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Title: Final Neutrino Oscillation Results from LSND

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FINAL NEUTRINO OSCILLATION RESULTS FROM LSND

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Abstract. The LSND experiment at Los Alamos has conducted searches for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations using $\bar{\nu}_\mu$ from μ^+ decay at rest and for $\nu_\mu \to \nu_e$ oscillations using ν_μ from π^+ decay in flight. For the $\bar{\nu}_\mu \to \bar{\nu}_e$ search, a total excess of $83.3 \pm 21.2 \pm 12.0$ events is observed with e^+ energy between 20 and 60 MeV, while for the $\nu_\mu \to \nu_e$ search, a total excess of $8.3 \pm 5.5 \pm 4.0$ events is observed with e^- energy between 60 and 200 MeV. If attributed to neutrino oscillations, the most favored allowed region from a fit to the entire data sample is a band from 0.2 to 2.0 eV^2. This result implies that at least one neutrino has a mass greater than 0.4 eV/c^2 and that neutrinos contribute more than 1% to the mass of the universe.

I INTRODUCTION

The LSND experiment collected data for six years, from 1993 to 1998, during which time the LAMPF/LANSCE accelerator operated for 17 months of calendar time and delivered 28,898 C ($\sim$ 0.3 g) of protons on target. Using partial data samples, evidence for neutrino oscillations has been published previously for both $\bar{\nu}_\mu \to \bar{\nu}_e$ [2,3] and $\nu_\mu \to \nu_e$ [4] oscillations. In this report we present the final LSND oscillation results that include the entire 1993-1998 data sample, that combines the two oscillation searches in a global analysis, and that makes use of a new event reconstruction that has greatly improved the event spatial and angular resolutions. An excess of events consistent with neutrino oscillations is observed and implies that at least one neutrino has a mass greater than 0.4 eV/c^2 and that neutrinos contribute more than 1% to the mass of the universe.

The old event position reconstruction was hampered due to the charge response of the 8" phototubes used in LSND (Hamamatsu R1408). For these phototubes, the single photoelectron distribution is essentially a broad Gaussian peak followed by an exponential charge tail that extends to arbitrarily high values. As the position and angle fits weight the hit phototubes by their charge, this charge tail has the effect of smearing the reconstructed event positions and angles. (It also has the effect of smearing the energy resolution. At 50 MeV the electron energy resolution is $\sim$ 7%, much worse than the $\sim 3\%$ resolution that would be expected from photon statistics alone.) To ameliorate this effect, a new reconstruction was developed that weights the hit phototubes by their expected charge and not by their actual charge. This has resulted in an improvement in the correlated positions for muon decay events. The mean reconstructed distance between the muon and decay electron has improved from 22 cm with the old reconstruction to 14 cm with the new reconstruction. For 2.2 MeV γ from neutron capture, the most likely distance has improved from 74 cm to 55 cm.

II DETECTOR

The Liquid Scintillator Neutrino Detector (LSND) experiment at Los Alamos [5] was designed to search with high sensitivity for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations from μ^+ decay at rest. The LANSCE accelerator is an intense source of low energy neutrinos due to its 1 mA proton intensity and 800 MeV energy. For the 1993-1995 running period the beam stop consisted of a 30-cm long water target (20-cm in 1993) followed by a water-cooled Cu Beam dump, while for the 1996-1998 running period the beam stop was reconfigured with the water target replaced by a close-packed high-z target for testing tritium production. The muon decay-at-rest neutrino flux with this new configuration is only 2/3 of the neutrino flux with the old beam stop; however, the pion decay-in-flight neutrino flux has been reduced to 1/2 of the original flux, so that the 1996-1998 data serve as a systematic check. The neutrino source is well understood because almost all neutrinos arise from π^+ or μ^+ decay; π^- and μ^- are readily captured in the Fe of the shielding and Cu of the beam stop. [6] The production of kaons and heavier mesons is negligible at these energies. The $\bar{\nu}_e$ rate is calculated to be only 4×10^{-4} relative to $\bar{\nu}_\mu$ in the $36 < E_\nu < 52.8$ MeV energy range, so that the observation of a significant $\bar{\nu}_e$ rate would be evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations.

