SEARCH FOR NEUTRINO OSCILLATIONS AT LAMPF*

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ABSTRACT

We propose an experiment at LAMPF to measure neutrino oscillations; $\bar{\nu}_u \rightarrow \bar{\nu}_e$ using optical detectors. The proposed sensitivity in δm^2, without neutron detection, is 0.03 - 0.05 $(eV)^2$. The detector, when filled with liquid scintillator, can study $\bar{\nu}_u \rightarrow \bar{\nu}_e$ oscillations by detection of e^+-delayed neutron coincidences. If successful, this technique could significantly increase signal to background ratio and provide increased sensitivity to δm^2. Our first order estimates show that δm^2 = 0.003 - 0.005 $(eV)^2$ with neutron-detection technique. The system would be useful to do subsequent neutrino experiments, either at LAMPF or at PSR and with higher energy neutrino beams. The principal request of LAMPF is for construction of a tunnel of approximate dimensions: diameter 5 m, length 150 m, at a depth of ~ 25 m to 35 m.

THEORETICAL DISCUSSIONS AND SOME PREVIOUS EXPERIMENTS

"There is no good reason or principle which requires neutrinos to be massless. For neutrinos with non-zero mass, there is no good reason or principle to avoid a mismatch between mass eigenstates and weak eigenstates."[1] In this situation, neutrino oscillations are to be expected at some level.[2] From a standard model, for simplicity, we assume two neutrino states, ν_1 and ν_2 with masses m_1 and m_2. The ν_e and ν_u are mixed states:

$$\nu_e = \nu_1 \cos\theta + \nu_2 \sin\theta \qquad (1)$$

$$\nu_\mu = -\nu_1 \sin\theta + \nu_2 \cos\theta \; .$$

Call $P_{\nu_e \rightarrow \nu_e}$ the probability of a type ν_e to remain itself after traveling a distance x (m), we have:

$$P_{\nu_e \rightarrow \nu_e} = 1 - \tfrac{1}{2}\sin^2\theta 2 \, (1 - \cos \frac{2\pi x}{L}) \qquad (2)$$

where L is the oscillation length, given by:

$$L(m) = \frac{2.5 \, E_\nu(\text{MeV})}{\delta m^2 (eV)^2} \qquad (3)$$

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TABLE I

EXISTING EXPERIMENTS ON ν-OSCILLATION AND THEIR SENSITIVITIES

Experiment	Accelerator	Oscillation	L(m)	E(MeV)	δm^2 $(ev)^2$
Solar neutrinos	Solar source	$\nu_e \rightarrow \nu_e$	1.5 x 10[illegible]	5	3.6×10^{-6}
Reactor	Savannah River	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	6	4	0.8
Medium Energy	CERN (Gargamelle)	$\nu_\mu \rightarrow \nu_e$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_e \rightarrow \nu_e$ $\bar{\nu}_e \rightarrow \bar{\nu}_e$	50	2×10^3	16
Medium Energy	BNL	$\nu_\mu \rightarrow \nu_\mu$	100	150	0.4 - 1.0
Medium Energy	LAMPF (Willis, et al.)	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	10	40	1
Medium Energy	LAMPF (Chen, et al.)	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	10	40	0.15
High Energy	CERN	$\nu_\mu \rightarrow \nu_e$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_e \rightarrow \nu_e$ $\bar{\nu}_e \rightarrow \bar{\nu}_e$	450	5×10^4	49

where $\delta m^2 = |m_1^2 - m_2^2|$.

Several experiments have been designed to measure neutrino oscillations. At LAMPF, we had an experiment basically proposed to study the additive and multiplicative law of lepton numbers.[3] The oscillation of the neutrinos can be extracted from this experiment. Table I shows the sensitivity of this experiment together with other experiments in the world.

We will discuss the results in turn:

1) Solar source neutrino experiment:[4] The observed neutrino oscillation

$$P_{\nu_e \rightarrow \nu_e} = \frac{\text{observed events}}{\text{calculated events}} = \frac{1.74 \pm 0.4 \text{ SNU}}{4.7 \text{ SNU}} = 0.37 \; . \qquad (4)$$

2) Reactor experiment:[5] This experiment was basically designed to measure charged current and neutral current events.[6] In this experiment NC of reaction $\bar{\nu}_e d \rightarrow n \, p \, \bar{\nu}_e$ has been observed with the CC

process $\bar{\nu}_e d \to nne^+$ using a D_2O target of 268 kg. Submerged in D_2O are He^3 filled gas proportional counters for neutron detection. The recently publicized result is:

$$R \equiv \left(\frac{CC}{CC}\bigg|\frac{expt}{theo}\Big/\frac{NC}{NC}\bigg|\frac{expt}{theo}\right) = 0.43 \pm 0.17 \ . \qquad (5)$$

It seems that systematic errors in this experiment are not well understood. We are not convinced that the data are adequate to show that there is oscillation in this experiment. Another reactor experiment performed at a reactor at Grenoble sees no effect on this mode at a much better sensitivity (this conference report).

3) LAMPF (1978) - Muon number conservation experiment: This experiment was performed, as mentioned above, to measure the ratio $\frac{\mu^+ \to e^+ \bar{\nu}_e \nu_\mu}{\mu^+ \to \text{all}}$. The results confirm the additive law of muon number, i.e., the standard V-A belief, and the ratio is -0.001 ± 0.040. This value can be used to extract the percentage of neutrino oscillation. The average ν_μ energy at LAMPF is 40 MeV, at a distance of 8 m, $\frac{L}{E} = \frac{8}{40} = 0.2$, as compared with the maximum oscillation of the reactor experiment at $\frac{L}{E} = 1.5$. The absence of neutrino oscillation in the LAMPF experiment gives the upper limit of $\delta m^2 \le 1.0\ (eV)^2$ for the $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation.

