DUMAND-6-94

Atmospheric Neutrino Oscillations Through the Horizon

VICTOR J. STENGER
Department of Physics and Astronomy, University of Hawaii
Honolulu, Hawaii 96822, USA

ABSTRACT

Underground experiments indicate an atmospheric muon neutrino deficit that could be evidence for neutrino oscillations with $\Delta m^2 \approx 10^{-2}$ eV^2 and $\sin^2 2\theta \approx 1$. If these parameters are correct, the zenith angular distribution should show a dip just above the horizon in experiments sensitive to neutrino energies of 1 GeV and higher. Deep underwater experiments that are sensitive to energies above 10-100 GeV will see the main effect below the horizon and by normalizing to their data above the horizon provide an important independent check.

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, $\sin^2 2\theta \approx 1$.[1] Recent results from a Kamiokande analysis of higher energy events in their sample strongly support this interpretation, showing for the first time a zenith angle effect.[2]

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

$$P = \sin^2 2\theta \, \sin^2 (2\pi \, L/\lambda \,) \qquad (1)$$

where θ is the mixing angle, L is the path length in km, and λ is the oscillation length. The latter is given by $\lambda = 5\ E/\Delta m^2$ km where Δm^2 is the neutrino mass square difference in eV^2 and E is the neutrino energy in GeV.

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.

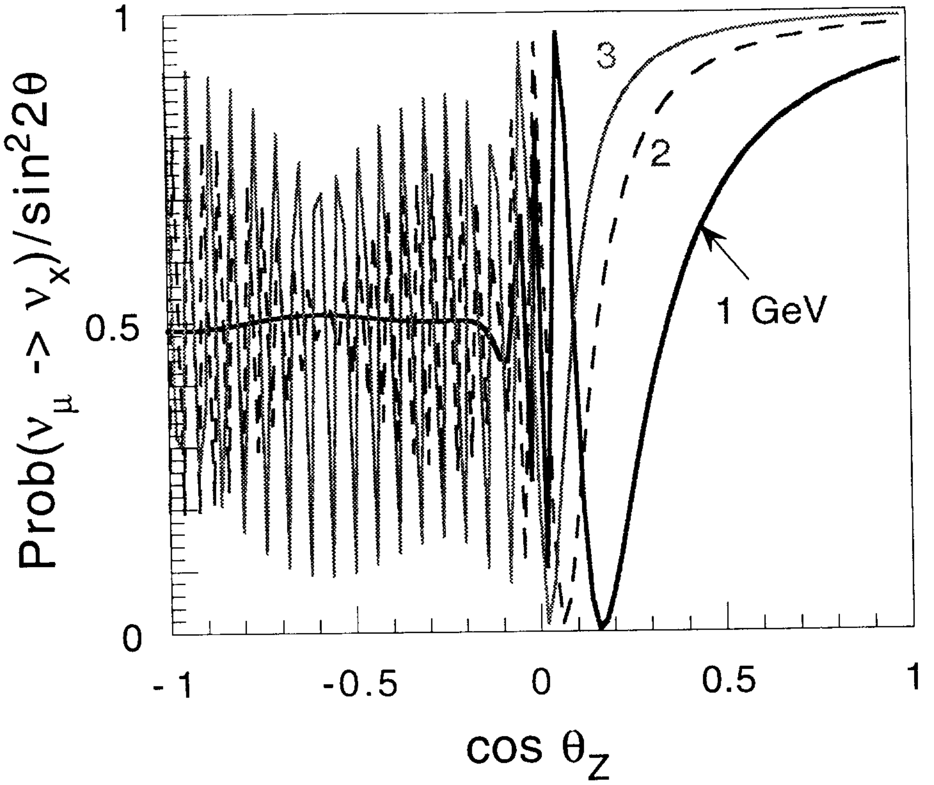

Figure .1 Oscillation probability as a function of zenith angle for fixed energies of 1, 2 and 3 GeV, for $\Delta m^2 = 0.01$ eV^2.

The current interpretation of observations of a ν_μ deficit rests on calculations that have uncertainties in their estimates of the absolute flux 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.[3]

2. Implications of the Kamiokande Results

The Kamiokande $\cos\theta_Z$ distribution for their multi-GeV sample, where θ_Z is the zenith angle, can be fit to equation (1) with $\Delta m^2 = 10^{-2}$ eV^2 and 100 percent mixing by integrating over the atmospheric neutrino spectrum above 1 GeV.

In Figs. 1 and 2, the $\cos\theta_Z$ distributions for six fixed energies are shown, for the same oscillation parameters. These illustrate a very interesting transition effect that could in principle be observed in cosmic ray experiments if these oscillation parameters are true. Below about 3 GeV, the oscillation lengths are comparable to the path lengths above the horizon, so this is the important region in this energy range. Below the horizon, the oscillations are very rapid and average out to P = 0.5.

