A Search for Neutrino Oscillations at LAMPF

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ABSTRACT

Experiment E645 is a search for neutrino oscillations, employing the LAMPF beam stop as a neutrino source. Data collection is now underway and we describe the experiment, the quality of the preliminary data, and the sensitivity to neutrino oscillations that we expect to reach by the end of the 1987 running cycle.

Attempts to discover neutrino masses and mixings by detecting neutrino oscillations now constitutes a mature area of experimental physics which exploits a wide variety of neutrino sources at accelerators and reactors. Pion factories are copious sources of low energy neutrinos produced from the decay of stopped pions and muons, and, a neutrino oscillation search, experiment E645, is now collecting data at the Los Alamos Meson Physics Facility (LAMPF). The E645 experiment is a collaboration between Argonne National Laboratory, California Institute of Technology, Lawrence Berkeley Laboratory, LAMPF, Louisiana State University, and Ohio State University.[1]

After passing through production targets the remaining $\simeq$ 600 μA of the LAMPF proton beam degraded to $\simeq$ 750 MeV, is absorbed in a water cooled copper beam dump. Most of the pions produced in the beam dump quickly thermalize. The negative pions are captured, and the positive pions decay, producing three types of neutrinos: $\pi^+ \to \mu^+ + \nu_\mu$ and $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$. There are $\simeq$ 0.09 stopped π^+ per incident proton.[2] The resulting source intensity is $\simeq 3 \times 10^{14}$ ν/sec of each type and Fig. 1 displays the neutrino energy spectra. Contamination of $\bar{\nu}_e$'s from negative pions which manage to decay before being captured is well below 10^{-3}. E645 is a simple appearance experiment: we look for the conversion of either ν_μ, $\bar{\nu}_\mu$, or ν_e into $\bar{\nu}_e$ with a detector sensitive only to $\bar{\nu}_e$.

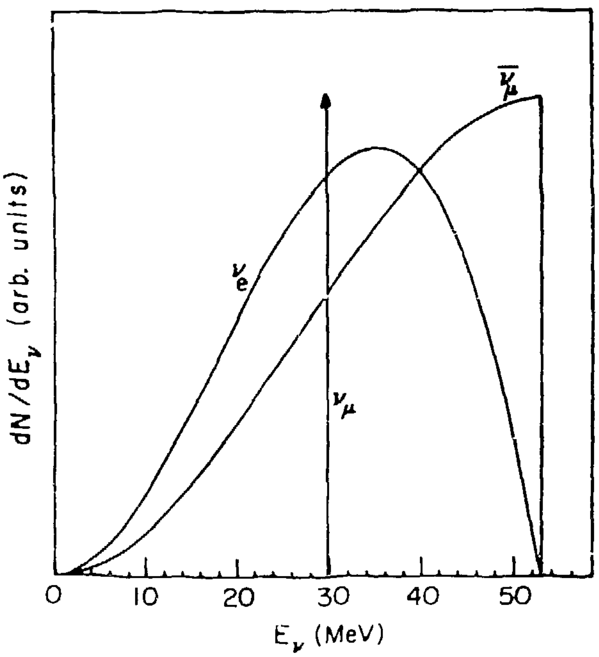

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Fig. 1 The energy spectra of the three types of neutrinos produced by stopping π^+ decay

Since there are yet no clear uncontroversial indications that neutrinos oscillate, it is convenient to discuss the sensitivities of experiments in terms of a simple two component mixing scheme. In the most common senario, a $\bar{\nu}_e$ signal would appear from $\bar{\nu}_\mu$'s, the probability depending on the neutrino energy E_ν (in MeV) and the distance to the source L (in meters). We have,

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = \sin^2 2\theta \ (1.27\ \Delta m^2 L/E_\nu)\ , \tag{1}$$

where $\Delta m^2 = |m_1^2 - m_2^2|$ is a measure of the neutrino eigenstate mass differences in eV^2 and θ is a fundamental mixing parameter. Of course the real physics might be much more complicated, involving more than two neutrino types and mixings between neutrinos and antineutrinos as well.

