Test of Neutrino Oscillations Using Atmospheric Neutrinos

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We study the distributions of 135 atmospheric neutrino events collected in 420 days of running in a large, deep underground detector. These events come from neutrinos with path lengths ranging from a few kilometers to over 10^4 kilometers. The average neutrino energy is 920 MeV. No evidence for neutrino oscillations is observed. Flux-independent limits for Δm_ν^2 in the range of 2.2×10^{-5} to 11.2×10^{-5} eV^2 are set for maximum mixing.

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We have employed a large imaging, water Cherenkov proton-decay detector[1] to search for oscillations of atmospheric neutrinos. The neutrinos arise from the decay of secondaries (pions and muons) from cosmic-ray interactions in the atmosphere.[2] Muon and kaon decays contribute a substantial ν_e fraction to a predominantly ν_μ flux. The $\nu_\mu/\bar{\nu}_\mu$ ratio is approximately the μ^+/μ^- ratio observed in cosmic rays (1.25). Since primary cosmic rays are incident all over the Earth there is a flux of neutrinos from every direction. The largest distance traversed is about 12 000 km. The mean energy of the observed neutrinos is 920 MeV.

The detector is massive (3300-ton fiducial mass) and well shielded at a depth of 610 m (1600 m water equivalent). Even at this depth the detector receives a flux of downward muons (230 000 per day). The neutrino interaction rate is estimated to be 1 per day. The detector is "shielded" with a 2-m-of-water veto region surrounding the fiducial volume and an additional 50 cm of water outside the sensitive region. Detection efficiency for neutrino interactions is about 90% for wide-angle isotropic type events and about 75% for single-prong topologies typical of quasielastic neutrino interactions.

Of 401 contained events, observed in 420 days of running, 305 had single-prong topologies. Such events have a well-defined direction. An additional fiducial cut of 2 m was made to guard against possible systematic errors. There is no evidence for any error. This reduced the sample to 135 events which are retained in the analysis.

The distance a neutrino has traveled is a function of its zenith angle:

$$L=[r^2-(r-d)^2\sin^2\theta]^{1/2}-(r-d)\cos\theta .$$

r is the Earth's radius, ≈ 6380 km, and d is approximately the scale height of the atmosphere, ≈ 10 km. We will only use this formula in the lower hemisphere where it is

$$L\approx -2r\cos\theta .$$

If neutrino oscillations occur we might expect to see differences between the neutrinos in the upward-going $\frac{1}{5}$ of the solid angle which travel a mean distance of 10^7 m and those in the downward-going $\frac{1}{5}$ of the solid angle that have only traveled $\sim 10^4$ m. If we compare up to down we may not be sensitive to wavelengths comparable to 10^4 m but this region can be tested with other experiments.[3]

The visible-energy distributions of the 25 events in the upward $\frac{1}{5}$ of solid angle and the 25 events in the downward $\frac{1}{5}$ of solid angle are shown in Figs. 1(a) and 1(b). Except for geomagnetic effects these distributions should be the same. If we rebin the data as in Table I we calculate $\chi^2=3.19$ for four degrees of freedom between the two energy distributions. There is no significant evidence for a difference. We employ a binning-free test, the Smirnov–Cramer–Von Mises test,[4] which is more powerful since it uses the known energies of each event. It is also a shape test, not necessarily a normalization test. The test compares the cumulative distribution function (CDF) for up to that for down. The CDF is defined, for a distribution

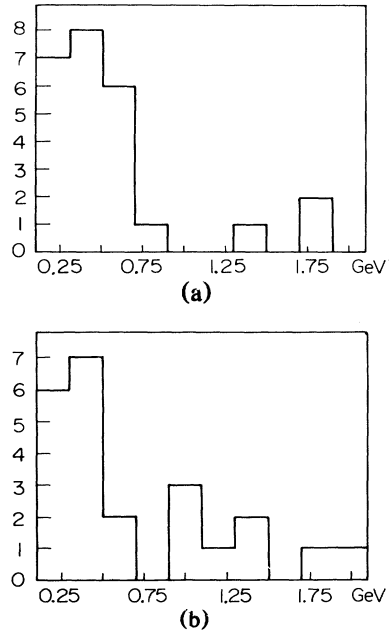

FIG. 1. The visible-energy distributions for the upward-going (a) and downward-going (b) neutrino samples.

