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A MOVABLE DETECTOR TO SEARCH FOR NEUTRINO OSCILLATIONS IN THE BNL NEUTRINO BEAM

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-Syracuse Collaboration[†]

ABSTRACT

A simple, straight-forward, and economic experiment utilizing a set of water Cherenkov counters is proposed to search for neutrino oscillations in the AGS neutrino beam. The detector will be movable and will be able to provide reasonable counting rates up to 2 km. downstream of the pion decay tunnel. Whereas previous accelerator experiments have sought to increase the ratio ℓ/p (with ℓ the neutrino path length and p its momentum) by decreasing p,[1] we suggest increasing ℓ instead. Further, by making measurements at several different values of ℓ with the same apparatus, many sources of systematic error are eliminated. The experiment will measure beam-associated muon- and electron- type events at each position. A change in the ratio of muon-to electron-type events as a function of position would be evidence for $\nu_\mu \to \nu_e$ oscillations.

Sensitivity in terms of $(\Delta m)^2$ (the square of the mass difference in the mass eigenstates) can be as low as 0.1 eV^2, for full mixing, which is below the most probable value found by Reines et al.[2] for Δm^2 in their electron neutrino reactor experiment. This experiment would be parasitic, running behind the usual neutrino beam experiments, assuming the nominal beam energy (peaked at 1 GeV), and would thus make a minimal demand on AGS support. It is suggested that the first two measurements be made inside the Isabelle tunnel at the points of intersection with the AGS neutrino beam. No further excavations would be required, and the data could be taken before ISA equipment is installed.

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INTRODUCTION

Interest in neutrino oscillations has quickened recently, following a short lull, due to the recent well-known results of two experiments. Reines, et al.[2], in early 1980, presented evidence for a depletion of $\bar{\nu}_e$ over distances of several meters. This could be explained by the oscillation of $\bar{\nu}_e$ into other neutrino states. At about the same time, Lyubimov et al.[3] reported evidence for a non-zero mass of the electron neutrino, deduced from observations of the Beta-spectrum (Kurie plot) from tritium decay. This Soviet experiment finds $14 < m_{\nu_e} < 46$ eV to

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[†] List of participants at end of proposal.

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99%. C.L. Since a non-zero mass for at least one of the physical neutrinos is required for oscillations to be possible, this result seemed to reinforce the indications found in the Reines experiment, and to make further neutrino oscillation experiments imperative, if it is desired to understand the fundamental properties of neutrinos and, by extension, those of weak interactions.

The possibilities of neutrinos having masses and being able to oscillate from one neutrino type to another have been discussed for some years[4,5]. In particular, Pontecorvo[5] suggested that such time-behavior of neutrino beams could explain the low (at the time, seemingly null) signal found by the solar neutrino experiment of Davis, et al.[6]. If a large fraction ($\sim 2/3$) of the ν_e's from solar fusion processes change into other neutrino types (to which the Davis experiment is not sensitive) on their way from the sun, then the anomalously low result could be explained.

Pontecorvo's model, in analogy with the K^0-$\overline{K^0}$ system, suggested that the evolution of a neutrino beam with time could produce oscillations between the ν_μ and ν_e states. A necessary requirement for this to occur would be a non-zero mass for at least one of the neutrino types. Also, of course, muon and electron lepton numbers would not be separately conserved. The argument has more recently been extended to many neutrino types by Mann and Primakoff[7]. Following their description of the process for two neutrino types

$$\begin{aligned} \nu_e &= \nu_1 \cos\theta + \nu_2 \sin\theta \\ \nu_\mu &= -\nu_1 \sin \quad + \nu_2 \cos\theta \end{aligned} \tag{1}$$

where ν_μ and ν_e are the physical states and ν_1 and ν_2 are the neutrino mass eigenstates; θ is the mixing angle.

