It is possible that the deuterim abundance may further fix the parameters, as it did in ref. 3. We plan to investigate this question further. We also intend to investigate the possibility that neutrino oscillations play a cosmological role at a time when the diameter of the universe is of the same order as the oscillation length.

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BUBBLE CHAMBER NEUTRINO OSCILLATION PROPOSALS

R.J. Loveless
University of Wisconsin, Madison, WI 53706

I. Wisconsin-Athens-Fermilab-Padova Proposal

A. Introduction

We have proposed a search for the oscillation of $\nu_e \rightarrow \nu_\tau$ or $\nu_e \rightarrow \eta$ where η is a new species of neutrino (possibly a singlet) which does not interact. The neutrino detector will be the Fermilab 15' BC with a heavy neon-Hydrogen mix and beam will be enriched with ν_e. The oscillation probability can be written:

$$P(\nu_e \rightarrow \nu_\beta) = \delta_{e\beta} - \sin^2 2\theta \sin^2(1.27 \frac{L}{E}\Delta)$$

where Δ (eV^2) = $m^2_{\nu e} - m^2_{\nu\beta}$, L(m) = length, E(MeV) = ν_e energy, and θ = mixing angle.

estimate this experiment would be sensitive to ∿ 2-3% oscillation probability if $\nu_e \rightarrow \nu_\tau$ and ∿ 10% if $\nu_e \rightarrow \eta$. Previous results on ν_e oscillations are:

$P(\nu_e \rightarrow \nu_e) = 1.00 \pm 0.14$ BEBC exp[1]

$P(\nu_e \rightarrow \nu_e) = 1.09 \pm 0.40$ Los Alamos exp[2]

Figure 1 shows a graphical comparison of these results and the results on $\nu_\mu \rightarrow \nu_e$ experiments.

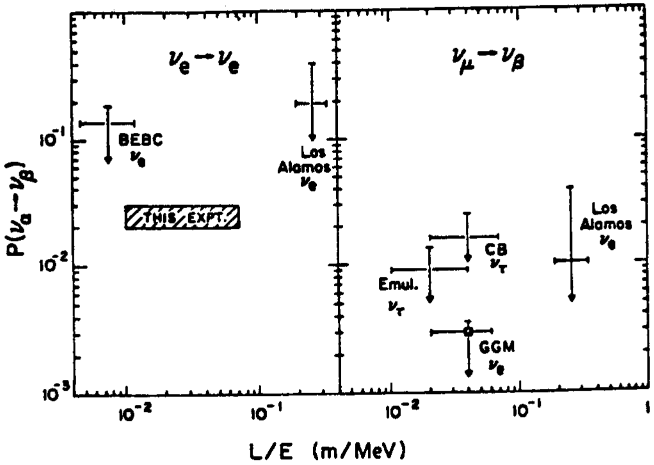

Figure 1) Oscillation probabilities for previous ν_e and ν_μ experiments as a function of L/E.

It is clear that to probe small mixing angles it is important that δP be as small as possible. As an illustration of this point Figure 2 shows the excluded region for the Los Alamos experiment. Since $\delta P/P \sim 0.4$ this experiment is not sensitive for $\sin^2 2\theta < 0.4$. Figure 2 also illustrates the cyclic behavior of the excluded region due to the small range of L/E (L = 9m, 25 MeV < E < 50 MeV). For our bubble chamber proposal the range of L/E is greater (L = 1000 m, 5 < E < 150 GeV) so the cyclic behavior is integrated out. Not only the mean L/E but also the range of L/E is important in determining the size of the excluded region.

The observation of $\nu_e \rightarrow \nu_\tau$ can only be achieved in high energy accelerator experiments. Because of the τ mass, ν_τ charged current interactions are suppressed relative to ν_e CC interactions as shown in Figure 3. Below $\sim$ 30 GeV any $\nu_e \rightarrow \nu_\tau$ oscillation will appear simply as a depletion of ν_e (i.e. $\bar{\nu}_e \rightarrow \bar{\nu}_n$). We hope to demonstrate that the observation of ν_τ CC interactions can best be achieved in a visual detector sensitive to all tracks (heavy liquid bubble chamber or nuclear emulsions). We emphasize the importance of observing many different signatures to demonstrate a consistent effect.