Appearance experiments with low backgrounds have good sensitivity for small θ and sensitivity at small Δm^2 comes from arranging for large L/E_ν. The E645 detector is about 24m from the LAMPF beam stop so $L/E_\nu \simeq 0.6$ and the overall sensitivity is similar to experiments at higher energy but larger distances at Brookhaven and CERN.

The experimental arrangement at LAMPF is shown schematically in Fig. 2. We detect $\bar{\nu}_e$'s via inverse beta decay, the $p(\bar{\nu}_e,e^+)n$ reaction, by observing the final state positron.

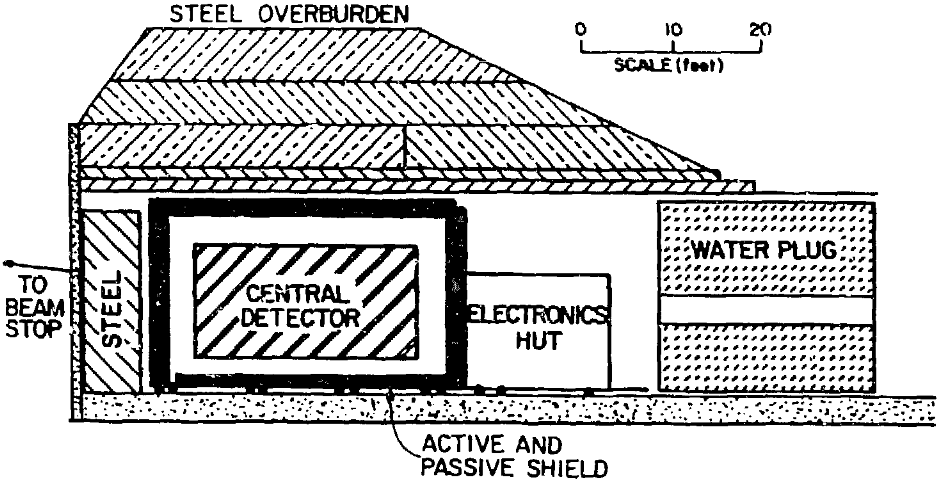

Fig. 2 The experimental arrangement. The neutrino detector and cosmic ray shield are housed in a tunnel under 2500 g/cm^2 of overburden 24m from the LAMPF beam stop. LAMPF itself is approximately 2200m above sea level

The LAMPF duty cycle, typically $\simeq$ 0.5 msec pulses at 120 Hz, is not at all ideal for neutrino experiments, making cosmic ray rejection a challenging problem. An unrecognized muon decay imitates the e^+ signal of $\bar{\nu}_e$-appearance and the muon veto must be nearly flawless. The active cosmic ray shield is a mostly continuous (there are actually three major isolated sections) 15cm thick cylindrical liquid scintillator tank surrounding the central detector. The liquid scintillator is viewed with 360 hemispherical phototubes each 13cm in diameter. A cosmic ray muon loses about 30 MeV in the shield and the scintillation light pulse is seen by several phototubes resulting in high rejection efficiency and low backgrounds from radioactivity.[4] Passive shielding consisting of 13cm thick lead and 5cm thick steel is put just inside the active shield to suppress spurious events from muon decay bremstrallung photons which would not be vetoed by the active shield. Neutral cosmic ray particles are suppressed by locating the entire detector in a tunnel under 2500 gm/cm^2 of overburden as shown in Fig. 2. The experimental trigger is coincident hits in three out of four consecutive central detector scintillation planes; the active shield is used on-line to suppress the trigger rate from cosmic rays.

Typically the detector is vetoed for 2 μsec for cosmic rays which interact with two isolated sections of the shield (passing muon veto) and 10 μsec when only one is hit (stopping muon veto). A potential 1.6 Hz trigger rate from cosmic rays is reduced to 0.5 Hz on-line.