The LSND detector consists of an approximately cylindrical tank 8.3 m long by 5.7 m in diameter. The center of the detector is 30 m from the neutrino source. On the inside surface of the tank 1220 8-inch Hamamatsu phototubes provide 25% photocathode coverage. The tank is filled with 167 metric tons of liquid scintillator consisting of mineral oil and 0.031 g/l of b-PBD. This low scintillator concentration allows the detection of both Čerenkov light and scintillation light and yields a relatively long attenuation length of more than 20 m for wavelengths greater than 400 nm. [7] A typical 45 MeV electron created in the detector produces a total of ~ 1500 photoelectrons, of which ~ 280 photoelectrons are in the Čerenkov cone. The phototube time and pulse height signals are used to reconstruct the track with an average r.m.s. position resolution of ~ 30 cm, an angular resolution of ~ 12 degrees, and an energy resolution of $\sim 7\%$. The Čerenkov cone for relativistic particles and the time distribution of the light, which is broader for non-relativistic particles, give excellent particle identification. Surrounding the detector is a veto shield [8] which tags cosmic ray muons going through the detector.

III DATA ANALYSIS

The primary oscillation search in LSND is the search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations, where the $\bar{\nu}_\mu$ arise from μ^+ decay at rest in the beam stop and the $\bar{\nu}_e$ are identified through the reaction $\bar{\nu}_e p \rightarrow e^+ n$. This reaction allows a two-fold signature of a positron with a 52 MeV endpoint and a correlated 2.2 MeV γ from neutron capture on a free proton. The positron/electron selection criteria (LSND is unable to determine charge) for this primary oscillation search is the following. First, in order to eliminate muon decay events, it is required that there be no event within 8 μs in the future or within 12 μs in the past. Second, the event particle identification parameter, χ_p, is required to lie in the range $-1.5 < \chi_p < 0.5$, where the precise range values are determined by maximizing the acceptance divided by the square root of the beam-off background. Third, there must be less than 4 veto hits associated with the event and the time of the nearest veto hit must be more than 30 ns from the event time. Fourth, the positron energy is required to be in the range $20 < E_e < 60$ MeV. Fifth, the event reconstructed position must be more than 35 cm from the nearest phototube surface. Finally, it is required that there be no more than one correlated γ with $R_\gamma > 10$ (see below) in order to reduce the background from cosmic-ray neutrons, which will typically knock-out additional neutrons.

The correlated 2.2 MeV γ selection criteria makes use of the likelihood ratio, R_γ, which is defined to be the likelihood that the γ is correlated divided by the likelihood that the γ is accidental. R_γ depends on three quantities: the number of hit phototubes associated with the γ (the multiplicity is proportional to the γ energy), the distance between the reconstructed γ and positron positions, and the time between the γ and positron. As checks of the likelihood distributions, Figs. 1 and 2 show the R_γ distributions for $\nu_e C \rightarrow e^- N_{gs}$ exclusive events, where the N_{gs} beta decays, and $\nu_\mu C \rightarrow \mu^- X$ and $\bar{\nu}_\mu C \rightarrow \mu^+ X$ and $\bar{\nu}_\mu p \rightarrow \mu^+ p$ inclusive events. By definition, the former reaction has no recoil neutron, so that its R_γ distribution should be consistent with a purely accidental γ distribution; indeed, a fit to the R_γ distribution finds that the fraction of events with a correlated γ, f_c, is $f_c = -0.004 \pm 0.007$ ($\chi^2 = 4.6/9$ DOF). For the latter reactions, correlated γ are expected for $\sim$ 14% of the events. [9] A fit to the R_γ distribution gives $f_c = 0.129 \pm 0.013$ ($\chi^2 = 8.2/9$ DOF), in agreement with expectations. Note that with the new reconstruction, the correlated γ efficiency has increased while the accidental γ efficiency has decreased. For $R_\gamma > 10$, the correlated and accidental efficiencies are 0.3929 and 0.0026, respectively. With the old reconstruction the correlated and accidental efficiencies were 0.230 and 0.006, respectively.

