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# Candidate Events in a Search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Oscillations

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## Abstract

A search for  $\bar{\nu}_e$ 's in excess of the number expected from conventional sources has been made using the Liquid Scintillator Neutrino Detector, located 30 m from a proton beam dump at LAMPF. A  $\bar{\nu}_e$  signal was detected via the reaction  $\bar{\nu}_e p \rightarrow e^+ n$  with  $e^+$  energy between 36 and 60 MeV, followed by a  $\gamma$  from  $np \rightarrow d\gamma$  (2.2 MeV). Using strict cuts to identify  $\gamma$ 's correlated with positrons results in a signal of 9 events, with an expected background of  $2.1 \pm 0.3$ . A likelihood fit to the entire  $e^+$  sample yields a total excess of  $16.4_{-8.9}^{+9.7} \pm 3.3$  events, where the second uncertainty is systematic. If this excess is attributed to neutrino oscillations of the type  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ , it corresponds to an oscillation probability of  $(0.34_{-0.18}^{+0.20} \pm 0.07)\%$ .

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Neutrino mass is a central issue for particle physics, because neutrinos are massless in the Standard Model, and for cosmology, because the relic neutrinos, if massive, would have profound effects on the structure of the universe. To search for such mass an experiment has been carried out using neutrinos from  $\pi$  and  $\mu$  decay at rest from the Los Alamos Meson Facility (LAMPF) beam stop. Observation of  $\bar{\nu}_e$  production above that expected from conventional processes may be interpreted as evidence for  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  oscillations (and hence mass) or some direct lepton number violating process.

Protons from the LAMPF 800-MeV linac produce pions in a 30-cm-long water target positioned approximately 1 m upstream from the copper beam stop. [1] The beam stop provides a source of  $\bar{\nu}_\mu$ , via  $\pi^+ \rightarrow \mu^+ \nu_\mu$  followed by  $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$  decay-at-rest; the relative  $\bar{\nu}_e$  yield is  $\sim 4 \times 10^{-4}$  [2] for  $E_\nu > 36$  MeV. The Liquid Scintillator Neutrino Detector (LSND) detects  $\bar{\nu}_e$  by  $\bar{\nu}_e p \rightarrow e^+ n$ , followed by a  $\gamma$  from  $np \rightarrow d\gamma$  (2.2 MeV). Requiring an electron energy above 36 MeV eliminates most of the accidental background from  $\nu_e^{12}C \rightarrow e^- X$ , while the upper energy requirement of 60 MeV allows for the  $\bar{\nu}_\mu$  endpoint plus energy resolution. The 7691 coulombs of protons were obtained in a 1.5-month run in 1993 and a 3.5-month run in 1994. The calculated  $\bar{\nu}_\mu$  decay-at-rest flux [3] totaled  $3.75 \times 10^{13} \nu/\text{cm}^2$  at the center of the tank, with an uncertainty of 7%.

The center of the detector is 30 m from the neutrino source and is shielded by the equivalent of 9 m of steel. The detector, an approximately cylindrical tank 8.3 m long by 5.7 m in diameter, is under 2kg/cm<sup>2</sup> of overburden to reduce the cosmic-ray flux and is located at an angle of 12° relative to the proton beam direction. On the inside surface of the tank 1220 8-inch Hamamatsu phototubes provide 25% photocathode coverage with uniform spacing. The tank is filled with 167 metric tons of liquid scintillator consisting of mineral oil and 0.031 g/l of b-PBD. The composition of the liquid is  $CH_2$ , including 1.1% of  $^{13}C$  and  $\sim 10^{-4}$  of  $^2H$ . The low scintillator concentration allows the detection of both Čerenkov light and scintillation light and yields an attenuation length of more than 20 m for wavelengths greater than 400 nm. A sample of  $\sim 10^6$  electrons from cosmic-ray muon decays in the tank was used to determine the electron energy scale and resolution. A typical electron at the

end-point energy of 52.8 MeV leads to  $\sim 1750$  photoelectrons, of which  $\sim 300$  are in the Čerenkov cone. The phototube time and pulse height signals are used to reconstruct the electron track with an average r.m.s. position resolution of  $\sim 30$  cm, an angular resolution of  $\sim 12^\circ$ , and an energy resolution of  $\sim 7\%$ . A liquid-scintillator veto shield [4] surrounds the detector tank with 292 5-inch phototubes.

