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AN EXPERIMENT TO INVESTIGATE $\bar{\nu}_\mu \to \bar{\nu}_e$ OSCILLATIONS AT LOS ALAMOS MESON PHYSICS FACILITY*

by

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ABSTRACT

An experiment, being planned at LAMPF, aims to investigate a possible neutrino oscillation channel, $\bar{\nu}_\mu \to \bar{\nu}_e$. If $\bar{\nu}_\mu$, produced in the LAMPF beam stop, oscillate to $\bar{\nu}_e$, then interactions $\bar{\nu}_e + p \to e^+ + n$, may be detected.

A large volume liquid scintillator (4470 liter) emplaced at 33 m from the beam stop, detects e^+ and n, after moderation in the hydrogenous liquid and capture in Gd, loaded into the scintillator.

Our anticipated signal rate is currently estimated at 1.67 $(\delta m^2)^2$/day assuming full amplitude oscillation. The corresponding counting rate, assuming all $\bar{\nu}_\mu$ have oscillated to $\bar{\nu}_e$ at the detector is 1.5/day. Cosmic rates are estimated at 0.033/day. Correlated backgrounds from the beam stop are calculated to be small in comparison to cosmic events, except for reactions of ν_e in Pb. These reactions may be reduced with an Fe shield within the detector.

With the above rate, a limit on the sensitivity of our experiment for the value of δm^2 is estimated at 0.12 eV^2 with 70 days of counting.

Detector features, estimated background rates, and sensitivity values are discussed.

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I. INTRODUCTION

The high, current interest in neutrino oscillation experiments is derived from the intense desire to demonstrate a nonzero neutrino mass. Experimental determination of upper limits on the oscillation coefficients provides important tests of unified theories.[1] We are currently fielding an experiment to investigate one possible oscillation mode, $\bar{\nu}_\mu \to \bar{\nu}_e$ with improved sensitivity over previous results.[2] In the two-state oscillation problem, the probability of a $\bar{\nu}_e$, given a $\bar{\nu}_\mu$ by a weak decay, at a distance X, is

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = [a]^2 \sin^2(1.27 \frac{\delta m^2 X}{E_\nu}) \quad (1)$$

where the neutrino energy, E_ν, is in MeV, X is in meters, and δm^2 is in eV^2. The quantity $\delta m^2 = m_2^2 - m_1^2$, where m_1 and m_2 are the masses of neutrino mass eigenstates in oscillation.

At Los Alamos Meson Physics Facility (LAMPF) $\bar{\nu}_\mu$ are generated from the decay of μ^+ in the beam stop. If these $\bar{\nu}_\mu$ oscillate to $\bar{\nu}_e$, they may be detected in our detector by the inverse β decay reaction,

$$\bar{\nu}_e + p \to e^+ + n \quad . \quad (2)$$

For small values of the function argument in Eq. (1), the sensitivity is nearly independent of detector distance; the signal varies inversely with X^2 but the probability in Eq. (1) increases directly as X^2. For our anticipated neutrino energy range of 20 to 53 MeV, the argument is sufficiently small for values of X up to ~ 70 m, provided a null result is obtained with a corresponding upper bound of ~ 0.1 eV^2 for δm^2. Consequently, we have chosen a value for our detector distance of 33 m, primarily influenced by convenience of logistics and adequacy of shielding from the beam stop. If, however, a positive signal is observed at the value of the limit for δm^2 previously determined,[2] 0.9 eV^2, then our signal will be reduced by a factor of 1.2 at 53 MeV and a factor of 3.9 at the threshold of 20 MeV.

In order to compare various proposed experiments, it is useful to compute a sensitivity to δm^2 based on a presumed null result, as will be described. If a <u>positive</u> result should be observed, then a huge incentive will have been generated for relocating the detector at other positions, thereby seeking confirmation of the oscillation phenomenon.

