A Measurement of the of Flux of Upward-Going Muons with the IMB Detector

R.Becker-Szendy[a], C.B.Bratton[b], D.R.Cady[c], D.Casper[d], S.T.Dye[e], W.Gajewski[f], M.Goldhaber[g], T.J.Haines[h], P.G.Halverson[f], D.Kielczewska[i], W.R.Kropp[f], J.G.Learned[a], J.M.LoSecco[c], C.McGrew[f], S.Matsuno[f], R.S.Miller[j], M.S.Mudan[k], L.Price[f], F.Reines[f], J.Schultz[f], H.W.Sobel[f], L.R.Sulak[e], and R.Svoboda[j]

[a] *The University of Hawaii, Honolulu, Hawaii 96822, USA*
[b] *Cleveland State University, Cleveland, Ohio 44115, USA*
[c] *The University of Notre Dame, Notre Dame, Indiana 46556, USA*
[d] *The University of Michigan, Ann Arbor, Michigan 48019, USA*
[e] *Boston University, Boston, Massachusetts 02215, USA*
[f] *The University of California, Irvine, California 92717, USA*
[g] *Brookhaven National Laboratory, Upton, New York 11973, USA*
[h] *The University of Maryland, College Park, Maryland 20742, USA*
[i] *Warsaw University, Warsaw, Poland*
[j] *The Louisiana State University, Baton Rouge, Louisiana 70803, USA*
[k] *University College, London WCIE6BT, U.K.*

ABSTRACT

Muon neutrinos produced as a result of cosmic ray interactions with the atmosphere can be used to search for $\nu_\mu \rightarrow \nu_\tau$ oscillations. The flux of such neutrinos can be measured indirectly via the detection of upward-going muons in deep underground detectors. In 2.53 years of live time, the IMB proton decay detector has measured an upward-going muon flux of 2.26 ± 0.11 (stat.) $cm^{-2}s^{-1}sr^{-1}$ compared to a Monte-Carlo calculated expected flux of 2.37 ± 0.02 (stat.) ± 0.36 (sys.) $cm^{-2}s^{-1}sr^{-1}$. These results are still preliminary, as acceptance factors have not yet been calculated for all periods of detector operation. Still, the measured flux is consistent with the expected flux. In addition, a search made for extraterrestrial neutrinos shows no significant points that can be claimed to be neutrino point sources.

I. INTRODUCTION

It is not known whether lepton number is absolutely conserved. It may be that neutrino flavor eigenstates are not be 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]. To date, 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], though there are disputed claims of a deficit of ν_μ in cosmic ray neutrinos [3] which could be interpreted as the oscillation of ν_μ to ν_τ [4].

The conflicting results in atmospherically produced cosmic ray neutrinos stem not only from the difficulty in separating muons from electrons inside the detectors (all of which were built to look for proton decay, not for neutrino oscillations), but also the uncertainties in the flavor content of the atmospheric neutrino flux and in the absolute interaction cross sections. These uncertainties can be reduced by using upward-going muons produced by high-energy (> 2 GeV) ν_μ interactions in the rock underneath the detector rather than the low energy interactions contained inside the detector. Electrons from ν_e interactions will quickly range out, so virtually all of the observed high energy upward-going particles will be of ν_μ origin. In addition, the higher energy muons will point back to the parent neutrino direction within a few degrees, and thus the baseline path uncertainties associated with the lower energy neutrinos is not as severe. This is important because the expected angular distribution of muon neutrinos about the nadir is not as uncertain as the absolute flux, and thus the observed angular distribution can be used to place normalization free limits on the oscillation of ν_μ to ν_τ or ν_e.

The first step in such an analysis is to obtain an accurate measurement of the angular distribution of upward-going muons. The preliminary measurements from the Irvine-Michigan-Brookhaven (IMB) detector are reported here. In addition, a search is made for possible astrophysical neutrinos using the same data set.

