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A SEARCH FOR $(\bar{\nu}_\mu, \bar{\nu}_e)$ OSCILLATIONS AT LAMPF

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ABSTRACT

We briefly discuss the reasons for searching for neutrino oscillations. We discuss in some detail an experiment in progress at the LAMPF beam stop which aims to be sensitive to the appearance of $\bar{\nu}_e$ from $\bar{\nu}_\mu$ at a level of approximately 10^{-3}. Progress, status and upcomping plans for this experiment are also discussed.

1. INTRODUCTION

The search for neutrino oscillations, or perhaps more properly neutrino flavor mixing, has the potential for discovering direct evidence of a higher symmetry for quarks and leptons.[1)] It has been realized for quite some time that the quarks are "Cabbibo mixed" with each other, insofar as the weak interactions are concerned. A fundamental description of this mixing is as yet unknown, however, the discovery of a similar mixing in the lepton sector would provide important additional experimental information. Recent data using reactor neutrinos suggest that this phenomenon has been discovered.[2)] Since at least one neutrino species must have a nonzero mass for this phenomenon to take place, we are also motivated by persistent reports of a nonzero rest mass for the ν_e.[3)]

To parameterize neutrino oscillations, we proceed in a standard fashion and assume a simplified two-state mixing problem and write

$$|\bar{\nu}_1\rangle = \cos\theta|\bar{\nu}_e\rangle + \sin\theta|\bar{\nu}_\mu\rangle \qquad (1a)$$

$$|\bar{\nu}_2\rangle = -\sin\theta|\bar{\nu}_e\rangle + \cos\theta|\bar{\nu}_\mu\rangle \quad (1b)$$

where $|\bar{\nu}_1\rangle$ and $|\bar{\nu}_2\rangle$ are the mass eigenstates with masses m_1 and m_2. Assuming further that the incident neutrino was prepared in a state of definite momentum, and that the neutrino energy is much greater than m_1 and m_2, we derive the probability of a $\bar{\nu}_\mu$ appearing as a $\bar{\nu}_e$ to be

$$P(\bar{\nu}_\mu \Rightarrow \bar{\nu}_e) = \sin^2 2\theta \sin^2 [1.27 (L/E_\nu) \Delta m^2] \quad (2)$$

where L is the distance from the neutrino source to the detector, E_ν is the neutrino energy, and $\Delta m^2 = |m_1^2 - m_2^2|$. (By convention, we measure L/E_ν in m/MeV and Δm^2 in eV^2.) A particular experiment then puts limits on $P(\bar{\nu}_\mu \Rightarrow \bar{\nu}_e)$ and consequently puts correlated limits on $\sin^2 2\theta$ and Δm^2.

2. LAMPF EXPERIMENT E645

We now discuss a particular experiment to study mixing between $\bar{\nu}_e$ and $\bar{\nu}_\mu$. This experiment, being carried out at the Los Alamos Meson Physics Facility (LAMPF) is a collaboration between Ohio state University, Argonne National Laboratory, Louisiana State University, California Institute of Technology, Lawrence Berkeley Laboratory and LAMPF.[4)]

For a neutrino source we use the LAMPF beam stop. LAMPF is a high intensity 800-MeV proton accelerator. Average beam currents at the beam stop are typically 670μA with a 6% duty factor and a beam pulse length of about 1ms. The beam is stopped in a water cooled copper beam dump. Virtually all of the π^+ and π^- produced by the incident beam come to rest in the beam dump. The π^+ thermalize and decay to $\mu^+ + \nu_\mu$ and the μ^+ subsequently decay to $e^+ + \nu_e + \bar{\nu}_\mu$. Most of the π^- are strongly absorbed and the ratio of π^- to π^+ decays is less than 10^{-3}. Consequently, the beam stop produces an effectively pure spectrum of ν_μ, ν_e, and $\bar{\nu}_\mu$ from the decays of stopped π's and μ's. The energy spectra for these neutrino species are shown in Fig. 1. It has been estimated that there are 0.089 stopped π^+ decays per incident proton under typical running conditions.[5)]

Appearance of $\bar{\nu}_e$ and $\bar{\nu}_\mu$ may be observed in our detector by observing the high energy ($20 < E < 50$ MeV) positron from inverse beta decay on the proton, i.e. $p(\bar{\nu}_e, e^+)n$. The "target" protons are simply part of the chemical composition of scintillation counters which provide a measurement of total energy and differential energy loss ("dE/dx"). These counters

