Contained neutrino interactions in an underground water detector

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We study 401 neutrino interactions which have been collected in a massive, well-shielded underground detector. The sample is used to test for neutrino oscillations with a sensitivity in $\Delta m^2 \geq 4.2\times 10^{-5}$ eV^2 at maximum mixing (90% confidence level). A search is made for terrestrial and extraterrestrial point sources of neutrinos. A limit on point sources in the energy range 500–2000 MeV is given. A search is made for possible evidence for geomagnetic effects on the data. Most of the neutrinos are likely of atmospheric origin.

INTRODUCTION

The use of the massive, well-shielded IMB (Irvine-Michigan-Brookhaven) detector for the search for baryon nonconservation has, as a by-product, yielded a sample of 401 contained interactions.[1,2] For the most part these are believed to be neutrino induced. These neutrinos come from natural, i.e., nonaccelerator, sources. In previous publications we had reported new physics results using this data sample including studies of matter oscillation effects,[3] studies of neutrino decay,[4] searches for evidence for dark matter by an increased flux of energetic neutrinos from the Sun,[5] and studies of off-diagonal neutral currents,[6] a matter effect sensitive to lepton-flavor violation in the weak neutral current.

In the present paper, these same neutrino interactions are used to study neutrino oscillations over very long distances, to search for point sources of neutrinos, and to search for effects resulting from the geomagnetic modulation of the primary-cosmic-ray flux.

The IMB-1 detector[7] is an 8000-metric-ton imaging water Cherenkov detector located at a depth of 6 10 m [1570 mwe (meters of water equivalent)] in a salt mine on the shores of Lake Erie, 42 km east of Cleveland, Ohio (181°, 17′ west 41° 45′ north). The detector is capable of reconstructing particle tracks provided the particle's velocity exceeds the Cherenkov threshold in water ($\beta \geq 0.75$). This corresponds to a threshold energy of 1.52 times the rest mass. Water attenuation and phototube thresholds have a negligible effect on the sensitivity to massive particles. Detector noise makes a practical trigger threshold about 30 MeV above the Cherenkov threshold. Reconstruction requirements (a minimum of 35 photomultiplier tubes) increases the minimum energy to be about 140 MeV above threshold. The detector measures the position of the interaction, the time the event occurred, the total light produced by the interaction (which may be related to the energy of the interaction), the direction and energy of the relativistic charged particles, and thus also a minimum multiplicity of the event. Particle decays occurring from 330 nsec to 7.5 μsec after the main trigger may also be observed.

To prevent contamination from entering particles a fiducial cut is made 2 m into the active volume of the detector. In addition, there is about 50 cm of water outside the active volume that is sensitive to entering tracks and increases the shielding depth for entering neutrals to 2.5 m. This is a minimum of 3 interaction lengths for strongly interacting particles. The fiducial mass of the detector is 3300 metric tons containing 2×10^{33} nucleons. The overall detector dimensions to the phototube planes are 22.9 m east to west, 16.8 m north to south, and 17.8 m vertically. As mentioned the total volume is larger due to the space behind the tubes.

The data sample discussed here has been collected over a period of 417 days of live time extending from September 1982 to June 1984.

THE DATA SAMPLE

The 401 events in this data sample have vertices that are reconstructed inside the fiducial volume. Neutrinos are the only known particles that will produce interactions uniformly throughout the detector. Except for small geomagnetic effects[8] the distribution of neutrino interactions should be isotropic in direction. The major backgrounds are associated with the underground cosmic-ray muon flux. The muons themselves are concentrated near the vertical with an approximately $\cos^3\theta$ distribution. Neutral secondaries from muon interactions are rare and strongly attenuated by the rock and water shield. Most entering neutrals would be accompanied by the primary muon. Those coming from the side enter at an angle and must go several absorption lengths, three at the very minimum to penetrate the fiducial volume.

To see whether the data are consistent with being a neutrino event sample, we examine the distribution of events within the detector volume. A sphere of 7-m radius at the center of the detector has 44% of the fiducial volume and contains (45±4)% of the data sample. There is no excess near the edges. The top half of the detector contains 200 of the events (50±4)%. There is no excess near the top. The vertical distribution for the events is shown in Fig. 1. Figure 2 is a scattering diagram of the vertical position against the cosine of the zenith angle. There is no correlation of vertical position with zenith angle.

Of the 401 events, 105 have a positive signal for a particle decay following the initial interaction. The time distribution for these events is plotted in Fig. 3. The mean decay time is 2.02 μsec, compatible with the decay of a mixture of μ^+ and μ^-.

