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Neutrino Oscillations in the Sea*

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ABSTRACT

The status of the proposals to do long baseline neutrino oscillation experiments with the Fermilab Main Injector beam is summarized. Because of their high cost they are difficult to justify as search experiments. A specially-designed experiment looking for oscillations in the atmospheric neutrino beam has a greater reach in L/E than is possible with an accelerator beam. The capabilities of underwater detectors for both accelerator and cosmic neutrino oscillation experiments are evaluated.

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 $\Delta m^2 \approx 10^{-3}$ eV^2 and large mixing, $\sin^2 2\theta \approx 0.8$.[1] This has partially motivated several proposals for long baseline neutrino experiments using the planned Fermilab Main Injector (MI) and other accelerator beams.[2]

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

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

where Δm^2 is in eV^2, E is in GeV, and L is in km. Following Bernstein and Parke[3], if P_{min} is the minimum detectable oscillation probability for a given experiment, then that experiment can measure the oscillation parameters with limits $\Delta m^2 \geq \sqrt{P_{min}} E/1.27\, L$ and $\sin^2 2\theta \geq P_{min}$.

The MI beam would produce neutrinos with $\langle E \rangle \approx 20$ GeV. If the beam were aimed toward a detector in the continental U.S.

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600 km away, that detector would need $P_{min} = 10^{-3}$ to reach $\Delta m^2 = 10^{-3}$ eV^2, while a detector 6,000 km away, say in the mid-Pacific, needs only to be able to measure $P_{min} = 0.145$ for the same limit in Δm^2. This illustrates that, in the case where mixing is large, the premium is in maximizing L, and reducing E if possible, rather than in the building of a very precise (and expensive) instrument. Precision instruments are required only in the case of small mixing or when sufficiently small E/L cannot be achieved.

2. Status of the U.S. Long Baseline Proposals

The following proposals have made to various U.S. accelerator labs for long baseline neutrino oscillation experiments:

Lab	Expt.	Detector	Distance (km)
Fermilab	P805	IMB	800
	P822	Soudan 2	600
	P824	DUMAND	6,482
Brookhaven	P889		1,320
SSC	EOI-14	GRANDE	≈500

With the demise of IMB, P805 is moot. Beam design work is underway on P822 and R&D funds have been received. Because of the high cost of aiming the beam 30° down to point toward DUMAND, approximately $30M, P824 has not been encouraged. It should also be noted that the Fermilab MI beam has not been approved for sufficient funding to proceed with construction in FY93. P899 at Brookhaven has not yet received funding. GRANDE was not approved, but perhaps things will change with the Governor of Arkansas moving into the White House.

Thus only Soudan 2 is moving ahead with any real effort and, for the reasons noted above, the path distance may be too small for a significant reach in parameter space. The consensus seems to be that marginal nature of the cosmic ray results does not justify great expenditure on long baseline experiments at this time unless they are coupled, as is P822, with other physics goals.

3. Long Baseline Underwater Detectors

Although the proposal to aim the Fermilab beam at DUMAND is currently inactive because of its high cost and

inadequate physics justification, it seems worthwhile to document the work that has been done in estimating the capability of DUMAND to study neutrino oscillations. These may be of some use for other underwater experiments, such as NESTOR, or as future developments may make the physics imperative.

3.1 Concepts

All underwater detectors operate on the principle of detecting Cherenkov light from charged particles passing though water. In the case of ν_μ charged current interactions, light will result from both the muon and hadronic cascade. In the case of ν_e charged current interactions, light is produced by both electromagnetic and hadronic cascades. Charged current ν_τ interactions will have some portion of light from muons that result when the τ decays muonically, 17% of the time, but most of the light will be hadronic. Neutral current interactions of any flavor will produce only hadronic cascades.

Accelerator beams are usually designed with long decay tunnels so that the neutrinos result from pion and kaon decay and are mostly ν_μ. Neutrino oscillations can then be searched for via the disappearance of ν_μ and the appearance of other flavors. Large underwater detectors will not likely have the ability to do much more than estimate the probability $P(\nu_\mu \rightarrow \nu_{e,\tau})$ by some measure of the differences between the spatial or temporal patterns of the Cherenkov light for the different types of interactions.

