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Atmospheric Neutrino Oscillations with DUMAND

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ABSTRACT

The DUMAND II Octagon array will be able to search for neutrino oscillations in the parameter region around $\Delta m^2 \approx 10^{-2}$ eV^2 and $\sin^2 2\theta \approx 0.5$ that is currently suggested by the atmospheric muon neutrino deficit problem. Because DUMAND is so deep, it can look above the horizon for neutrinos and use the events observed to provide a normalization that does not depend on a knowledge of the absolute flux of atmospheric neutrinos.

1. Introduction

The deficit in cosmic ray ν_μ interactions compared to ν_e interactions observed in Kamiokande and IMB has a possible interpretation in terms of neutrino oscillations with $\Delta m^2 \approx 10^{-2}$ eV^2 and large mixing, $\sin^2 2\theta \approx 0.5$ that is not ruled out by other experiments, at least for $\nu_\mu \to \nu_\tau$.[2] In this paper we consider the capabilities that the DUMAND II Octagon array[3] will have in searching for neutrino oscillations in the allowed parameter region, using the already-existing cosmic neutrino beam.

In the case where the mixing of only two flavors needs to be considered, the oscillation probability is given by

$$P = \sin^2 2\theta \, \sin^2 (1.27\, \Delta m^2\, L/E) \tag{1}$$

where Δm^2 is in eV^2, E is the neutrino energy in GeV, and L is the path length in km. Following Bernstein and Parke[4], if P_{min} is the minimum detectable oscillation probability for a given experiment, then that experiment can measure the oscillation parameters with limits $\Delta m^2 \geq \sqrt{P_{min}} E/1.27L$ and $\sin^2 2\theta \geq 2P_{min}$.

Cosmic ray neutrinos provide greater reach than accelerators in the search for neutrino oscillations, as underground experiments dedicated to other purposes have already demonstrated. The "beam" of neutrinos produced by cosmic rays hitting the atmosphere offers both the possibility of lower E, down to a few GeV, and greater L, up to 12,000 km. For example, an experiment with $P_{min} = 0.1$ at 5 GeV could measure $\Delta m^2 \geq 10^{-4}$ eV^2. To achieve the same sensitivity, a "long baseline" accelerator experiment with L = 1200 km would need to have $P_{min} = 10^{-3}$.

The current interpretation of observations of a ν_μ deficit rests on calculations which have uncertainties in their estimates of the absolute flux that are almost as large as the effect, although the ν_μ / ν_e ratio is more reliable. An alternative method that does not depend on absolute fluxes looks at the variation of the cosmic ray neutrino signal with zenith angle.[5]

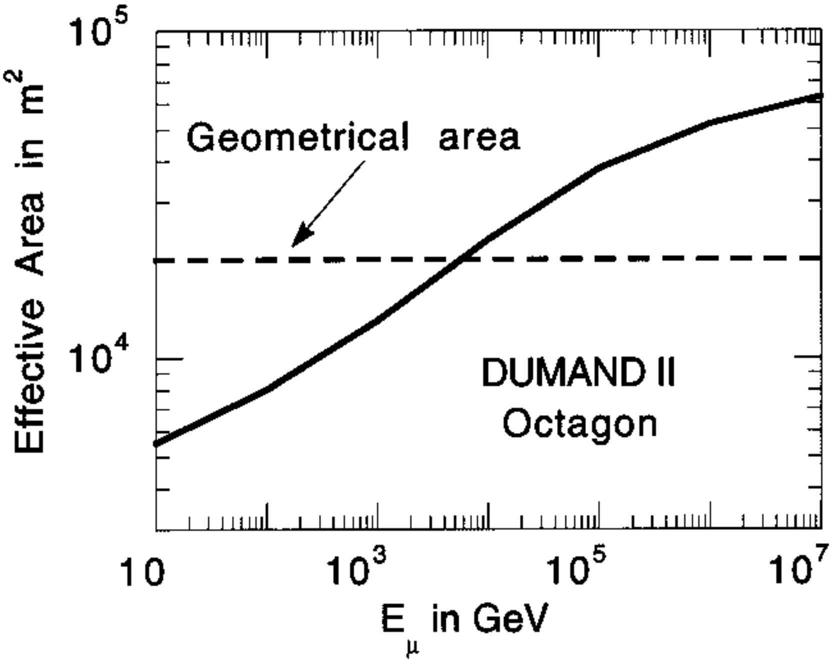

Figure 1 . Effective area of the Octagon for fully-reconstructed through-going muons as a function of muon energy. The geometric area shown is averaged over directions.

