# A STUDY OF ATMOSPHERIC NEUTRINOS WITH THE IMB DETECTOR

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## ABSTRACT

A sample of 401 contained neutrino interactions collected in the 3300 metric ton fiducial mass IMB detector is used to study neutrino oscillations, geomagnetic modulation of the flux and to search for point sources.

1. Introduction. The IMB detector is an 8000 metric ton imaging water Cherenkov detector (1). The device has been used to search for nucleon decay. The active dimensions are 22.5 m × 17 m × 18 m. The detector is shielded at a depth of 1570 m.w.e. and has a fiducial mass of 3300 metric tons. In a 417 day exposure, 401 contained events have been recorded. The majority (>95%) of these events are attributable to neutrino interactions. For the most part, these neutrinos are believed to originate as tertiary products of cosmic ray interactions in the atmosphere. The neutrinos are a mixture of $\nu_e$ and $\nu_\mu$. They may be used to study some fundamental problems in particle physics, cosmic rays and astronomy.

2. Neutrino Oscillations. Neutrinos are incident on the detector from all directions. According to theory, neutrino oscillations should manifest themselves as an Energy ($E$)/Distance ($L$) dependence of the neutrino rate. The detector measures the visible energy $E_{vis}$ deposited by a track. This is the energy of a photon with the equivalent light output. The visible energy may be converted to an energy and momentum if a particle mass is assumed ($\pi$, $\mu$, $e$, $\gamma$). The direction of tracks is also measured. The event direction can be projected back to determine the point the neutrino entered the Earth. So the distance traveled is also measured. The distance varies from a few kilometers for nearly vertical neutrinos to 13,000 kilometers for those going upward. The mean energy is about 950 MeV.

A neutrino oscillation disappearance experiment has been carried out (2) (on a 135 event subset of these data) by comparing the energy spectrum of the downward neutrinos ($\theta_z < 53°$) to that of upward neutrinos ($\theta_z > 127°$). The comparison was done using the Smirnov-Cramer-Von Mises test. This yields an excluded region in $\sin^2 2\eta$ and $\Delta m^2$ seen in Figure 1. We can exclude masses as low as $2.2 \times 10^{-5}$ eV$^2$ at maximum mixing.

This result can be extended. Electron neutrino and muon neutrino interactions may be distinguished by the presence of a muon in the final state. The detector has an efficiency of about 50% to observe the muon decay following the initial interaction. Muons coming from pions produced in electron neutrino interactions can be suppressed by using only single track events in the

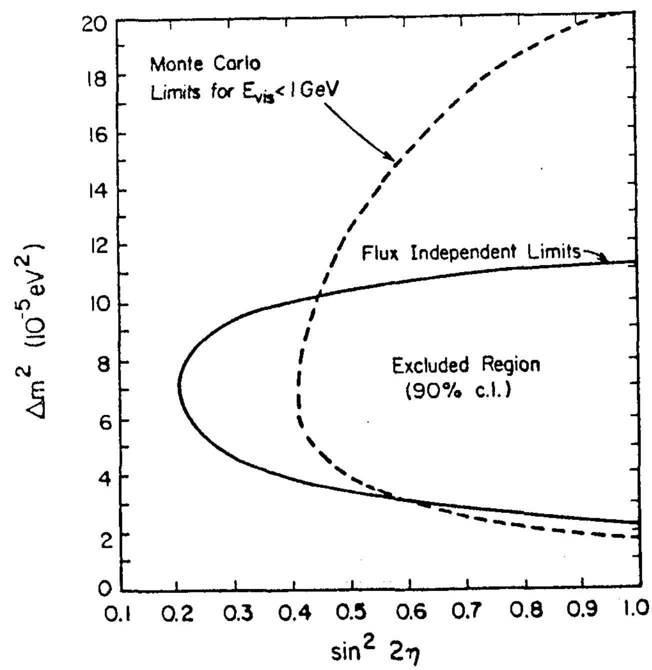


Figure 1. The excluded region for a test of oscillations into sterile neutrinos.The dashed curve is the result of a Monte Carlo test. The solid curve is from a comparison of the shapes of the energy distributions.

analysis (quasi-elastic charged current events). We select events that have a definite muon decay signature. There are 15 in the upward 1/5 solid angle sample and 21 in the downward 1/5 solid angle sample. By comparing the energy spectrum of these two samples we can get limits on the oscillation of muon neutrinos. This gives the excluded region seen in Figure 2. It may be possible to identify and distinguish showering tracks from muons and so a similar analysis can be performed on a purely $\nu_e$ sample.