Since the above tests show no evidence for contamination of the sample from entering muons or neutral parti-

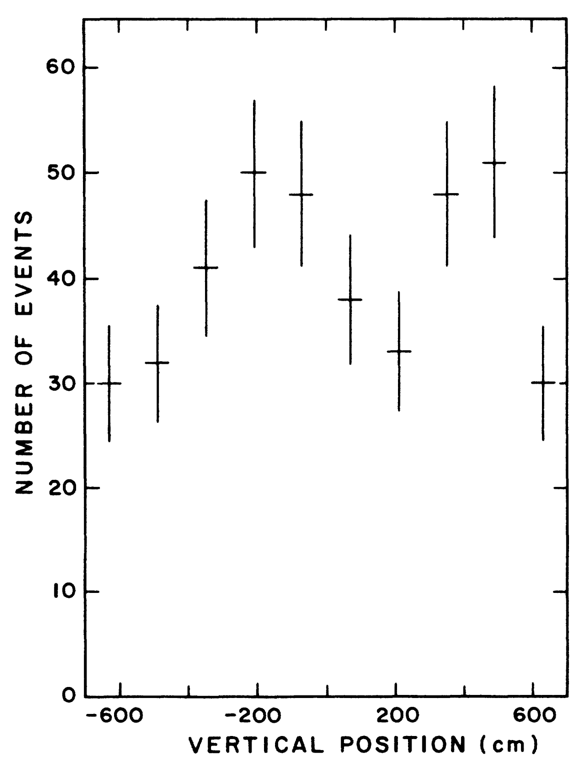

FIG. 1. Vertical distribution of events in the detector.

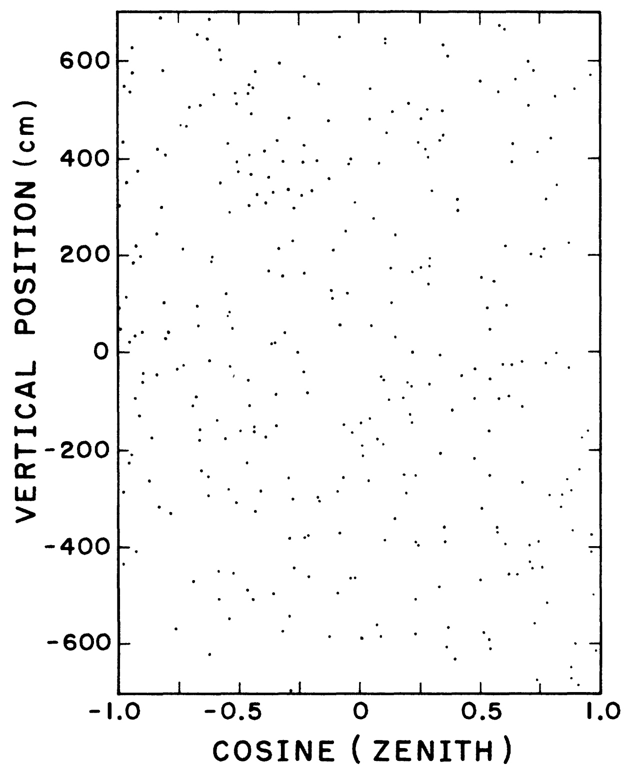

FIG. 2. Zenith angle plotted against Z vertex position.

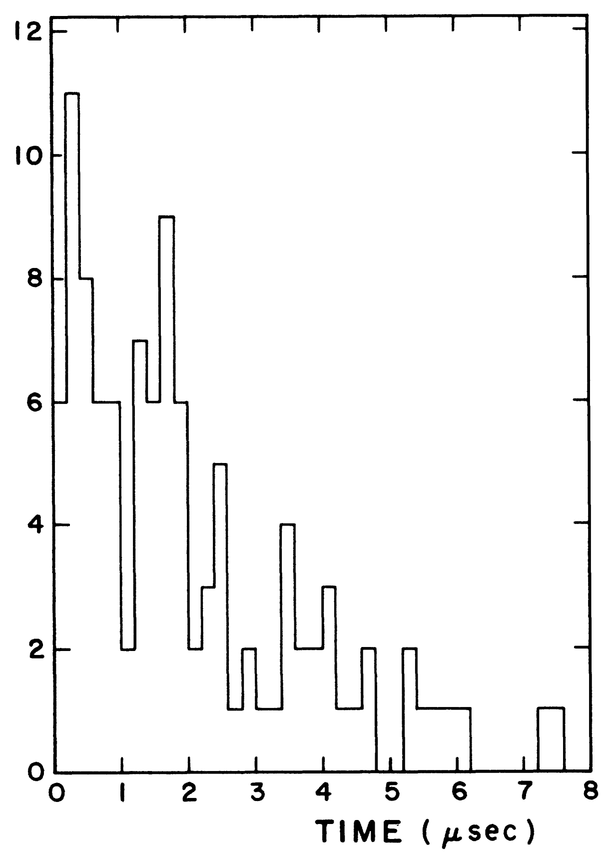

FIG. 3. Time of the decay signal for the 105 events that show a muon decay.

cles, we analyze the data assuming all the events are neutrino interactions. We do not, however, want to preclude the possibility that some small contribution ($\leq 5\%$) could come from nucleon decay or other unexpected sources.