II. OBSERVATIONS AND RESULTS

The Irvine-Michigan-Brookhaven (IMB) detector is an 8 kilotonne water Cherenkov detector located at a depth of 600 meters (1570 m.w.e) at the Morton Salt Mine in Cleveland, Ohio, USA (latitude 41.72°N, longitude 81.27°W). It consists of a $18m \times 17m \times 22.5m$ tank of water surrounded on all six sides by 2048 20-cm diameter photomultiplier tubes (PMTs). The PMTs are mounted on waveshifter plates for increased light collection. Details of the construction have been published elsewhere [5]. The IMB detector has the world's largest sensitive area for upward-going muons and has been in operation since 1982. The data set used here consists of 474 events taken over 2.53 years of live time from February 7, 1983 to April 30, 1989. During this period, the detector has seen two major changes, the addition of the waveshifter plates (IMB-2) and the replacement of the 13.6-cm PMTs with 20-cm PMTs (IMB-3). This has changed the threshold of the detector over time. When cuts on the minimum number of firing tubes in an event are adjusted via Monte Carlo-based cuts, the total number of events is reduced to 430 for an effective threshold of 2 GeV. The zenith angle distribution of these events is shown in figure 1. The various software cuts necessary to separate the upward-going muons (recorded at a rate of about one every two days) from the downward-going cosmic ray muon background (about 2.7 per second) are described elsewhere [6]. Manual scanning is used to determine the final acceptance or rejection of an event.

III. DISCUSSION

In order to determine the absolute flux of upward-going muons as a function of zenith angle it is necessary to know the effective area as a function of zenith angle. A Monte Carlo calculation is used to accomplish this. The calculation uses the atmospheric neutrino fluxes calculated by Volkova [7] and the neutrino and antineutrino cross-sections obtained by integrating the Eichten-Hinchliffe-Lane-Quigg (ELHQ) parton distributions [8] for the u and d valence quarks and the u,d,s, and c sea quarks (t and b are not important at these energies). These

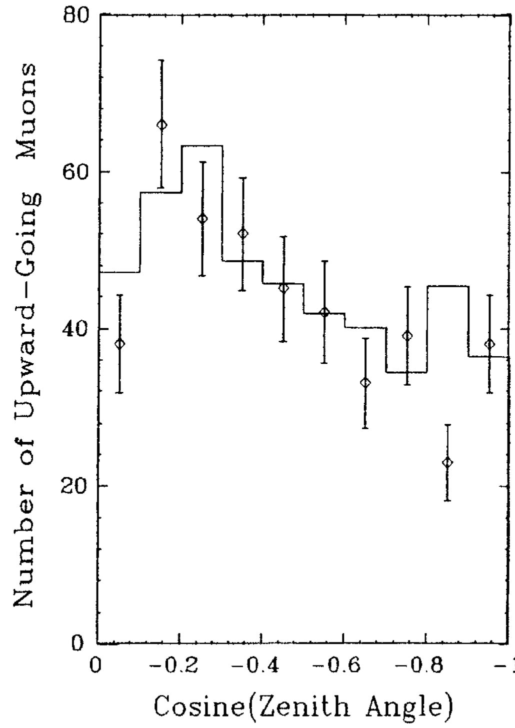

Figure 1: The zenith angle distribution of the 430 upward-going muon events. The histogram represents the expected distribution from a Monte Carlo calculation

distributions are also used (in the Q^2 region of 5 GeV^2) when the maximum possible muon scattering angle is greater than 1 degree. Scattering less than 1 degree is not a significant factor in the angular distribution when compared with the detector resolution of $\sigma = 4.6°$. For this same reason, muon multiple scattering in the rock is ignored, since it is also on the order less than a degree. In general, angular errors of a few degrees are not important in measuring the upward-going muon zenith angle distribution since there are large statistical errors and, given the relatively flat distribution, as many events scatter into a given angular bin as scatter out.