The time evolution of a beam which is ν_μ at $t=0$,

$$\nu(t) = -\nu_1 \sin\theta\, e^{-iE_1 t} + \nu_2 \cos\theta\, e^{-iE_2 t}\,,$$

implying,

$$P_{\nu_\mu \to \nu_e}(t) = \frac{1}{2}\sin^2 2\theta\,[1 - \cos(E_1 - E_2)t]$$

and

$$\begin{aligned} P_{\nu_\mu \to \nu_\mu}(t) &= 1 - P_{\nu_\mu \to \nu_e}(t) = \\ & 1 - \frac{1}{2}\sin^2 2\theta[1 - \cos(E_1 - E_2)t]. \end{aligned} \tag{2}$$

Expressed in terms of matrix elements,

$$\tan 2\theta = \frac{m_{e\mu}}{m_{\nu_\mu} - m_{\nu_e}}\,, \text{ and } \sin^2 2\theta = \frac{m_{e\mu}{}^2}{[m_{\nu_\mu} - m_{\nu_e}]^2 + m_{e\mu}{}^2} \tag{3}$$

with $m_{e\mu}$ = the off-diagonal matrix element which gives rise to $\nu_e - \nu_\mu$ mixing, and m_{ν_i} the masses of the physical particles. Also

$$E_1 - E_2 = \frac{1}{2p}[m_{\nu_1} - m_{\nu_2}][m_{\nu_1} + m_{\nu_2}]$$

and

$$(E_1 - E_2)t = \frac{m_{\nu_1}{}^2 - m_{\nu_2}{}^2}{2}\,\frac{\ell}{p} \tag{4}$$

where the masses are those of the mass eigenstates, ℓ is the neutrino drift length, and p the neutrino momentum.

For maximum mixing ($\theta = 45^0$), after many oscillations, the intensities of ν_e and ν_μ are equal. That is, each has a probability amplitude of $\frac{1}{2}$. For more than 2 neutrino types, each neutrino type is equally represented. In other words, if one starts with a pure ν_μ beam, after many oscillations, there will be a fraction 1/N of ν_μ's in the beam, the rest being equally divided among the other neutrino types. Thus, for long drift lengths, information on the number of neutrino types could be deduced. This would likely reflect the number of leptons, and possibly, according to recent theories, the number of quark flavors.

A recent survey by Barger, et al.[8] discusses possible indications of neutrino oscillations, among each of ν_μ, ν_e, and ν_τ, in past experiments. Also listed are current and future reactor experiments to search for various of these oscillations. Additionally, a recent experiment by Némethy, et al.[9] at the Los Alamos Meson Factory was reported for 30 - 50 MeV ν's and recent results from a reactor experiment at Grenoble were announced.[10] No experiment, apart from the above-mentioned work of Reines, et al.[2] has found clear evidence for neutrino oscillations. The best current limits for ν_μ-type oscillations are around $(\Delta m)^2 = 1$ eV^2.

Our proposed experiment will reduce this limit by (up to) an order of magnitude. The technique is simple and economical; it is also free of many sources of systematic error, since several observations are made with the same apparatus and the same beam, while varying ℓ, the neutrino drift length.

THE DETECTOR

The envisioned apparatus is centered around a water Cherenkov counter which serves as both target and detector. The detector will be sensitive to the quasi-elastic reactions

$$\nu_\mu + n \rightarrow p + \mu^- \qquad (5)$$

and

$$\nu_e + n \rightarrow p + e^- \qquad (6)$$

A basic feature of the detector is its modular nature and movability. Moving the same detector downstream in the beam, while measuring ν_μ and ν_e reaction rates along the way, allows one to take data at several points along the oscillation curve, rather than at just one. This is done while maintaining and monitoring constant beam conditions. Detector efficiencies will have no effect on the experiment (as long as they are held constant), since what is measured is $R(\ell) = \frac{N_{\nu_e}(\ell)}{N_{\nu_\mu}(\ell)}$ (the ratio of electron type events to muon-type events) at each point. In this way it is clear that many sources of systematic error, which are inherent in stationary oscillation experiments, are eliminated.