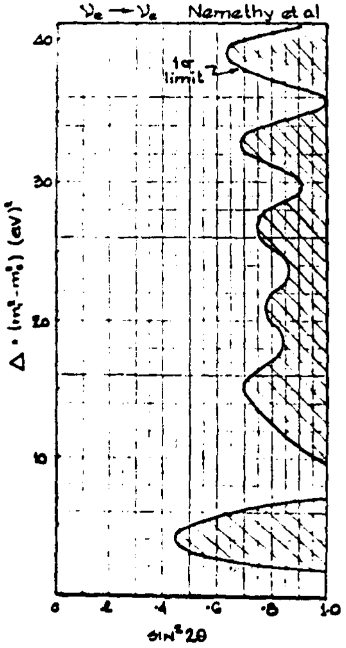

Figure 2) Oscillation results from the Los Alamos exp. The sensitive region is shaded.

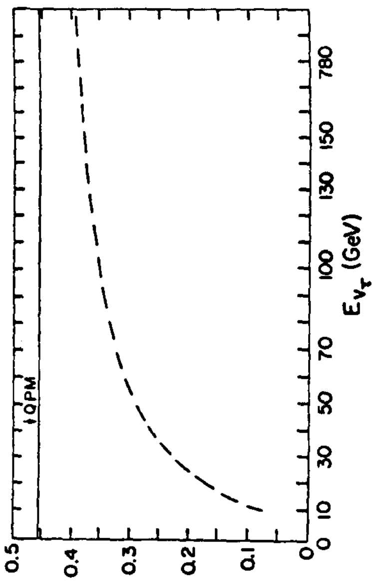

Figure 3) Threshold suppression for ν_τ CC interactions compared to QPM (ν_e).

B. Beam

We wish to maximize the relative number of ν_e to ν_μ and the best we can expect is $\nu_e \sim \nu_\mu$. A beam dump experiment (although having $\nu_e \sim \nu_\mu$) is unacceptable because of the low absolute ν_e flux and the consequent contamination of ν_μ flux due to upstream interactions or other sources. The CERN beam dump experiments[3] illustrate this difficulty in calculating the flux ratio ($\nu_e/\nu_\mu = 0.6 \pm 0.3$), a result which is not currently understood. We intend to produce a K_L° beam by inserting a dipole magnet downstream of the target and sweeping all charged particles aside. A second dipole somewhat farther downstream will sweep aside charged decay particles from $K_S^\circ \rightarrow \pi^+\pi^-$ and $\Lambda^\circ \rightarrow p\pi^-$. Neutrinos are produced from $K_L^\circ \rightarrow \pi^-\ell^+\nu$ (or $\rightarrow \pi^+\ell^-\bar{\nu}$). Our calculations indicate that above 20 GeV $\nu_e \sim \nu_\mu$.

About 1000 ν_e events are needed to be sensitive to $\sim$ 2-3% oscillation. This requires approximately 10^{19} protons on target at 400 GeV. At a rate of 10^{18} per week we need 10 weeks of running and $\sim$ 350K pictures. Table 1 shows the event rates we expect for such a run. The ν rates for this beam are approximately an order of magnitude larger than the ν rates from prompt ν in our target.

C. Heavy Liquid Bubble Chamber

The 15' BC has a number of features which make it one of the best detectors for neutrino events:

Approximately 90-95% of all electrons have two or more visible signatures such as bremsstrahlung, direct pairs, etc. Thus we determine both sign and momentum for electrons, distinguishing ν_e and $\bar{\nu}_e$. The muons are tagged with $\sim$ 80% efficiency by a two plane EMI consisting of MWPC chambers downstream from the bubble chamber. The gamma conversion probability in the heavy neon-H_2 liquid is $\sim$ 90% (rad.length = 40-50 cm) and the neutral hadron interaction length is $\sim$ 200 cm.

The bubble chamber has good efficiency for understanding complex events. Most tracks are cleanly visible, neutral decays are measureable. In particular, the region around the vertex is generally visible about 1/2-1 cm downstream. For an expected lifetime of 3 x 10^{-13} sec we expect to see 5-10% of all τ decays. In a comparable experiment in the 15' BC, Ex.546, we observed decay vertices for 10% of the charm events ($\mu^- e^+$), which have a similar lifetime. The ability to see τ decays could be enhanced by adding a high resolution camera to the current triad of cameras.

D. τ Search

1) Leptonic decays.

The distinguishing characteristics of $\tau \rightarrow e\nu\bar{\nu}$ are best described in a plane transverse to the neutrino direction (see Figure 4b). The missing $p_\perp$ due to ν_τ and $\bar{\nu}_e$ is large and the angle, ϕ, between the electron (muon) and the missing $p_\perp$ is small.

