Muon neutrinos produced as a result of cosmic-ray interactions with the atmosphere are used to search for ν_μ oscillations into ν_τ by comparing the measured rate of upward-going muons in the Irvine-Michigan-Brookhaven detector with the expected rate. In addition, the ratio of upward-going muons which stop in the detector to those which exit is used to search for deviations from the expected spectrum. This latter technique is free of flux and cross-section normalization uncertainties. No evidence for oscillations is found. 90% C.L. limits on δm^2 are derived in the range $(1-2)\times 10^{-4}$ eV^2 for $\sin^2 2\theta > 0.5$.

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It is not known whether the lepton number is absolutely conserved. It may be that neutrino flavor eigenstates are not identical with the mass eigenstates (if neutrinos have mass). Many experiments have been performed to look for such flavor mixing at reactors, at accelerators with cosmic rays, and with solar neutrinos [1]. Until recently, only the solar neutrino experiments have obtained confirmed results that might be construed as positive evidence for the mixing of ν_e with either ν_μ or ν_τ [2]. However, there is now evidence for a deficit of ν_μ in low-energy cosmic-ray neutrinos [3] which could be interpreted as the oscillation of ν_μ to ν_τ [4]. In this paper we report the results of an independent search for ν_μ to ν_τ oscillations in *high-energy* (> 1 GeV) cosmic-ray neutrinos using the Irvine-Michigan-Brookhaven (IMB) proton decay detector.

The IMB detector is an 8-kt water Cherenkov detector located at a depth of 600 m [1570 mwe (meter of water equivalent)] at the Morton Salt Mine in Cleveland, Ohio. It consists of an 18 m×17 m×22.5 m tank of water surrounded on all six sides by 2048 20-cm-diam photomultiplier tubes (PMTs). The PMTs are mounted on waveshifter plates for increased light collection. The detector tracks charged particles via the Cherenkov light emitted as they pass through the water of the tank. Details of the construction and operation have been published elsewhere [5].

Much of the uncertainty in using atmospherically produced cosmic-ray neutrinos to look for neutrino oscillations comes not only from the difficulty in separating muons from electrons inside the detectors, but also from the predictions for flavor content and in the knowledge of the interaction cross sections. The uncertainty in flavor content can be reduced by using upward-going muons produced by high-energy (> 1 GeV) ν_μ interactions in the rock underneath the detector rather than the low-energy interactions contained inside the detector. This is because electrons from ν_e interactions quickly range out in rock. Monte Carlo simulations predict the expected contamination of electron neutrino interactions in the IMB upward-going external event sample to be about 1%. Thus ν_e is essentially "sterile." In addition, these simulations also show that if *all* the atmospheric muon neutrinos oscillated to ν_τ, the upward-going muon rate would be only 6% of its expected value. Thus ν_τ is also essentially sterile, so the oscillation of ν_μ into ν_τ would produce a deficit of upward-going muons.

The oscillation of ν_μ to ν_τ may be governed by the well-known two-component vacuum oscillation formula:

$$P_{\nu_\mu \to \nu_\tau} = \sin^2(2\theta)\sin^2(1.27\delta m^2 L/E), \qquad (1)$$

where P is the probability that a ν_μ becomes a ν_τ, L is the distance from the neutrino production point (km), E is the neutrino energy (GeV), and $\sin^2 2\theta$ and δm^2 are parameters to be determined. The energy range of the experiment considered here is roughly 5 to 500 GeV. Typical path lengths vary from 90 km (horizontal) to 12800 km (vertical).

The data set used here consists of 617 events taken over 3.6 yr of live time from 7 February 1983 to 30

March 1991. In 1985–6 the detector underwent two major changes: (1) the addition of the wave-shifter plates (IMB-2) and (2) the replacement of the 13.6-cm PMTs with 20-cm PMTs (IMB-3). The number of events recorded and the duration of each period of detector operation are 402 events in 183 days (IMB-1), 19 events in 53 days (IMB-2), and 415 events in 863 days (IMB-3).