Particle identification (PID) for relativistic particles is based upon the Čerenkov cone and the time distribution of the light, [5] which is broader for non-relativistic particles. Three PID quantities are used: the Čerenkov cone fit quality, the event position fit quality, and the fraction of phototubes hit at a time corresponding to light emitted more than 12 ns later than the reconstructed event time. Comparing electrons from cosmic-ray muon decays with cosmic-ray-produced neutrons of similar deposited energy, a neutron rejection of  $\sim 10^{-3}$  is achieved with an electron efficiency of 79%.

Each phototube channel is digitized every 100ns and the data is stored in a circular buffer. A primary event trigger is generated when the total number of hit phototubes in two consecutive 100 ns periods exceeds 100. However, no primary triggers are allowed for a period of  $15.2\mu\text{s}$  following veto shield events with  $> 5$  hit veto phototubes in order to reject electrons from the decay of stopped cosmic-ray muons in the detector. The trigger operates independently of the state of the proton beam, so the beam duty factor of 7.3% allows 13 times more beam-off than beam-on data to be collected. After a primary trigger with  $> 125$  hit phototubes ( $> 300$  in 1993), the threshold is lowered to 21 hit phototubes for a period of 1 ms in order to record the 2.2 MeV  $\gamma$  from  $np \rightarrow d\gamma$ , which has a  $186 \mu\text{s}$  capture time. In addition, “activity” events are recorded for any event within the previous  $51.2 \mu\text{s}$  and having  $> 17$  hit detector phototubes or  $> 5$  hit veto shield phototubes.

The first step in searching for  $\bar{\nu}_e$  interactions is to select electrons (the detector cannot distinguish between electrons and positrons) with more than 300 hit phototubes (highly efficient for energies above 28 MeV), PID information consistent with a  $\beta \sim 1$  particle,  $< 2$  veto shield hits, and no “activity” events in the previous  $40 \mu\text{s}$ . The reconstructed position of the track midpoint is required to be  $> 35$  cm from the locus of the phototube faces.

Finally, events with three or more associated  $\gamma$ 's are consistent with cosmic-ray neutrons and are eliminated. The overall electron selection efficiency is  $28 \pm 2\%$ . In the  $36 < E_e < 60$  MeV energy range, there are 135 such electron events with the beam on and 1140 with the beam off, giving a beam-on excess of  $46.1 \pm 11.9$  events.

The second step is to require a correlated 2.2 MeV  $\gamma$  with a reconstructed distance,  $\Delta r$ , within 2.5 m of the electron, a relative time,  $\Delta t$ , of less than 1 ms (imposed by the trigger), and a number of hit phototubes,  $N_\gamma$ , between 21 and 50. The efficiency for a neutron to be captured by a free proton and for the 2.2-MeV  $\gamma$  to be found by these cuts is 63%. To determine if such a  $\gamma$  is correlated with the electron or from an accidental coincidence, a function  $R$  of  $\Delta r$ ,  $\Delta t$ , and  $N_\gamma$  is defined to be the ratio of approximate likelihoods for the two hypotheses. Distributions of these quantities for correlated  $\gamma$ 's are measured using cosmic ray neutron events. We also compute the  $\Delta r$  distribution with a Monte Carlo simulation. The  $R$  distributions for accidental  $\gamma$ 's are measured as a function of electron position using the large sample of electrons from cosmic-ray muon decays. The  $R$  distributions are shown in Fig. 1a, and Fig. 1b shows the  $R$  spectrum for the beam-on minus beam-off data sample.

Requiring that a  $\gamma$  be found with  $R > 30$  has an efficiency of 23% for events with a recoil neutron and an accidental rate of 0.6% for events with no recoil neutron. Fig. 2 shows the beam on minus beam off energy distribution for events with  $R > 30$ . There are 9 beam-on and 17 beam-off events between 36 and 60 MeV, corresponding to a beam-on excess of 7.7 events. Table I lists the locations and energies for the 9 beam-on events. When any of the electron selection criteria is relaxed, the background increases slightly, but the beam-on minus beam-off event excess does not change significantly.