The secondary oscillation search in LSND is the search for $\nu_\mu \rightarrow \nu_e$ oscillations, where the ν_μ arise from π^+ decay in flight in the beam stop and the ν_e are identified through the reaction $\nu_e C \rightarrow e^- X$. The electron selection criteria for this primary oscillation search is almost the same as for the primary search, except that the electron energy is required to be in the range $60 < E_e < 200$ MeV and there must be no associated 2.2 MeV γ.

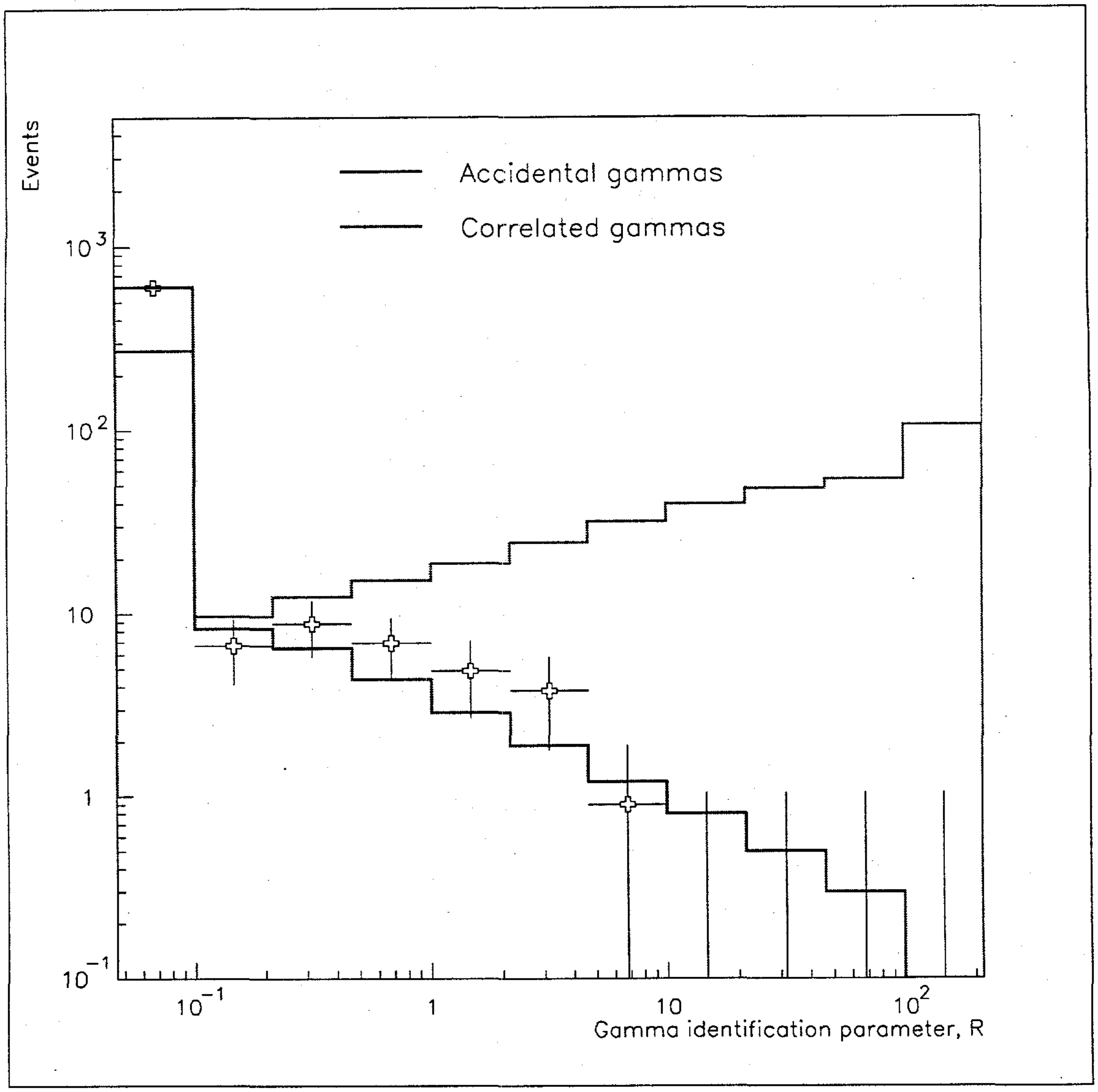

FIGURE 1. The R_γ distribution for $\nu_e C \rightarrow e^- N_{gs}$ exclusive events, where the N_{gs} beta decays.