Table 1

Event Rates Expected for 15 Ton and 10^{19} Protons on 1 λ_{abs} Target

	CC$^{(a)}$			NC$^{(b)}$			e/μ Ratio		
	10-40	>40	total	10-40	>40	total	10-40	>40	total
ν_e	150	870	1020	45	260	305			
$\bar{\nu}_e$	75	420	495	25	143	168			
ν_μ	240	960	1200	72	288	360	.63	.91	.85
$\bar{\nu}_\mu$	125	330	455	43	112	155	.60	1.25	1.09
$\nu_\tau^{(c)}$			<4						

(a). From spectra in Figure 3 assuming $\sigma^\nu = 0.62E \times 10^{-38}$, $\sigma^{\bar{\nu}}/\sigma^\nu = 0.48$. 75 prompt ν_e, ν_μ (36 $\bar{\nu}_e$, $\bar{\nu}_\mu$) events are included (CERN beam dump result).

(b). NC/CC = 0.30 for ν, 0.34 for $\bar{\nu}$.

(c). Assumes $F\bar{F}/D\bar{D} = 0.1$, $BR(F \to \tau\nu) = 0.03$.

The backgrounds for τ leptonic decays come from ordinary CC events with larger than average missing hadronic energy. To estimate these backgrounds we have used a sample of 1500 ν_μ CC events from a previous experiment, E28. The hadronic showers in these events are representative of the showers we expect from the K_L° beam. By choosing $\phi < 2.0$ radius and missing $p_\perp > 1.6$ GeV/c we estimate the background is 0.3% of CC events.

We then simulate a ν_τ interaction by assuming each of the muons was a τ and calculating $\tau \to e\nu\nu$ by Monte Carlo. With the same cuts we accept 11% of all $\tau \to e\nu\nu$ events. This analysis represents a realistic estimate of the difficulties of identifying ν_τ events since resolution effects, missing hadron energy, etc. are included the measured sample.

For 1000 ν_e events we estimate a background of three events. If we require the signal equal the background and correct for branching ratio, detection efficiency, and ν_τ threshold suppression we find

$$3 \times \frac{1}{.17} \times \frac{1}{.11} \times \frac{1}{.78} = 206 \ \nu_\tau \text{ events}$$

that 200 ν_τ events must be present for us to observe a signal. Thus the sensitivity of this channel is $P \gtrsim 21\%$ (i.e. unless the oscillation probability is at least 21% this channel cannot observe oscillations). For this channel we note that the sensitivity is independent of the number of ν_e interactions.

2) Hadronic decays.

a) $\tau \to \pi\nu$ For hadronic decay modes of the τ the backgrounds come from NC events. To estimate this background we again use the sample of 1500 CC events from E28 and assume the μ^- is an unseen ν_μ from an NC event. We select a π^- which has the largest momentum transverse to the remaining hadrons in the plane transverse to the neutrino direction (Figure 4a). For $\tau \to \pi\nu$ the angle φ between the chosen π^- and the missing $p_\perp$ will be small. In this plane the transverse

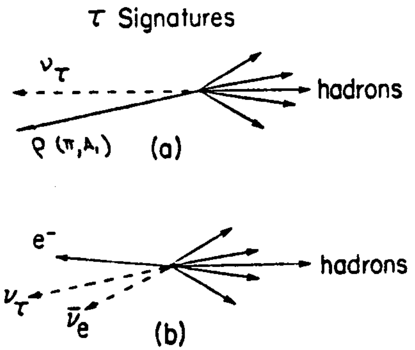

Figure 4) Topologies for ν_τ CC interactions in plane transverse to ν_τ for (a) hadronic τ decays and (b) leptonic τ decays.

axis (TA) is formed from the vector sum of the remaining hadrons. The projection of the chosen π^- onto this axis should be large and negative for $\tau \rightarrow \pi\nu$. And the longitudinal momentum of the π will be large for τ decay. From Figure 5 the background from NC events can be estimated to be $\sim$ 0.3% with the cuts as shown. Using a simulated $\tau \rightarrow \pi\nu$ decay Figure 6 shows these cuts accept 30% of $\tau \rightarrow \pi\nu$ events. Since we expect $\sim$1000 NC events (see Table 1) the background will be three events. The sensitivity for $\tau \rightarrow \pi\nu$ becomes

$$3 \times \frac{1}{.09} \times \frac{1}{.3} \times \frac{1}{.78} = 142 \text{ events} \rightarrow 14\%$$