Table II lists the expected number of background events in the  $36 < E_e < 60$  MeV energy range for  $R > 30$ . The *beam-unrelated background* is well determined from the thirteen-fold larger data sample collected between accelerator pulses. To set a limit on *beam-related neutron backgrounds*, events were selected which failed electron PID criteria but were otherwise consistent with the correlated  $e\gamma$  signature and in the electron energy range of interest. The yield of beam-related neutron events of this type was  $< 3\%$  of all

neutrons when the beam was on. Applying this ratio to neutrons *passing* electron PID criteria, the beam-related neutron background is bounded by 0.03 times the total beam-unrelated background, and is thus negligible. The largest *neutrino background*, due to  $\mu^-$  decay at rest in the beam stop followed by  $\bar{\nu}_e p \rightarrow e^+ n$  in the detector, is calculated using the Monte Carlo beam simulation [3]. Another background with a recoil neutron arises from  $\bar{\nu}_\mu p \rightarrow \mu^+ n$  (including  $\bar{\nu}_\mu C \rightarrow \mu^+ n X$ ) if the muon is lost (due to the “activity” threshold or trigger inefficiency) or if it is misidentified as an electron (e.g., if a fast decay made the  $\mu$  and  $e$  look like a single particle). This background is determined from our measurement of  $\nu_\mu C \rightarrow \mu^- X$  [6] and from our Monte Carlo detector simulation. [7] Finally, the sum of all backgrounds involving *accidental*  $\gamma$ 's is computed from the yield of electrons without correlated neutrons, which is measured using the likelihood fit described below. The total estimated beam-related background for  $R > 30$  is thus  $0.79 \pm 0.12$  events, which implies a net excess of 6.9 events in the  $36 < E_e < 60$  MeV energy range. The probability that this excess is due to a statistical fluctuation is  $< 10^{-3}$ .

While the  $R > 30$  sample demonstrates the existence of an excess, the size of the excess is better determined by utilizing all electron data between 36 and 60 MeV. The total numbers of beam-on and beam-off electron events with correlated  $\gamma$ 's are obtained from a likelihood fit to the R distributions at the electron positions. The two ways of estimating the R distribution for correlated photons give excesses of  $18.3^{+9.5}_{-8.7}$  events (Monte Carlo method) and  $19.9^{+10.0}_{-9.1}$  events (cosmic neutron method). Averaging these numbers and subtracting the neutrino background with a neutron (2.7 events) gives an oscillation probability of  $(0.34^{+0.20}_{-0.18} \pm 0.07)\%$ , where the first error is statistical and the second systematic. The latter arises primarily from uncertainties in the neutrino flux (7%), effective fiducial volume (10%), and  $\gamma$  efficiencies (10%). The average of the fits implies that  $27.0^{+8.9}_{-9.7}$  of the beam-correlated electron events have no recoil neutron. Background estimates from  $\nu_e {}^{12}\text{C} \rightarrow e^- {}^{12}\text{N}$ ,  $\nu_e {}^{13}\text{C} \rightarrow e^- {}^{13}\text{N}$ ,  $\nu e \rightarrow \nu e$ , and other known neutrino interactions predict  $\sim 14$  events. [1]

Cosmic-ray background is especially intense in the outer regions of the detector and where the veto has gaps – beneath the detector (low y), and near the lower corner of the



upstream end (low  $y$  and low  $z$ ). In an effort to find anomalous spatial concentrations of the oscillation candidates, we performed Kolmogorov tests on distributions of various quantities, among which were  $y$ , distance from the lower upstream corner, and distance from the surface containing the photomultiplier faces. These tests, done both with no photon criteria and with  $R > 30$ , gave probabilities above 25% of consistency with what is expected, with the exception of one distribution not expected to be sensitive to background; the distribution in  $x$ , with no photon criteria, had a probability of 4%.

We have also investigated alternative geometric criteria. Removing the 5% of the total volume having  $y < -120$  cm and  $z < 0$  removes 32% of the beam-off background, and results in a net excess of  $20.6_{-8.7}^{+9.5} \pm 4.1$  events, corresponding to an oscillation probability of  $(0.45_{-0.19}^{+0.21} \pm 0.10)\%$ . None of the  $R > 30$  events is in this area of largest beam-off background.

The neutrino oscillation probability for two-generation mixing can be expressed as  $P = (\sin^2 2\theta) \sin^2(1.27\Delta m^2 L/E)$ , where  $L$  is the distance (meters) between the reconstructed positron position and the neutrino production point and  $E$  is the neutrino energy (MeV) obtained from the measured positron energy and direction. A possible concern is the presence of  $R > 30$  events near and above 60 MeV. But the Kolmogorov probability of consistency with a large  $\Delta m^2$ , for example, oscillation hypothesis is 71% for  $36 < E_e < 60$  MeV and 13% for  $36 < E_e < 80$  MeV (ignoring any possible contribution from decay-in-flight oscillation events).