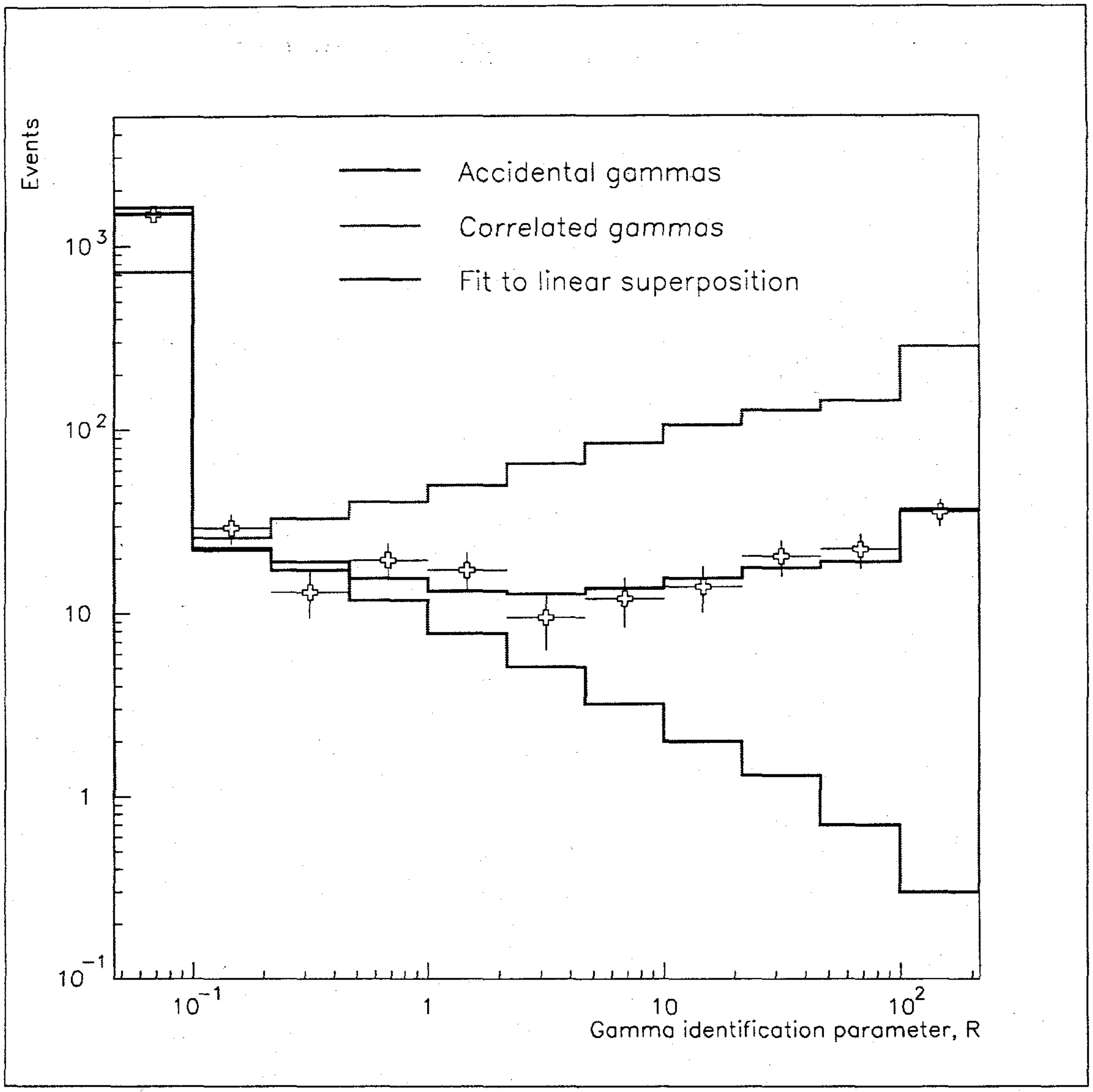

FIGURE 2. The R_γ distribution for $\nu_\mu C \to \mu^- X$ and $\bar{\nu}_\mu C \to \mu^+ X$ and $\bar{\nu}_\mu p \to \mu^+ p$ inclusive events.

TABLE 1. Numbers of beam-on events that satisfy the selection criteria for the primary $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation search with $R_\gamma > 1$, $R_\gamma > 10$, and $R_\gamma > 100$. Also shown are the correlated γ efficiencies, the beam-off background, the estimated neutrino background, and the excess of events that is consistent with neutrino oscillations.

Selection & Efficiency	Beam-On Events	Beam-Off Background	ν Background	Event Excess
$R_\gamma > 1$ (51.15%)	195	98.1 ± 2.4	37.7	59.2 ± 14.2
$R_\gamma > 10$ (39.29%)	83	33.7 ± 1.4	16.6	32.7 ± 9.2
$R_\gamma > 100$ (16.86%)	25	7.9 ± 0.7	5.4	11.7 ± 5.0

IV NEUTRINO OSCILLATION RESULTS

Table 1 gives the statistics for events that satisfy the selection criteria for the primary $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation search. An excess of events is observed over what is expected from beam-off and neutrino background that is consistent with neutrino oscillations. A fit to the R_γ distribution, as shown in Fig. 3, gives $f_c = 0.0578 \pm 0.0108$ ($\chi^2 = 9.2/9$ DOF), which leads to a beam on-off excess of 113.3 ± 21.2 events with a correlated neutron. Subtracting the neutrino background from μ^- decay at rest followed by $\bar{\nu}_e p \to e^+ n$ scattering (21.6 events) and π^- decay in flight followed by $\bar{\nu}_\mu p \to \mu^+ n$ scattering (8.4 events) [10] leads to a total excess of 83.3 ± 21.2 events or an oscillation probability of $(0.25 \pm 0.06 \pm 0.04)\%$. (Note that with the old reconstruction the oscillation probability was determined to be $(0.33 \pm 0.09 \pm 0.05)\%$.)

