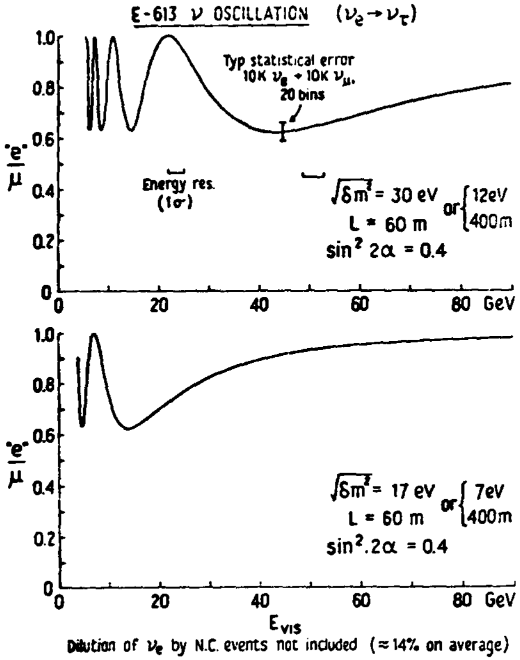

Fig. 4. Expected behavior of e/μ ratio with detected energy in the calorimeter.

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NEUTRINO OSCILLATIONS IN DUMAND

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ABSTRACT

A Monte Carlo simulation of a one-year experiment with a 0.6 km^3 DUMAND Array yields 18,656 expected events with one muon from ν_μ charged-current interactions. It is shown that neutrino oscillations resulting from eigenmass-squared differences in the range .1 to 1000 eV^2 would be detectable as a modulation of the one-muon event rate with zenith angle. Using several proposed models, it is shown that the statistics and measurement precision are adequate to aid in the determination of mass differences and mixing angles and perhaps provide unique information on matter oscillations.

INTRODUCTION

The DUMAND (Deep Underwater Muon and Neutrino Detection) project is a proposal to place a large array of light sensors at a depth of 4-5 km in the ocean off the Hawaiian islands. The detector would be capable of observing the Cerenkov light from high energy muons and hadronic cascades produced by neutrino interactions in the water. The direction of the muon, its energy and the energy of the cascade would be measured. Thus it will be possible to study the properties of neutrino interactions above 500 GeV, using neutrinos produced by cosmic rays hitting the atmosphere, and search for extraterrestrial sources of high energy neutrinos.

Because of the large range in path length for neutrinos passing through the earth, experiments deep underground or underwater offer unique possibilities in the study of neutrino oscillations. This report considers those possibilities for DUMAND. By means of a Monte Carlo simulation, it is shown that the reaction

$$\nu_\mu N \rightarrow \mu X$$

will be modulated by neutrino oscillations of the type which have been recently considered[1,2]. This modulation would be detectable with sufficient statistics and precision to provide important information on the mass difference and mixing matrix elements involved.

In Fig. 1 we define the zenith angles, θ at the detector and θ* at the production point in the atmosphere, and show how the path length L is related to θ. Other Monte Carlos[3] have shown that DUMAND is capable of measuring the muon direction and thus θ, to an accuracy of 10 mr for muons above 1 TeV, so L would be well-determined. In particular, we note the large dynamic range in L, from 20 to 12,000 km, which makes this experiment, and the others proposed for deep mines, a powerful probe of neutrino oscillations.

If we consider energies above 1 TeV or so, the range in L/E for DUMAND is $\sim 10^{-3}$ to 10 m/MeV and thus the detectable range of neutrino eigenmass-squared differences is 0.1 to 10^3 eV^2. While this range is not unique and will be explored by a number of upcoming experiments at reactors and accelerators, the energy is considerably higher than what can be studied in the much less massive deep mine experiments and so effects, such as matter oscillations[4], which may depend on L and E separately, might be uniquely studied.