b) $\tau \rightarrow \rho\nu$

This decay is similar to $\tau \rightarrow \pi\nu$ but more sensitive because of the larger branching ratio and the restriction that three particles ($\pi\gamma\gamma$) have a ρ mass. We estimate background to be 0.2% of the NC events using a plot similar to Figure 5. From a simulated $\tau \rightarrow \rho\nu$ decay calculation the cuts accept $\sim$ 35% of all these decays. The detection efficiency due to gamma conversion is $\sim$ 0.8 so the overall detection efficiency for $\tau \rightarrow \rho\nu$ is 0.28. The background estimate is 1.5 events so the sensitivity becomes

$$1.5 \times \frac{1}{.22} \times \frac{1}{.28} \times \frac{1}{.78} = 31 \text{ events} \rightarrow 3\% \text{ sensitivity.}$$

This is the most sensitive exclusive channel and will set the limits on ν_e oscillation if no signal is observed.

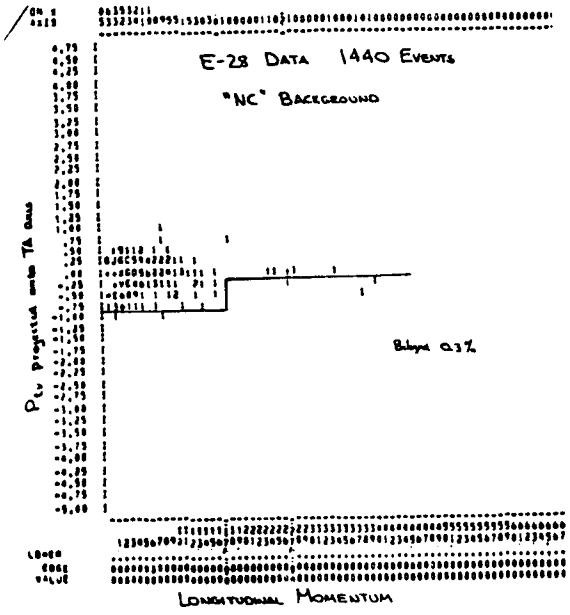

Figure 5) Background estimates for $\tau \rightarrow \pi\nu$.

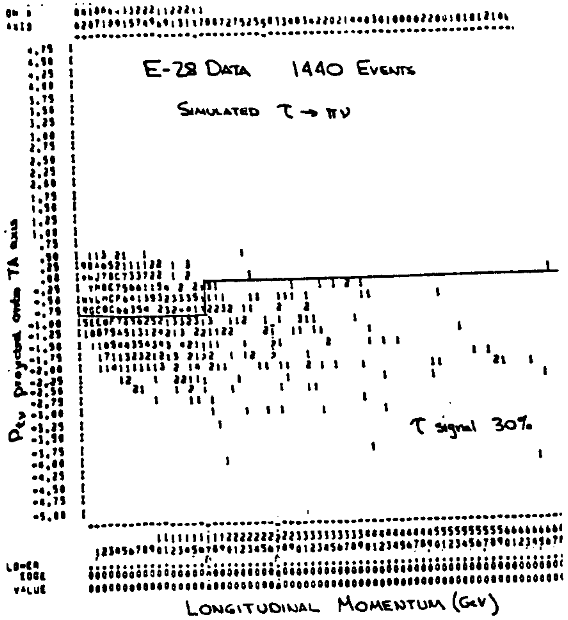

Figure 6) Monte Carlo estimates for $\tau \rightarrow \pi\nu$.

c) $\tau \rightarrow n\pi\nu$

These decays are also similar to $\tau \rightarrow \pi\nu$ but, since $n \geq 3$, the backgrounds are expected to be larger and the hadron direction less accurate. The expected background is < 1% for cuts which accept $\sim$ 30% of the τ decays. This implies a sensitivity of 14% for $\tau \rightarrow n\pi\nu$. Table 2 shows the sensitivity limits for each τ mode assuming 1000 ν_e events. Figure 7 shows the number of ν_τ interactions as a function of $\sin^2 2\theta$, the mixing angle, and Δ, the mass squared difference of ν_e and ν_τ.