The neutrino detector consists of 40 vertical modules, each consisting of a layer of 12 liquid scintillation counters and two layers of 45 proportional drift tubes (PDT), one oriented vertically and one horizontally. Scintillation counters are made from 0.4cm-wall extruded acrylic tanks 3cm × 7.6cm × 3.7m with a photomultiplier at each end. Since the detector is incapable of distinguishing positrons from electrons materials which have large cross sections for ν_e interactions (odd neutron nuclei like ^{27}Al) are avoided. The PDT's are constructed with laminated paper and only a thin layer of aluminium. The PDT cross sectional area is 3.8cm × 7.6cm but they are capable of better than 1cm tracking resolution.[5] The scintillators measure both total energy and differential energy loss (dE/dx) which is important for finding positrons in a background of neutron induced recoil protons. A minimum ionizing particle at normal incidence loses about 9 MeV in each module. Each scintillator layer is covered with a plastic sheet coated with gadolinia (Gd_2O_3) which can be used to detect the neutron remnants of inverse beta decay. Some of these neutrons thermalize inside the fiducial volume, capture on gadolinium, and register as delayed γ-ray signals in the scintillators. The use of a delayed coincidence with neutrons decreases the overall detection efficiency by nearly a factor of 5, but it is a useful contingency in the event that a substantial beam excess of events is found. In all the detector weights ≃ 20 metric tons of which 2.3 tons is proton target.

Signals from phototubes and PDT's are shaped, amplified, and digitized in flash ADC's every 80 nsec for the detector and every 150 nsec for the shield. The results are stored in individual memories and a 150 μsec long "event history" is read out for each on-line trigger. Later, stringent off-line cuts are applied to the data in the event histories. The detector is calibrated and monitored with cosmic rays. Stopping muons are a particularly valuable since the decay electron characteristics approximates the $\bar{\nu}_e$-appearance signal (without a neutron left over of course). Figure 3 is an example of a stopping muon event. The data that is in time with the trigger shows a minimum ionizing track consistent with an electron with $E < 50$ MeV and there are no corresponding hits in the shield. The information from 3 μsec before the trigger, however, clearly indicates the electron signal is from a cosmic-ray muon which was seen by the shield and stopped in the detector.

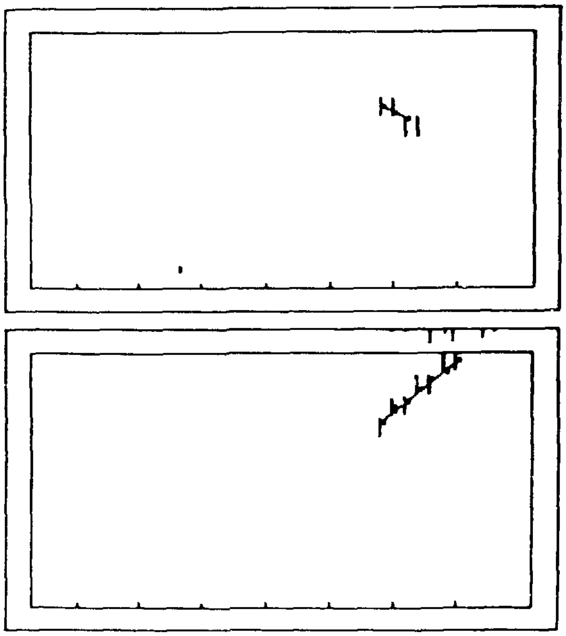

Fig. 3 Graphical display of a stopping muon event. The top panel shows the scintillator and PDT hits along the decay electron track. The lower panel is the detector 3 μsec earlier showing the track of the muon which entered the detector through the active shield

The experiment operated with beam for a few weeks in the winter of 1986, and the data allowed us to find a hole in the beam stop shielding. With improved shielding the experiment began taking production data in June 1987; it has operated nearly without interruption since then. There are already several different preliminary analyses of the data and depending on the severity of the cuts the cosmic-ray background has been rejected to a level between 0.1 to 0.5 per LD (LD = the effective time the beam is on per day about 5600 sec). The trigger efficiency is ≃ 52% from a Monte Carlo analysis and the off-line analysis efficiencies vary from 30% to 50%, again depending on the cuts imposed. At some level we expect beam associated backgrounds from ν_e-nucleus scattering and from decaying μ's produced with very low momentum by energetic ν_μ's from π's decaying in flight. The bulk of the signal of ν_e-nucleus scattering (most of the scattering should come from $^{12}C(\nu_e,e^-)^{12}N$) would appear below 35 MeV. Scattering of ν_e's from ^{27}Al and ^{13}C is a potential background of higher energy electrons but at a much lower rate. The "decay-in-flight" neutrino backgrounds should be associated with other events in which the produced μ is observed before it decays, but there is yet no evidence for a significant rate. If we assume that no signal of neutrino oscillations is seen by the end of the 1987 LAMPF running cycle we can estimate our final sensitivity from our presently measured backgrounds and analysis efficiencies. Figure 4b shows our "expected" limits for 1987.