SIMULATION OF EXPERIMENT

For this study one year's supply of events in a 0.6 km^3 array (e.g., DUMAND G2[5]) were generated. The assumptions were:

1. The atmospheric muon neutrino and anti-neutrino flux is given by[6]

$$\Phi(>E_\nu) = 125 E_\nu^{-3.8} \sec\theta^* km^{-2} s^{-1} sr^{-1}$$

2. $\nu_\mu = 2\bar{\nu}_\mu$[7].

3. The cross section is given by the standard theory, with $M_W = 80$ GeV and QCD effects included.

Measurement errors are simulated by a Gaussian wiggling of the true values with standard deviations of 10 mr for the muon angles θ_μ (which we take to be the zenith θ), and 40% in the muon and hadron energy. These are based on results of array simulations [3].

Applying a cut to the simulated measured neutrino energy E_ν of 1 TeV, we get 15,212 ν_μ and 3,444 $\bar{\nu}_\mu$ charged-current (one-muon) events, or a total of 18,656 for a one-year simulated run.

We then proceed to study these events as if they were real data. All the results presented thus will have statistical and systematic errors which hopefully realistically represent those for actual experiment.

EFFECT OF OSCILLATIONS

A wide range of oscillation possibilities exists, especially in the framework of 3 neutrinos. In order to be able to get some indication of the sensitivity of DUMAND to oscillations specific models which take into account the range of available data from all relevant experiments have been used to calculate the probability $P(\nu_\mu \rightarrow \nu_\mu)$[1,2]. These are listed in Table I, along with the mass-squared differences assumed. The matrix elements are not given and the reader is referred to the references for these. However, it is to be remarked that all except Barger et al. Model B suppress ν_μ oscillations for the second mass-squared difference listed in the table.

Table I. Neutrino oscillation models and the mass-squared differences assumed.

Model		δm^2 (eV^2)	
De Rujula et al.[1]		1	100
Barger et Al.[2]	A	.05	1
	B	.05	.25
	C	1	50

In this analysis the effects of matter oscillations have been neglected, although these are expected to be important for large L and may, in fact, prove to be very interesting in DUMAND. Also neglected is the possible oscillation of ν_e in the "beam" into ν_μ. Since $\nu_e << \nu_\mu$ in the TeV range, because of the large time dilation of the muon lifetime, this is a reasonable assumption and another advantage of DUMAND over lower energy experiments.

RESULTS

In Fig. 2 we present the simulated path length distribution showing what is expected for no oscillations compared with the various models. The strange shape of the distribution is a result of the rapid variation of L as θ passes through 90° (see Fig. 1).

We see that oscillation effects are evident in the region of L > 1000 km, and all models studied are distinguishable. The De Rujula model gives the most dramatic effect, resulting from the large $\delta m^2 = 1$ eV^2 oscillation. This same oscillation is suppressed in Barger A, but the .05 eV^2 oscillation is just beginning to be evident in the simulated data. The other models, Barger B and C, also show detectable, and distinguishably different, effects.

In Fig. 3 we see the results for the distribution of L/E. Here again the oscillation is evident except for Barger A which shows no effect. It is to be remarked that L is very well determined since it depends only on the well-measured θ, while L/E depends on E which is measured to only 40% precision. Nevertheless effects are still seen in L/E.

The distributions of L and L/E have very pronounced variations which result purely from geometry and the $\sec\theta^*$ distribution of the "beam". When looking for an effect, it is nice to have a variable which is flat in the absence of the effect. Such a variable is defined as

$$\zeta = \ln\cos\theta^* / \ln\cos\theta^*_{max}$$

where θ^* is the zenith angle at the production point in the atmosphere (Fig. 1) and $\theta^*_{max} = 87°$ corresponds to $\theta = 90°$.

