LA-UR-95-1238

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Author(s):

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Submitted to:

http://lib-www.lanl.gov/la-pubs/00393973.pdf

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

C. Athanassopoulos[12], L. B. Auerbach[12], D. A. Bauer[3], R. D. Bolton[7], B. Boyd[9], R. L. Burman[7], D. O. Caldwell[3], I. Cohen[6], B. D. Dieterle[10], J. B. Donahue[7], A. M. Eisner[4], A. Fazely[11], F. J. Federspiel[7], G. T. Garvey[7], M. Gray[3], R. M. Gunasingha[8], V. Highland[12 †], R. Imlay[8], K. Johnston[9], W. C. Louis[7], A. Lu[3], J. Margulies[12], K. McIlhany[1], W. Metcalf[8], R. A. Reeder[10], V. Sandberg[7], M. Schillaci[7], D. Smith[5], I. Stancu[1], W. Strossman[1], M. K. Sullivan[4], G. J. VanDalen[1], W. Vernon[2,4], Y-X. Wang[4], D. H. White[7], D. Whitehouse[7], D. Works[12], Y. Xiao[12], S. Yellin[3]

[1] *University of California, Riverside, CA 92521*

[2] *University of California, San Diego, CA 92093*

[3] *University of California, Santa Barbara, CA 93106*

[4] *University of California Intercampus Institute for Research at Particle Accelerators, Stanford, CA 94309*

[5] *Embry Riddle Aeronautical University, Prescott, AZ 86301*

[6] *Linfield College, McMinnville, OR 97128*

[7] *Los Alamos National Laboratory, Los Alamos, NM 87545*

[8] *Louisiana State University, Baton Rouge, LA 70803*

[9] *Louisiana Tech University, Ruston, LA 71272*

[10] *University of New Mexico, Albuquerque, NM 87131*

[11] *Southern University, Baton Rouge, LA 70813*

[12] *Temple University, Philadelphia, PA 19122*

† *deceased*

(August 23, 1995)

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 behind the LAMPF beam stop. The $\bar{\nu}_e$ are detected via $\bar{\nu}_e\, p \rightarrow e^+\, n$ with e^+ energy between 36 and 60 MeV, followed by a γ from $np \rightarrow d\gamma$ (2.2 MeV). Using strict cuts to identify γ's correlated with e^+ yields 9 events with only 2.1 ± 0.3 background expected. A likelihood fit to the entire e^+ sample results in a total excess of $16.4^{+9.7}_{-8.9} \pm 3.3$ events. If attributed to $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations, this corresponds to an oscillation probability of $(0.34^{+0.20}_{-0.18} \pm 0.07)\%$.

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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 was carried out using neutrinos from π and μ decay at rest from the Los Alamos Meson Physics 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 about 1 m upstream from the copper beam stop, [1] which provide 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 $E_\nu > 36\,\text{MeV}$. The Liquid Scintillator Neutrino Detector (LSND) detects $\bar{\nu}_e$ by $\bar{\nu}_e p \rightarrow e^+ n$, followed by a γ from $np \rightarrow d\gamma$ (2.2 MeV). Requiring an e^+ energy above 36 MeV eliminates most of the accidental background from $\nu_e^{12}C \rightarrow e^- X$ (the detector not distinguishing between e^+ and e^-), while an upper energy requirement of 60 MeV allows for the $\bar{\nu}_\mu$ endpoint plus energy resolution. Runs of 1.5 months in 1993 and 3.5 months in 1994 used 7691 coulombs of protons, for a calculated $\bar{\nu}_\mu$ decay-at-rest flux [3] totalling $(3.75 \pm 0.26) \times 10^{13} \nu/\text{cm}^2$ at the center of the tank.

The experiment is located about 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 $\sim 2\text{kg/cm}^2$ of overburden to reduce the cosmic-ray flux and is inside a liquid scintillator veto shield with 292 5-inch phototubes [4]. On the inside surface of the tank 1220 8-inch Hamamatsu phototubes provide 25% photocathode coverage with uniform spacing. The tank contains 167 metric tons of liquid scintillator consisting of mineral oil (CH_2) and 0.031 g/l of b-PBD. The low scintillator concentration allows the detection of both Čerenkov and scintillation light and gives an attenuation length larger than 20 m for wavelengths above 400 nm.