To conclude the first part of this proposal, we would mention the theoretical work on the grand unified theories where the neutrino is expected to oscillate at some level.

In GUT of the strong, weak and electromagnetic interactions, in which baryon and lepton number are generally not conserved, neutrinos are likely to have non-zero masses. In the simplest grand unified model, the SU(5) model,[7] this does not occur, because there are no right-handed neutrinos that could combine with the left-handed neutrinos to form a massive Dirac fermion, and a Majorana mass term for the left-handed neutrinos is prevented by the exact conservation of baryon minus lepton number. The next simplest model is O(10),[8] which unites the fermions of each generation very elegantly. The O(10) model does contain right-handed neutrinos, and they raise an apparent difficulty. Unless eliminated in some way, the right-handed neutrinos will combine with the left-handed neutrinos to form Dirac fermions with mass comparable to the usual quark and lepton masses. Recently, it has been pointed out[9] that this can be avoided if the right-handed neutrinos receive a large Majorana mass. (A Majorana mass term is simply an ordinary mass term which violates fermion number conservation by coupling two fermions or two antifermions rather than a fermion and an antifermion.)

In such a theory, the left-handed neutrino will itself acquire a small but perhaps detectable mass. In fact, in the absence of the Majorana mass of the right-handed neutrino, one could describe the right-handed and left-handed neutrinos by a two-by-two mass matrix

$$\begin{pmatrix} 0 & m \\ m & o \end{pmatrix} \qquad (6)$$

where m, as we have noted, has the magnitude of a typical quark or lepton mass. Including the large mass M of the right-handed neutrino, the mass matrix becomes

$$\begin{pmatrix} M & m \\ m & o \end{pmatrix} . \qquad (7)$$

For M >> m, the eigenvalues of this matrix are approximately M and $\frac{m^2}{M}$. The mass of the left-handed neutrino is $\frac{m^2}{M}$.

It is possible to produce the large mass M at the free level if one includes a 126-plet of Higgs scalar. However, the vacuum expectation of the 126 is then a free parameter, so there is no prediction as to the value of M. Witten[10] has looked at the mechanism of the neutrinos acquiring mass at the two-loop level. Then the right-handed mass can be calculated to be:

$$m_{\nu_R} = \frac{mq}{Mw}\,\varepsilon\left(\frac{\alpha}{\pi}\right)^2 M \ . \qquad (8)$$

If $M = 10^{15}$ GeV, $\varepsilon = \frac{1}{10}$, then $m_{\nu R} = 10^7$ mq. For mq = 5 MeV for up quark, $m_{\nu R} = 10^5 - 10^6$ GeV. The mass of the ordinary left-handed neutrinos can be found from the matrix:

$$\begin{pmatrix} m_{\nu_R} & m \\ m & o \end{pmatrix} . \qquad (9)$$

In O(10) model with a single Higgs 10, m = mq, the up quark mass. (This is analogous to the well-known relations $m_\tau = m_c$, $m_s = m_\mu$, $m_d = m_e$.). Then,

$$m_{\nu_L} = \frac{m_q^2}{m_{\nu_R}} \quad \text{and} \quad m_{\nu_L} = \frac{m_q}{\varepsilon(\alpha/\pi)^2}\frac{M_W}{M} \qquad (10)$$

with $M = 10^{15}$ GeV, $\varepsilon = \frac{1}{10}$, $m_{\nu_L} = 10^{-7}$ for each generation.

For the electron neutrino, this means $m_{\nu_e} \simeq \frac{1}{3}$ eV, while the muon neutrino $m_{\nu_\mu} \simeq 10^{-7}\ m_c \simeq 100$ eV and $m_{\nu_\tau} \simeq 10^{-7}\ m_t \simeq 1 - 10$ KeV. Experimentally, we know $m_{\nu_e} < 35$ eV, $m_{\nu_\mu} < 510$ KeV, $m_{\nu_\tau} <$ few hundred MeV. However, there is a much more stringent bound of cosmological origin. In order for neutrinos remaining from the big bang not to exceed in mass the total cosmic density, the sum of all neutrino masses must be less than about 40 eV. (A review has been given by Weinberg.) Extra suppression has to be found to be consistent with the cosmological bound. The richness of the O(10) model is used here only as an example of mechanisms where neutrinos could acquire masses and could oscillate. The main task of experimentalists is to find the best way of pushing the limit of δm^2 to a smallest value within reasonable time and effort. Except for solar neutrino sources, we have found that from the economic standpoint,

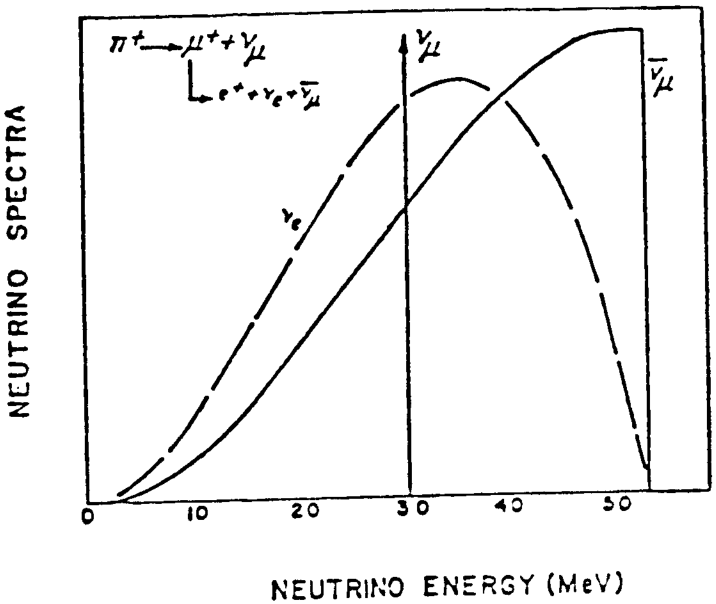

Fig. 1. LAMPF neutrino beam.