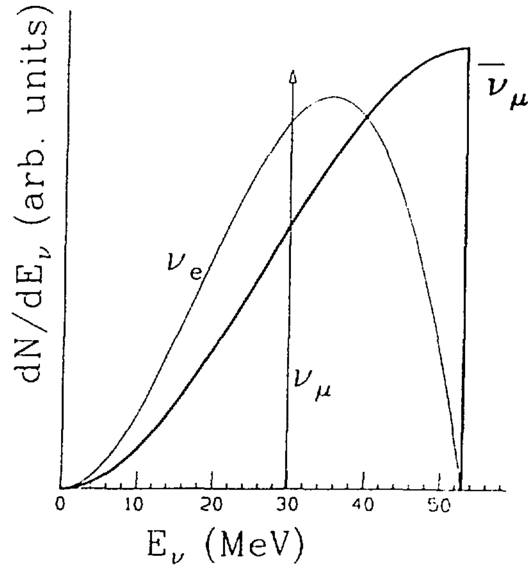

Fig. 1 The energy spectra of the various neutrino species produced at the LAMPF beam stop.

are arranged in 40 vertical planes of 12 counters each. The planes are perpendicular to the direction of the neutrino beam. Each counter consists of an extruded acrylic "tank" with dimensions 3cm × 30cm × 3.7m which is filled with liquid scintillator and fitted with photomultiplier tubes on each side. In between the scintillator planes are planes of vertical and horizontal proportional drift tubes (PDT). The PDT each have a cross sectional area of 3.8cm × 7.6cm and are stacked 45 to a plane. They provide ≈ 1cm position resolution for tracking as well as additional dE/dx information.[6)] Each scintillator plane is covered with a thin sheet of plastic painted with GdO which provides for detection of the free neutron from the inverse beta decay reaction via its radiative capture on Gd. (This feature is not used in the analysis described in this paper). A schematic diagram of the apparatus, showing its position relative to the beam stop, is depicted in Fig. 2. A minimum ionizing particle loses approximately 8 MeV at normal incidence through one plane of the detector. The individual components are calibrated using through-going cosmic ray muons.

A potentially hazardous background for this experiment are cosmic ray muons which stop in the detector and subsequently decay to electrons. (The detector cannot distinguish between electrons and positrons and we make no distinction in this text.) These electrons are virtually identical to the signal from inverse beta decay. To reject this background, as

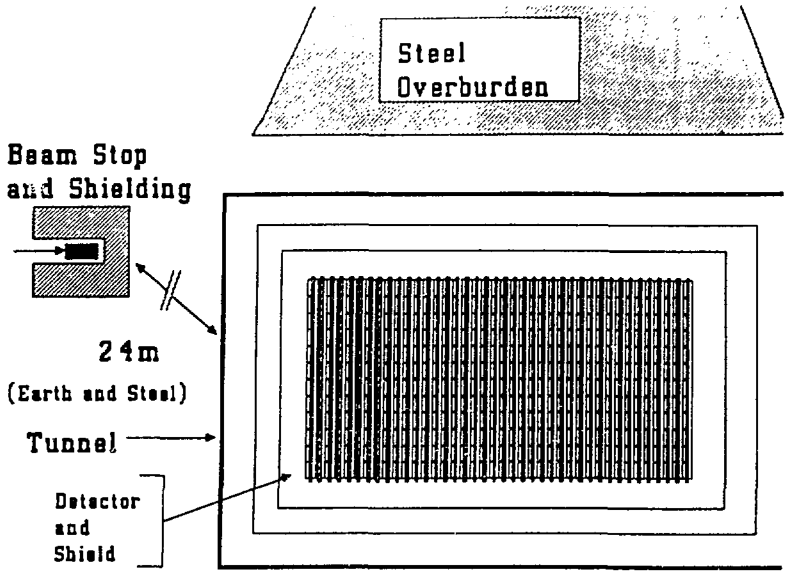

Fig. 2 A schematic diagram of the E645 apparatus.