of N events, by

$$S_N(E) = \sum_{E_i < E} N^{-1}.$$

It runs from 0 for $E < E_1$ to 1 for $E > E_N$. We use the statistic

$$W^2 = \frac{NM}{N+M} \langle [S_{N_{\rm up}}(E) - S_{N_{\rm down}}(E)]^2 \rangle$$

which has a 90%-confidence-level (C.L.) significance at 0.347. N and M are the number of events in each of the two samples. For our measured visible energy distribution we find $W^2 = 0.257$ and so cannot reject the hypothesis that the distributions are identical.

For the neutrino-oscillation hypothesis the energy distribution should be distorted. For oscillations into sterile neutrinos we have

$$P(\nu \to \nu) = 1 - \sin^2 2\eta \sin^2 \left(1.27 \frac{L}{E_\nu} \Delta m^2 \right).$$

To test oscillations we can use the Smirnov–Cramer–Von Mises test to compare the measured upward CDF to the downward CDF modified by this formula for an assumed $\sin^2 2\eta$ and Δm^2. Two approximations must be made. The detector measures visible energy not the true neutrino energy. The visible energy is the energy of an electromagnetic shower with the same light output. A fit to Monte Carlo neutrino events selected according to the same criteria as used for data yields

TABLE I. Comparison of upward-going and downward-going neutrino events in solid angle bins of $4\pi/5$. $\chi^2 = 3.19$ with four degrees of freedom.

Visible energy (MeV)	Number upward	Number downward
$E_{\rm vis} < 270$	7	5
$270 < E_{\rm vis} < 391$	4	5
$391 < E_{\rm vis} < 550$	5	5
$550 < E_{\rm vis} < 1310$	6	5
$1310 < E_{\rm vis}$	3	5
Total	25	25

the relationship

$$E_\nu \cong 0.758 E_{\rm vis} + 410.$$

We will compare the CDF's of $E_{\rm vis}$ but will convert $E_{\rm vis}$ to E_ν to calculate oscillation effects. The second approximation involves the distance L, a function of the zenith angle. The detector does not measure the true neutrino direction but instead a reconstructed direction based on the visible tracks above Cherenkov threshold. The average difference between these is 40° but the most likely difference is 20°. Only the Z projection of this angle contributes to a length error. Monte Carlo studies indicate the error in L is about 16% full width at half maximum. Since in the upward $\frac{1}{5}$ of solid angle the distance varies from $2r$ to $1.2r$ we will use a constant of $L = 1.6r = 10.2 \times 10^6$ m which is at most a 20% error. Calculating L for the data sample itself gives a mean value of 10.5×10^6 m, uniformly distributed in the region.

The region of $\sin^2 2\eta$ and Δm^2 which produces a significant deviation between the observed upward visible-energy distribution and that predicted from the modification of the observed downward distribution is shown as the solid curve in Fig. 2. For maximal mixing we exclude the region

$$2.2 \times 10^{-5}\ {\rm eV}^2 < \Delta m^2 < 11.2 \times 10^{-5}\ {\rm eV}^2.$$

Because of limited statistics our limit exists for $\sin^2 2\eta > 0.22$.

The major significance of the measurement error in E_ν and L is to smear our distribution of $E_{\rm vis}$ in both the upward and the downward samples. Such a smearing will mask differences between the two CDF's and so make it more difficult to distinguish an oscillation effect. This then restricts the sensitivity to the region shown in Fig. 2.