LAMPF is the only place where the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ mode could be investigated to a δm^2 of < 0.1 $(eV)^2$ for the least amount of tonnage of the detector. The sensitivity of the proposed experiment will be discussed in detail.

SENSITIVITY OF A NEW LAMPF NEUTRINO OSCILLATION EXPERIMENT

The neutrino spectrum at LAMPF is shown in Fig. 1, and will be discussed in the design section.

Suppose a detector with proton target is used. A segmented water Cerenkov counter setup is ideal for this purpose. From Fig. 1, ν_e and ν_μ do not interact with protons from charge conservation $(\Delta Q = 2)$. We may have the reaction:

$$\bar{\nu}_\mu p \rightarrow \mu^+ n \qquad (11)$$

but this would not occur due to energy conservation. If there is no oscillation, a water target detector would see only background, mostly due to cosmic rays. However, if oscillation exists, we would see e^+ in the final state from the reaction:

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e p \rightarrow e^+ n \ . \qquad (12)$$

If $P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e}$ is the probability of a $\bar{\nu}_\mu$ oscillating to $\bar{\nu}_e$ at a length of X, we can write

$$P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e} = \sin^2 2\theta \, \sin^2 \frac{(1.27)(X)(\delta m^2)}{E_{\bar{\nu}_\mu}} \ . \qquad (13)$$

In the absence of a signal, one can estimate the sensitivity of the experiment as follows: assuming maximum amplitude, $\sin^2 2\theta = 1$, then knowing the background and expected signal, one can calculate the sensitivity. Table I shows the typical sensitivities of existing experiments. For the proposed experiment, we have parametrized the cross section of $\bar{\nu}_e p \rightarrow e^+ n$ [11] at LAMPF energy to be:

$$\sigma = 1.3 \times (3.465 \times 10^{-3} E^2_{\bar{\nu}_e} + 0.1755 E_{\bar{\nu}_e} - 1.870) \times 10^{-41} \ cm^2 \ , \qquad (14)$$

where E is in MeV. From the decay of μ^+, $\bar{\nu}_\mu$ spectrum can be simply parametrized as:

$$\frac{dN}{dE_{\bar{\nu}_e}} = No \ E_{\bar{\nu}_e} \equiv No \ E \ . \qquad (15)$$

Assuming a 750 μA primary proton beam with A_1, A_2, A_3 target inserted, we have 1.73×10^{12} $\bar{\nu}_\mu$ per day at 10^m from the beam stop. Then:

$$No \int_0^{52.8} E dE = N_o \frac{E^2}{2} = 1.73 \times 10^{12} \qquad (16)$$

or $No = 1.24 \times 10^9$/day. The integrated cross section of $\bar{\nu}_e p$ for the LAMPF spectrum is:

$$\langle\sigma\rangle = \int_0^{52.8} 1.24 \times 10^9 \, E(3.465 \times 10^{-3} E^2 + 0.1755E - 1.87) \times 10^{-41} \times \frac{2}{18} \times 6 \times 10^{23} \times 4 \times 10^7 \times 0.5$$

$$= 1.3 \ 210\text{/day at a } 10^m \text{ distance} \ . \qquad (17)$$

This is for a 40-ton detector.

The number of counts/day if maximum oscillation occurs is:

<X>m	<σ>/day
10	210 × 1.3
20	52.5 × 1.3
50	8.4 × 1.3
75	3.7 × 1.3
100	2.1 × 1.3

In the following discussions on the sensitivity, we do not take into account the detection of neutrons in coincidence with the e^+. In the absence of a signal, the sensitivity δm^2 of the experiment is background dominated. We have followed the methods of calculation of H. H. Chen (private communication) and data of cosmic ray background from the measurement of H. H. Chen et al.[13] to determine the sensitivity of the experiment. The sensitivity δm^2 is determined by two types of background: the cosmic ray background and the ν-induced background. The latter, with the threshold of 35 MeV on the energy $E_{e^\pm}$, arises mainly from the carbon-13 contamination of the detector material via

$$\nu_e \; {}^{13}C \rightarrow e^- \; {}^{13}N \qquad (18)$$

which has a small Q value. The standard estimate of this background compared with $\bar{\nu}_e p \rightarrow e^+ n$ is 1:500. In the experiment, this background starts to dominate after a running time greater than 180 days (or more, depending on the nature of the gamma background).

In this proposal, the ν_e background is negligible compared with the cosmic ray background since the cosmic ray background is independent of distance <X> in the range 10 m - 300 m, while the former decreases quadratically with distance. From Ref. 13 and from private communication with H. H. Chen, we believe that most, if not all, neutral background is due to gamma rays, which may come from either muon bremsstrahlung or muon-decay electron bremsstrahlung. Muon bremsstrahlung will be vetoed if it is directed towards the detector. Only bremsstrahlung which arises from the dirt shield on the periphery of the detector would not be vetoed. Hence these muon bremsstrahlung gammas would scale with the linear dimension of the detector, i.e., $m^{1/3}$ where m is the detector mass.

The electron bremsstrahlung gammas will scale as $m^{2/3}$. Since the ratio of the two mechanisms is not known, we will estimate the background from two extreme cases. In case A, m scales as $m^{1/3}$ and in case B, as $m^{2/3}$. The measured cosmic ray background in a ±15° backward and forward cone in a 0.4-ton test detector was 1.5 event/day. H. H. Chen advised that with longer time delay between the μ and e, and with better coverage of the veto counter cracks, the number is 1/day or 0.06 event/Los Alamos day, taking 6% duty cycle into account. With a 40-ton test detector (a 30-ton detector would change the δm^2 by 10% only), 50% efficiency, the full solid angle value of the background is 1.4 event LA day for case A and 6.4 event/LA day for case B. We have taken a reduction of 3.0 due to 25 m of the tuff shielding in this estimate. The thickness of gamma absorber is 4 inches of lead.

