PROPOSED VERY LONG BASELINE EXPERIMENT TO SEARCH FOR NEUTRINO OSCILLATIONS WITH DUMAND

The DUMAND Collaboration:
P. Bosetti[1], J. Bolesta[4], P.E. Boynton[14], H. Bradner[09], U. Camerini[15], S.T. Dye[3], P.K.F. Grieder[2], T. Hayashino[10], M. Ito[10], H. Kawamoto[10], T. Kitamura[7], K. Kobayakawa[6], S. Kondo[4], P. Koske[5], J.G. Learned[4], C. Ley[1], J.J. Lord[14], R. March[15], S. Matsuno[4], K. Miller[13], P. Minkowski[2], K. Mitsui[11], Y. Ohashi[11], A. Okada[11], V.Z. Peterson[4], M. Sakuda[12], D. Samm[1], V.J. Stenger[4], H. Suzuki[10], S. Tanaka[10], S. Uehara[12], C. Wiebusch[1], M. Webster[13], R.J. Wilkes[14], A. Yamaguchi[10], K.K. Young[14]

1) Technische Hochschule Aachen, Germany; 2) University of Bern, Switzerland; 3) Boston University, USA; 4) University of Hawaii, USA; 5) University of Kiel, Germany; 6) Kobe University, Japan; 7) Kinki University, Japan; 8) Okayama Science University, Japan; 9) Scripps Institution of Oceanography, USA; 10) Tohoku University, Japan; 11) ICRR, University of Tokyo, Japan; 12) KEK, Tsukuba, Japan; 13) Vanderbilt University, USA; 14) University of Washington, USA; 15) University of Wisconsin, USA.

Paper presented by V.J. Stenger

The DUMAND II array currently under construction will have significant capabilities for the detection of neutrino oscillations in a neutrino beam aimed from 6,500 km away. This preliminary study indicates that it may be possible to explore as low as $\Delta m^2 = 10^{-3}$ eV^2 *and* $\sin^2 2\theta = 10^{-2}$.

Introduction

The DUMAND Collaboration has proposed that the Fermilab Main Injector (MI) neutrino beam[1] be pointed toward DUMAND.[2] The straight path length from Fermilab to DUMAND is 6,482 km. In principle, this allows a lower reach in Δm^2 than other long-baseline proposals using existing underground facilities. Further, matter oscillation effects would greatly enchance the sensitivity to small mixing angles for $\nu_\mu \rightarrow \nu_e$ oscillations.[3]

The accessible range of neutrino mass square differences Δm^2 depends on E/L: $\Delta m^2 \geq (\sqrt{\epsilon}/1.27)(E/L)$ and $\sin^2 2\theta \geq \epsilon$, where E is the neutrino energy in GeV, L is the path length in km, and ϵ is the detectable oscillation probability from one type of neutrino to another.[4] For the proposed Fermilab MI beam, $<E> = 20$ GeV and DUMAND II is capable of exploring down to $\Delta m^2 \cong 10^{-3}$ eV^2 or less, depending on ϵ. With matter oscillations, it becomes possible to explore neutrino mixing down to $\sin^2 2\theta \cong 10^{-2}$, where θ is the vacuum mixing angle.[3,4]

Presented at the 22nd International Cosmic Ray Confernce, Dublin Ireland, 11-23 August 1991.

Effective Detector Mass

A Monte Carlo calculation was used to estimate the effective detector mass for triggering and reconstructing low energy neutrino events and the ability to distinguish ν_μ from ν_e or ν_τ. Events were generated randomly within a volume of 6×10^6 m^3; the enclosed volume of the array is 2×10^6 m^3. The neutrino direction is taken as fixed, pointing to Fermilab about 30° below the horizon at the array, a region of negligible cosmic ray muon background and maximum array sensitivity.

For ν_e and ν_τ events that might result from oscillations, the electronic and hadronic energy is assumed to convert fully into a cascade of particles that emit Cherenkov light starting from the point of interaction. For ν_μ events, the energy is divided among the muon and the hadronic cascade. For neutral current events, only the hadronic cascade produces light.