To transport the muons, the parametrizations of Bezrukov and Bugaev [9] are used to simulate the continuous energy loss of muons through the rock to the detector. Detector response is calculated using the standard IMB-1 and IMB-3 Monte Carlo programs. The same simulation program is used to calculate IMB-1 and IMB-2 acceptance, since the thresholds are very similar and the data reduction algorithms are identical. On the other hand, completely different algorithms were used for IMB-3 and so the detector response functions can be expected to be somewhat different. 27.64 years of simulated Monte Carlo data was generated for both IMB-1 and IMB-3. Since these data must also be manually scanned (a very lengthy process), only about one-third the IMB-1 simulated data have been scanned to date. The results presented here are preliminary in that the detector effective area is calculated using only these simulated data. Figure 2 shows the effective area of IMB-1 as a function of zenith angle. The smoothed curve is fitted to the Monte Carlo data shown and is used in subsequent calculations. This curve takes into account not only the physical size of the detector, but also the efficiency of the data reduction algorithms and scanning. Figure 3 shows the flux of upward going muons as a function of zenith angle. The error bars are statistical only. The solid curve is the expected flux (> 2 GeV) from the Monte Carlo. The dashed lines indicate the systematic error in the flux of 15% estimated by Volkova.

It can be seen that the measured flux is consistent with the calculated flux assuming no ν_μ to $\nu_\tau$oscillations. Thus there is no evidence for such oscillations in these data. Quantitative limits will be calculated following completion of the Monte Carlo analysis.

IV. SEARCH FOR ASTROPHYSICAL SOURCES

There is currently a good deal of interest in the possibility that there might exist astrophysical point sources of high energy neutrinos [10]. Several groups have carried out searches for correlation between the arrival directions of upward-going muons and known gamma or x-ray sources [11]. None have been found. It is possible, however, that sources may be obscured by dense dust or gas clouds that absorb the gamma and x-rays. In order to search for such "hidden" sources, a 50×100 grid was laid out on the sky. At each grid point, the number of upward-going muons arriving within the point spread resolution (taken as seven degrees) was determined. The directions of the muons were then scrambled by changing the time of arrival. The grid point procedure was then repeated. By repeating this cycle many times, a background map was determined. Each data grid point was then compared with the corresponding background point, and the Poisson probability of obtaining the observed num-

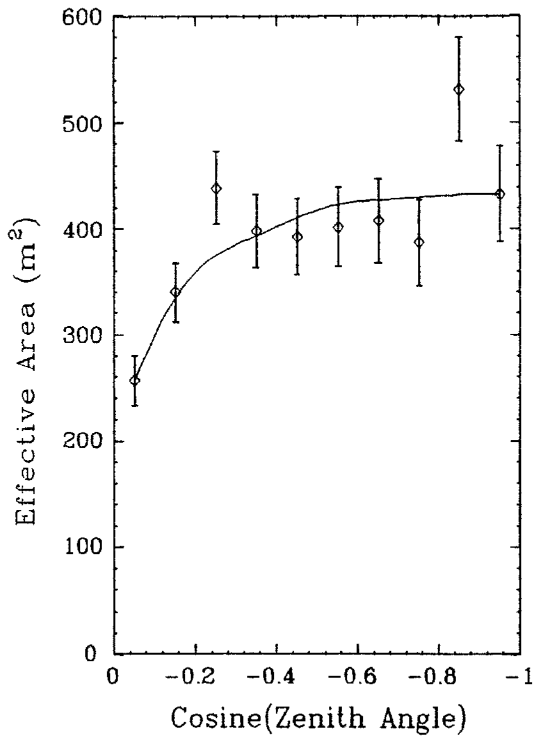

Figure 2: The effective area of IMB-1 as a function of zenith angle as determined by Monte Carlo simulated data