In 200 days of running the signal S is:

$S = 280 - 280 = 0 \pm 16.7$ (case A)

$S = 1280 - 1280 = 0 \pm 35.8$ (case B).

The probability of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ is then:

$$P = \frac{0}{S_o} \pm \frac{16.7}{S_o} \quad \text{(case A)}$$

$$P = \frac{0}{S_o} \pm \frac{35.8}{S_o} \quad \text{(case B)} \qquad (19)$$

where S_o is the number of $\bar{\nu}_e p$ cc expected if the maximum oscillation occurs. For $\sin^2 2\theta = 1$, $\langle E \rangle = 35.2$ MeV, $S_o = 270 \times 200(10/\ X\ )^2$, (we have used the same calculation for signal of H. H. Chen, where the cross section is 30% higher):

$$\sin^2 \frac{1.27 \langle X \rangle \, \delta m^2}{35.2} = \frac{16.7}{5.4 \quad 10^6} \langle X \rangle^2 \quad \text{(case A)}$$

$$\sin^2 \frac{1.27 \langle X \rangle \, \delta m^2}{35.2} = \frac{35.8}{5.4 \quad 10^6} \langle X \rangle^2 \quad \text{(case B)} \qquad (20)$$

and

$$\delta m^2 = \frac{\sin^{-1}(1.82 \times 10^{-3} \langle X \rangle)}{3.6 \times 10^{-2} \langle X \rangle} \quad \text{(case A)}$$

$$\delta m^2 = \frac{\sin^{-1}(2.67 \times 10^{-3} \langle X \rangle)}{3.6 \times 10^{-2} \langle X \rangle} \; . \quad \text{(case B)} \qquad (21)$$

These sensitivities as functions of distance and running time are shown in Table II and in Fig. 1A.

The ν-induced background is now estimated. From Willis et al.,[14] the background due to ${}^{12}C$, ${}^{16}O$ is negligible when the threshold of the energy $E_e \pm > 35$ MeV. However, the background due to ${}^{13}C$ is 2×10^{-3} of the signal $\bar{\nu}_e p \rightarrow e^+ n$. We then have:

$$\sin^2 \frac{1.27 \langle X \rangle \, \delta m^2}{35.2} = 2 \times 10^{-3}$$

$$\delta m^2 = \frac{\sin^{-1}(4.47 \times 10^{-2})}{3.6 \times 10^{-2} \langle X \rangle} \; . \qquad (22)$$

The sensitivity δm^2 gets better as <X> increases for this type of background. Also, we can see that it is independent of the running time. At <X> = 50 m, $\delta m^2 = 0.025 (\mathrm{eV})^2$ (Table II and Fig. 1A).

The dependence on the mass of the detector is slow. We can see, for non-ν background:

$$\delta m^2 \propto m^{-\frac{5}{12}} \, T^{-\frac{1}{4}} \quad \text{(case A)}$$

$$\delta m^2 \propto m^{-\frac{1}{3}} \, T^{-\frac{1}{4}} \quad \text{(case B)} \; . \qquad (23)$$

These calculations, as mentioned earlier, do not take into consideration the detection of neutrons in coincidence with e^+ in the final state. With this coincidence scheme, the sensitivity δm^2 will become better than the numbers quoted; how much better depends on the neutron detection efficiency and on the delay time between the e^+ and the neutron.

TABLE II

40-TON DETECTOR

$<X>$ m	δm^2 (eV)^2		
	From Cosmic Ray		From ν
	Case A	Case B	
10	0.030 (0.034)	0.050 (0.055)	0.125
50	" "	" "	0.025
100	" "	" "	0.013
150	" "	" "	0.010
200	" "	" "	0.006
300	" "	" "	0.004

The number in parenthesis is for a 30-ton detector.

The final estimate of the sensitivity with neutron detection in coincidence with the position depends on several parameters. Basically, about 30% of the events will have a neutron of threshold 1 MeV/c which traverses 40 cm of scintillation in 16 ns. From H. H. Chen et al. background study, with 24-in. × 48-in. slab viewed by only one phototube, the single cosmic ray or tube noise background is 226/s. The threshold was 8 MeV. This study shows the background does not change more than 20% with threshold lower than 4 MeV. Triple coincidence study shows that most of this background is due to tube noise. Using this number, we expect 165 events/s background in 70-in. × 12-in. slab. The probability of seeing a background event within 16 ns is 7.9×10^{-6} if any of the three slabs that detect e^+ fires. Running for 200 days, we expect to see 2.4×10^{-3}. With neutron detection, the real event rate will be reduced by a factor of 8.3, assuming 30% detection efficiency due to neutron threshold and 40% light detection efficiency. The δm^2 varies as the square root of the probability of oscillation $(\frac{n}{So})^{1/2}$. The numerator will decrease by $\sqrt{343}$ and the denominator will decrease by $\sqrt{8.3}$. The final sensitivity will be improved by a factor of 6.4. As mentioned before, with phototubes at both ends of the slab, we would reduce the tube noise considerably, hence, an improvement of a factor of 10 in δm^2 may not be too unrealistic.

THE DETECTOR SYSTEM

A. Design Principles. The detection system that we propose to employ has been arrived at by consideration of the following design principles:

Low costs • Every component of the overall system has been judged against competing effective technologies by comparing costs.

Tunnel • The principal passive shielding of the detector will be achieved by placing the detector system in a deep tunnel, bored in the tuff adjacent to the beam stop.

Portability • Since the principal dynamic signature of the effect to be sought (neutrino oscillation) is that of oscillation with distance, the detector(s) must be portable.

Signal to background enhancement • This is a major aspect of the proposed design and new methods of accomplishing this feature are proposed that allow the coincident detection of the e^+ and n particles produced in the final state of $\bar{\nu}_\mu \to \bar{\nu}_e p \to e^+ n$.