3. Geomagnetic Effects. In the preceding work we assumed that neutrino spectrum (shape) was independent of distance. The Earth's magnetic field tends to deflect the lower energy primaries incident near the equator. For our detector (52° N geomagnetic latitude) this implies a lower flux of neutrinos coming upward, since the mean magnetic field is greater than the local field that affects the downward going, locally produced neutrinos. Notice this effect is similar to the effect of neutrino oscillations. The lowest energy upward going neutrinos appear to be attenuated. Our previous results could be strengthened and extended if the geomagnetic effects were well understood. For the present, we will just compare our data to predictions (3). In Figure 3, we plot log $E/L$ for our data and compare with expectations. An isotropic distribution would reverse the height of the two peaks. The geomagnetic modulation is a better fit to the data. The neutrino energy spectrum and zenith angular distribution also agree well. The double peaks in Figure 3 reflect the solid angle subtended. Most of the solid angle is either nearby or on the other side of the Earth.

The $\chi^2$ comparison of the two curves gives $\chi^2 = 29$ with 14 degrees of freedom. But almost half of this comes from the bin centered at $\log(E/L) = -2.23$. This corresponds to $E/L = 5.8 \times 10^{-3}$ MeV/meter. Removing this bin yields a $\chi^2$ of 17 for 13 degrees of freedom. Only statistical errors have been included in these calculations.

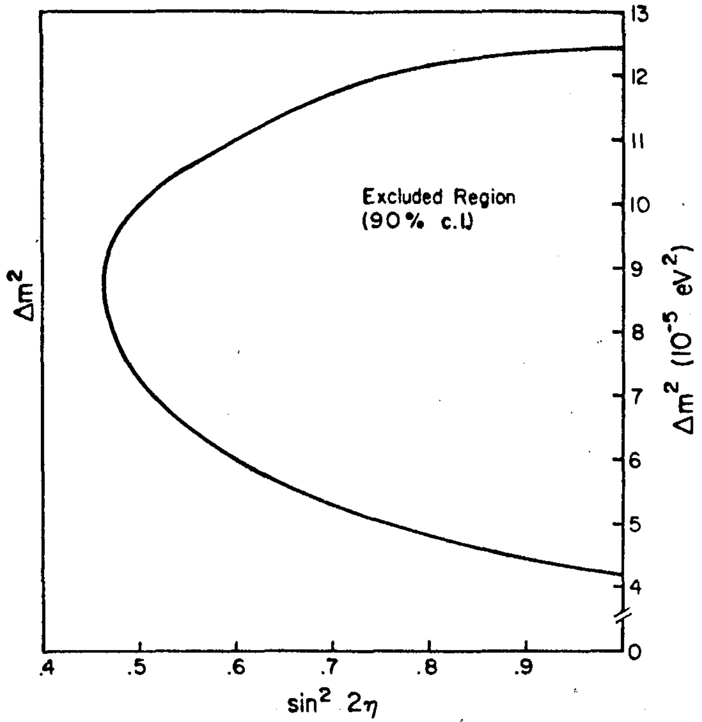


Figure 2. The excluded region for a test of $\nu_\mu$ oscillations. This comes from a comparison of the energy distribution for muon containing single prong events in the upward and downward 1/5 of the solid angle.

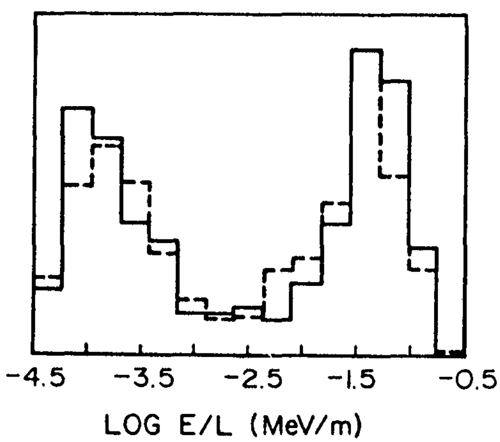


Figure 3. A comparison of the log $(E/L)$ distribution with that predicted by theory (dashed curve). The good agreement supports the theory which includes geomagnetic modulation of the flux.

4. Point Sources. Our data rate corresponds to a neutrino flux of about 4.1 ± .6 ν/(min cm$^2$ str.) with an energy above ~400 MeV. These data may be used to search for point sources of neutrinos. All terrestrial point sources (reactors, accelerators, etc.) are normally too small to be seen. A search may be made for extraterrestrial neutrino sources. The events have been plotted in right

ascension and declination and various cuts have been imposed to enhance any signal. Topological cuts to retain only single prong events have been tried. At the present time, no statistically significant evidence for a point source is known to be present in the data.

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References

1. H. S. Park, G. Blewitt *et al., Phys. Rev. Lett.* **54**, 22 (1985), and references quoted therein.
2. J. M. LoSecco *et al., Phys. Rev. Lett.* **54**, 2299 (1985), May 27, 1985.
3. T. K. Gaisser, T. Stanev, S. A. Bludman and H. Lee, *Phys. Rev. Lett.* **51**, 223 (1983). Our comparison is with a distribution supplied by Gaisser and Stanev in early 1985.