II. DETECTION EFFICIENCY

The detector features and characteristics have been described in detail elsewhere.[3] A central volume (4470 liter) of xylene-based liquid scintillator contains 2.2×10^{29} free proton targets. A bank of 20 cm-dia photomultipliers (EMI D340 B) views the scintillator and converts the positron energy deposition into an electrical signal. The neutron generated in reaction (2) moderates in the scintillator until captured in Gd, which is dissolved in the scintillator. Upon capture, gamma rays are produced with 8 MeV total energy. These two events, occurring within the moderation time of ~ 30 μs, constitute a signature for reaction (2).

Calculated detection efficiencies for various factors have been described[3] for the configuration illustrated in Fig. 1. Currently, these values are estimated as follows: dead time factor, 0.98, assuming 25 μs gate time on the anticoincidence events; positron detection efficiency, 0.77, assuming 20 MeV threshold; neutron capture probability, 0.8, assuming 0.5% Gd loading, and capture within a gate time of 27 μs; neutron capture gamma detection efficiency, 0.77, assuming 4 MeV threshold. A total detection efficiency of 0.46 is thus anticipated although actual operating conditions and measured values for efficiencies may alter this value.

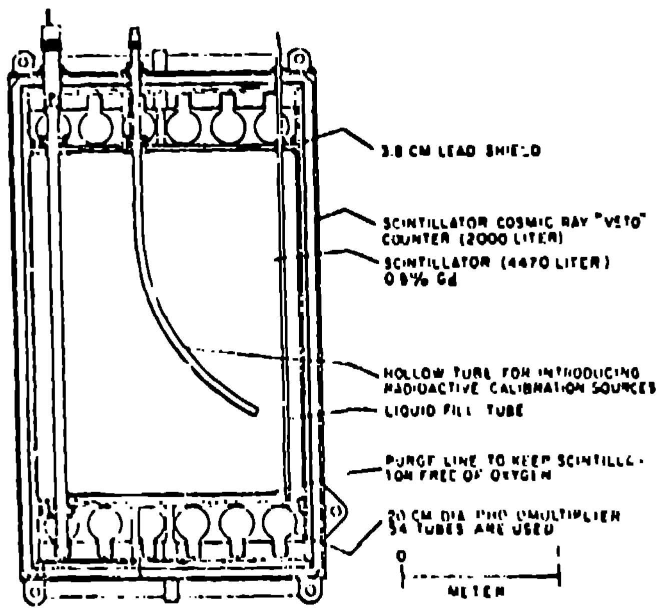

Fig. 1. Neutrino Detector Assembly

III. SIGNAL RATES

We expect $3x10^7\ \bar{\nu}_\mu\ s^{-1}\ cm^{-2}$ at 8 m from the beam dump with 750 μa primary proton beam current. At 33 m, we then anticipate $1.8x10^6\ s^{-1}\ cm^{-2}$ or $1.5x10^{11}\ cm^{-2}$ LA day^{-1} (the LA day is 1/16 of normal day due to LAMPF duty factor).

Our anticipated counting rate, R, is given by

$$R = N_0 \int_0^{52.8} N(E)\ \sigma(E) Np\ V\ P(E)\ F\ dE \tag{3}$$

$N_0 = 1.5x10^{11}\ cm^{-2}\ day^{-1}$

$N(E) = 2\ \varepsilon^2 (3-2\ \varepsilon)/52.8;\ \varepsilon = E/52.8$

$\sigma(E) = (3.465x10^{-3}\ E_{\bar{\nu}}^2 + 0.1755\ E_{\bar{\nu}} - 1.870)\ X\ 10^{-41}\ cm^2$

Np is the number of protons/cm^3, $4.9x10^{22}\ cm^{-3}$

V is the detector volume, $4.47x10^6\ cm^3$

P is from Eq. (1)

F is the detection efficiency, 0.46

E is the neutrino energy in MeV

The resulting value for R is $1.47[a]^2 day^{-1}$ for $P(E) = [a]^2$. Retaining the dependence on energy in P(E), in the integral, the value for R is $1.67x(\delta m^2)^2[a]^2$ LA day^{-1}.

IV. BACKGROUND ESTIMATES

Cosmic backgrounds may best be determined by actual measurements with our detector in position. At this time we can only estimate various components and attempt to identify those that are important.