well as to reduce the on-line trigger rate from through-going muons, the detector is surrounded by an active cosmic ray shield designed to identify charged particles with high efficiency. This shield is essentially a continuous layer of liquid scintillator, 15cm thick, viewed by 360 hemispherical photomultiplier tubes. The combination of large scintillator thickness (implying ≈ 30 MeV of deposited energy for a cosmic ray muon) and high redundancy of photomultipliers yields a detector that is highly efficient for charged particles but rather insensitive to radioactive backgrounds.[7)]

To reduce backgrounds from beam and cosmic ray neutrons, the detector is shielded from the beam stop by ≈ 18m of earth and 2m of steel and is situated in a tunnel underneath approximately 2000 gm/cm^2 of steel. Residual neutron backgrounds, which are detected via their recoil protons in the detector, are rejected using total energy and dE/dx information. Cosmic ray photons (which may be produced by the bremmstrahlung of electrons from muon decay) that enter the detector may produce electron-like background through pair creation or compton scattering. This background is suppressed by the addition of a "passive shield" consisting of 5" of lead sandwiched in-between two 1" shells of steel just inside the active shield.

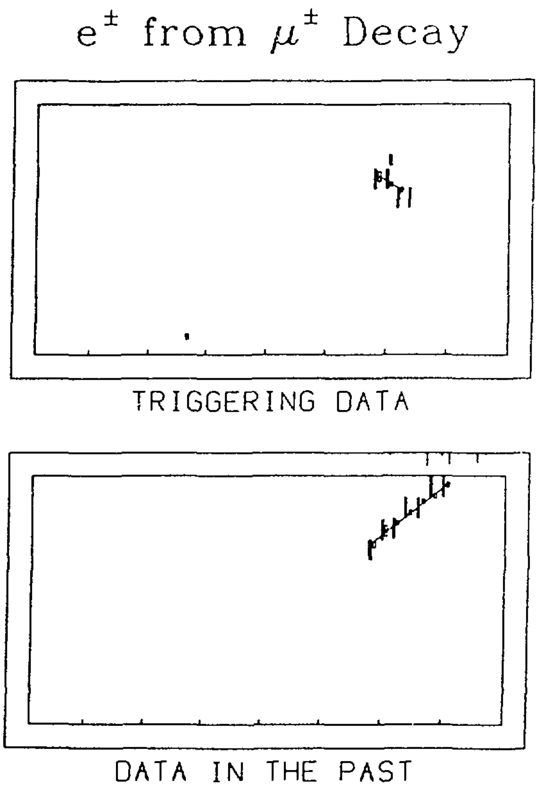

Fig. 3 An event display showing the electron from the decay of a stopping muon, and the stopping muon itself.

The apparatus is triggered by requiring both photomultipliers on any detector scintillation counter to fire in four out of six consecutive planes. Electronics for the active shield photomultipliers provide a relatively loose veto signal of adjustable length that reduces the trigger rate from through-going and stopping muons. The hardware veto does not look for correlated hits between nearby photomultipliers in the shield. Signals from all photomultipliers on the shield and detector as well as the PDT are continuously digitized using "flash ADC's" and the results kept in a RAM memory. When a valid trigger is generated, this digitization is stopped and 150μsec of "history" in the detector and shield is read by the data acquisition computer including a 50μsec record before the trigger (to study triggers due to stopping muons) and 100μsec after the trigger (to search for the Gd capture of thermalized neutrons). Figure 3 shows an event display of a muon decay electron which triggered the detector, as well as data several μsec before the trigger showing the stopping muon track.

3. PERFORMANCE OF THE APPARATUS

During the period from October to December 1986 the apparatus operated with beam on target and with most components working. Analysis of these data is proceeding at this writing with the aim of understanding the calibrations and of identifying sources of backgrounds.

Stopping muons provide a signal which is close to the expected signal from $\bar{\nu}_e$ appearance, and so these events are valuable for understanding our detector response. By setting the active shield veto length to be ≈ 2μsec, we acquire data rich in electrons from muon decay. (Recall that the muon mean life is 2.2μsec.) It is rather straightforward to select offline a very clean sample of stopping muons using the event history. The decay time of such events is histogrammed in Fig. 4. These data are consistent with a single exponential decaying with the muon lifetime and no background. The total energy of the triggering particle in these events is histogrammed in Fig. 5, where it is compared to the expected distribution using an EGS Monte Carlo simulation to propogate the decay electron.