Detectors such as DUMAND and NESTOR which are deep enough to look above the horizon for neutrinos can search for a sharp variation in the event rate as the event direction sweeps through the horizon and the neutrino path length in the earth goes through a huge variation. Shallow detectors like

Baikal and AMANDA are swamped by cosmic ray muon background at the and above the horizon and so are unable to exploit this sensitive technique.

2. Oscillation Capabilities of the DUMAND II Octagon

The DUMAND II Octagon array was primarily designed for detecting muons and cascades from neutrino interactions above 100 GeV. However, as seen in Fig. 1, the effective detection area is still substantial at lower energies. In Fig. 2 the atmospheric neutrino flux spectrum is shown, along with the spectrum of fully reconstructed charged current ν_μ events determined by Monte Carlo. While the flux peaks at about 3 GeV, the detector will only be sensitive to neutrinos above 10–20 GeV, with the bulk of events above ~50 GeV; the average energy is close to 1 TeV.

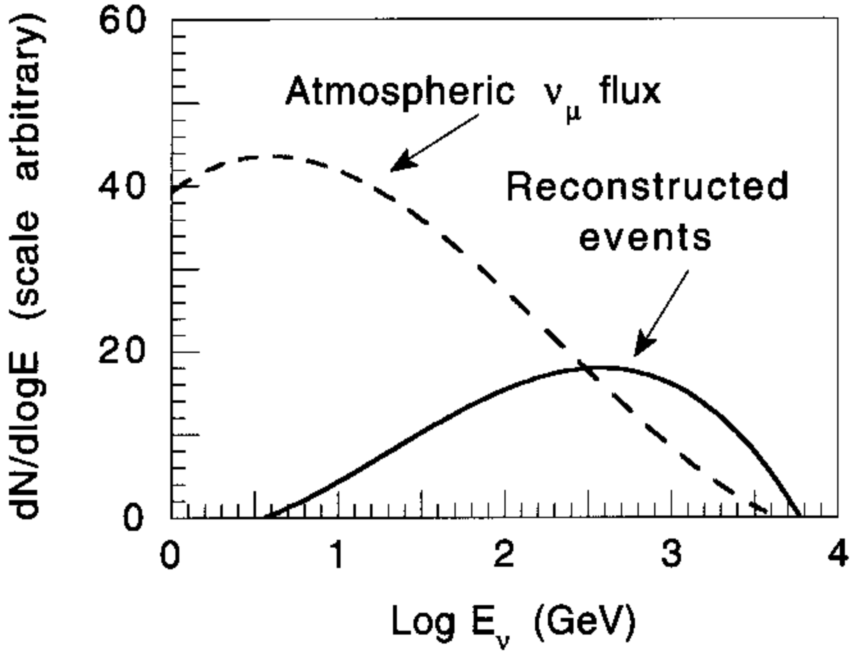

Figure 2 . The spectrum of fully-reconstructed atmospheric neutrino events compared to the spectrum of the incident flux. The scales are arbirary.

To illustrate how the zenith angle distribution of muons from neutrino events can signal neutrino oscillations, we smooth out the zenith angle distribution that is normally expected without oscillations. At these energies, this is given approximately by

$$dN/d\cos Z^* = \sec Z^* \tag{2}$$

where Z^* is the zenith angle at the top of the atmosphere where the cosmic ray interaction takes place and is related to the zenith angle Z at the detector by

$$\sin Z^* = (R_e - d) \sin Z / (R_e + h) \tag{3}$$

where d is the mean depth of the detector below sea level (4.7 km for DUMAND) and h is the height of the top of the atmosphere (≈20 km).

We define the variable η as follows:

$$|\eta| = 1 - \ln \cos Z^* / \ln \cos Z^*_o \tag{4}$$

where Z^*_o is the value of Z^* at $Z = 90^\circ$, that is, for events arriving horizontally. The sign of η is chosen to equal the sign of cosZ so that events from below the horizon have negative η; e.g., $\eta = -1$ corresponds to $\cos Z = -1$ and $\eta = 0$ is at the horizon. The maximum value of η for DUMAND is about 0.4, corresponding to $Z = 70^\circ$ or 20° above the horizon. Note that the region $0 < \eta < 0.4$ provides 40% of the events from the upper hemisphere.