A secθ^* distribution in the neutrino flux will result in a flat distribution in ζ. In Fig.4 the simulated results are shown for the distribution of ζ with conclusions similar to those for L and L/E. The models except Barger A give distinguishable differences with very nice oscillations evident. In particular, note the 3 cycles of oscillation detected for De Rujula's model, and the one full oscillation for Barger B.

CONCLUSIONS

If neutrino eigenmass-squared differences on the range $.1 < m^2 < 1000$ eV^2 exist, they could be detectable in DUMAND unless they happen to be suppressed by small mixing matrix elements. More than this, the statistics and measurement precision would be adequate to help pin down the parameters of the oscillation. While the region of L/E explored is not unique but will be covered by experiments involving synthetic neutrinos, it is the only experiment proposed which will explore this entire range, 10^{-3} to 10 m/MeV, in one experiment. Finally, the energy is much higher than what will be studied in deep mines so that effects which depend on L or E separately, such as matter oscillations, might be explored in a unique fashion.

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FIGURE CAPTIONS

1. Neutrino path length through the earth as a function of zenith angle.
2. Path length distribution for a one year simulated experiment. Shown are the results for no oscillations and the four oscillation models discussed in the text: D = DeRujula, et al.[1], A,B,C = Barger et al.[2].
3. Distribution of L/E for a one year simulated experiment. Shown are the results for no oscillations and the four oscillation models discussed in the text: D = DeRujula, et al.[1], A,B,C = Barger et al.[2].
4. Distribution of ζ for a one year simulated experiment. Shown are the results for no oscillations and the four oscillation models discussed in the text: D = DeRujula, et al.[1], A,B,C = Barger et al.[2].

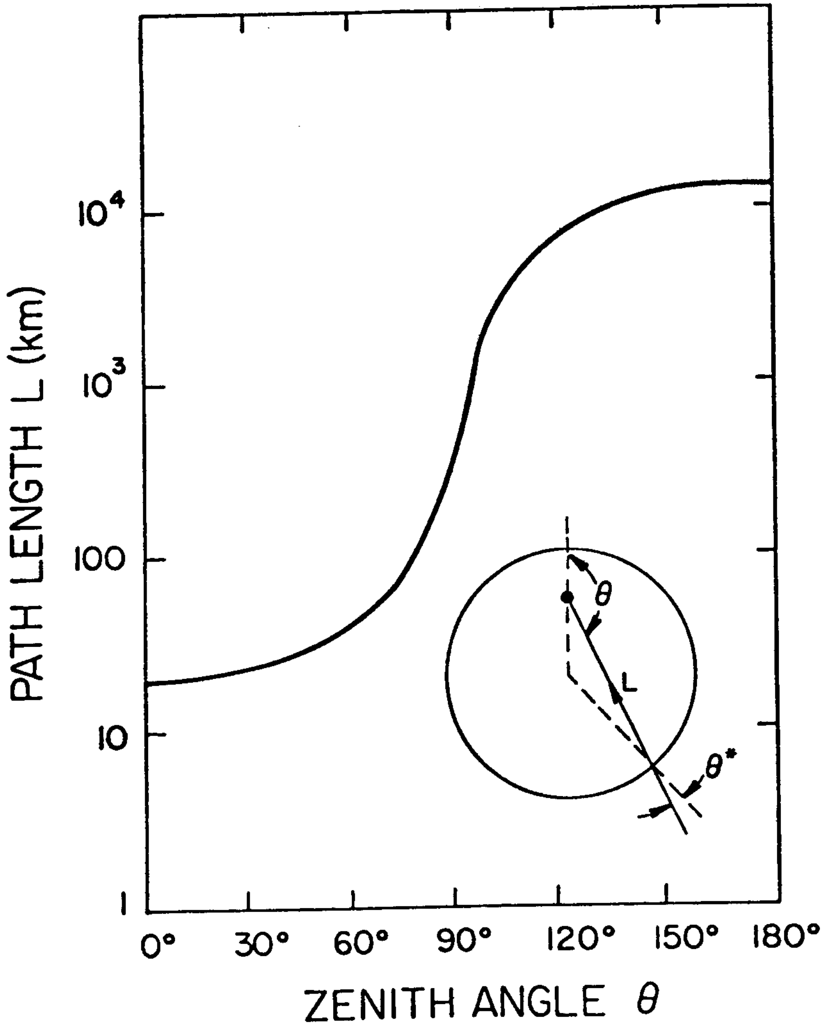
PATH LENGTH L (km)
10^4
10^3
100
10
1
0°
30°
60°
90°
120°
150°
180°
ZENITH ANGLE θ
θ
L
θ*