Table 2
Sensitivity Limits for $\nu_e \rightarrow \nu_\tau$ Oscillation

τ decay	BR	Det. Eff.	Background	Sensitivity
$e\nu\bar{\nu}$	17%	11%	0.3% of ν_e CC	21%
$\mu\nu\bar{\nu}$	17%	9%	0.3% of ν_μ CC	25%
$\pi\nu$	9%	30%	0.3% of NC	14%
$\rho\nu$	22%	34%	0.2% of NC	3%
$n\pi\nu$	31%	30%	1.0% of NC	14%

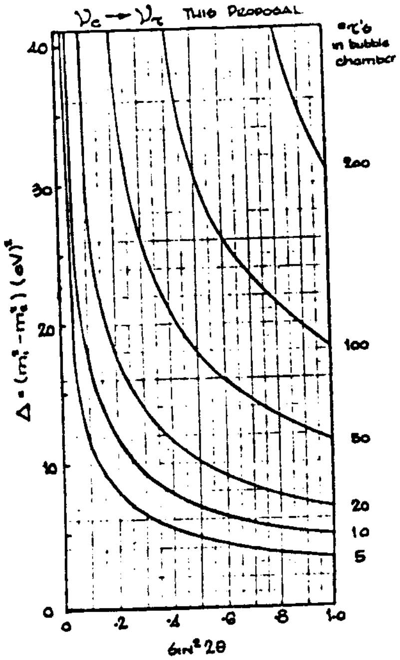

Figure 7) Number of ν_τ CC interactions expected for 10^{19} protons. At 2% sensitivity 20 ν_τ CC interactions can be detected.

3) Visual Decays

All film will be carefully scanned for visual evidence of τ decays. A recent experiment (E546)[4] observed four charm decays in 46 $\mu^- e^+$ events. Thus even without a high resolution camera we should be able to observe at least 10% of τ decays due to the higher momentum of the τ. Hence 20 ν_τ interactions could be observed as two visual decays, leading to a 2% sensitivity. By adding a high resolution camera (or cameras) which does not greatly restrict the fiducial volume this sensitivity can be enhanced.

D. Other Oscillation Signatures

1) e/μ ratio.

Most current experiments (CERN Beam Dump, Los Alamos, Irvine, Grenoble, etc.) use this signature to measure the attenuation of ν_e flux. It requires a good knowledge of the ν_e beam. Unfortunately there are usually few opportunities to check the reliability of the estimate of ν_e flux. If ν_e oscillates into a new neutrino which doesn't interact (η), this is the only signature. The e/μ ratio can be written

$$R(e/\mu) = \frac{\phi(1-P) + .17\phi P\sigma^\tau}{1 + .17\phi P\sigma^\tau}$$

where $\phi = \nu_e/\nu_\mu$, P = oscillation probability, and σ^τ is the ratio of ν_τ interaction to ν_μ (or ν_e) interaction.

For P small, $R(e/\mu) \sim \phi(1-P)$. For 1000 ν_e events R can be measured to ∼ 7%. If φ can be computed to ∼ 5% the sensitivity can be measured to ∼ 10%.

2) Ratio of events with and without leptons.

In order to cleanly measure NC/CC an experiment must separate ν_e and NC events. This presents no difficulty for the neon bubble chamber. The ratio of events without to with leptons can be written

$$R(No/N_\ell) = \frac{R + R(1-P)\phi + .66\phi P\sigma^\tau + R\phi P}{1 + \phi(1-P) + .34\phi P\sigma^\tau}$$

where R = NC/CC for ν_μ interactions = 0.3.

For $\phi \ll 1$ $R(No/Ne) \approx (1 + \frac{5}{2}P\phi)R$ which is difficult to distinguish from R when $\phi \ll 1$.

For $\phi \approx 1$ $R(No/N_\ell) \approx (1 + \frac{5}{4}P)R$. We expect to measure

$\frac{\delta R(No/Ne)}{R(No/N_\ell)} \approx .10$ so for P small we can measure

$\delta P \approx 0.08$.

II. Padova-Pisa-Athens-Wisconsin Proposal

A. Introduction

This proposal intends to use a low energy ν_μ beam (∼1/2 GeV) derived from the CERN PS beam of 12 GeV-protons. The detector would be the BEBC bubble chamber filled with a 75% mix of neon in hydrogen to allow identification of electrons. Since the proton beam has low energy few K's are produced and, consequently, the ν_e flux is less than 10^{-3} the ν_μ flux (Figure 8).

B. $\nu_\mu \to \nu_e$ Oscillation

The film is scanned, looking for ν_e CC interactions. Such candidates if found come from ν_μ oscillation into ν_e, rather than K_{e3} decay. For 10^{19} protons we expect approximately 400 ν_μ events. The limit of sensitivity is given by the ν_e flux as shown in Figure 8. At this limit of sensitivity (for $\sin^2 2\theta = 1$) we can set a limit of $\Delta = m^2_{\nu\mu} - m^2_{\nu e} \leq 0.05\ \mathrm{eV}^2$ at 90% CL.