With this definition, $dN/d\eta$ is isotropic in the absence of oscillations. In Fig. 3 the effect of oscillations on the η distribution is shown for the case of maximal mixing: $\sin^2 2\theta = 1$. (For lower mixing, reduce the difference between no oscillations and oscillations by $\sin^2 2\theta$). As we see in Fig. 3, dramatic effects can be found in the η distribution if oscillations are present. If wiggles of the type shown for $\Delta m^2 = 0.1$ were to be seen in any experiment, little doubt would remain that oscillations truly exist. Unfortunately, the DUMAND energy threshold is a bit too high to see such a convincing effect for the currently interesting parameters $\Delta m^2 \approx 10^{-2}$ eV^2 and $\sin^2 2\theta \approx 0.4$. However, these may still be detectable.

A total of 1835 atmospheric neutrinos events are expected in the DUMAND II Octagon in one year, with the stringent cuts that have been applied in this study to assure that the background of fake events induced by downward cosmic ray muons and K^{40} in the ocean is negligible. Thus we expect about 130 events per year per 0.1 bin in η. For $\Delta m^2 \approx 10^{-2}$ eV^2 and $\sin^2 2\theta \approx 0.5$, a deficit of 128 events occurs in the upward hemisphere.

We have estimated the sensitivity of DUMAND to $\nu_\mu \rightarrow \nu_\tau$ oscillations as follows: Let U be the total number of upward events for oscillations with a given Δm^2 and maximal mixing and let D be the total number of downward events observed in one year. Since, as noted above, D is 40% of the total downward events because of the 20° limit to the search above the horizon, the total number of downward events is $D' = D/0.4$. The oscillation probability for maximal mixing, averaged over path length and energy, then

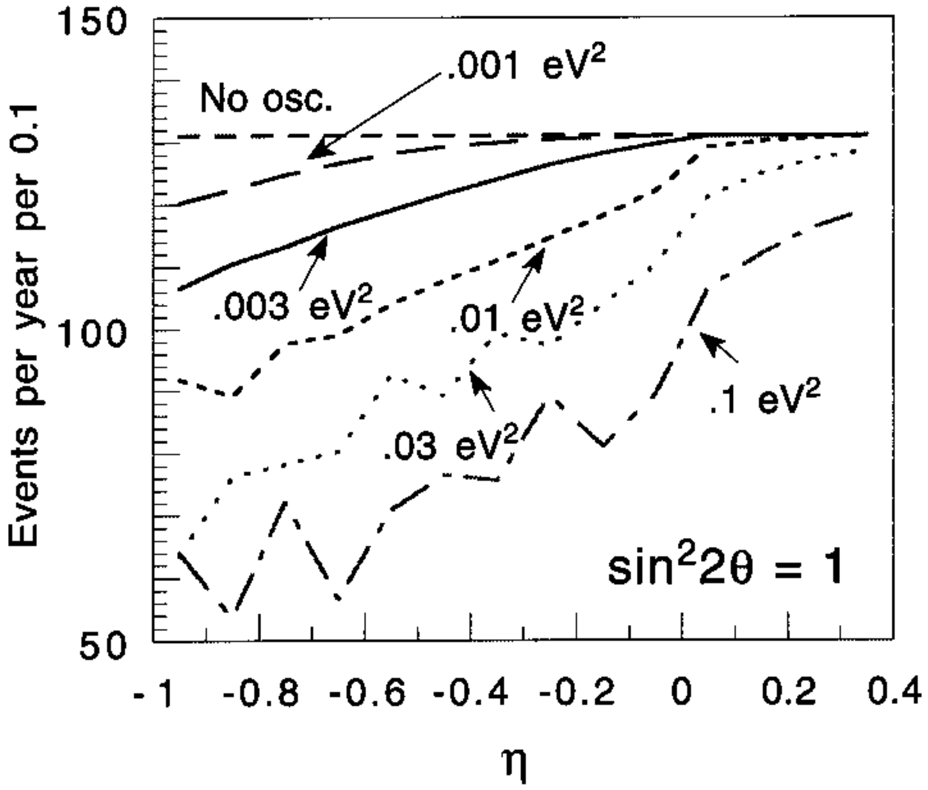

Figure 3 . Distribution of events in one year as a function of the variable η that flattens out a sec Z^* distribution. The effects of oscillations are shown for maximal mixing.

is

$$P_{max} = 1 - U / D' \tag{5}$$

The statistical error in P_{max} is

$$\sigma = (1 - P_{max}) [\, 1 / U + 1 / D \,]^{1/2} \tag{6}$$

and the 95% C.L. minimum mixing parameter then is

$$\sin^2 2\theta_{min} = 2\sigma \, / \, P_{max} \, / \, 0.83 \tag{7}$$

where the 0.83 factor accounts for the 17% branching fraction for $\tau \rightarrow \mu$.