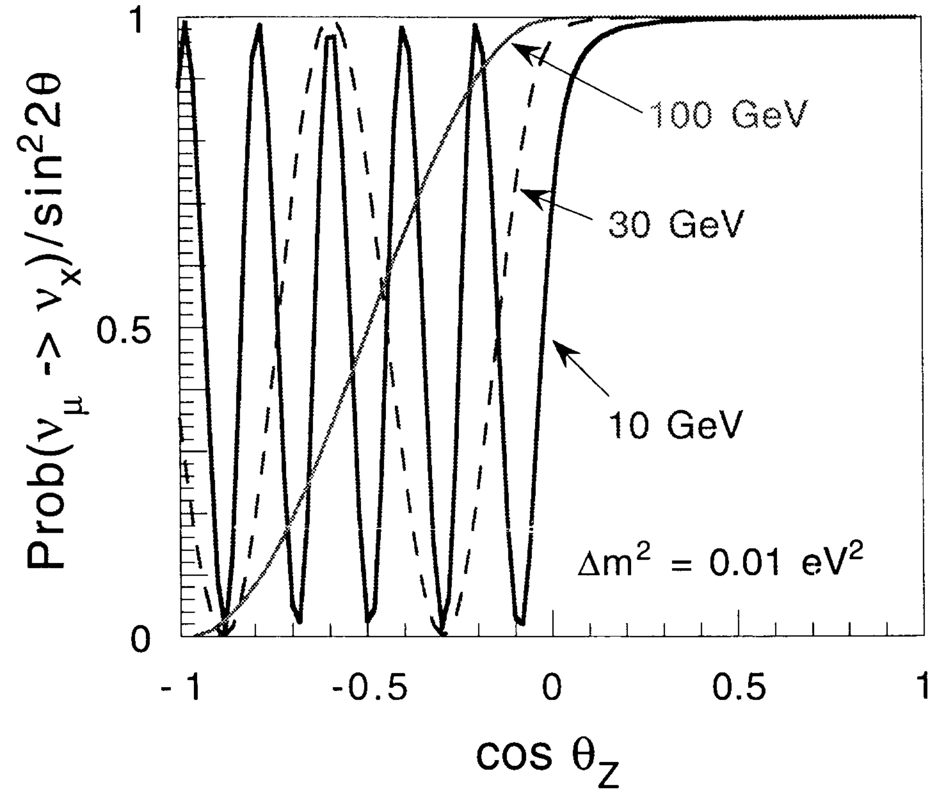

Figure .2 Oscillation probability as a function of zenith angle for fixed energies of 10, 30 and 100 GeV, for $\Delta m^2 = 0.01\ \mathrm{eV}^2$.

Above about 10 GeV, the action switches to below the horizon, where very dramatic zenith angle distributions result. To give an idea of the sensitivity of cosmic ray experiments to neutrino oscillations, Fig. 3. shows the energy at which the path length equals the oscillation length for various Δm^2 as a function of zenith angle.

This suggests that higher energy cosmic rays, in the 10-100 GeV range, might provide strong confirming evidence for neutrino oscillations. In Fig. 4, the $\cos\theta_Z$ distribution of oscillation probability integrated over the cosmic ray neutrino spectrum with minimum energies of 1 and 100 GeV is shown. The lower band corresponds to the Kamiokande range, while the upper would apply to deep underwater detectors such as DUMAND. Note the interesting dip above the horizon which might be seen with Super Kamiokande.