B. Kinematics of the Reaction $\bar{\nu}_\mu \sim \bar{\nu}_e p \to e^+ n$. In Fig. 1 the spectra of the three types of neutrinos produced at the beam stop are shown. It is noted that a majority of the $\bar{\nu}_\mu$ spectra lies between 30 and 53 MeV. This is the band of $\bar{\nu}_\mu$ energies that we will seek to employ to detect the oscillation $\bar{\nu}_\mu \sim \bar{\nu}_e$ through the reaction $\bar{\nu}_e p \to e^+ n$.

We do not expect significant contamination of electronic events in the detected final state due to the ν_μ or ν_e beams since the reactions are either energetically forbidden or are highly suppressed by the detector not having "free neutrons" as targets.[12]

Typical kinematics of the sought-for reaction is shown in Fig. 2. It is also important to recall that for $E_{\bar{\nu}_e} \sim 30 - 50$ MeV, the angular distribution (laboratory or c.m.) of the electrons is almost spherically symmetrical. Thus we note that

The e^+ are produced almost uniformly in all directions, and of almost a constant energy (and range) which is approximately equal to the $\bar{\nu}_e$ energy. The range R of these electrons is $6 < R < 9$ in. in CH_2 approximately.

The neutrons are produced with $0 < E_n < \sim 4$ MeV with about half of the forwards neutrons having an energy of $1.0 < E_n < 4$ MeV. These neutrons have flight times of $35 <$ TOF Neutron < 70 nsec/m and have a very large probability of producing a recoil proton (of energy $> 1/4\ E_n$) in a one meter flight through H_2O or CH_2 material.

These kinematic facts suggest that a Cerenkov or liquid scintillation detector can measure the electron energy, that a segmented scintillator or Cerenkov detector can crudely measure the electron range, and that a segmented scintillation detector can also detect the neutron by its time of flight.

These features of the kinematics along with the general principles stated above are used to arrive at a detector design.

C. Preliminary Detector Design.

The detector • We propose that a modular detector be constructed in one or more Sea Containers (SC). These inexpensive, standardized steel containers have the specifications: Dimensions--8' × 8' × 20'; Weight--(net) 2 tons (metric); Internal Load--20 tons; Top Load--40 tons. The sensitive volume of this detector would be about 15 tons. See Fig. 3.

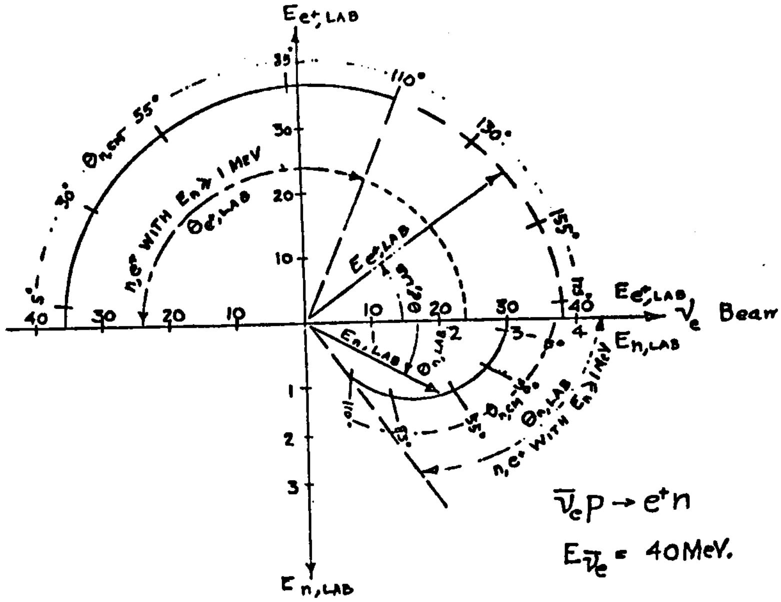

Fig. 2. $\bar{\nu}_e p \to e^+ n$

$E_{\bar{\nu}_e}$ = 40 MeV

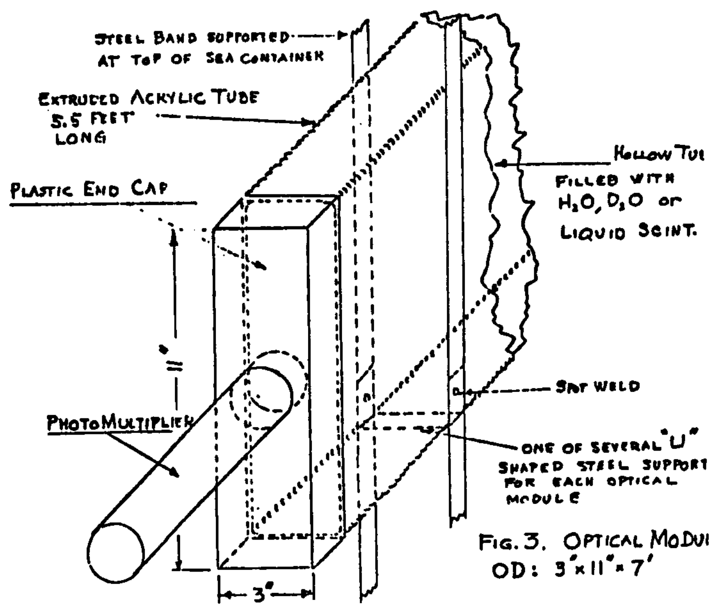

Fig. 3. Optical Module

OD: 3" × 11" × 7'

The scintillation modules • The sensitive detector volume would be composed of tightly-packed modules (432 modules) each with the specifications:

- mass ∿ 75 lbs. (filled with H_2O, or CH_2)
- length 5'6"
- height 11"
- width 3" .