The overall rate of neutrino interactions can be interpreted in terms of an average flux of neutrinos. The observed rate corresponds to a flux of 5.1 ± 0.9 neutrinos/cm^2min sr for neutrinos and antineutrinos with an energy in excess of 400 MeV. We have assumed a $\nu/\bar{\nu}$ flux ratio of 1.25 for this estimate and used measured values for the low-energy neutrino and antineutrino cross sections from Argonne[9] and Gargamelle.[10] We have a 90% efficiency for charged-current (CC) events and about 25% efficiency for neutral-current (NC) interactions. We take $\sigma_{\text{NC}}/\sigma_{\text{CC}}=0.33$. The mean neutrino energy for our events is 920 MeV.

Since there is as much as a 20% uncertainty in the neutrino cross sections at these energies we will also estimate the flux using the asymptotic values for neutrino and antineutrino cross sections[11] and the efficiencies and flux ratios from above. This gives a flux of 5.9 ± 0.9 neutrinos/cm^2min sr.

NEUTRINO OSCILLATIONS

Neutrinos are incident on the detector from all directions. This provides path lengths of from 10 to 13 000 km. The energy spectrum is almost directionally independent. This is an ideal situation for the study of neutrino oscillations. Rather than varying the path length by moving the detector or by using multiple detectors we can study the variation over three decades of source to detector distance by using the continuous atmospheric source. In particular, a comparison of downward-going neutrinos ($L\approx 10$ km) to upward-going neutrinos ($L\approx 10\,000$ km) provides a sensitive test free of systematic errors associated with flux calculations.

There are a number of difficulties. In the first place, the neutrino flux is a mixture of ν_μ, $\bar{\nu}_\mu$, ν_e, and $\bar{\nu}_e$. Particle identification is limited so that the simplest experiment, to look for any distance-dependent rate differences, only test a region of oscillation parameter space. A sophisticated analysis would be needed to explore the implications of a simple rate experiment for various oscillation hypotheses. In the present work we avoid these problems by considering only two-component mixing between ν_μ and ν_τ or some other noninteracting, i.e., "sterile" neutrino species. We will denote such a generic species of neutrino as ν_s.

A number of measurement errors associated with the neutrino energy and direction need to be considered. The total light output lacks information about particles below the Cherenkov threshold. In general, energy carried off by nucleons or nuclear fragments is lost. The energy in particle masses is also unobserved. We have corrected for this by fitting Monte Carlo-generated neutrino events of known energy and with the energy distribution expected from atmospheric neutrino interactions to the visible energy of the total light output. This was done for a variety of experimental cuts.

For a prior analysis using all single-prong neutrinos, we used[1] the approximate relation

$$E_\nu=0.758E_{\text{vis}}+410\text{ MeV}\ . \tag{1}$$

In the current analysis of only events with a muon-decay signature we have used

$$E_{\nu_\mu}=0.821E_{\text{vis}}+525\text{ MeV}\ . \tag{2}$$

In both cases E_{vis} is the energy corresponding to the total light output.

The direction reconstructed for an event is not the true direction of the neutrino but the average direction of the final-state particles above Cherenkov threshold. This direction is the best estimate for the true neutrino direction. Because of the slow variation of the neutrino path length (Fig. 4) for vertical neutrinos the scattering error in direction contributes little to the error in the distance used to calculate neutrino oscillations. We estimate[1] an error of at most 16% [full width at half maximum (FWHM)] on the path length near vertical. A more extensive discussion of angular errors, which are energy dependent, can be found in Ref. 12.

The effect of oscillations into noninteracting neutrinos in a two-component model will be to modulate the energy spectrum:

$$P(\nu_\mu\rightarrow\nu_S)=(\sin^2 2\eta)\sin^2\left[1.27\frac{L}{E_\nu}\Delta m^2\right]\ , \tag{3}$$

Δm^2 and $\sin^2 2\eta$ are parameters to be determined.