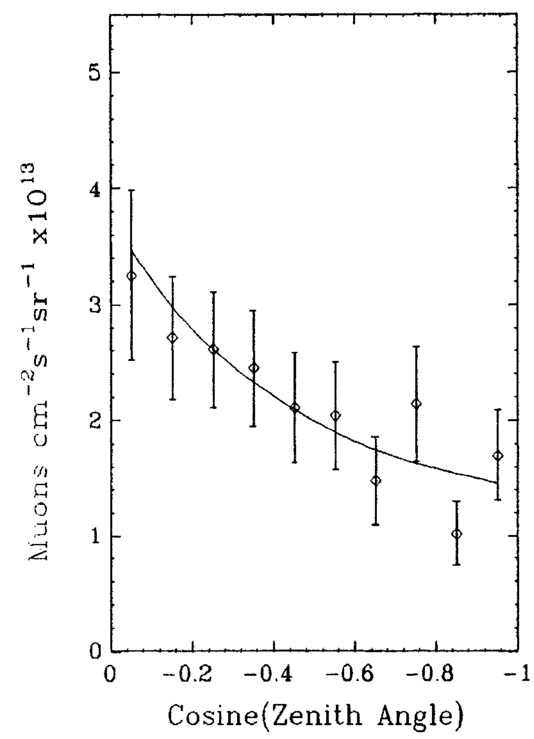

Figure 3: The flux of upward-going muons > 2 GeV, based on a preliminary analysis of 2.53 live years of IMB data. The solid curve is the expected Volkova flux. The dashed lines indicate the systematic error in the expected flux.

ber of events or greater from the background was calculated. Figure 4 shows the results of this procedure as a contour plot. Each contour represents a factor of ten in probability. The most "unlikely" points are located at galactic latitude and longitude +11,+279 and +0,+271. The probabilities here are about 0.0003, but of course there were many trials made (though not all independent). Taking the number of independent trials to be given approximately by the number of independent resolution bins (135), then the probability is really only about 0.041 and therefore not significant. It is interesting, however, to note that these points lie on the galactic plane, which subtends less than 15% of the sky.

V. CONCLUSIONS

Figure 3 shows that the measured upward-going muon flux is consistent with the expected flux within errors. The total upward-going muon flux obtained by integrating figure 3 over the lower hemisphere is $2.26 \pm 0.11 \times 10^{-13} cm^{-2} s^{-1} sr^{-1}$. The error is statistical only and does not take into account uncertainties in the effective area. The expected total flux is 2.37 ± 0.02 (stat.) ± 0.36 (sys.) $\times 10^{-13} cm^{-2} s^{-1} sr^{-1}$. Thus the measured flux is consistent with being entirely due to atmospheric neutrinos with no oscillations. In addition, there is no evidence for nearby "hidden" sources of neutrinos.