As one moves downstream, from Eqns. (2) and (4) the electron beam intensity is:

$$|\nu_e|^2 = \frac{1}{2}\sin^2 2\theta \left(1 - \cos\frac{1}{2}(m_1^2 - m_2^2)\frac{\ell}{p}\right) \qquad (7)$$

and the muon beam intensity is

$$|\nu_\mu|^2 = 1 - |\nu_e|^2 \qquad (8)$$

For long oscillation events $|\nu_e|^2 \propto (\frac{\ell}{p})^2$. together with the $\frac{1}{\ell^2}$ fall-off in beam intensity (since our detector is much smaller than the beam cross section), this would indicate a ν_e event rate constant with distance. If there are oscillations, then, as one goes along the beam line, ν_e events should fall off more slowly than $\frac{1}{\ell^2}$, the fall-off being due to the drop in the initial contamination of ν_e in the beam. However, ν_μ events would fall off more rapidly than $\frac{1}{\ell^2}$. If there are no oscillations in our range of sensitivity, then both ν_e and ν_μ events would fall as $\frac{1}{\ell^2}$. Put another way, if there are oscillations, $R(\ell)$ should increase with ℓ; otherwise, $R(\ell) \equiv R$ = constant.

The counter, which is a line target, will be modular in nature, composed of units of approximately 1 Tonne. At present, a set-up including about 25 of these units is proposed, each one observed by 4 EMI D312 5" hemispherical phototubes. The water Cherenkov tanks are approximately 150 × 110 × 68 cm³ (Figure 1). Located behind a 3-deep array of 24-27 of these tanks will be a scintillation counter hodoscope consisting of vertical strips 7.6 cm wide. Following this, will be several centimeters of lead, followed in turn by another set of scintillators. This is, simply a muon filter.

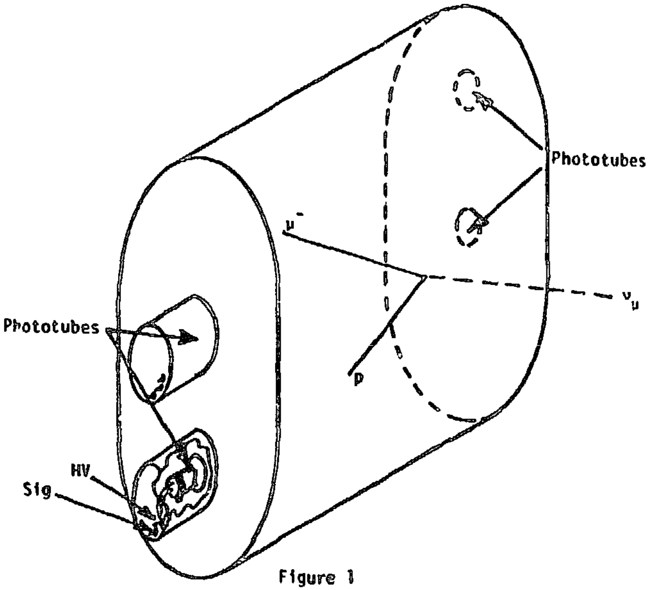

Figure 1

Sketch of one of the Cherenkov Units

Electrons will be detected through their showering properties. Pulse heights, proportional to the product of the number of "Cherenkoving" particles and their path lengths, will be measured and recorded. Muons will yield one particle intensities in the Cherenkov counter modules, downstream of the module in which the interaction occurs. Electrons will show large pulse heights in the downstream module since more particles are Cherenkoving for the whole width of the counter. For interactions occurring in the last module, one looks for multi-particle triggers in the vertical hodoscope (see Figure 2) as an indication of showering electrons.

The whole apparatus is surrounded by anti-counters to assure that an interaction occurs within the apparatus. The fast logic is gated by a signal from the AGS, so that the experiment is "live" only during the 12 pulses of ~ 40 ns width when neutrinos are

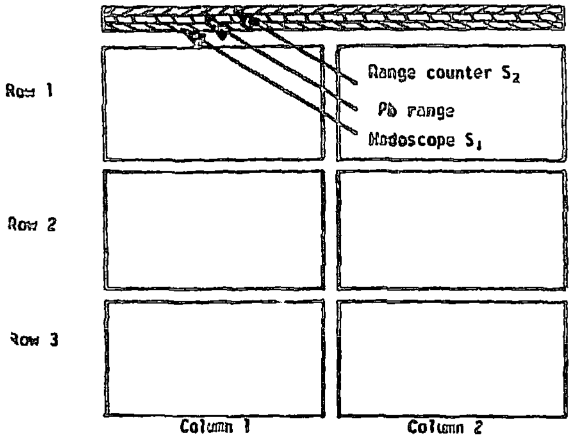

Figure 2
Plan View of a Group of Six Modules. This will be repeated four times to constitute the entire detector.

actually delivered in the beam.