By varying the direction we can vary the path length:

$$L=\sqrt{r^2-(r-d)^2\sin^2\theta}-(r-d)\cos\theta\ . \tag{4}$$

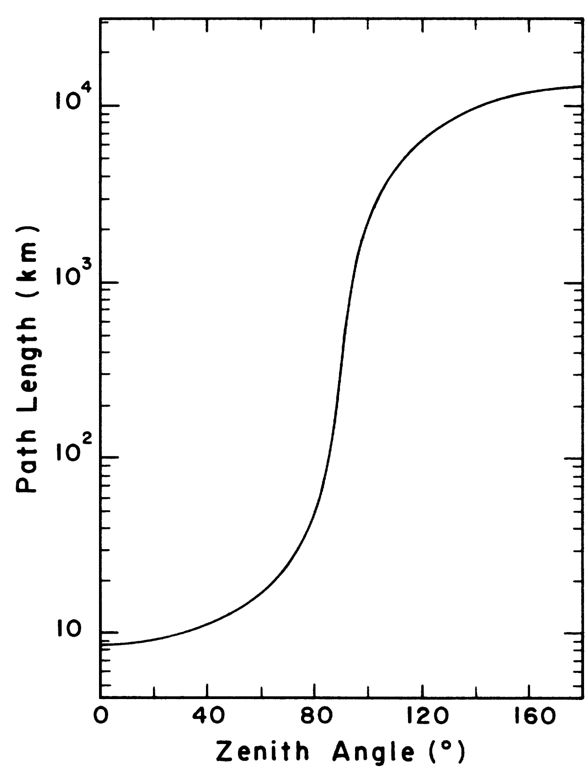

FIG. 4. Path length as a function of zenith angle. Note the logarithmic vertical scale.

In this equation, r is the Earth's radius, 6380 km, d is approximately the scale height of the atmosphere ≈ 10 km, and θ is the zenith angle. The dependence of path length on zenith angle $L(\theta)$ is plotted in Fig. 4. If we choose narrow bands in zenith angle, the events come from neutrinos with similar path lengths. By comparing the energy spectra for two different path lengths we can get a flux-independent limit on neutrino oscillations.

Of the 401 events, 310 have patterns expected of single-prong events and could be used in our analysis. Of these 310 single-prong events, 79 have a muon-decay signature. Only a fraction of the ν_μ's produce a muon that gives a decay signal. If we restrict ourselves to single-prong topologies and events with muon decays, we will have negligible background from ν_e interactions.

In our prior work[1,13] we analyzed *all* neutrino interactions for an E/L-dependent modulation. Since the sample contained ν_μ, $\bar{\nu}_\mu$, ν_e, and $\bar{\nu}_e$ fluxes we regarded the ν_e and $\bar{\nu}_e$ contributions as negligible. At the time it was generally agreed that matter effects, while present, would be small. They were also neglected in Ref. 1.

With the work of Mikheyev and Smirnov[14] it was realized that under certain resonance conditions electron neutrinos could have significantly larger oscillation amplitudes than they would have in the absence of matter. This enhancement would also extend to any neutrinos coupled to the electron-neutrino sector. We have looked at this question.[3] The present analysis assumes no projection of the propagating ν_μ on ν_e. Such oscillations would be manifested by an E/L-dependent attenuation of the interacting ν_μ flux and not depend on the density distribution of the matter traversed. Matter effects would distort the simple E/L dependence for electron neutrinos due to inhomogeneities in the density of the Earth. If the Earth's density were uniform our prior experimental results[1] could be mapped into a set of parameters for vacuum oscillations.

We can carry out the analysis for $\nu_\mu \rightarrow \nu_S$ oscillations by using the 79-event subsample of single-prong events with a muon-decay signature. These are known to come from ν_μ and $\bar{\nu}_\mu$ interactions.

We will use bins with $\frac{1}{5}$ of the total (4π) solid angle to always have a significant sample of events to work with. We will take the distance traveled to be the average distance for the band chosen. The bands are chosen concentric about the zenith.

Comparison of the energy spectra at two different distances can be carried out. This has been done using the Smirnov–Cramer–Von Mises test[15] on the spectrum measured at two distances. This test uses the cumulative distribution function of the energy spectrum (integral spectrum). A major advantage is that it is a binning-free test that uses all the information in the data. The two different neutrino spectra coming from different distances are compared as a function of the neutrino energy.

This test can be used to determine if the two samples from different distances are identical. To determine an excluded region in the $\Delta m^2 - \sin^2 2\eta$ region we need to determine how sensitive our test is to neutrino oscillations. For the spectrum shape test, the actual measured downward spectrum was modified by a hypothetical set of Δm^2 and $\sin^2 2\eta$ and compared with the measured upward spectrum. The Δm^2, $\sin^2 2\eta$ values were excluded when the spectra differed at the 90% C.L.

The sample was selected form the 79 single-prong events with a muon decay signature. The sample consisted of 15 upward-going and 21 downward-going single-track neutrino interactions in $\frac{1}{5}$ solid-angle cones ($\theta_Z < 53°$ or $\theta_Z > 127°$)

The region of neutrino oscillations into sterile neutrinos excluded by this analysis is shown in Fig. 5. A more detailed discussion of this method is given in Refs. 1 and 13.