Our result can be checked with an atmospheric neutrino simulation. For the observed data we find, for events with $E_{\rm vis} < 1$ GeV, the ratio of events (in $\frac{1}{5}$-solid-angle bins) upward to those downward is

$$\tfrac{22}{16} = 1.375 \pm 0.45 > 0.80 \text{ at 90\% C.L.}$$

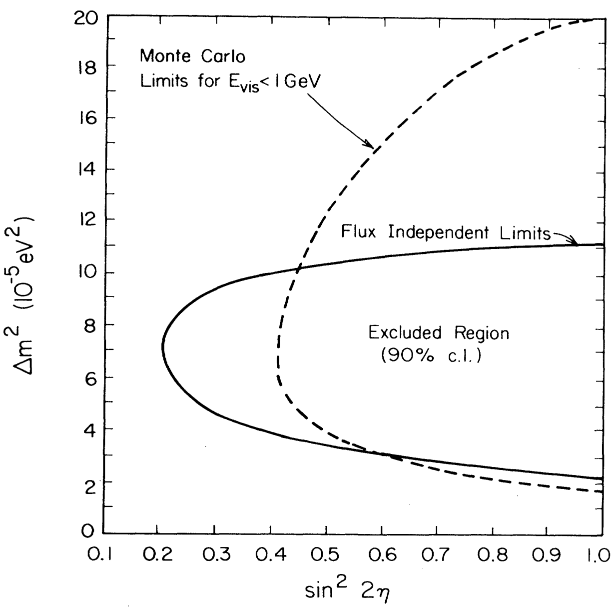

FIG. 2. The region of $\sin^2 2\eta$ and Δm_ν^2 excluded by our analysis. The solid line indicates the region excluded by the Smirnov–Cramer–Von Mises test. The dashed region is excluded by an explicit Monte Carlo calculation of the up-to-down event ratio.

In the simulation, oscillation effects were considered on events of known neutrino energy and direction. The events were selected from bubble-chamber data according to the expected atmospheric spectrum but were uniformly distributed in direction. They were reconstructed and analyzed in the same manner as the data. The contour in $\sin^2 2\eta$ and Δm^2, in which less than 80% of the simulated events with $E_{vis} < 1$ GeV would be found, is shown as the dashed region in Fig. 2. It includes, for the most part, the region of our flux-independent analysis.

Since the initial atmospheric neutrino flux is a mixture of ν_μ, $\bar{\nu}_\mu$, ν_e, and $\bar{\nu}_e$ it is somewhat difficult to interpret our results. For $\nu_\mu \leftrightarrow \nu_e$ oscillations one might expect a difference in the ν_μ and ν_e rates in the upward and downward samples. Particle identification is limited. Muons (μ^-) produce a decay signal only 55% of the time. Still they give a positive identification on a small sample. We find that (40 ± 15)% of both the upward and the downward sample have a muon decay signature.

Our results are rather limited at present. In principle the experiment has a range of 10^{-1} to 2×10^{-5} MeV/m in E/L and so can span a similar range in Δm^2 (in electronvolts squared). But to do this experiment one must have a believable flux calculation valid for all directions and energies. Our present result is flux independent and ignores any geomagnetic contribution to the spectrum shape or normalization. As more data become available the test can be extended over a larger range.

Neutrino oscillations, in fact, involve at least three mixing angles and three masses. In the present test we have restricted our search to the first oscillation wavelength. To extend it to multiple oscillations one must give careful consideration to the effect of all components of the mixing matrix.

We have not attempted to consider the effects of possible matter oscillations.[5]

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[1]The detector is described in the following references: R. Bionta *et al.*, Phys. Rev. Lett. **51**, 27 (1983); S. Errede *et al.*, Phys. Rev. Lett. **51**, 245 (1983); T. W. Jones *et al.*, Phys. Rev. Lett. **52**, 720 (1984); B. Cortez *et al.*, Phys. Rev. Lett. **52**, 1092 (1984); H. S. Park *et al.*, Phys. Rev. Lett. **54**, 22 (1985).

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[3]In particular, the interaction of atmospheric ν_μ in rock as observed in our detector is sensitive to this region. See J. Learned *et al.*, in *Proceedings of the Eleventh International Neutrino Conference, Dortmund, 1984,* edited by K. Kleinknecht and E.A. Paschos (World Scientific, Singapore, 1985); and R. Bionta *et al.*, in *Proceedings of the Nineteenth Rencontre de Moriond, La Plagne, France, 1984,* edited by J. Tran Thanh Van (Editions Frontieres, Gif-sur-Yvette, France, 1984).

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