A sample of $\sim 10^6$ $e^\pm$ from cosmic-ray muon decays in the tank was used to determine the $e^\pm$ energy scale and resolution. A typical $e^\pm$ at the end-point energy of 52.8 MeV leads to ~ 1750 photoelectrons, of which ~ 300 are in the Čerenkov cone. The phototube time and pulse height signals are used to reconstruct the $e^{\pm}$ track with an average r.m.s. position resolution of ~ 17 cm in each coordinate, an angular resolution of $\sim 12^{o}$, and an energy resolution of $\sim 7\%$.

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 $e^{\pm}$ from cosmic-ray muon decays with cosmic-ray-produced neutrons of similar deposited energy demonstrates a neutron rejection of $\sim 10^{-3}$ at an $e^{\pm}$ efficiency of 79%.

Each phototube channel is digitized every 100ns. A primary event trigger requires ≥ 100 hit phototubes in a 200 ns period. However, in order to reject $e^{\pm}$ from the decay of stopped cosmic-ray muons, a 15.2μs veto is imposed following the detection of > 5 hit phototubes in the veto shield. The trigger is always operative, 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 γ from $np \rightarrow d\gamma$, which has a 186 μs capture time. In addition, "activity" events are recorded for any event within the previous 51.2 μs having > 17 hit detector phototubes or > 5 hit veto-shield phototubes.

The first step in searching for $\bar{\nu}_e$ interactions is to select e^+ candidates with PID information consistent with a $\beta \sim 1$ particle, < 2 veto shield hits, and no "activity" events in the previous 40 μs. The reconstructed position of the track midpoint is required to be > 35 cm from the locus of the phototube faces. Within this region the energy resolution and efficiency are well understood. Events with three or more associated γ's are consistent with cosmic-ray neutrons and are eliminated. The overall e^+ selection efficiency is $28 \pm 2\%$. For $36 < E_e < 60$ MeV, there are 135 such events with the beam on and 1140 with the beam off, giving a beam-on excess of 46.1 ± 11.9 events.

The second step is to search for a correlated 2.2 MeV γ. Loose initial cuts require a reconstructed distance, Δr, within 2.5 m of the e^+, a relative time, Δt, of < 1 ms, and a number of hit phototubes, N_γ, between 21 and 50. The neutron detection efficiency is 0.87 from these cuts times 0.72 from uncorrelated vetos, for 0.63 overall. The three quantities discriminate correlated γ's from accidental signals, which increase with Δr *vs.* being confined, are flat *vs.* exponential in Δt, and have lower average N_γ. Rather than apply tighter cuts, we make more effective use of the information by defining a function R of Δr, Δt, and N_γ to be approximately the ratio of likelihoods for correlated and accidental hypotheses [1]. Distributions of these quantities for correlated γ's are approximately independent of position and are measured using cosmic-ray neutron events, and the Δr distribution is also calculated with a Monte Carlo simulation. Accidental γ distributions are measured as a function of e^+ position using the large sample of $e^\pm$ from cosmic-ray muon decays. Fig. 1 shows both the expected and observed R distributions [1].

Finding a γ 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 e^+ selection criterion is relaxed, the background increases slightly without significant change in the excess.

Table II lists the expected number of background events with $36 < E_e < 60$ MeV for $R > 30$. The *beam-unrelated background* is well determined from the data sample collected between accelerator pulses. To set a limit on *beam-related neutron backgrounds*, events were selected having the correlated $e\gamma$ signature and in the e^+ energy range of interest, but meeting neutron (rather than e^+) PID criteria. Fewer than 3% of these events were beam-related during the period when the beam was on. Assuming this ratio applies to neutrons passing e^+ 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*,