The above result may be extended. By raising the lower zenith angle we can study shorter path lengths and larger Δm^2. It is more reliable to study higher Δm^2 with shorter path lengths than to depend on multiple oscillations. If we were to study multiple oscillations it would be less clear which components of the possible 3×3 mixing matrix were responsible for the effect. By using shorter path lengths we can study regions of larger Δm^2 while still using only the first oscillation wavelength.

In Fig. 6 we show the excluded region found by selecting regions of $\frac{1}{5}$ of the (4π) solid angle from the vertical (nadir) region to one just below the horizon. We have used 13 regions. The range of distances varies from 10^7 m for the vertical to 2.6×10^6 m for the region just below the horizon. We have used the flux-independent, Smirnov–Cramer–Von Mises comparison[15] with the vertically downward component. The samples are drawn from single-prong events in the full fiducial volume with a muon decay. The plot shown in Fig. 6 is the overlap of all excluded regions. The irregular shape at the boundary

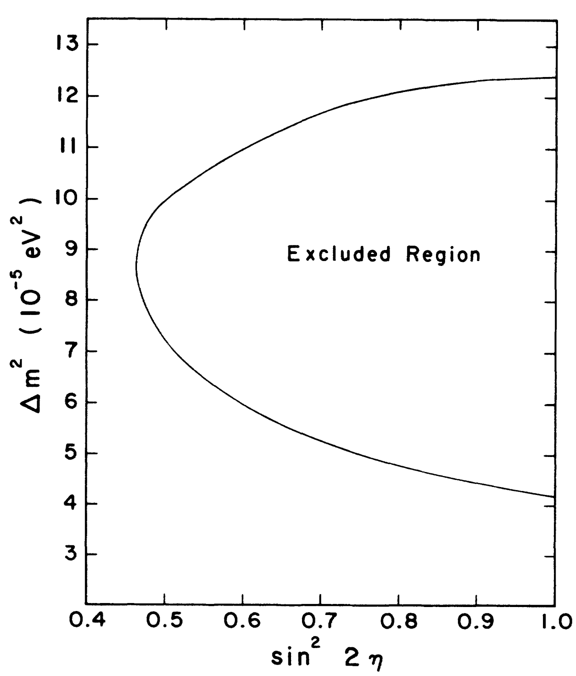

FIG. 5. The region excluded by the analysis of upward $\frac{1}{5}$ and downward $\frac{1}{5}$ of single-prong events with a muon-decay signature. This is the excluded region for a two-component ν_μ oscillation with no mixing to the electron neutrino.

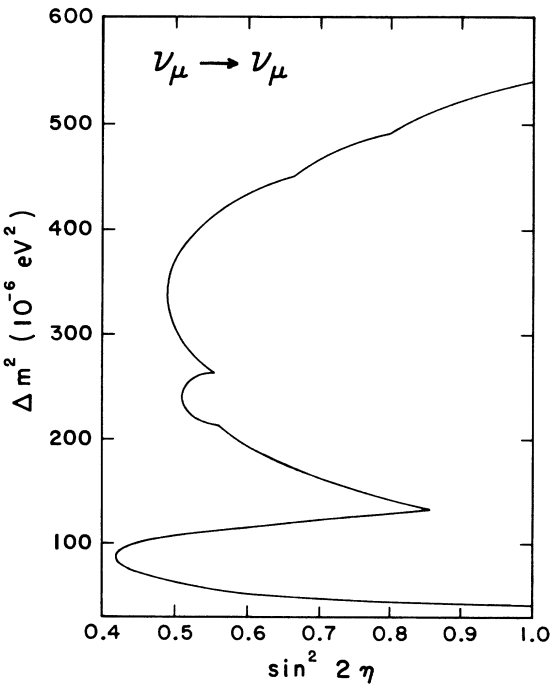

FIG. 6. Extended excluded region for the muon-neutrino oscillation experiment using all single-prong events coming from below the horizon having a muon-decay signature. The irregular shape is an artifact of the use of 13 overlapping regions with $\frac{1}{5}$ solid angle each.

is due to fluctuations in the data sample considered. It is an artifact of the use of 13 overlapping regions. We can exclude mixing masses as large as $\Delta m^2 = 540 \times 10^{-6}$ eV^2 for maximum mixing.

Since we have been studying the oscillation of muon neutrinos into τ neutrinos or other sterile neutrinos we have not needed to include matter effects which would be of importance if electron neutrinos were involved. Such considerations have been studied[3] with these data over a narrow range of Δm^2. To extend the range of Δm^2 sensitive to matter effects requires a better understanding of muon and electron discrimination.

NEUTRINO POINT SOURCES

In spite of a relatively large angular error ($\approx 30°$) it is possible to use these data to search for point sources of neutrinos. The angular error is energy dependent[5] varying from 51° [half width at half maximum (HWHM)] at about 500 MeV to 16° HWHM above 1500 MeV. For the total data sample we have estimated that the resolution for the single-prong events used in this analysis is about 18° HWHM (Ref. 5).