The resulting accessible parameter space is shown in Fig. 4, superimposed on the allowed oscillation parameter region from the Kamiokande contained events that show the ν_μ deficiency and the region excluded by IMB through-going muons. Although not shown, the remaining allowed region is not excluded by other experiments and encompassed by the allowed region for IMB contained events.

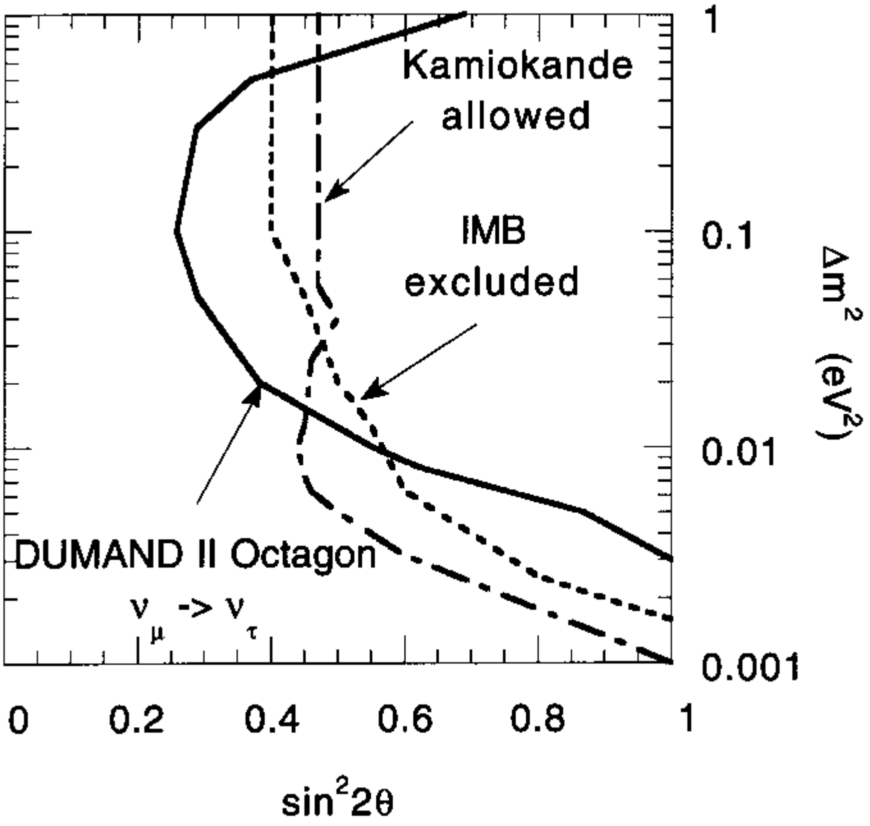

Figure 4 . The range of oscillation parameters accessible to DUMAND II. Shown are the regions allowed by Kamiokande and excluded by IMB.

As seen, the DUMAND II Octagon is sensitive to the region around $\Delta m^2 \approx 10^{-2}$ eV^2 and $\sin^2 2\theta \approx 0.5$, although unfortunately does not extend to as low value of Δm^2 as still remains viable. Note that a deep underwater detector sensitive to lower energy neutrinos than DUMAND could readily cover that region. NESTOR may be such an experiment.

3. Matter Effects

As was pointed out by Pantaleone in the context of long baseline experiments, matter effects can greatly increase the sensitivity of DUMAND to lower mixing angles for $\nu_\mu \rightarrow \nu_e$.[6] However, the interpretation of the atmospheric data seems to rule out this channel and a detailed analysis of matter effect for atmospheric neutrino oscillations in DUMAND has not yet been performed.

4. Conclusions

Two underground experiments have reported a deficit in cosmic ray ν_μ's relative to ν_e's, which could be interpreted as neutrino oscillations. This interpretation rests on still-uncertain estimates of absolute neutrino fluxes produced by cosmic rays, especially at lower energies. Deep underwater detectors such as DUMAND and NESTOR offer an alternative way to search for oscillations by comparing the zenith angle distribution of events above and below the horizon. These correspond to path length variations of several orders of magnitude. The range of oscillation parameters currently suggested by the data is such that, at the energies for which the DUMAND II Octagon will be sensitive, a measurable deficiency of events from the upward hemisphere compared with those from the region up to 20° above the horizon where cosmic ray muons are negligible.

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