μ^- decay at rest in the beam stop followed by $\bar{\nu}_e p \to e^+ n$ in the detector, is calculated using the Monte Carlo beam simulation [3]. Another background with a recoil neutron arises from $\bar{\nu}_\mu p \to \mu^+ n$ or $\bar{\nu}_\mu C \to \mu^+ n X$, with the muon failing to satisfy the "activity" trigger or misidentified as an $e^\pm$. This background is determined from our measurement of $\nu_\mu C \to \mu^- X$ [6] and from our detector simulation. [7] The sum of all backgrounds involving *accidental* γ*'s* is computed from the yield of $e^\pm$ without correlated neutrons, which is *measured* using the likelihood fit described below. The total estimated beam-related background for $R > 30$ is 0.79 ± 0.12 events, which implies a net excess of 6.9 events with $36 < E_e < 60$ MeV. The probability that this excess is 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 e^+ data between 36 and 60 MeV. The total numbers of beam-on and beam-off e^+ events with correlated γ's are obtained from a likelihood fit of the observed events to the expected R distributions. The fit took into account the strong dependence on e^+ position of the accidental γ rates. The two ways of estimating the R distribution for correlated photons give excesses of $18.3^{+9.5}_{-8.7}$ events (Monte Carlo) and $19.9^{+10.0}_{-9.1}$ events (cosmic neutrons). Averaging these numbers, subtracting the neutrino background with a neutron (2.7 ± 0.4 events), and interpreting the remainder as due to neutrino oscillations 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 statistical error is non-Gaussian; the result has only 0.7% probability of being ≤ 0. The systematic error arises primarily from uncertainties in the neutrino flux (7%), effective fiducial volume (10%), and γ efficiencies (10%). The remaining $27.0^{+8.9}_{-9.7}$ beam-correlated $e^\pm$ events have no recoil neutron. Background estimates from $\nu_e\ {}^{12}C \to e^-\ {}^{12}N$, $\nu_e\ {}^{13}C \to e^-\ {}^{13}N$, $\nu e \to \nu e$, etc. predict ~ 14 events. [1]

The cosmic-ray background is larger in the outer regions of the detector and where the veto has gaps – beneath the detector (low Y), and around the periphery of the upstream end (low Z). To test for 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 for neutrino interactions, 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 also studied alternative geometric criteria to minimize cosmic-ray background, although it is reliably measured from beam-off data. A cut removing 6% of the acceptance ($Y < -120$ cm and $Z < 0$ cm) removes 32% of the beam-off events and gives an oscillation probability of $(0.45^{+0.21}_{-0.19} \pm 0.09)\%$ with no loss of events in the $R > 30$ region. A region with 51% of the acceptance ($Y > -50$ cm, $Z > -250$ cm, and distance from the phototubes > 50 cm) has only 11.5% of the beam-off background and yields an oscillation probability of $(0.10^{+0.18}_{-0.13} \pm 0.02)\%$, with 2 beam-on events for $R > 30$ and an expected background of 0.7 event. The latter result shows no significant excess, but is statistically consistent with the result from the full fiducial volume (probability 20%). An alternative analysis [8] finds no excess using similarly restrictive fiducial cuts, but without using the full data sample or all of the particle identification information. However, such constraints on fiducial volume should be avoided and are not required for our analysis due to the precision of the beam-off subtraction and the suppression of cosmic ray background by use of powerful techniques to determine the $e\gamma$ coincidence.

A possible concern is the presence of $R > 30$ events near and above 60 MeV. But the Kolmogorov probability that the energy distribution is consistent with a large Δm^2 oscillation hypothesis is 68% for $36 < E_e < 60\,\mathrm{MeV}$ and 11% for $36 < E_e < 80\,\mathrm{MeV}$ (including known backgrounds, but ignoring possible contributions from decay-in-flight oscillation events). The dotted curve in Fig. 2 demonstrates visually that there is no incompatibility between such an oscillation hypothesis and the data excess, given the present statistical errors.

The two-generation neutrino oscillation probability is $P = (\sin^2 2\theta)\sin^2(1.27\Delta m^2 L/E)$, where E is the neutrino energy (MeV), L is its flight distance before interaction (m), and Δm^2 is the mass-squared difference (eV^2). The 90% C.L. upper and lower limits of P, found using the R distributions of all e^+ data between 36 and 60 MeV, were converted using this equation into 90% C.L. limits on $\sin^2 2\theta$ as functions of Δm^2. The calculation took into account $\bar{\nu}_e p$ kinematics, detector resolution, the uncertainty of the ν production vertex, and background subtraction [1]. These limits bound the shaded area (approximately 80% C.L. interval) of Fig. 3. Some of the allowed region is excluded by the ongoing KARMEN experiment [9] at ISIS, E776 at BNL [10], and the Bugey reactor experiment [11].

In conclusion, the LSND experiment observes 9 e^+ events within $36 < E_e < 60$ MeV which satisfy strict criteria for a correlated low energy γ. The total estimated background from conventional processes is 2.1 ± 0.3 events, so the probability that the excess is a statistical fluctuation is $< 10^{-3}$. If the excess obtained from a likelihood fit to the full e^+ sample arises from $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations, it corresponds to an oscillation probability of $(0.34^{+0.20}_{-0.18} \pm 0.07\%)$ leading to 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 μ^+ decay, then the violation rate is the same as the above oscillation probability. We will collect more data and continue the study of backgrounds and detector performance to improve our understanding of this excess.