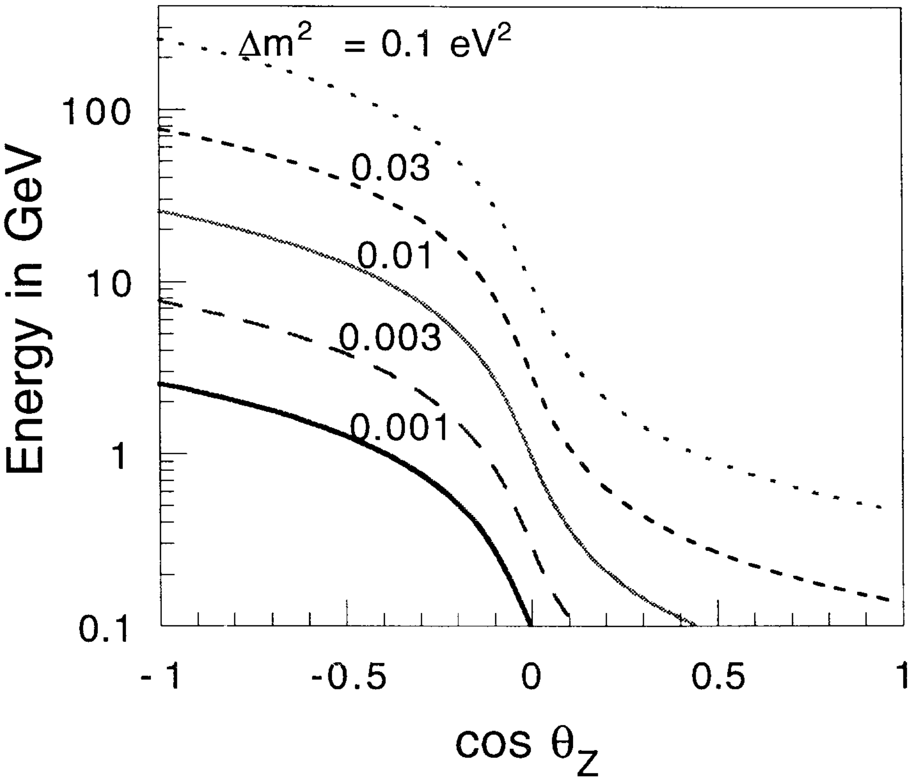

Figure 3 . Neutrino energy at which the oscillation length equals the path length a function of zenith angle, for several values of Δm^2.

The higher energy experiments would provide and independent check by looking for a strong zenith dependence in the region below the horizon. 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.

3. Conclusions

New data on the atmospheric neutrino anomaly strongly suggest that neutrino oscillations may be occurring with $\Delta m^2 \approx 10^{-2}$ eV^2 and $\sin^2 2\theta \approx 1$. The higher energy data from Kamiokande show a zenith angle effect. If oscillations exist in this parameter range, oscillation effects with atmospheric neutrinos will be most pronounced above the horizon in the energy range above 1 GeV, and below the horizon in the energy range above 100 GeV. Super Kamiokande should see a dip in their $\cos\theta_Z$ distribution at 0.2. Underwater experiments should see a fall-off below the horizon. Those that are sufficiently deep to look above the horizon will be able to normalize their data without relying on flux calculations.

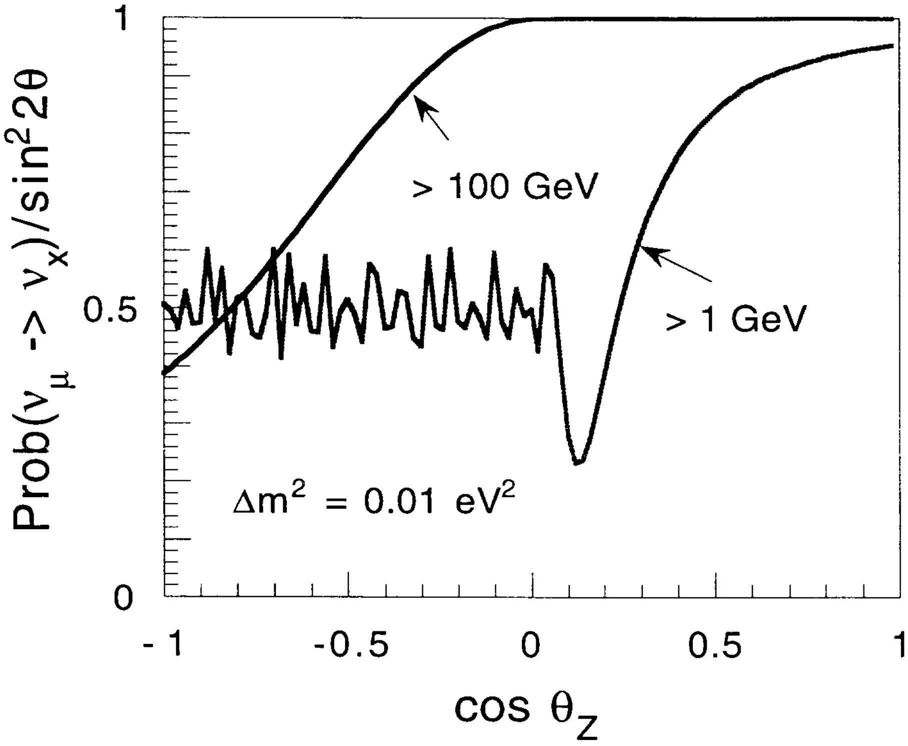

Figure 4 . Oscillation probability as a function of zenith angle integrated over t cosmic ray neutrino spectrum above minimum energies that correspond to underground and underwater experiments, for $\Delta m^2 = 0.01$ eV^2.

References

1. K. S. Hirata et al., *Phys. Lett.* **B** 205, 416 (1988); D. Casper et al., *Phys. Rev. Lett.* **66**, 2561 (1991).

2. Y. Fukuda et al., to be published in *Phys. Lett B.*

3. V. J. Stenger, *Proceedings of the Neutrino Mass Mini-Conference,* Telemark, Wisconsin, 1980, V. Barger and D. Cline ed., p. 174.