After some preliminary filtering to reduce background PMT hits,[5] a series of fits of two types is performed, with bad points tossed out and the fits re-done until they are either satisfactory or fail: (1) a track fit in which all the detected light is assumed to be emitted along a muon track pointing back to Fermilab, and (2) a vertex fit in which all the detected light is assumed to be emitted from a cascade starting at the interaction point and aligned in the direction of Fermilab. The two fit types differ in the estimated hit times and PMT charges that go into the χ^2. The lowest χ^2 is sought by varying only three parameters, the coordinates of the interaction point x_0, y_0, and z_0, with the direction of the neutrino forced to point back to Fermilab. This directional constraint is a powerful aid to the reconstruction process.

The resulting effective detection volumes and equivalent masses for various neutrino interactions are is shown in Fig. 1, as a function of neutrino energy, for both trigger and fully reconstructed ν_μ and ν_e charged current events. When the actual spectral shape expected from Fermilab neutrinos are folded in, the effective detector masses for fully fitted $\nu_\mu N \rightarrow \mu X$ events is 310 kilotons.

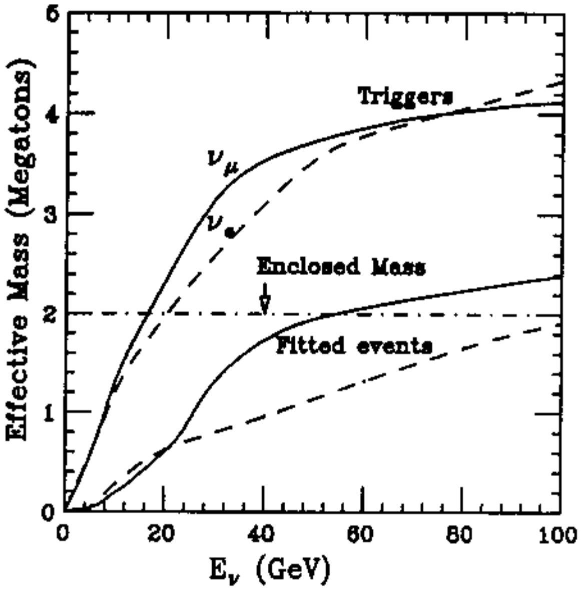


Fig. 1. Effective detector masses of ν_μ and ν_e charged current triggers and fit events, as a function of neutrino energy.

Ability to Detect Neutrino Oscillations

The planned DUMAND II array cannot efficiently distinguish ν_μ from ν_e or ν_τ events on a one-to-one basis at low energy. However, the time differences between light arriving from the interaction point and light arriving from a muon track appears to provide sufficient discrimination that a statistical statement about the relative fraction of of ν_e to ν_μ can be made for a beam from a fixed and known direction.

An event is categorized as muonless if it gives a lower χ^2 for the *vertex fit* described above and as muonful if the *track fit* is better. From the measured ratio of events in these two categories, the oscillation probability P can be extracted. A preliminary analysis of expected statistical and systematic errors indicates that it should be possible for DUMAND II to measure $P(\nu_\mu \rightarrow \nu_e)$ to about 10% and $P(\nu_\mu \rightarrow \nu_\tau)$ to about 20%.

The estimated sensitivity of DUMAND II in neutrino oscillation parameter space is shown in Fig. 2. It is important to remark that this analysis was done using the full spectrum of the MI beam. Although the mean energy of the beam is about 20 GeV, and the maen energy of events fully reconstructed is about 30 GeV, sufficient events at lower energy contribute to provide a lower sensitivity in Δm^2 than might be expected from the avergage energy alone. The parameters correspond to $\nu_\mu \rightarrow \nu_e, \nu_\tau$ vacuum oscillations, with matter effects taken into account for ν_e. DUMAND II sensitivity is compared with the limits set by existing experiments, including the possible neutrino oscillation point suggested by Kamiokande,[6] and the estimate for the MI beam directed toward IMB 600 km away.[1] Also shown is an estimate for a detector at 600 km capable of measuring P to 1%.[4] Such a detector, if it could be built, would be comparable to DUMAND II in vacuum parameter sensitivity, but will still not explore matter effects. Ideally one would like a 1% detector a great distance away.