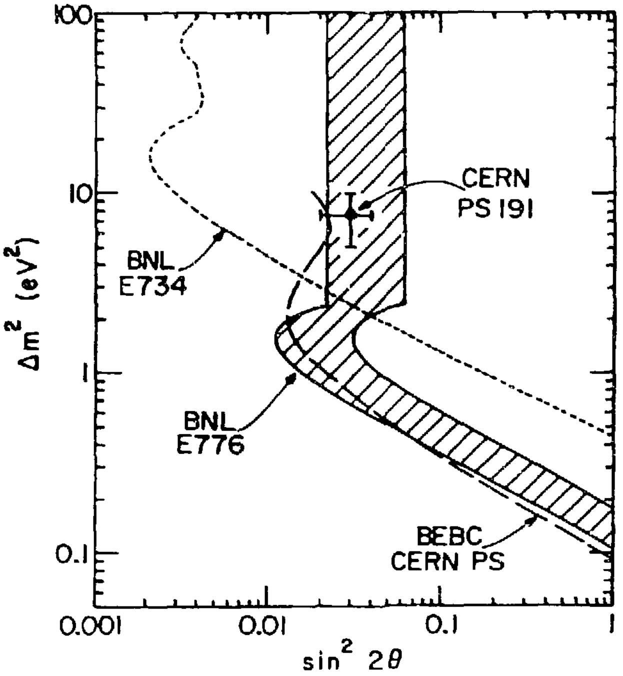

Fig. 4a Exclusion limits (90% cl) and possible positive indications (1σ) from $\nu_\mu \to \nu_e$ searches. (See References in the text, especially Refs. 7 and 8)

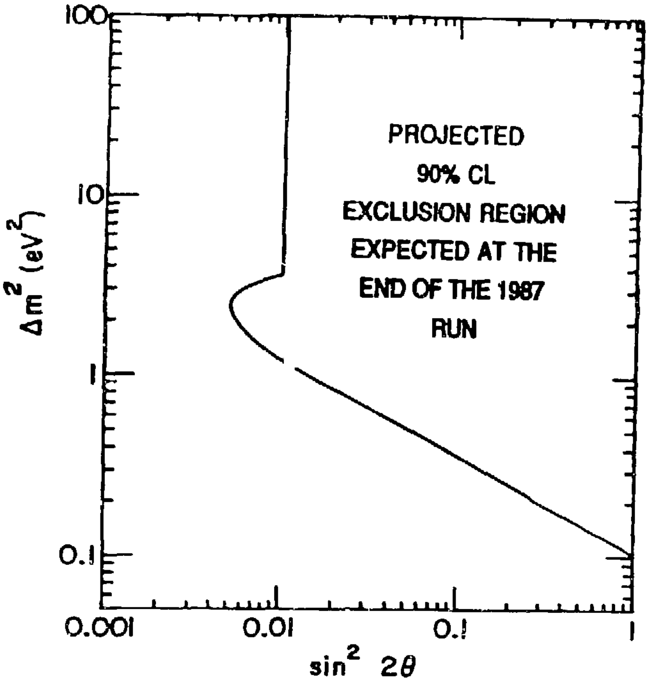

Fig. 4b Projected limits (90% cl) from the present E645 $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance search. The limits indicate the expected sensitivity if no evidence for neutron oscillations is seen in the rest of 1987 run

Figure 4a shows the most stringent existing limits from $\nu_\mu \to \nu_e$ appearance experiments at Brookhaven[5] and CERN.[6] Two preliminary observations of excess electron-like events, which could indicate that neutrinos oscillate from two other experiments are also shown.[7,8] The positive indications for neutrino oscillations are very preliminary and obviously needs further scrutiny; there are already indications of inconsistencies with limits from other experiments. We expect that E645 will reach adequate sensitivity to help settle the issue by the end of 1987.

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