The various software cuts used to separate the upward-going muons from the downward-going cosmic-ray muon background (about 2.7/second) have been described elsewhere [6,7]. Essentially, a real-time computer algorithm does a rough track fit and saves events with track directions greater than 72° from the zenith for off-line analysis. Off-line analysis consists of a combination of routines to remove events with poor fits, downward-going multiple muon showers, and events with directions less than 85° from the zenith (as determined by a maximum likelihood track fitting algorithm). Events passing these cuts (about 10/day) are manually scanned and fitted by physicists. In this way, a discrimination factor of about 2×10^{-8} is achieved for upward-going muons of neutrino origin versus downward-going cosmic-ray muons [7].

Simulations show that the muon threshold energy ($\epsilon=0.5$) is about 1.8 GeV (1 GeV) for IMB-1,2 (IMB-3). The corresponding neutrino threshold energy is roughly 2.5 GeV (1.5 GeV). In addition, previous studies have shown [6] that manually fitted events have a space angle error of 4.6° (1σ for IMB-1). Though the overall efficiency of the reduction chain is not important for this analysis, it is about 85% (after a minimum firing tube cut) based on an effective area of 400 m^2.

Monte Carlo simulations are used to determine the expected number of events. The simulations use the atmospheric neutrino fluxes calculated by Volkova [8] above about 15 GeV and those of Lee and Koh [9] below. Two models are used because the Volkova model ignores geomagnetic effects (important at low energies) while Lee and Koh consider only low energies in their calculation. The neutrino and antineutrino cross sections are obtained by integrating the Eichten-Hinchliffe-Lane-Quigg (EHLQ) parton distributions [10].

To transport the mouns from the simulated muon neutrino interactions, the energy-loss parametrizations of Bezrukov and Bugaev [11] are used. Electron neutrino events were also simulated in order to take into account their expected small contribution. For electron events occurring in the rock, the GEANT program was used to propagate the resulting shower to the detector. Neutral current events were simulated inside the detector for IMB-3 only. This is due to the fact that no simulated neutral current events survived the IMB-3 data reduction chain, and IMB-1 is even less sensitive than IMB-3 to such interactions. The low sensitivity to neutral currents is due mainly to their low energy deposition and poor fit to a single-track hypothesis.

A total 27.6 yr of simulated Monte Carlo data were generated for both IMB-1 and IMB-3. These simulated events were passed through the same data reduction programs as the real data and then manually scanned to determine which events would fulfill the selection criteria of the upward-going sample. The Monte Carlo events were smeared in angle by 4.6° to simulate the detector resolution. A final cut was made to discriminate against showering events by rejecting tracks with abnormally high energy deposition and in which the fraction of light outside the Cherenkov cone exceeds 32% (42%) for IMB-1,2 (IMB-3). This cut removes 63% of the simulated ν_e events while cutting less than 1% of the simulated ν_μ events.

In the analysis that follows, it will be important to distinguish in an objective way between tracks which enter the detector and then stop from those which enter and then exit. This is done by using the observation that stopping tracks and through-going tracks make distinctively different Cherenkov patterns in the IMB detector. The Cherenkov cone of a through-going track projected into a plane perpendicular to the track becomes a filled circle, with very high light levels at the center (where the particle exited the detector). A stopping track does not exit, and hence the high light levels seen near the projected exit point are absent. The pattern is thus that of a hollow ring, since the only light at the center is from scattered photons.

Figure 1 shows the distribution of light yield in photoelectrons (p.e.) per cm in the last 5 m of projected track for the upward-going muon data. The histogram shows the distribution predicted by the Monte Carlo simulation. The peak at low p.e./cm due to stopping tracks can be clearly seen. Events with less than 0.15 (0.3) p.e./cm are designated as stopping in IMB-1,2 (IMB-3). The peak at high p.e./cm due to exiting muons is shifted slightly from the Monte Carlo expectation due to PMT saturation effects at the high light levels encountered near a muon exit point. It is clear that this saturation shift has little effect in the ability to distinguish exiting from stopping tracks. Table I shows the number of measured and predicted exiting and stopping tracks both before and after the showering event cut. Errors shown for the data are statistical while errors given for the simulations are systematic.