Acknowledgements The authors gratefully acknowledge the support of Peter Barnes and Cyrus Hoffman, the performance of the operating staff at LAMPF, the technical contributions of V. Armijo, K. Arndt, D. Callahan, B. Daniel, S. Delay, C. Espinoza, C. Gregory, D. Hale, G. Hart, W. Marterer, and T. N. Thompson, and the help of the students M. Albert, G. Anderson, C. Ausbrooks, B. Bisbee, L. Christofek, M. Davis, D. Evans, J. George, B. Homann, R. Knoesel, S. Lueder, S. Mau, M. Nolta, T. Phan, F. Schaefer, M. Strickland, B.J. Vegara, M. Volta, S. Weaver, K. Williams, and K. Yaman. This work was supported by the U. S. Department of Energy and the National Science Foundation.

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[2] The $\bar{\nu}_e$ to $\bar{\nu}_\mu$ ratio is given approximately by the product of the π^-/π^+ ratio (0.2), the probability of π^- decay in flight (0.03), and the probability of μ^- decay at rest before capture in the Cu beam stop (0.12). The $\bar{\nu}_e$ spectrum is also softer than that of $\bar{\nu}_\mu$.

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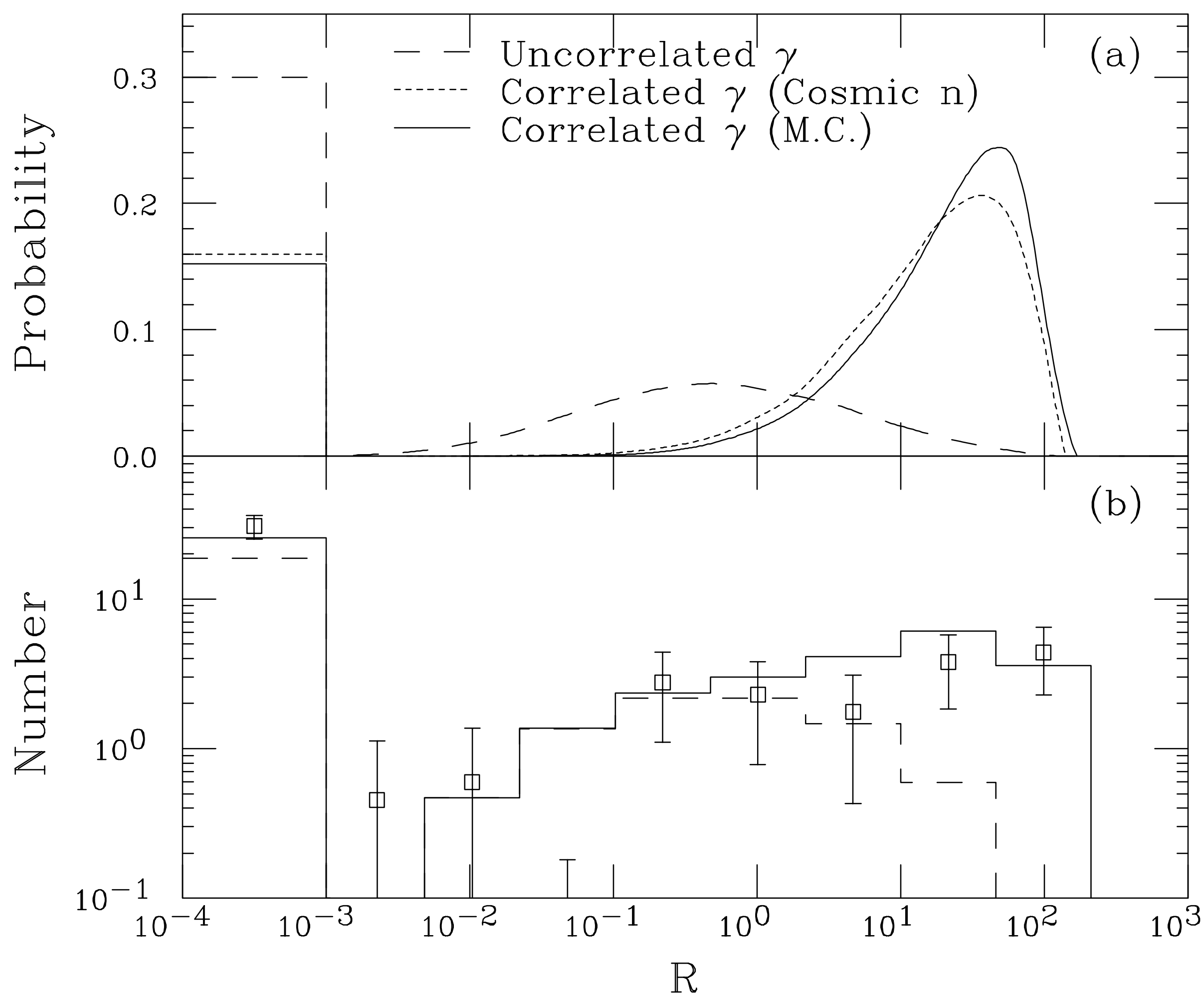
FIGURES