Fig. 1

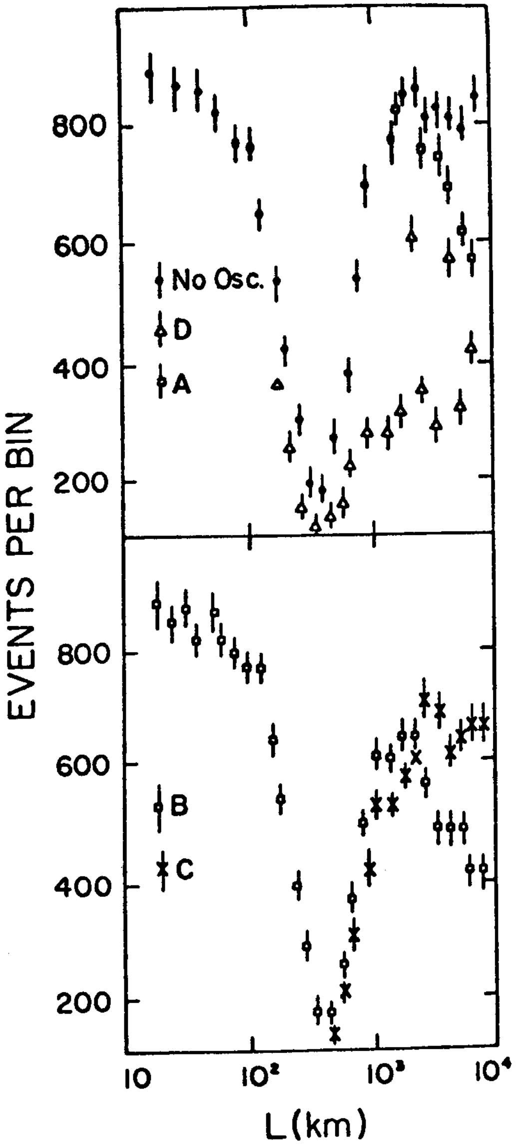
EVENTS PER BIN
800
600
400
200
No Osc.
D
A
B
C
10
10^2
10^3
10^4
L (km)

Fig. 2

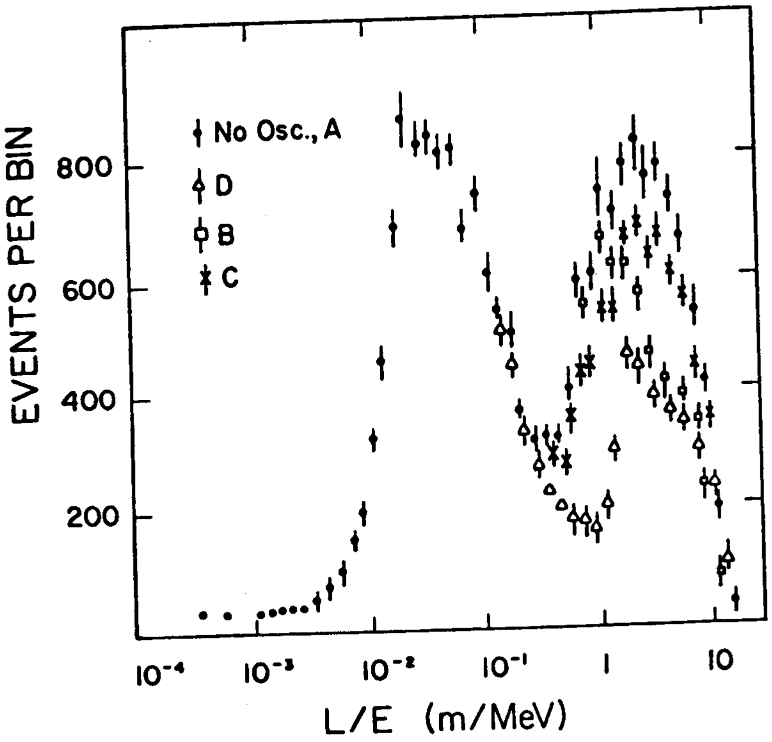
No Osc., A
D
B
C
EVENTS PER BIN
800
600
400
200
10⁻⁴
10⁻³
10⁻²
10⁻¹
1
10
L/E (m/MeV)