A. Accidental Cosmic Coincidence Rate

We have estimated single counting rates anticipated within the energy window of (20-60) MeV for e^+ and (4 to 9) MeV for neutrons. Assuming a 27 μs gate time, the accidental rate is .011 LA day^{-1}.

B. Beam Associated Rates

Concrete and tuff shielding between the beam stop and our detector is about 7 m equivalent Fe. Consequently we estimate negligible accidental coincidence rates from the beam stop.

High-energy neutrons from the beam stop region may give energy deposition from proton recoil and subsequent capture, giving rise to a correlated background. Such events will be discriminated against with PSD (pulse shape discrimination) technique. The resultant rate is expected to be ~ .001/LA day.

Another beam-associated rate results from the interactions[4] ν_e + Pb → Bi + n + e^-. This reaction has a negative Q value of 18.5 MeV and therefore a maximum electron energy of 34.5 MeV. We anticipate this rate to be ~ 0.06/LA day for events in the energy range 20–34.5 MeV.

C. Correlated Cosmic Background Rates

There are several possible mechanisms for producing correlated events [those that have a two-pulse signature like the one corresponding to reaction (1)]. We believe there are three areas of major concern.

1. High-energy neutrons give energy from recoil protons and subsequent capture. Attempts to compute such rates are in progress. The sand and Pb above the detector comprise 2.4 m Fe equivalent and rejection of 500/1 by PSD is assumed. If necessary, additional Fe shielding may be installed. A correlated rate of .005/LA day has been estimated.

2. Undetected muons may enter the detector and subsequently decay. Even with charged cosmic rejection of 10^6 supplied by the two veto counters, ~ .02/LA day events may be expected. Only 4% of the decay electrons, however, would appear in the (4–9) MeV window, so our estimated correlated rate is .001 LA day^{-1}.

3. Direct reactions of muons outside the detector give high-energy neutron-gamma pairs that may simulate a neutrino event. We expect that many of these events are associated with other charged reaction products, somewhere in the cascade, which might be detected in our double veto counter. Two layers of Pb (total 7.6 cm) provide additional shielding for these gammas as well as for muon bremsstrahlung. A rate of ~ .015/LA day is estimated but we are uncertain of this value.

The total estimated background may be tabulated as follows:

	Counts/LA Day
Accidental cosmic coincidence	.011
Beam-associated accidental coincidence	.000
Beam-associated coincidence	.001
Cosmic neutron	.005
Undetected cosmic muon	.001
Muons outside detector	.015
Total	.033/LA Day

V. SENSITIVITY TO NEUTRINO OSCILLATION

The signal is 1.67 $(\delta m^2)^2 [a]^2$ LA day^{-1}. For full amplitude oscillation with $\delta m^2 = 0.1$ eV^2, the counting rate is .0167 LA day^{-1}.

In the absence of a net positive signal, a limit results due to the background uncertainty, $\sqrt{BD}$, during the beam-on time, where B is the background rate, .033/LA day, and D is the number of days counting. A limit of 0.1 eV^2 may then be set in D days if

$$\sqrt{.033\ D} = .0167\ D$$

$$D = 118 \text{ days} .$$

This limit is based on the estimates referred to and is qualified by our ability to achieve 10^6 charged cosmic rejection efficiency, pulse shape discrimination rejection efficiency of 500, and cosmic correlated background rates as low as estimated.

We also have ignored the effect of ν_e reactions in Pb, believing that these can be effectively reduced with an Fe shield located inside the detector, between the scintillator and Pb shield. In the absence of such a shield, the sensitivity would be based upon signals occurring above the 34.5 MeV maximum e^- energy from these reactions. This eliminates about 15 percent of the signal events; the time required to achieve a given sensitivity is increased ~ 15 percent.

In the absence of the Fe shield, the estimated counting time to achieve a limit on δm^2 of 0.1 eV^2, thus becomes 136 days. The corresponding time to achieve a sensitivity limit of 0.12 eV^2 is 70 days.

Observation of reaction (4) events occur at a rate several times the estimated background, in the e^- energy range of 20 to 34.5 MeV. Such a recognizable signal may be quite welcome if reaction (2) is not observed.

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