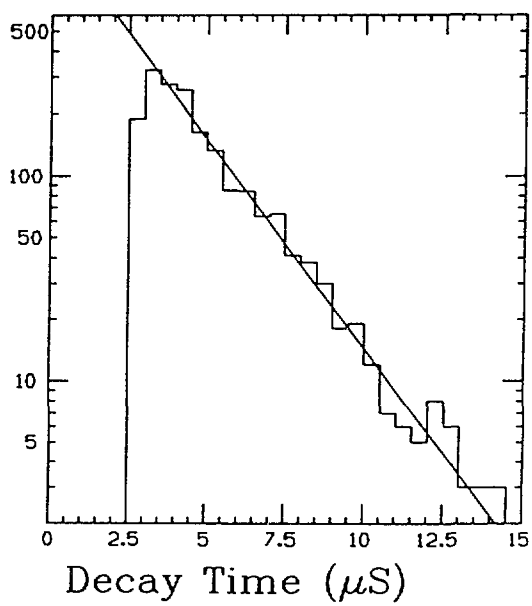

Fig. 4 Decay time of stopping muons.

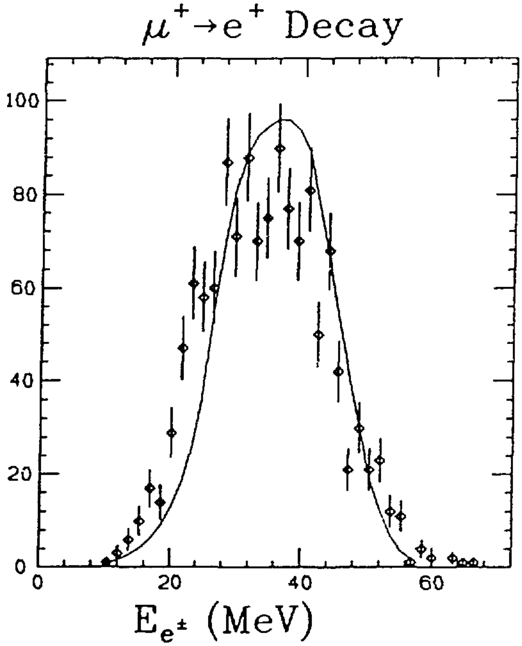

Fig. 5 Kinetic energy spectrum of electrons from muon decay. The solid line is a Monte Carlo prediction.

We search for positrons from $\bar{\nu}_e$ appearance offline using data taken with an 11μsec active shield veto. After removing events that are not fully contained inside the detector (which are primarily through-going muons which pass the loose on-line veto) we histogram the number of events versus dE/dx and total energy for beam on and beam off. The result is shown in Fig. 6. The large peak at low dE/dx and total energy is due to electrons from stopping muons. The number of these events is reduced by nearly three orders of magnitude by examining the history in the active shield for correlated pulses. The events with high dE/dx and large total energy are due to protons recoiling against incident neutrons from the beam stop and from cosmic rays. Clearly there is a preponderance of neutrons from the beam. However, using the energy information it is possible to reject proton events as $\bar{\nu}_e$ appearance candidates to better than 1 part in 250.

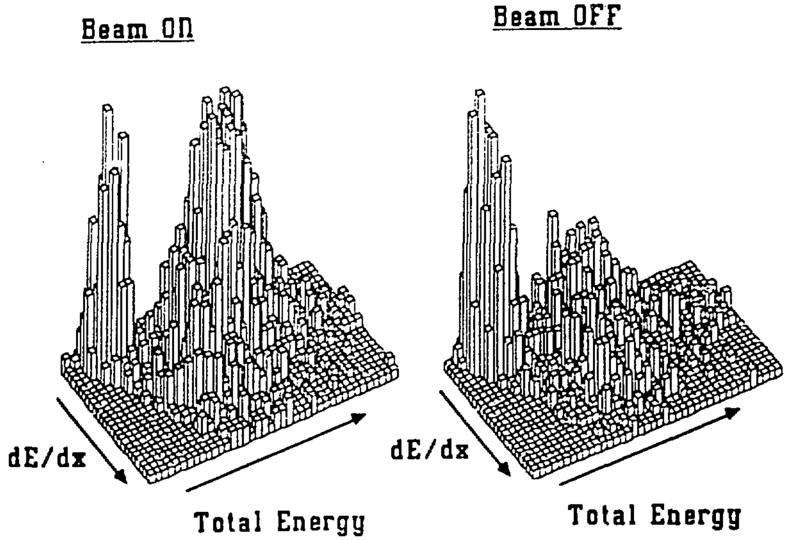

Fig. 6 Histograms versus dE/dx and total kinetic energy for events with the beam on and off.