One can conceive of terrestrial and celestial sources and so the search has been carried out in both coordinate systems. A cone with a 30° half opening angle will contain 6.7% of the (4π) solid angle. If the events are perfectly uniformly distributed one would expect 20.8 events in the solid angle subtended by such a cone. If we do a whole sky search for the direction with the maximum number of events we must be careful not to overestimate the statistical significance[16] of the fluctuation that we find. Such a whole sky survey in 51 200 overlapping bins of right ascension and declination yields a cone in the direction right ascension = 1.2 h, declination = 26° with 38 events.

This fluctuation to 1.8 times the ambient flux is not significant. The Poisson probability of finding 38 events when expecting 20.8 is 2.16×10^{-4}. But since we have explicitly searched for the largest cluster in our data sample we must use another statistical test[16] which explicitly accounts for the effect of the extra degrees of freedom present in a whole-sky search. This test indicates a probability of 31.2%. Since this is the largest cluster we have found we can conclude that none of them are significant. Note that had we looked in an *a priori* direction Poisson statistics could be used to calculate the significance of any excess found.

In Table I we show the results of a source search in a 30° cone about a number of preselected astronomical directions.[17] Our direction of maximum flux is included

TABLE I. Selected source search.

Source	Number of events	Poisson probability of $\geq N$
LMC X4	19	0.683
Centaurus A	16	0.881
Vela X1	17	0.826
Crab (NGC 1952)	18	0.760
Hercules X1	21	0.512
Cygnus X3	22	0.425
M31 (NGC224)	27	0.109
SS433	21	0.512
3C237	20	0.599
Galactic Center	24	0.269
Cassiopeia A	16	0.881
Scorpius X1	31	0.022
α Centauri	20	0.599
Maximum[a]	38	0.000 45

[a]Not an *a priori* direction.

for comparison. There is no significant measured excess neutrino flux from any of the sources tried.

A search in local coordinates could identify the Earth as a source of neutrinos from perhaps capture and annihilation of supersymmetric particles.[18] The maximum of 38 events comes from the direction $(-0.810, 0.550, 0.203)$. (0,0,1) is straight up. The x axis points east. There is no evidence for a source of excess neutrinos within the Earth. [Our result also indicates negligible contamination from the surface of the Earth nearest the detector. This direction would be $(0,0,-1)$.]

GEOMAGNETIC EFFECTS

We have assumed in our analysis until now that there are no directional dependences for the neutrino flux or neutrino-energy spectrum. This is an approximation in which small geomagnetic effects[8] have been neglected. In general, these effects are most significant at low neutrino energies (<300 MeV) and are due to the magnetic deflection of low-energy cosmic-ray primaries. Because the neutrinos from above originate in the vicinity of the detector and because there are local variations of magnetic field at different latitudes one expects to see small effects. For the IMB detector located fairly far north (52° geomagnetic latitude) there is less attenuation of low-energy neutrinos locally than for the Earth at large. The significance for the neutrino oscillation test is that one would expect the upward neutrino flux to be less than the downward flux at low energies. This effect has the same sign as a possible neutrino oscillation. Failure to include it makes our oscillation results more conservative. At present our oscillation results are statistics limited. We will attempt to account for these effects when the enlarged data sample requires it.

In Fig. 7 we plot the zenith angular distribution as a function of $\cos\theta_Z$, the neutrino direction. The neutrino direction is opposite the direction of the source of the neutrino. The distribution is similar to what one would expect at this location[19] with a neutrino threshold of 400–500 MeV.

The neutrino energy distribution averaged over all angles, Fig. 8, is in good agreement with expectations[8] for this location. In Figs. 9(a) and 9(b) we show the *visible* energy distribution for the 55 events in the upward $\frac{1}{5}$ of solid angle [9(a)] and the 65 events in the downward $\frac{1}{5}$ of solid angle [9(b)]. The geomagnetic effect could be seen as a small excess in the low-energy bins of the downward sample. Comparison with isotropically generated Monte Carlo events indicates that this is not an acceptance effect. Since we do have an excess of 5 ± 7 events coming downward at visible energies below 400 MeV, these data could be indicative of geomagnetic effects. At best they can only be used to set limits.