In summary, the triggers are:
For muon quasi-elastic scattering:

$$\mu_j \equiv \bar{A} \times (\check{C}_1 \times \check{C}_2 \times \check{C}_3) \times S_1 \times S_2 \quad \text{or}$$

$$\bar{A} \times (\check{C}_2 \times \check{C}_3)_j \times S_1 \times S_2 \quad \text{or}$$

$$\bar{A} \times (\check{C}_3)_j \times S_1 \times S_2$$

where $\bar{A}$ is the absence of an anti-counter signal, C_i is a signal from a Cherenkov counter in the ith row; subscript j indicates the jth column of modules (see Figure 2); S_1 is a signal from the vertical hodoscope, and S_2 is a signal from the counter beyond the lead range.

For the electron quasi-elastic scattering:

$$e_j = \bar{A} \times [(\check{C}_1 \times \check{C}_2 \times \check{C}_3) \times E_2 \times E_3]_j \times \bar{S}_2 \quad \text{or}$$

$$\bar{A} \times [(\check{C}_2 \times \check{C}_3) \times E_3]_j \times \bar{S}_2 \quad \text{or}$$

$$\bar{A} \times (\check{C}_3)_j \times S_{1_e} \times \bar{S}_2$$

where E_2 and E_3 are pulse heights above electron showering threshold in Cherenkov counters in the 2nd and 3rd rows respectively. S_{1_e} is more than 2 counters firing in hodoscope S_1. Note that for an interaction in the first row, pulse heights are checked only in the following counters. This is because, when an interaction occurs in one counter, the particle path length can be anything from nearly zero to the whole module width. However, if an interaction has occurred in the previous counter, the path length is essentially the whole width; if an electron, the showering mechanism will increase the Cherenkov light in the module by giving more particles over this path length. The radiation length in water is 36 cm.; there are about 2 lengths in each module.

The detector will be placed at various distances downstream of the muon-neutron shielding in the neutrino beam line. To see how far downstream we can go, we estimate event rates as a function of neutrino drift distance ℓ. Conservatively considering only the quasi-elastic scattering reactions (5 and 6), we take a cross section of $\sigma = 0.8 \times 10^{-38}$ cm^2 E_ν.[11] Again conservatively, we evaluate this as the average beam energy, 1 GeV. Table 1 shows event rates as a function of distance for μ's, assuming no oscillations, and for e's, assuming maximal mixing and 50% oscillations at the particular value of ℓ quoted. The standard characteristics of the AGS neutrino beam are used.

The rates are tractable, out to further than 1 km. 800 hours of running at each of 250 and 1250 m would give about 5700 and 240 events, respectively for ν_μ events. This assumes 100% detection efficiency, which is, of course, optimistic. Estimates of geometrical efficiencies indicate about 70% acceptance.

There is also the possibility that additional reactions will be useful

$$\nu_\mu + p \rightarrow \mu^- + p + \pi^+ \qquad (9)$$

$$\nu_\mu + p \rightarrow \mu^- + p + \pi^0 \qquad (10)$$

$$\nu_\mu + n \rightarrow \mu^- + n + \pi^+ \qquad (11)$$

The first allows us to use proton targets as well as neutrons. The cross section for 9 is about 0.6×10^{-38} cm^2 at $E_\nu = 1$ GeV.[11] The other two reactions add about 0.3×10^{-30} cm^2 at the same energy.[9] The effect would be to increase the event rate if we can detect the μ^-. Monte-Carlo calculations indicate that with the projected muon filter about 50% of such events will be detected.