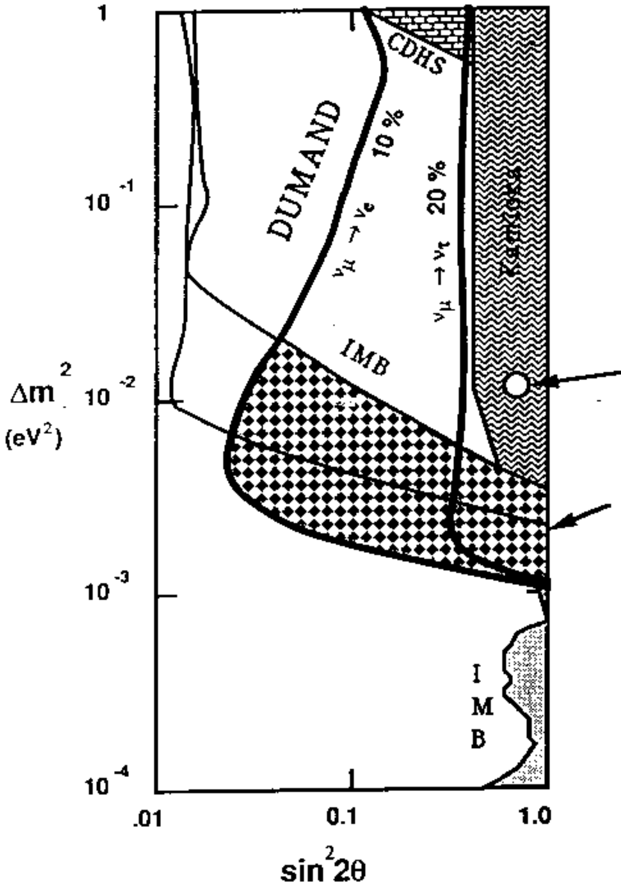
In the case of $\nu_\mu \rightarrow \nu_\tau$ oscillations, matter effects are not present. This and other characteristics of ν_τ interactions make DUMAND II less sensitive to ν_τ oscillations. So, while we cannot explore to the same low level of mixing as with $\nu_\mu \rightarrow \nu_e$, the greater distance of DUMAND II still offers and advantage of greater reach in Δm^2 than those at shorter path lengths.

Conclusions

If the DUMAND II array currently under construction is exposed to the proposed Fermilab Main Injector neutrino beam, with a mean energy of 20 GeV, it would have an effective target mass for ν_μ charged current events of 310 kilotons. Because of the large detector spacing, PMT hit time differences for light from the interaction point and muon track can be appreciable. Exploiting this, a statistical determination of the fraction of electron or tau neutrinos in the beam that might have resulted from neutrino oscillations can be attempted. Since DUMAND II will be located 6,482 km from Fermilab, as the neutrino flies, matter effects make it possible to explore to smaller mixing angles than would otherwise be possible.

References

1. R. Bernstein, et al., "Conceptual Design Report: Neutrino Physics after the Main Injector Upgrade," Fermilab (1991).
2. Fermilab Proposal P–824, Letter of Intent, Hawaii DUMAND Center (1990); J.G. Learned and V.Z. Peterson, HDC–11–89 (1989).
3. J. Pantaleone, Phys. Letters B 246, 245 (1990).
4. R.H. Bernstein and S.J. Parke, Fermilab–PUB–91/59–T (1991).
5. V.J. Stenger, DUMAND External Report HDC–1–90, Hawaii DUMAND Center (1990).
6. K.S. Hirata et al., Physics Letters B 205 (1988).



Kamioka
best fit

"Ideal" 1%
detector at
600 km
(6000 km is
even
better)

Fig. 2. The allowed parameter space for $\nu_\mu \to \nu_e$ and ν_τ oscillations. The checkered region is the estimate for DUMAND II determined in this work.