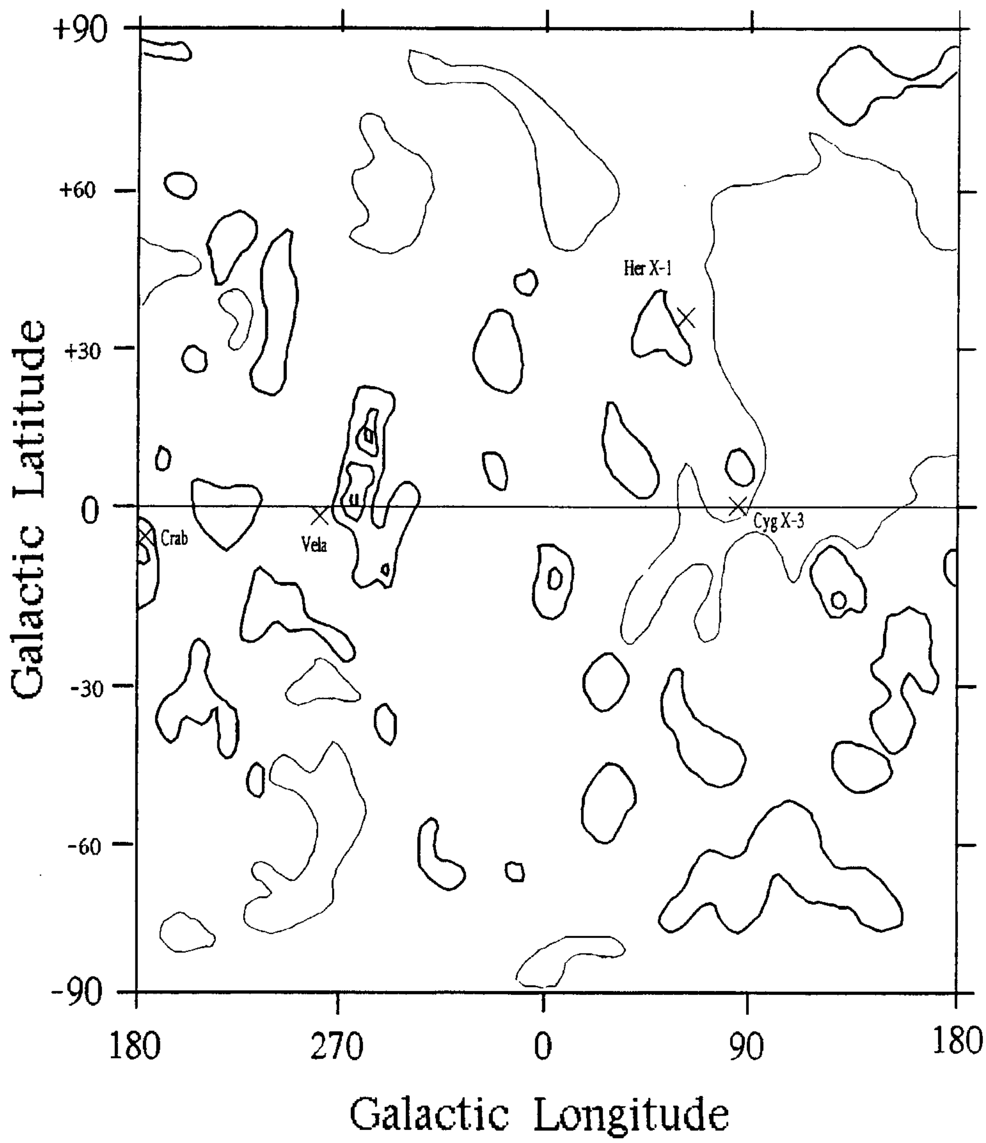

Figure 4: Contour plot of the upward-going muon arrival directions in galactic coordinates. Each dark contour represents a factor of 10 in pre-trials probability. The light contours indicate regions for which there is no data.

REFERENCES

1. J. Bouchez, *Proc. of Neutrino 88 Conf.* (1989) 28. Also see F. Vannuci pg. 46.
   R.M. Bionta et al., *Phys. Rev.* **D38** (1988) 768.
   Y. Oyama et al, *Phys. Rev.* **D39** (1989) 1481.

2. H.A. Bethe, *Phys. Rev. Lett.* **63** (1989) 837.
   M. Cherry, *Nature* **347** (1990) 708.

3. K.S. Hirata et al., *Phys. Lett.* **B205** (1988) 416.
   Ch. Berger et al.,*Phys. Lett.* **B245** (1990) 305.
   D. Casper et al., Boston Univ. preprint 90-23, submitted to Phys. Rev. Lett..

4. J.G.Learned, S. Pakvasa, and T.J. Weiler, *Phys. Lett.* **B207** (1988) 79.

5. R.M. Bionta et al.,*Phys. Rev. Lett.* **51** (1983) 27.
   R. Claus et al.,*Nucl. Instr. and Meth.* **A261** (1987) 540.
   R. Becker-Szendy et al.,*Phys. Rev.* **D42** (1990) 2974.

6. R. Svoboda et al.,*Astrophys. J.* **315** (1987) 420.

7. L.V. Volkova, *Soviet J. Nucl. Phys.* **31** (1980) 784.

8. E. Eichten, I. Hinchliffe, K. Lane, and C. Quigg, *Rev. of Modern Phys.* **56** (1984) 579.

9. L.B. Bezrukov and E.V. Bugaev, *Proc.* 17^{th} *Int. Cosmic Ray Conf.* , Paris, (1981) Vol. 7 102.

10. T.K. Gaisser, *Science* **247** (1990) 1049.
    M.H. Reno and C. Quigg,*Phys. Rev.* **D37** (1988) 657.

11. R. Svoboda, *Nucl. Phys.* **B14A** (1990) 97.