In Ref. 13 we reported an experimental deficiency of events having a value of E/L of 5.8×10^{-3} MeV/m. This can be identified with a deficiency of low-energy neutrino interactions at 90° (near the horizontal). Figure 10 illustrates the visible energy spectrum for the 57 events found in the $\frac{1}{5}$ solid-angle band centered on the horizon. This deficiency is not found in isotropically gen-

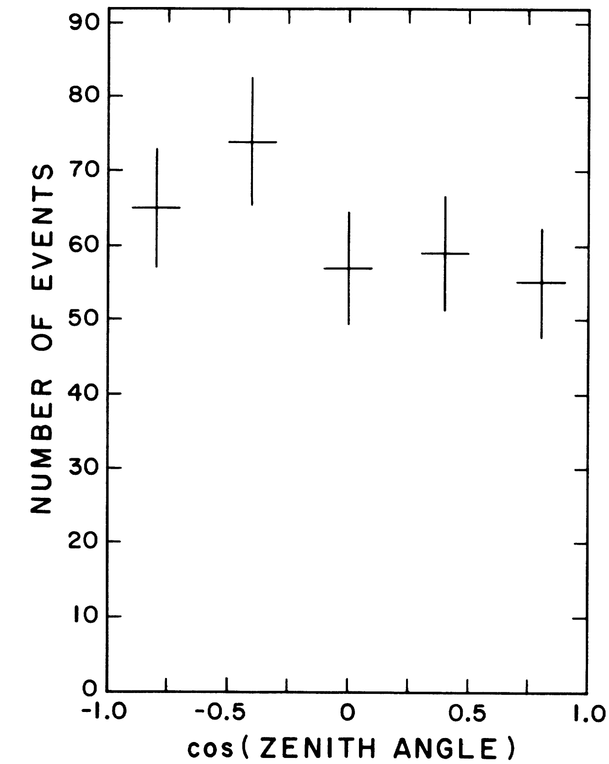

FIG. 7. Zenith-angular distribution for the contained single-prong events. Upward-going tracks are on the right.

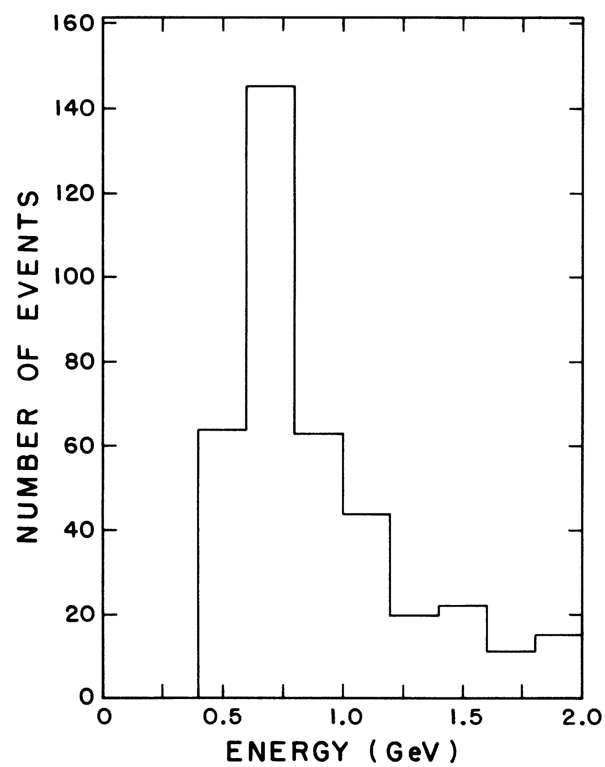

FIG. 8. Neutrino-energy distribution for single-prong events. We have used the approximate expression given in the text to convert visible energy to neutrino energy.