A total of 49 events were cut from the data sample as showering tracks, while 17 events were cut from the Monte Carlo sample. Many of the events cut in the data are clustered in the range of 400–550 hit PMT's. Since the threshold of the analysis is 400 hit PMT's and the efficiency for recovering showering events through the data reduction chain is very low (about 16%), it may be that most of these events represent "leakage" from ν_e interactions near the analysis threshold energy. The possibility that these events represent an anomalous ν_e flux cannot be ruled out, however. Since these showering events were removed from the sample, they have no effect

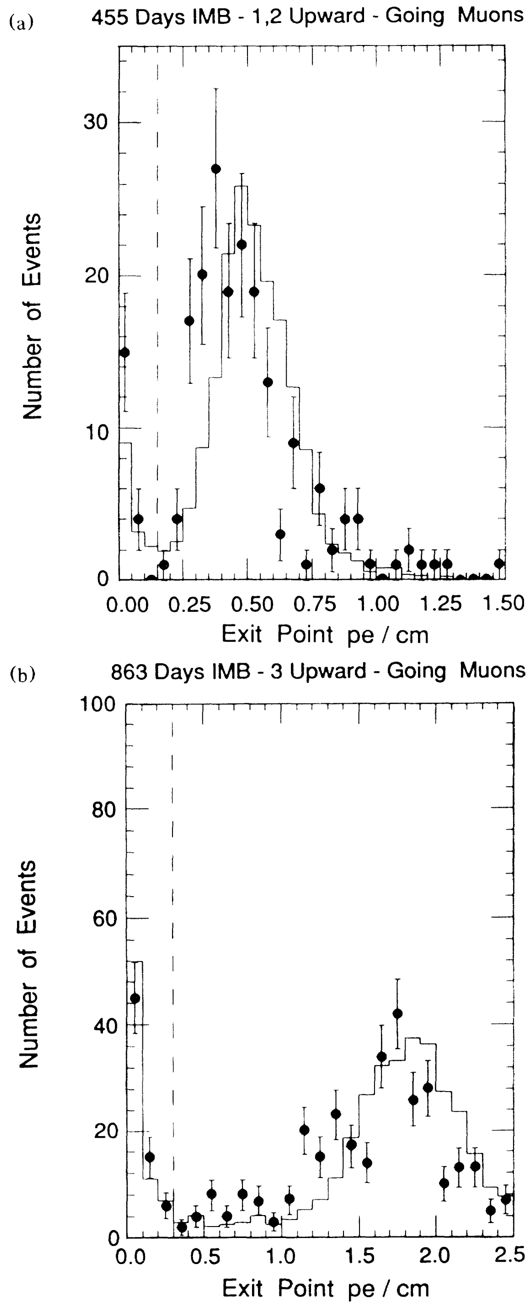

FIG. 1. p.e./cm near the projected exit point of the muon track for (a) IMB-1 and 2, and (b) IMB-3. The solid histogram shows the distribution predicted from the Monte Carlo simulation. The dashed line shows the cut made to separate out the stopping muons.

on the muon neutrino disappearance search which follows.

From Table I it can be seen that the daily rate of upward-going muons is predicted to be 0.455 d^{-1}. Comparison with the measured rate of 0.47 ± 0.02 d^{-1} shows no evidence for a muon neutrino deficit. It then becomes interesting to set limits on possible values of $\sin^2 2\theta$ and δm^2.

TABLE I. Number of stopping and exiting events.

	Measured		Predicted	
	Before cut	After cut	Before cut	After cut
All events	666 ± 26	617 ± 25	617 ± 124	600 ± 120
Exiting events	535 ± 23	532 ± 23	517 ± 103	516 ± 103
Stopping events	131 ± 11	85 ± 9	101 ± 20	84 ± 17

The major uncertainty in the predicted rate comes from the absolute normalization of the muon neutrino flux, estimated by Volkova to be as much as 20%. Additional uncertainty comes from the total neutrino cross section, about 6% between 20 and 250 GeV [12]. Below 20 GeV the data points on the total cross section have a large scatter and individual error bars of 15% or more. Above 1 TeV there are no direct data on the neutrino cross section or on the parton distributions. In order to assess the effect of this uncertainty on the limits that can be set on $\sin^2 2\theta$ and δm^2, two cross-section models are constructed which have quite different behavior than EHLQ at the high- and/or low-energy regions.