These modules, each made of a thin walled, extruded acrylic, rectangular cross section tube, would be sealed at each end with plastic end caps, carrying an optically coupled photomultiplier, PM. The system would require about 864 PM. A similar system has been successfully developed and prototyped by BNL/Penn/Brown neutrino collaboration, and a 170 ton instrument is nearing completion. We have been very impressed with this technology since it seems to fit nicely into our general design principles as well as being adaptable to our particular goals for this experiment.

For this detector, using loose black plastic paper light shields around the acrylic a pulse height loss, from 0 to 5.5', is expected to be only 1/3 due to the excellent light collection resulting from good internal reflection. Thus the difference of P.H. at the two ends will allow a reasonable measure of position of the event along the long dimension and the summed, corrected P.H. should allow a good meausre of the electron energy (with H_2O C light or with liquid scintillation CH_2 material). These modules are expected to result in $\Delta PH/PH \simeq 0.1$. The light flash TOF difference (time of flight) to the two ends will also give a reasonably good position measurement. Using NE235A mineral oil, CH_2, scintillation liquid, the device will also allow neutron detection by np elastic scattering of 1 - 4 MeV neutrons and will allow their TOF to be measured.

The BNL/Penn/Brown devices (longer: 4m) have a simple method of independent support of each module using thin steel banding materials. This technique allows very close packing of the modules, with very little mass in the supports.

A module is shown in Fig. 4. A total of 432 of these modules would comprise one S/C detector, as shown in Fig. 3.

The electronics system • Each P.M. will have an electronic system that will record, temporarily, the pulse height, PH, and time T, after a trigger pulse, of each pulse above a selected threshold. Unless a readout command, RO, is received within a holding period, the PH and T will be reset and the PM output will be allowed to be sensitive again. The goal of the design is to make the system a four-dimensional bubble chamber.

Various Space-Time Topologies will be used as triggers. For example, an Event, E, trigger could be defined as:

$$\text{Event} \equiv 2 \text{ or more adjacent modules triggered}$$

within a time $\tau (\tau \simeq 5$ ns) and $30 < \Sigma PH < 60$ MeV with the constraint that the anti-coincidence shield was not fired and the near-surface modules were not fired preceding the Event by, e.g., 30 μsec. This

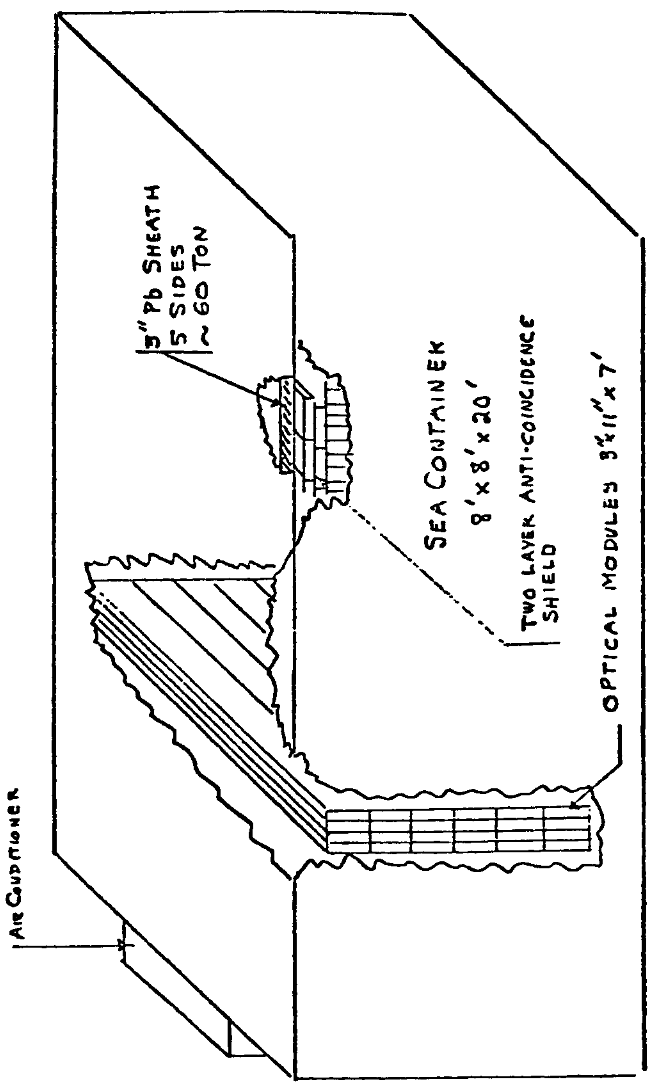

Fig. 4. One sea container detector system.

Event logic satisfaction would then be followed by a Readout RO command.

Upon RO, the Event P.H. (e^+ energy and range) and module numbers, would be read out. There are two additional possibilities: either (1) there is or (2) is not a pulse, PH > $\sim$ 0.5 MeV, in any module in the downstream detector volume. Such an event might correspond to a coincident, TOF, neutron occurring at a TOF of less than 200 nsec.

This logic would allow all possible $\bar{\nu}_e p \to e^+ n$ electronic events to be recorded and not be confused with stopping $\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$ events of the same e^+ energy. However, it also allows a subset of these events to be identified with TOF coincident neutrons. The efficiency of the electronic part of the event should be very high ($\to$ 100%) while that of also detecting the TOF neutron in proper delayed coincidence is expected to be about 30%. We estimate the cosmic ray accidental background for this e^+n detection as being only 10^{-4}.[13]

This trigger exemplifies the great power of the proposed method: The electronic (e^+) signal still has the possibility that it was a γ-ray induced event, that penetrated undetected elsewhere, to produce the electron E and R. However, observing the neutron in delayed coincidence strongly reduces this background with only a modest loss of event rate but with greatly enhanced signal-to-noise ratio.