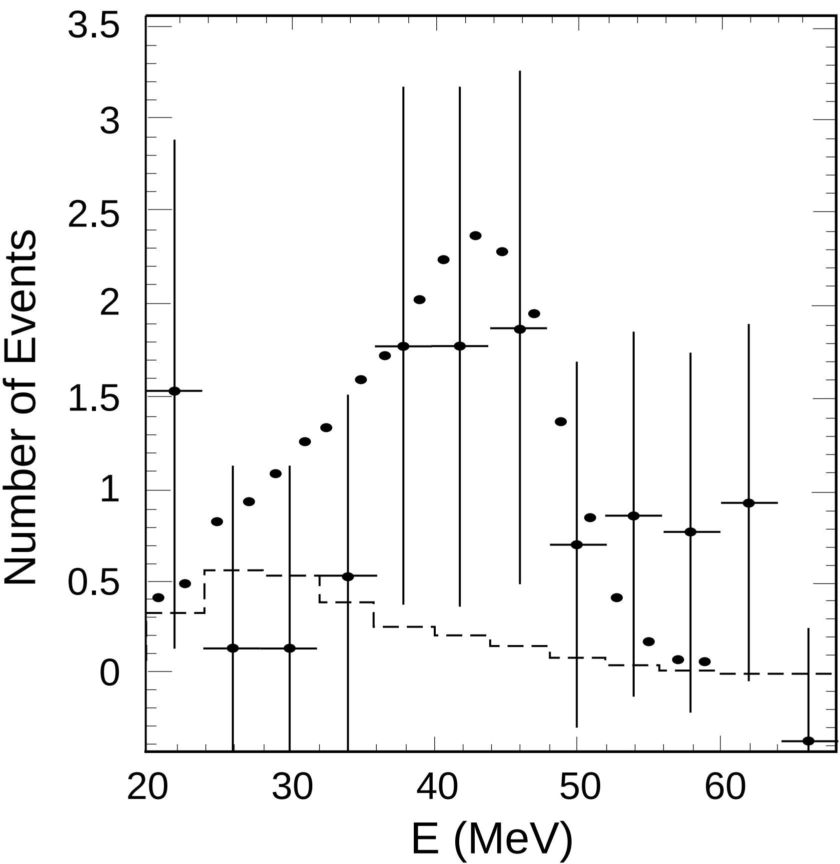
FIG. 1. The distribution of R, the γ likelihood parameter. The leftmost bin corresponds to no γ found within cuts (R=0), properly normalized in area. (a) Accidental photons (averaged over the tank) and correlated photons (2 methods, described in text). (b) Beam-on minus beam-off spectrum for events with $36 < E_e < 60$ MeV. 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.