3.2 An Underwater Algorithm

DUMAND was not optimized for energies as low as 20 GeV. However, its capabilities at low energy are far from negligible. Fig. 1 shows the effective mass of the DUMAND II array, currently under construction, as a function of neutrino energy. This was estimated using a Monte Carlo program in which the direction of the neutrino was assumed to be from Fermilab (30° below the horizon – an optimal direction) and the events were fully reconstructed in the presence of simulated background noise. We see that DUMAND II has an effective mass for 20 GeV neutrinos of 500 kilotons.

Because of the wide spacing between the optical detectors, no attempt was made to use the different *spatial* characteristics of the light from muon and electromagnetic or hadronic cascades. Instead, the large lever arm is exploited to sense the *temporal* differences between the two types of signals. The Cherenkov light

from a muon will reach a detector before the light from a cascades starting at the same point, because of the greater speed of the muon compared to that of light in water.

The following algorithm was developed to utilize this feature.[4] Two event reconstruction χ^2 fits are performed on each event. The first assumes all the light is continuously emitted from a muon as it traverses the array; the second assumes all the light emerges from a point at the position of the interaction, inside or outside the array. These fits assume the neutrino direction is known, pointing to the source, and that the axis of the light pattern follows that direction. Then, just three parameters need be searched for, viz., the coordinates of the interaction point, and the fit is very robust. An event is classified as *muonless* if the second fit is better, and *muonful* if the first fit, assuming a muon, is better.

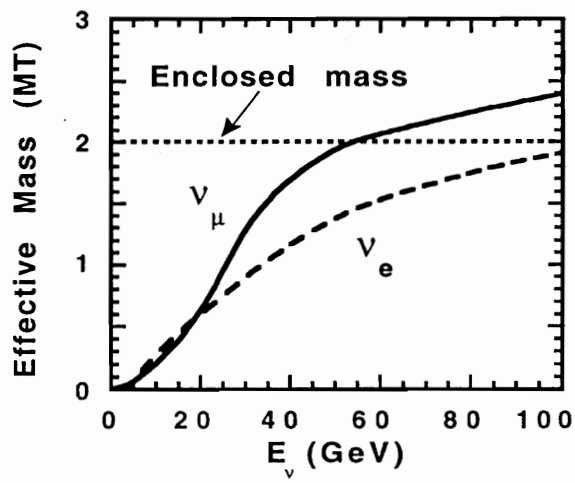

Figure 1 . Effective mass of DUMAND II as a function of energy for fully reconstructed ν_μ and ν_e charged current events. At high energies, events outside the instrumented volume are detected.

By generating charged current and neutral current neutrino events of all flavors in a Monte Carlo program, a matrix of probabilities for each being classified muonful or muonless is determined. In Fig. 2, the simulated measured ratio of muonless to muonful events is plotted as a function of oscillation probability, for ν_μ transforming into either ν_e or ν_τ. If we had a perfect detector, this ratio would be R_{NC} = 0.31; 31% of ν_μ interactions should be muonless. In fact, the algorithm classifies some 65% of ν_μ events as muonless. However, despite this

crudity, we see that the measured ratio increases monotonically with oscillation probability, leaving open the possibility to determine P experimentally. An analysis of both statistical and systematic errors leads to the conclusion that P can be measured to about 10% for $\nu_\mu \rightarrow \nu_e$ and 20% for $\nu_\mu \rightarrow \nu_\tau$. The latter is more difficult both because of the 17% of τ's which decay into μ's, and because the ν_τ cross section is reduced at low energy due to threshold and helicity effects.