Another Space-Time Topology that is of great interest is that due to stopping $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ decays since they are one of the largest backgrounds of possibly interfering electronic events. However, our proposed system would identify these events and would use them to calibrate automatically the system in real-time. This topology could be defined as Stopping Mu-Decay.

Stopping Mu-Decay $\equiv$ coincidence of anti-shield and one or more detector modules, but no bottom modules to provide RO of all modules after a recording time of, say, 30 μsec. If, in addition, on-line software analysis showed that there were several adjacent modules that received 30 to 50 MeV of summed energy, then this event would be recorded as a μ-decay. These events, very numerous, would probably be scaled by a large factor, and only a fraction recorded to tape. However, they would provide an excellent on-line check of system operation, timing and energy calibration of all modules. It is noteworthy that these μ-decays should not have a delayed neutron pulse.

Additional possibilities for the system include identifying e^+ (against e^-) events by annihilation γ-ray detection and slow neutron detection via np capture gamma ray detection. However, these will not be discussed in detail now.

Computer system • A sophisticated on-line computer system will be required for the experiment. The proposers are very experienced in the development and use of modern fast electronic data handling systems and are very confident that the proposed system can be quickly and effectively built.

The tunnel and anticoincidence shields • (1) We regard the results of the work of H. H. Chen[13] and collaborators and of H. Kruse and collaborators studying cosmic ray backgrounds to be very encouraging. We shall test various passive coincidence shielding techniques with test modules in vaults in the Omega Canyon. However, it is our present hope that the shielding will consist of tuff alone, which will considerably simplify the problems of detector mobility, detector maintenance, and lower the construction costs of the tunnel, especially the strength of the floor. We, therefore, tentatively request, contingent upon further testing, that a 5 m diameter tunnel be bored into the tuff of depth 35 m and of length 150 m, stopping 20 m before the beam stop with a flat floor. We would suggest that narrow gauge railroad tracks be laid for easy transport of detectors along the tunnel. We plan that all detection apparatus used in a tunnel of this depth be sufficiently light ($\sim$ 60 tons) so that no serious loading problems will arise.

(2) Since our proposed apparatus consists entirely of modules sensitive and highly efficient for the detection of all charged particles, we in principle need no active anticoincidence shield. However, to maximize the active volume useful for neutrino detection, we will arrange the scintillators on the outer perimeter of each (SC) module and the internal scintillators as well so that the probability of any charged particle entering the detector and stopping or interacting without producing a detectable signal in at least one module beforehand is less than 10^{-8}. We will, however, build some 15-20% additional identical modules if necessary which can be filled with liquid scintillator and used for an anti-shield against charged particles with an inefficiency of less than 10^{-3} when appropriately arranged.

Tunnel • We advocate that the previously mentioned tunnel be built as the Laboratory's contribution to the Neutrino Facility. Any variety or number of neutrino detectors may be located in this tunnel as long as the loading is not too great. We therefore emphasize that it should be deep enough so that no additional heavy shielding is needed other than tuff and that a railroad track be build for easy transport of equipment along it.

Because of implications on the expansion of the universe, the question of the existence of neutrino mass continues to be of interest to cosmologists. Basically, within clusters and groups of galaxies, binary galaxies, and halos of galaxies, cosmologists find a discrepancy between the cosmological mass implied by observed rates of expansion and that derived from luminosities. The study of galactic halos yields "rotational curves": the gas velocity distribution, v, as a function of distance to the galactic center, R, is obtained from observations of the Doppler shift of the hyperfine splitting of lines of hydrogen. From the virial theorem, the required mass distribution is:

$$M(R) = \frac{v^2 R}{G} \qquad (24)$$

corresponding to a mass density:

$$\rho = \frac{A}{R^2}, \quad A = 1.3 \times 10^{75} \text{ eV/kpc} \qquad (25)$$

and requires a total mass perhaps an order of magnitude larger than that of the visible, localized component. Cosmologists suggest that the missing mass may be accounted for by neutrinos.[8]

The photon-baryon ratio in the universe is 10^8. Photons are seen as 2.7 K background radiation; their contribution to the universal density is only 10^{-4} that of baryons. A neutrino with a Majorana mass of a few eV/c^2 will contribute as much as the observed baryon density since the number of neutrinos is approximately the same as the number of photons.

Neutrinos of heavy mass ν_H should eventually decay into a lighter ν_L and a photon:

$$\nu_H \rightarrow \nu_L + \gamma \; . \tag{26}$$

Detection of this decay photon can be accomplished with high efficiency in the detector proposed for Exp. 559. The best present limit on the lifetime of this process ($\nu \rightarrow X + \gamma$) is $\tau > 2.6 \times 10^4 \; m_{\nu_\mu} s$ where m_{ν_μ} is in MeV (Rev. Mod. Phys. 52, S17 (1980)).

In the proposed experiment we can improve on this limit by orders of magnitude.

Assuming isotropic decay of ν_μ (or $\bar{\nu}_\mu$) in the ν_μ rest frame, the photon energy is:

$$E_\gamma \simeq 0.5 \, E_\gamma (1 + \cos\Theta_\gamma^{cm}) \; . \tag{27}$$

We have assumed $m^2_{\nu_e} << m^2_{\nu_\mu} << E^2_{\nu_\mu}$. Defining $\Theta_L = m_{\nu_\mu}/E_{\nu_\mu}$ and assuming $\Theta_L << 1$,

$$\frac{\Theta_\gamma}{\Theta_L} \simeq \frac{\sin^2\Theta_\gamma^{cm}}{1 + \cos\Theta_\gamma^{cm} - \frac{\Theta_L^2}{2}} \tag{28}$$

and from this we can see that most of the phase space lies within a couple of degrees in the forward direction. The number of photons that will eventually be detected in the detector is:

$$N_\gamma = \int_{E_c}^{\infty} \varepsilon(E\;) \frac{dN_\gamma}{dE_\gamma} \, dE_\gamma \tag{29}$$

where E_c is the cutoff photon energy and ε is the conversion efficiency. The photon energy spectrum is:

$$\frac{dN_\gamma}{dE_\gamma} \simeq \int_{E_c}^{\infty} \frac{\ell}{cE_\nu} \frac{1}{\tau_o} \frac{dN_{\nu_\mu}}{dE_\nu} \, dE_\nu \tag{30}$$

where ℓ is the length of the detector.