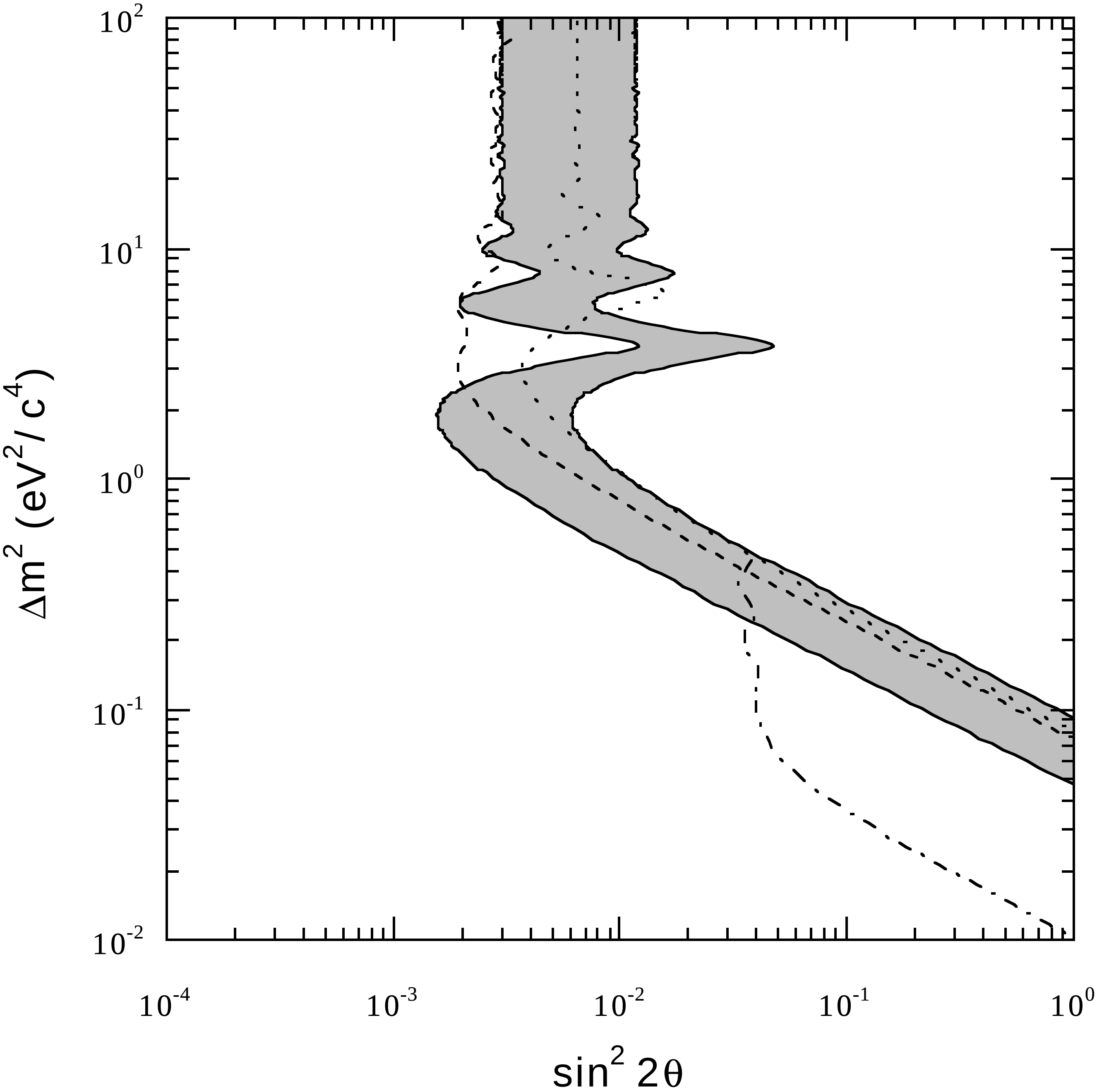
FIG. 2. The e^+ energy distribution, beam-on minus beam-off, for events with an associated 2.2 MeV γ with $R > 30$. The e^+ efficiency drops for $E < 28$ MeV. The dashed histogram shows the expected background from known neutrino interactions. The dotted curve is the expected distribution for neutrino oscillations in the limit of large Δm^2, normalized to the excess between 36 and 60 MeV.

FIG. 3. Results from interpreting the excess signal from all e^+ data as due to two-generation neutrino oscillations. The two edges of the shaded band are the 90% C.L. limits of $\sin^2 2\theta$ as a function of Δm^2. Not included is the 20% systematic uncertainty in the LSND normalization. Also shown are 90% C.L. limits from Ref. 8 (dotted histogram), Ref. 9 (dashed histogram), and Ref. 10 (dot-dashed histogram).



Uncorrelated γ
Correlated γ (Cosmic n)
Correlated γ (M.C.)
(a)
(b)
Probability
0.3
0.2
0.1
0.0
Number
10^1
10^0
10^{-1}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
R


3.5
3
2.5
2
1.5
1
0.5
0
20
30
40
50
60
Number of Events
E (MeV)



10^2
10^1
10^0
10^{-1}
10^{-2}
Δm^2 (eV^2/c^4)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
$\sin^2 2\theta$

TABLES

TABLE I. The position, energy, and distance to the phototubes for the 9 beam-on events in $36 < E_e < 60$ 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 π and μ 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 ± 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 ± 0.06
$\bar{\nu}_\mu p \rightarrow \mu^+ n$	$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$ DIF	0.19 ± 0.08
Accidentals	π, μ DAR,DIF	0.16 ± 0.06
Total		2.12 ± 0.34