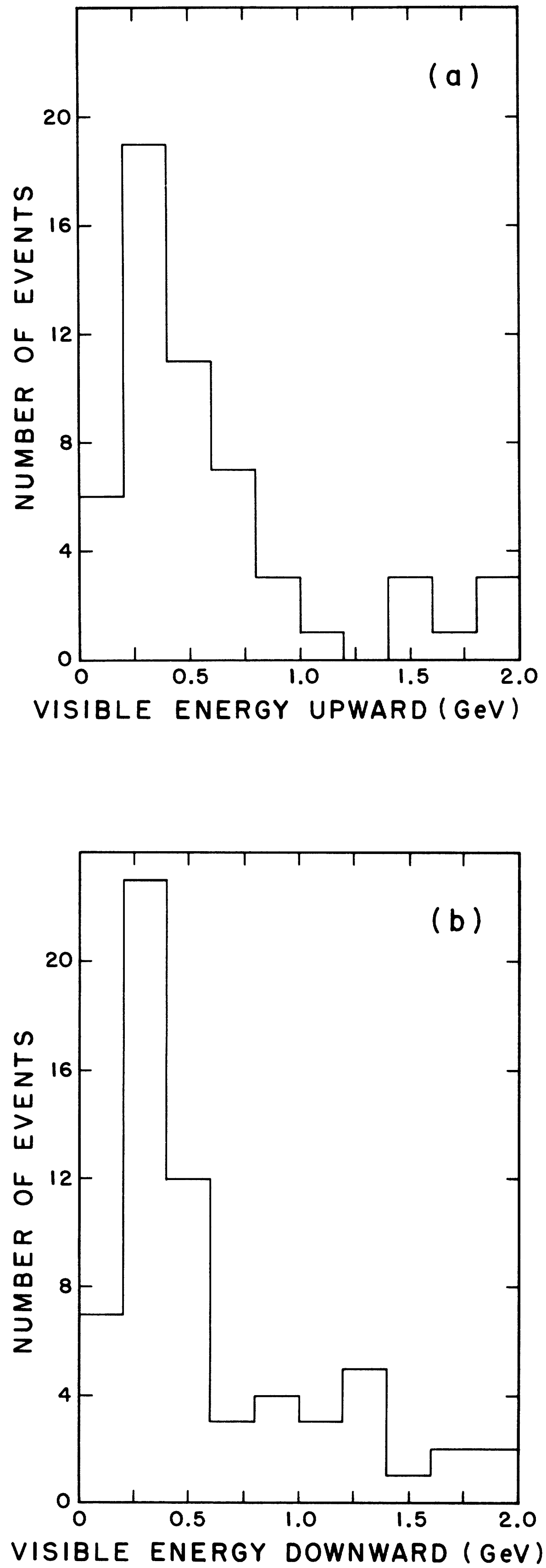

FIG. 9. (a) Visible-energy distribution for the 55 upward events. (b) Visible-energy distribution for the 66 downward events.

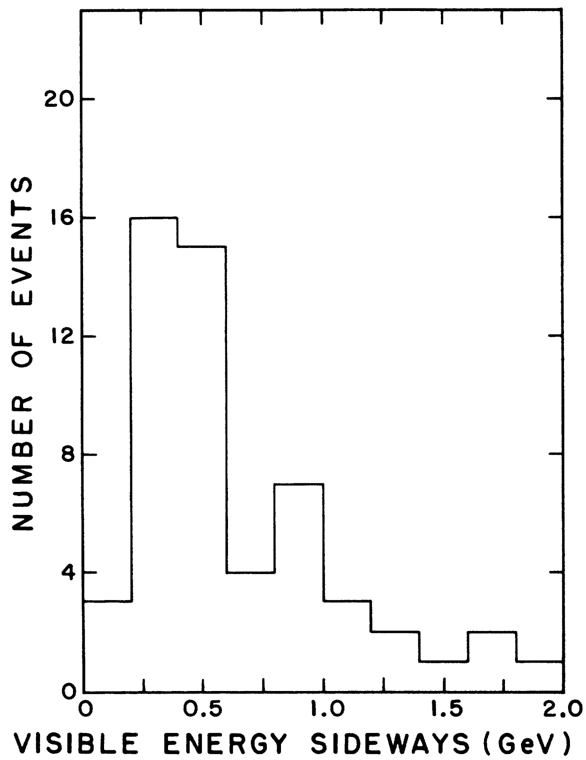

FIG. 10. Visible energy distribution for the 57 events in horizontal $\frac{1}{5}$ solid angle.

erated Monte Carlo data. The 19 events found with visible energies below 400 MeV in this sample can be compared with the 30 events below 400 MeV visible energy present in the downward sample. The difference of 11 ± 7 is not statistically significant.

Some indication of an east-west effect may be seen in the 57-event horizontal sample. Nine events are found in the western quadrant as compared to 17 in the eastern one. More data are needed before this effect can be considered significant. A much smaller effect would be expected for near-normal incidence or upward-going events. For the single-prong sample of all zenith angles, 76 events are found in the western quadrant and 85 in the eastern one.

CONCLUSIONS

Searches for neutrino oscillations, and for point sources of neutrinos on Earth or in celestial coordinates, have failed to yield any significant effect.

Our lower bound on excluded values is $\Delta m^2 \geq 4.2\times 10^{-5}$ eV^2 for oscillations of muon neutrinos into noninteracting neutrinos. This bound has been extended up to $\Delta m^2 \leq 5.4\times 10^{-4}$ eV^2 by using shorter path lengths for the neutrinos. Both of these bounds are quoted for maximum mixing.

We have failed to find any clusters indicative of point sources of neutrinos with a probability of coming from a fluctuation of less than 31%. This search was limited by the angular resolution of the events which is caused by a combination of neutrino kinematics and detector resolution. Potential high-energy sources would possibly give a narrower peak than our 30° search window. Presently there are not enough data at high energies to carry out a meaningful whole sky search.

We have looked for and found some indications of geomagnetic effects on the neutrino flux. These indications are not yet statistically significant. We anticipate a gradual increase in data sample size with time as the detector continues to collect information at the rate of about one event per day.

Our data sample shows good agreement with the event energy distribution expected from atmospheric neutrino interactions.

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