The spectrum of ν_μ is monochromatic at LAMPF, peaking at 30 MeV. The number of photons detected would then be:

$$N_\gamma = \frac{N_{\nu_\mu} \ell}{cE_{\nu_\mu}} \frac{m_{\nu_\mu}}{\tau_o} \varepsilon \; . \tag{31}$$

Assuming 1 mA current, the ν_μ flux per cm^2 per day is 2.3×10^{12} at 10 m, which corresponds to 8×10^{15} ν_μ per day or 9.6×10^{10} per second at 50 m for 3 m × 3 m cross section. The expected background for this process is similar to that of the ν-oscillation, i.e., 1.4 event/day. However, if we have phototubes at both ends of the liquid scintillator in the detector, we may expect 0.7 event/day or 8.1×10^{-6} event/s. For the decay process, since most of the phase space is within ± 7° or less (the multiple scattering is ≃ 7°), an extra suppression factor is obtained:

$$\frac{2 \times 2 \; (1 - \cos 7°)}{4\pi} = 7.5 \times 10^{-3} \; . \tag{32}$$

Hence the number of γ expected is $6 \times 10^{-8}\ s^{-1}$.

The expected limit on the lifetime is:

$$\tau_o > m_{\nu_\mu} \frac{N_{\nu_\mu} \ell \varepsilon}{cE_{\nu_\mu}} \frac{1}{6 \times 10^{-8}}$$

$$\tau_o > m_{\nu_\mu} \frac{9.6 \times 10^{10} \; \nu_\mu \; s^{-1} \times 300 \text{ cm} \times 0.5}{3 \times 10^{10} \text{ cm } s^{-1} \times 30 \text{ MeV} \times 6 \times 10^{-8} \; s^{-1}} \tag{33}$$

$$\tau_o > 2.7 \times 10^8 \; m_{\nu_\mu} \; s \; \text{MeV}^{-1} \; .$$

Since we have both ν_μ and $\bar{\nu}_\mu$ at LAMPF, assuming the decay rate is the same for both ν's, we obtain a further factor of two gain in the lifetime,

$$\tau_o > 5.3 \times 10^8 \; m_{\nu_\mu} \; s \; \text{MeV}^{-1} \tag{34}$$

or a factor of two less if we use a 2 m × 2 m detector.

To conclude, incorporating the ability to measure e^+, e^- in the detector, we can expect to increase the limit on the lifetime of the ν_μ from the present value of $\tau_o > 2.6 \times 10^4 \; m_{\nu_\mu}$ by about four orders of magnitude.

To insure this small background, we propose to sandwich X-Y drift chambers between layers of liquid scintillator. The spatial resolution required is approximately 2 mm, thus the spacing required between sense wires is 10 cm. The readout electronics would cost about \$20,000. The total cost of the chambers, the gas system, and the H. V. system will amount to \$100,000 per module of 15 T detector. This new expenditure is to be incorporated in the detector cost estimate.

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EXPERIMENT TO SEARCH FOR FINITE MASS NEUTRINOS AT LOS ALAMOS

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ABSTRACT

The strong current interest among physicists of the possibility of finite mass neutrinos has resulted in several proposals at Los Alamos for experiments to detect nonzero neutrino masses. I will discuss here three experiments which are now underway and three proposed experiments at LAMPF.

Two experiments are now underway at Los Alamos to look for the oscillation channel $\bar{\nu}_\mu \to \bar{\nu}_e$ by observing $\bar{\nu}_e + p \to n + e^+$. These experiments are being done at the LAMPF beam dump where pion and muon decay at rest generate $\bar{\nu}_\mu$, ν_μ, and ν_e with average energies of about 35 MeV. The contamination of $\bar{\nu}_e$ from μ^- decay is about 1 part in 5000 since these neutrinos originate from π^- production which are strongly absorbed before they can decay. Thus the observation of the $\bar{\nu}_e$ induced reaction $\bar{\nu}_e + p \to n + e^+$ at rates higher than that expected from the small amount of $\bar{\nu}_e$ produced in the beam dump would be taken as evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation.

The first of these experiments is a University of California at Irvine - Los Alamos collaboration (H. Chen et al.). The primary purpose of this experiment is to measure accurately (±10%) the $\nu_e - e$ elastic scattering cross section. However, it will also set a limit of $\Delta m^2 \gtrsim 0.3$ eV^2 for $\bar{\nu}_\mu \to \bar{\nu}_e$. The 14-ton detector is a sandwich detector comprised of plastic scintillator and flash chambers which provide position information on the e^+ in the final state. The assembly sits 10 meters from the LAMPF beam dump and is surrounded by an anticoincidence counter and iron shielding to suppress cosmic-ray backgrounds. The limit of sensitivity of this experiment is due to ν_e interactions on materials like aluminum, ^{13}C, and chlorine in the detector.

The second experiment is a LASL experiment (H. Kruse et al.) originally designed to search for $\bar{\nu}_e$ oscillations at the Nevada Test Site (NTS) using fission weapons tests as the neutrino source and measuring $\bar{\nu}_e$ fluxes at distances up to a kilometer from the source. The detector being developed for the NTS is now being modified to search for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations at LAMPF by observing $\bar{\nu}_e + p \to n + e^+$. The detector consists of 4470 liters of gadolinium loaded liquid scintillator. The positron gives a prompt signal in the scintillator, and the neutron moderates and is