4. EXPECTED SENSITIVITY

If all $\bar{\nu}_\mu$ interacted as $\bar{\nu}_e$ the expected signal rate is given by

$$R_{max} = \Phi \times n_p \times \langle\sigma\rangle \times \varepsilon \tag{3}$$

where Φ is the neutrino flux at the detector, n_p is the number of free protons in the detector, $\langle\sigma\rangle$ is the cross section for $p(\bar{\nu}_e,e^+)n$ averaged over the $\bar{\nu}_\mu$ energy spectrum, and ε is the overall detection efficiency. With our detector at a distance of L = 24m, we calculate a neutrino flux $\Phi = 5.0 \times 10^6/(cm^2 sec)$. Accounting for the liquid scintillators and acrylic tanks in the detector, gives $n_p = 1.41 \times 10^{30}$. Using a thorough treatment of the inverse beta decay cross section,[8] we find $\langle\sigma\rangle = 1.05 \times 10^{-40} cm^2$ and an average neutrino energy of 42 MeV. (Note that a value of $\langle\sigma\rangle = 1.6 \times 10^{-40} cm^2$ has been incorrectly reported in the literature[9]). Finally, we estimate that our trigger efficiency (using four out of six planes) to be 0.34; the fiducial fraction of the detector volume after forcing all events to be "contained" is 0.67; and the efficiency of off-line cuts is 0.76. Consequency, $\varepsilon = 0.17$ and $R_{max} = 11$/day. During our upcoming running period at LAMPF, we anticipate 150 days of data taking. The hardware veto and computer readout combine to give a live time fraction of approximately 0.85. Assuming that we do not discover a signal for $\bar{\nu}_e$ appearance, we expect to demonstrate that

$$P(\bar{\nu}_\mu \Rightarrow \bar{\nu}_e) < N_{events}/(R_{max} \times 150 \text{ days} \times 0.85) \qquad (4)$$

$$= 1.6 \times 10^{-3} \text{ for 0 background events}$$

$$= 3.6 \times 10^{-3} \text{ for 0.1 background events/day}$$

at 90% confidence level. With $L/E_\nu = 24m/42$ MeV we derive the excluded limits on $\sin^2 2\theta$ and Δm^2 shown in Fig. 7.

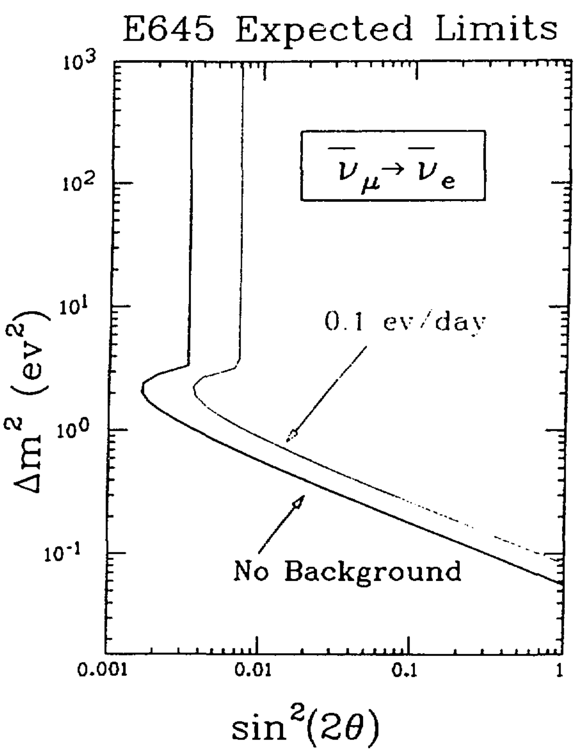

Fig. 7 Expected limits on $\sin^2 2\theta$ and Δm^2 for E645.

We are currently concentrating on increasing our trigger efficiency (mainly by reducing the number of planes required to trigger) and improving our neutron shielding we are also continuing to improve our analysis procedures. A long production run is expected to begin in the Summer of 1987.

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5. REFERENCES

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