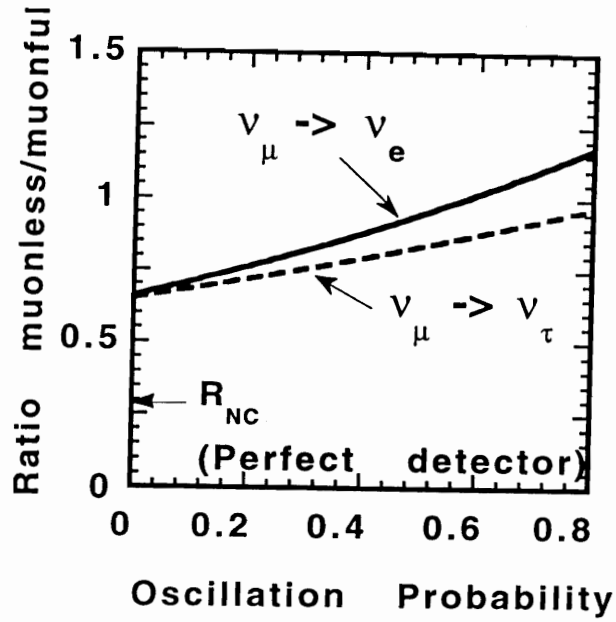

Figure 2 . Simulated measured ratio of muonless to muonful events as a function of oscillation probability.

3.3 Sensitivity in Parameter Space

The estimated sensitivity of DUMAND II exposed to the Fermilab MI beam is shown in Fig. 3. The vacuum oscillation parameters are used, although matter effects are taken into account. As was pointed out by Pantaleone, matter effects at the 6,482 km distance between Fermilab and Hawaii greatly increase the sensitivity of DUMAND to lower mixing angles.[5] They are negligible for all the other proposed long baseline experiments listed above. Note that matter effects take away some of the reach in Δm^2 as a price for greater reach in $\sin^2 2\theta$. In any case, the parameter region suggested by the cosmic ray experiments is covered for either $\nu_\mu \rightarrow \nu_e$ or $\nu_\mu \rightarrow \nu_\tau$.

4. Cosmic Ray Neutrino Oscillations

While a dedicated long baseline accelerator experiment is undoubtedly the best way to make precision measurements on neutrino oscillations, their limited range in E/L make them far from ideal for search experiments. This, added to their great cost, accelerator experiments unjustified unless strong indications already exist that oscillations exist within their parameter reach. That is, oscillations should be found elsewhere first, then a long baseline experiment done to measure Δm^2 and $\sin^2 2\theta$ precisely.

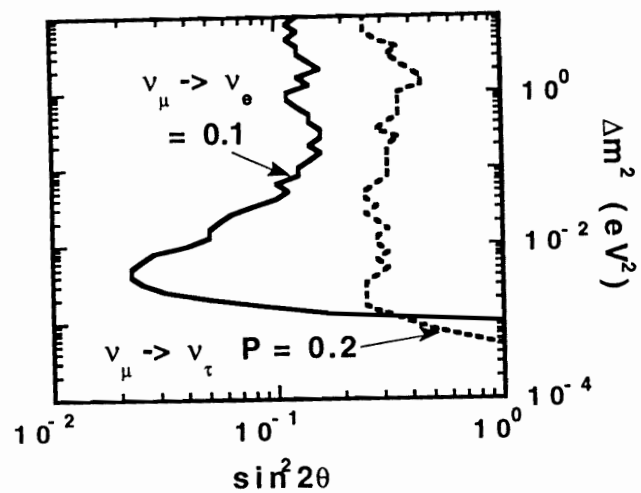

Figure 3 . Oscillation sensitivity of DUMAND II with the Fermilab beam.

Cosmic ray neutrinos offer the possibility of a 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 energies as low as 5 GeV could measure $\Delta m^2 \geq 10^{-4}$ eV^2.

Not only a lower but a greater variation in E/L occurs in cosmic ray experiments. The energy spectrum covers a wider range than accelerator beams, and L varies all the way from the depth of the detector of a few km to 12,000 km. I have long urged searching for neutrino oscillations in the variation of the cosmic ray neutrino signal with zenith angle.[6] The principle is illustrated

in Fig. 4. 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 just above the horizon and so are unable to exploit this sensitive technique.