Because of possible conflicts with other experiments, it may be necessary to use 19 GeV protons, increasing both the ν_μ energy and the ν_e background. In this circumstance we expect approximately 130 ν_μ events per 10^{19} protons and can set a limit of $\Delta < 0.12\ \mathrm{eV}^2$ at 90% CL.

C. $\nu_\mu \to \nu_\tau$ Oscillation

By measuring the NC/CC ratio this experiment is sensitive also to ν_μ oscillations into ν_τ, which all interact as neutral currents because the ν_τ energy is essentially below the ν_τ CC threshold due to the large mass of the τ. Figure 9 shows the NC/CC ratio as a function of the oscillation probability. We estimate the sensitivity of this method is $\Delta \leq 0.5\ \mathrm{eV}^2$. As an experimental check, the momentum dependence of the NC/CC ratio should correspond to the oscillation predictions.

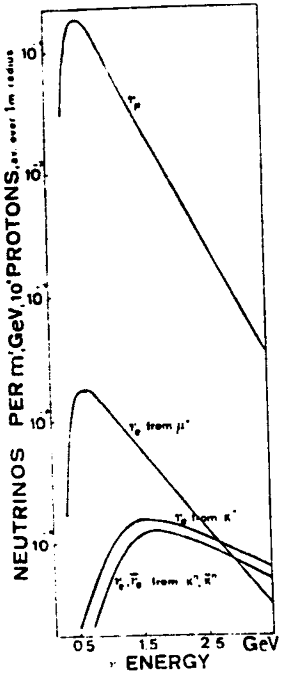

Figure 8) The calculated ν_μ and ν_e spectra in BEBC for 12 GeV protons from the CERN PS.

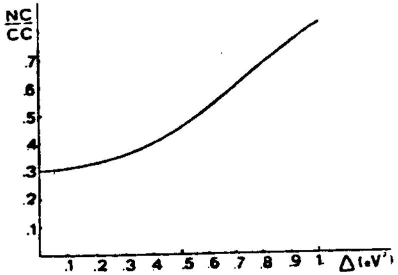

Figure 9) The ratio of neutral current to charged current events as a function of the mass difference squared.

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THE NEUTRINO BEAM DUMP EXPERIMENT AT FERMILAB (E613)

R. Ball, C.T. Coffin, H.R. Gustafson, L.W. Jones, M.J. Longo,
T.J. Roberts, B.P. Roe and E. Wang
University of Michigan, Ann Arbor, MI 48109

M. Duffy, G. Fanourakis, R.J. Loveless, D.D. Reeder
D. Schumann and E. Smith
University of Wisconsin, Madison, WI 53706

M. Crisler, J. Hoftun, T.Y. Ling, T. Romanowksi and J. Volk
Ohio State University, Columbus, OH 43210

G. Conforto and A. Raspini
University of Florence, Firenze, Italy

S. Childress
University of Washington, Seattle, WA 98195

Presented by: M. Longo

ABSTRACT

E613, an experiment to study prompt neutrino production, is now set up in the M2 beam line at Fermilab. In contrast to the pioneering ν beam dump experiments at CERN, our experiment was specifically designed to study ν's from the decay of charmed (or other massive) particles. The detector, a 200 ton lead-scintillator calorimeter, is approx. 60 m from the target in comparison to the CERN detectors which were ≃ 900 m. As a result, our event rates will be many times higher and background from non-prompt ν's much lower. Our experiment will be sensitive to $\nu_e \rightarrow (?)$ oscillations if $\delta m^2 \gtrsim 100\ eV^2$. For favorable δm^2 we would be sensitive to $\sin^2 2\alpha \geq 0.1$.

E-613 had a test run last May with approx. half the detector in place and instrumented. We expect to resume detector tuneup and data taking this November. During the test run the muon background in our detector was higher than expected. This problem will be solved by adding more passive shielding ahead of the detector.

The layout of the experiment is shown in Fig. 1. The proton beam is incident from the left on a thick target (tungsten, copper, or beryllium). The pitching magnet just ahead of the target pitches the beam up about 5 mr so that the prompt neutrino events in our detector will be centered well above background ν events from upstream sources. The target is immediately followed by a beam dump consisting of approx. 11 m of magnetized iron and another 11 m of unmagnetized iron.