Fig. 3

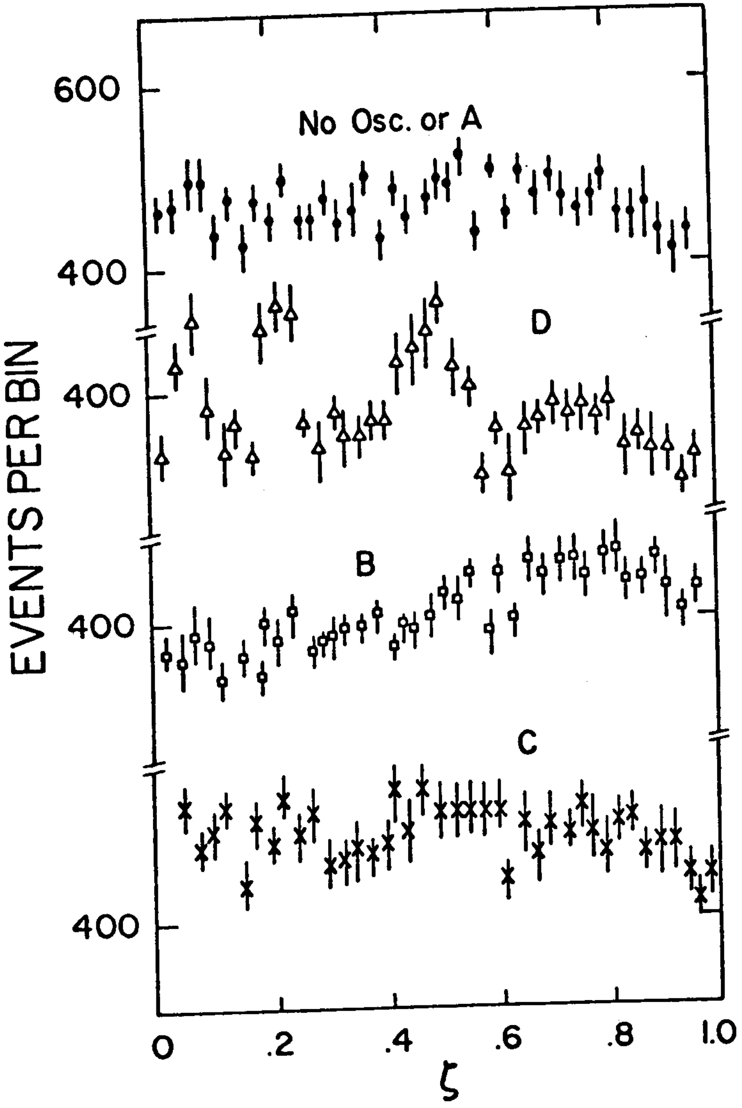
600
400
No Osc. or A
400
D
400
B
C
400
EVENTS PER BIN
0
.2
.4
.6
.8
1.0
ζ

Fig. 4