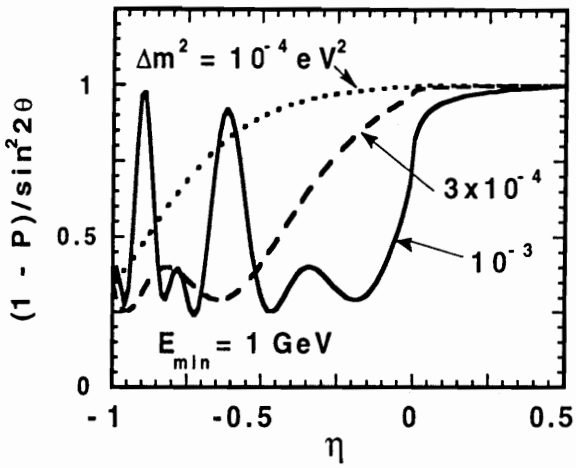

Figure 4. Disappearance probability as a function of a variable η that flattens out the zenith angle distribution of atmospheric neutrino events. The detector is assumed to have a neutrino energy detection threshold of 1 GeV and the spectrum is integrated over. Upward events have $\eta = -1$, horizontal events have $\eta = 0$. The effect for three values of Δm^2 are shown. Note the importance of being able to look above the horizon for the purpose of normalization.

Unfortunately, the algorithm described above for the determination of the muonless to muonful ratio in DUMAND II with the Fermilab beam does not work for the cosmic ray beam, at least at the lower energies one would like. The difficulty arises from the three additional parameters needed to determine the neutrino direction in the latter case. While DUMAND II will be capable of excellent directional reconstruction for muon energies greater than 100 GeV, too few detectors over too small a lever arm are excited to allow for direction reconstruction at lower energies. The technique may perhaps be made to work for energies greater

than 50 GeV, yielding sensitivity for $\Delta m^2 \gtrsim 10^{-3}$ eV^2 and $\sin^2 2\theta \gtrsim 0.5$, but this needs to be checked by further simulations.

DUMAND was optimized for very high energy neutrino astronomy and has limited capability for neutrino oscillations as a result. However, another underwater experiment, or an enhanced DUMAND, in which optical detectors are placed closer together, could significantly extend the parameter space beyond that so far explored. It would be both better and cheaper than a long baseline experiment with an accelerator. Such an experiment should have good sensitivity down to a few GeV, some ability to estimate or cut on that energy, and angular resolution of at least 10°. It should also be deep and have an isotropic directional sensitivity so that the zenith angle distribution can be compared with that expected with no oscillations.

4. Conclusions

While 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, the results are too marginal to justify expensive accelerator long baseline experiments capable of probing a limited region of parameter space. A deep cosmic ray experiment with energy sensitivity down to a few GeV, about 10° angular resolution, and isotropic acceptance would offer a cheaper search experiment with greater parameter reach.

The only U.S. long baseline experiment currently under active development is Fermilab-to-Soudan 2 at 800 km distance. However this experiment has limited range and is only justified by other physics considerations. The Fermilab-to-DUMAND proposal at 6,000 km has not been encouraged because of the high cost of aiming a beam 30° down, though it would be able to probe the parameter region suggested by the oscillation interpretation of cosmic ray results and also allow matter effects to be exploited. The capabilities of this experiment, and the technique for extracting the oscillation probability, are none-the-less worth documenting for future use by NESTOR or other underwater experiments that may appear more attractive in the future. The array currently being readied for deployment will have some limited capability for studying cosmic ray neutrino oscillations and should be able to check the oscillations hypothesis suggested by the underground data.

5. Acknowledgements

The author is grateful to M. Goodman for information on the status of long baseline experments.

6. References

1. K. S. Hirata *et al., Physics Letters* **B** 205, 416 (1988); R. Becker-Szendy *et al.,* BUHEP-91-24, submitted to *Phys. Rev.* **D**.

2. R. Bernstein et al., 1991. *Conceptual Deasign Report: Main Injector Neutrino Program,* Fermilab; *Proceedings of the Workshop on Long-Baseline Neutrino Oscillation,* Fermilab, 17-20 November, 1991, M. Goodman ed.

3. R.H. Bernstein and S.J. Parke, *Phys. Rev.* **D 44**, 2069 (1991).

4. V.J. Stenger, *Proceedings of the Workshop on Long-Baseline Neutrino Oscillation*, Fermilab, 17-20 November, 1991, M. Goodman ed., p. 317. See also J. Hauptman, *ibid.,* p. 413.

5. *J. Pantaleone, Phys. Lett.* **D 246**, 245 (1990).

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

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