TABLE I

Rates with 25 Tonne H_2O Detector-Target
(Quasi-Elastic Scattering only)

$\frac{\ell}{p}$	μ's/hour(if no oscillation)	e's/hour(if 50% oscillation)	ℓ (drift length)
0.25	7.2	3.6	250 m.
0.5	1.8	0.9	500 m
0.75	0.8	0.4	750 m
1.0	0.45	0.2	1000 m
1.25	0.3	0.15	1250 m
2.5	0.07	0.04	2500 m

We propose beginning with two measurements at 250 and 1250 meters. A look at a map of the area shows an interesting fact (Figure 3): The neutrino beam intersects the ISABELLE tunnel at *precisely these points!* This stroke of fortune would allow us to place the detector in a zone of moderate climate, with electricity already supplied, and with over 4 meters of packed sand acting as an overhead shield against possible sky-shine and cosmic ray problems. The experiment would, of course, have to run before magnet installation, namely, within the next year or so, for these regions of the ring.

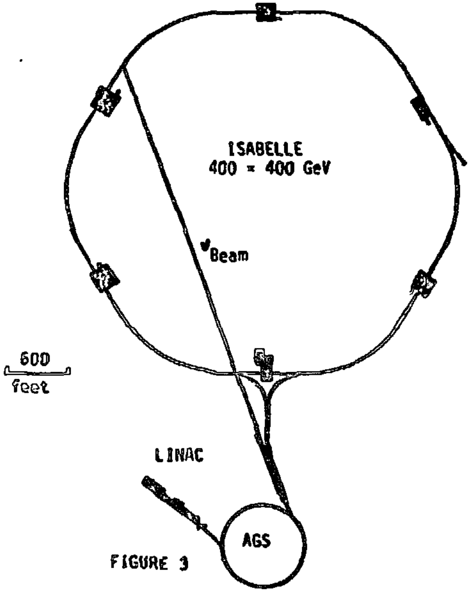

FIGURE 3

AGS Neutrino Beam and ISABELLE

We note that 1250 meters give an $\frac{\ell}{p}$ of 1.25, quite favorable when compared with past accelerator experiments.[12] Assuming maximal mixing, and just observing ν_μ fall-off would give a Δm^2 of ~ 0.4 eV². Using ν_e information, one can do better. Just how much better, depends on the background of ν_μ - induced electron triggers and ν_e contamination in the beam. If the ν_e background is very low, $\Delta m^2 \sim 0.1$ eV² could be obtained.

A prototype module for testing in the tunnel should be ready in a few weeks. Background measurements will be made and the general response of the detector will be observed.

Background:

a) Cosmic Rays

The cosmic ray flux is about 1/cm²/min/sr. This amounts to $\sim 5 \times 10^3$/sec over the apparatus. There are several methods available for eliminating cosmic rays. First, the beam at the AGS is extracted in 12 bursts of ~ 40 ns per 1.4 seconds repetition rate.

$\frac{12 \times 4 \times 10^{-8}}{1.4} \approx 0.34 \times 10^{-6}$ -live time fraction. The cosmic rate is then 1.7×10^{-3}/sec $\sim$ 5/hr. This is already nearly down to event rate levels. Now, as a second level, an anti-counter efficiency of 99.9%, which is feasible, cuts this rate to a negligible level. If necessary, the cosmic rate can be cut down further by requiring a real event to be a horizontal particle moving downstream, using timing and position information among anti-counters and the Cherenkov counter.

b) $\mu^{+} \to e^{+}\bar{\nu}_{\mu}\nu_{e}$.

This decay produces ν_e which could provide spurious e^- signals in the detector through $\nu_e n \to pe^-$. In flight, only a few of μ's decay. The average energy of ν_e is much smaller than ν_μ (Monte-Carlo calculations show $\sim 1/3$) and, since cross section is linear in the energy, these spurious events are suppressed to a level of 3 by this fact. Further, these ν_e have a spread of well over 60 mr at the AGS, which reduces their intensity by another large factor. Most of this reaction occurs with stopped μ's, which produce much more widely spread ν_e's which are, in addition, out of time.

c) $\nu p \to \nu \underset{\llcorner\to p\pi^{0}}{\Delta^{+}} X^{0}$ and $\nu n \to \nu \underset{\llcorner\to n\pi^{0}}{\Delta^{0}} X^{0}$