The first model uses the EHLQ parton distributions, but normalizes the total cross section to the data in the linear region. This model will be called "empirical" since it is driven by simply getting the best fit to the cross-section data. There is no increase in cross section due to QCD evolution at high energies, but there is a turnover due to finite W mass at about 10 TeV. The second model uses EHLQ at all energies above 10 GeV, but forces the simple linear proportionality seen above 10 GeV to continue on down to 1 GeV. For this reason it is called "hybrid." This gives a lower cross section at these low energies by as much as 15%.

The predicted number of events for the various cross-section, flux, and parton distribution models are given in Table II. The EHLQ model is selected as the "nominal" model since it predicts the largest event rate, and thus yields the least restrictive, conservative oscillation limits when compared with the data, though it is clear that the variation between models is much less than the 20% uncertainty in the absolute flux.

Figure 2 shows the 90% C.L. limit exclusion area obtained by a simple rate comparison. In addition to statistical errors, a 20% normally distributed systematic error in the predicted rate is assumed. This error by far

TABLE II. Number of upward-going muons and stopping fraction.

Model	Number of events	Stopping fraction
Measured data	617	0.160 ± 0.019
EHLQ	600	0.163
Hybrid	597	0.160
Empirical	588	0.154
PDG	585	0.158
LKV	598	0.161

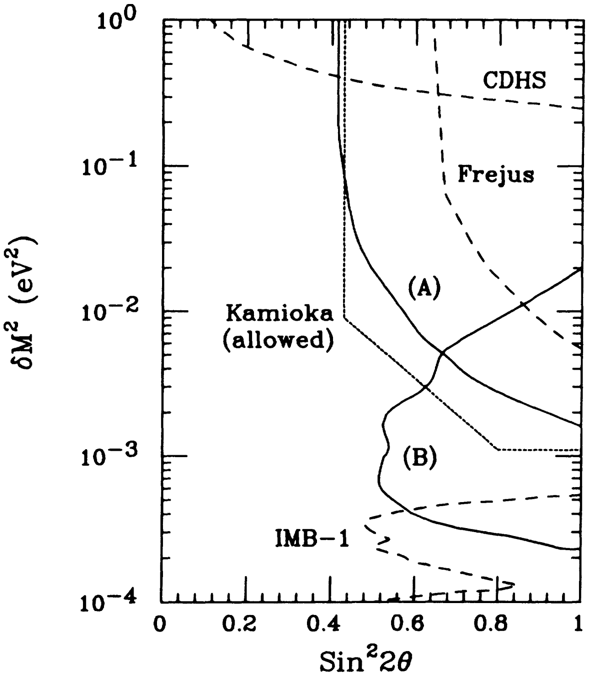

FIG. 2. 90% C.L. limits on ν_μ to ν_τ oscillations from rate (A) and stopping fraction (B). Dashed curves show limits from IMB-1 [14], Frejus [3], and CERN-Dortmund-Heidelberg-Saclay (CDHS) [15]. Dotted curve shows the allowed region from Kamiokande [16]. The Frejus limit is 95% C.L.; others are 90%.

dominates all others. Limits from other experiments are shown for comparison.

In order to avoid the 20% error in the knowledge of the absolute flux, the rate of upward-going muons which stop in the detector can be compared with the rate of those which pass through and exit. In this way absolute flux and cross-section errors cancel. Since the median energy of the stopping muons is calculated to be 6 GeV as compared to 100 GeV for the through-going ones (though both spectra have a long tail extending to high energies), the fraction of stopping muons to through-going ones is a sensitive parameter to neutrino oscillations.

Table II gives the stopping fraction for the data and several of the different cross-section and flux models. In addition, the stopping fractions calculated by using the empirical parton distributions from the Particle Data Group (PDG) [12] and the Lohmann-Kopp-Voss (LKV) [13] energy-loss parametrizations [12] are also shown. In all instances the measured data are consistent with the hypothesis of no neutrino oscillations. The nominal EHLQ model predicts the highest stopping fraction and thus gives the most conservative limits. These are shown in Fig. 2.

These limits rule out much (but not all) of the "allowed" region of parameter space if the muon neutrino deficit measured by IMB and Kamiokande at low energies is due to ν_μ oscillations to ν_τ. In addition, the high mixing angle region from 5×10^{-4} to 5×10^{-3} eV^2 is newly excluded.

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