If the observed excess is due to neutrino oscillations, Fig. 3 shows the allowed region (95% C.L.) of  $\sin^2 2\theta$  vs.  $\Delta m^2$  from a maximum likelihood fit to the L/E distribution of the 9 beam-on events in the  $36 < E_e < 60$  MeV energy range with  $R > 30$ . The result is renormalized to the measured oscillation probability of 0.34% given above. The fit includes background subtraction, smearing due to positron energy, position, and angular resolutions, and the uncertainty of the neutrino production vertex. The allowed region is not in conflict with previous low energy decay-at-rest neutrino experiments E225 [8] and E645 [9] at LAMPF. Some of the allowed region is excluded by the ongoing KARMEN experiment [10] at ISIS, the E776 experiment at BNL [11], and the Bugey reactor experiment [12].

In conclusion, the LSND experiment observes 9 electron events in the  $36 < E_e < 60$  MeV energy range which are correlated in time and space with a low energy  $\gamma$ . The total estimated background from conventional processes is  $2.1 \pm 0.3$  events, so that the probability that the excess is due to a statistical fluctuation is  $< 10^{-3}$ . If the observed excess is interpreted as  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  oscillations, it corresponds to an oscillation probability of  $0.34_{-0.18}^{+0.20} \pm 0.07\%$  for the allowed regions shown in Fig. 3. If the excess is due to direct lepton number violation and the spectrum of  $\bar{\nu}_e$  is the same as for  $\bar{\nu}_\mu$  in  $\mu^+$  decay, then the violation rate is the same as the above oscillation probability. We plan to collect more data, and backgrounds and detector performance continue to be studied. These efforts are expected to improve the understanding of the phenomena described here.

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## FIGURES

FIG. 1. The distribution of  $R$ , the  $\gamma$  likelihood parameter. The leftmost bin corresponds to no  $\gamma$  found within cuts ( $R=0$ ), properly normalized in area. (a) Accidental photons (averaged over the tank) and correlated photons (2 methods, described in text). (b) Beam-on minus beam-off spectrum for events in the  $36 < E_e < 60$  MeV energy range. The dashed histogram is the result of the  $R$  likelihood fit for events without a recoil neutron, while the solid histogram is the total fit, including events with a neutron.

FIG. 2. The electron energy distribution, beam-on minus beam-off, for events with an associated 2.2 MeV  $\gamma$  with  $R > 30$ . The dashed histogram shows the expected background from known neutrino interactions. The dotted curve is the expected distribution for neutrino oscillations in the limit of large  $\Delta m^2$ , normalized to the excess between 36 and 60 MeV.

FIG. 3. The determination of  $\sin^2 2\theta$  vs.  $\Delta m^2$  from a maximum likelihood fit to the  $L/E$  distribution of the 9 events which satisfy the  $R > 30$  requirement, where  $L/E$  is the neutrino distance to energy ratio, normalized to the oscillation probability extracted from the photon likelihood fit. The shaded area is the allowed region (95% C.L.) from LSND. Not shown is the 20% systematic uncertainty in the LSND normalization. Also shown are 90% C.L. limits from KARMEN (dotted histogram), the BNL E776 experiment (dashed histogram), and the Bugey reactor experiment (dot-dashed histogram).

## TABLES

TABLE I. The position, energy, and distance to the phototubes for the 9 beam-on events in the  $36 < E_e < 60$  energy range with  $R > 30$ . X, Y, and Z are the lateral, vertical, and longitudinal coordinates relative to the tank center.

Event	X(cm)	Y(cm)	Z(cm)	E(MeV)	D(cm)
1	-66	-84	-77	47.8	115
2	56	-96	53	51.4	103
3	-36	196	-203	40.3	53
4	69	-146	153	44.3	53
5	-156	-79	-207	36.4	84
6	-221	-24	-309	56.9	36
7	-91	119	209	37.9	109
8	71	-99	-259	55.8	100
9	6	211	173	43.8	38

TABLE II. Expected number of background events in the  $36 < E_e < 60$  energy range for  $R > 30$ . The neutrinos are from either  $\pi$  and  $\mu$  decay at rest (DAR) or decay in flight (DIF). Neutrino backgrounds with an accidental neutron signature are measured using the R likelihood fit described in the text.

Background	Neutrino Source	Events with $R > 30$
Beam-unrelated		$1.33 \pm 0.32$
Beam-related n's		$< 0.04$
$\bar{\nu}_e p \rightarrow e^+ n$	$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$ DAR	$0.44 \pm 0.06$
$\bar{\nu}_\mu p \rightarrow \mu^+ n$	$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$ DIF	$0.19 \pm 0.08$
Accidentals	$\pi, \mu$ DAR, DIF	$0.16 \pm 0.06$
Total		$2.12 \pm 0.34$