Another background for detection of an e^- signal could be a neutral current production of π^0's which decay into 2 γ's, then converting into e^-'s, which can give a e^- signal. There are several items which help us in dealing with this. First of all, the gamma spread will be large, reducing the rate compared with $\nu_e n \to e\bar{p}$, through geometrical considerations; secondly, the cross sections for such processes are below the $\nu p \to \mu^- p\pi^+$ cross section by a factor of 9 or so.[13] Finally, the segmentation of the shower counter into strips allows us to veto non-adjacent shower pairs or particle-shower pairs, reducing the event rate still further. A detailed Monte-Carlo analysis will be used to optimize the counter. In any event, these events should decrease in rate with distance from the neutrino production area, whereas electrons from a ν_e should not. This is true for all backgrounds to $\nu_e n \to e^- p$ except cosmics.

d) $\nu p \to \nu p$

Elastic scattering is down in cross section from the charged current quasi-elastic by a factor of at least three. The absorber will eliminate most of the protons while permitting about 90% of the muons to pass. Also, few protons will be above the 1.1 GeV/c Cherenkov threshold for protons in water.

e) $K^+ \to \pi^0 e^+ \nu_e$

This has a 5% branching ratio and is suppressed for similar reasons as in section b).

Table II shows, for several background sources, the methods of discrimination which are foreseen, relative both to detecting muons from ν_μ and electrons from ν_e.

SUMMARY

We have proposed an experiment, using a movable water Cherenkov Detector to look for neutrino oscillations in the AGS neutrino beam. This measurement would be taken parasitically, behind any normally - running neutrino experiments, with the neutrino spectrum peaked at 1 GeV. Thus, no perturbation of schedules or specific dedication of the AGS is required.

We suggest, as the first phase of a possibly longer term program, taking two runs at 250 m and 1250 m, with the apparatus located in the already-excavated ISABELLE tunnel. In this way, a neutrino oscillation experiment can be done at Brookhaven without incurring large expense and time delay for building shielding and/or further excavations. The run at 1250 m. would require 800 hours, while that at 250 m. would demand ~ 200 hours. An additional 200 hours of test and set-up time would be desirable. Testing could start in early 1981 with data-taking beginning around June of the same year.

TABLE II

PRINCIPAL BACKGROUND SOURCES AND COUNTERMEASURERS

BACKGROUND SOURCE	COUNTERMEASURES FOR $\nu_\mu n \to \mu^- p$	COUNTERMEASURES FOR $\nu_e n \to e^- p$
$\nu_\mu n \to \mu^- p$	SIGNAL	No shower
$\nu_e n \to e^- p$	No μ^- signal (100% suppression)	SIGNAL
COSMICS	Anti-Counters, Time Gate	Level reduced to ~ 1% of signal
$\mu^+ \to \nu_\mu \nu_e e^-$	No μ^- signal	ν_e energy low; ν_e's usually late; since most come from μ's at rest with $\tau = 2.2$ μs; ν_e's have greater angular spread and then reduced in flux further
$\nu p \to \nu\pi^0 X$	No μ (~ 100%)	Segmented counter, rate low, spread in γ's
$\nu p \to \nu p$	Muon absorber, low cross section; p usually won't give Cherenkov radiation	No shower-like behavior from p; p usually won't give Cherenkov radiation
$np \to \gamma X$ $\pi^0 X$ pX	Shielding; also any neutrons would be late	

The sensitivity obtained will be in the region or $0.1 \le \Delta m^2 < 0.4$ (eV²) for maximal mixing. Reines' value of $0.5 - 0.8$ in the mixing factor would increase these limits proportionally.

A major advantage of this type of an experiment, using the same detector and same reactions at different distances, is the elimination of many possible sources of systematic error which are present in experiments with a stationary detector. In their recent critique of the Reines experiment, Feynman and Vogel[14] note:

"The crucial test of neutrino oscillation, independent of spectrum uncertainties, is that the same reaction measured at the same energy gives two different results at two different distances". This is precisely what we propose for an accelerator-type oscillation experiment.

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