A fairly clean sample of oscillation candidate events can be obtained by requiring $R_\gamma > 10$, where as shown in Table 1, the beam on-off excess is 49.3 ± 9.2 events while the estimated neutrino background is only 16.6 events. Fig. 4 displays the energy distribution of events with $R_\gamma > 10$. The shaded region shows the estimated neutrino background while the curves show the expected distributions from a combination of neutrino background plus neutrino oscillations at high or low Δm^2. The data agree well with the oscillation hypothesis. Fig. 5 shows the spatial distribution for events with $R_\gamma > 10$, where z is along the axis of the tank (and approximately along the beam direction), y is vertical, and x is transverse. The data agree well with the distributions from $\nu_e C \to e^- N_{gs}$ scattering (solid histogram), where the reaction is identified by the N_{gs} beta decay.

A test of the oscillation hypothesis is to check whether there is an excess of events with > 1 correlated γ. If the excess of events is indeed due to the reaction $\bar{\nu}_e p \to e^+ n$, then there should be no excess with > 1 correlated γ because the recoil n is too low in energy (< 5 MeV) to knock out additional neutrons. If, on the other hand, the excess involves higher energy neutrons (> 20 MeV), then one would expect a comparable excess with > 1 correlated γ. However, as shown in Table 2, the excess of events with > 1 correlated γ is approximately zero, as expected for the reaction $\bar{\nu}_e p \to e^+ n$.

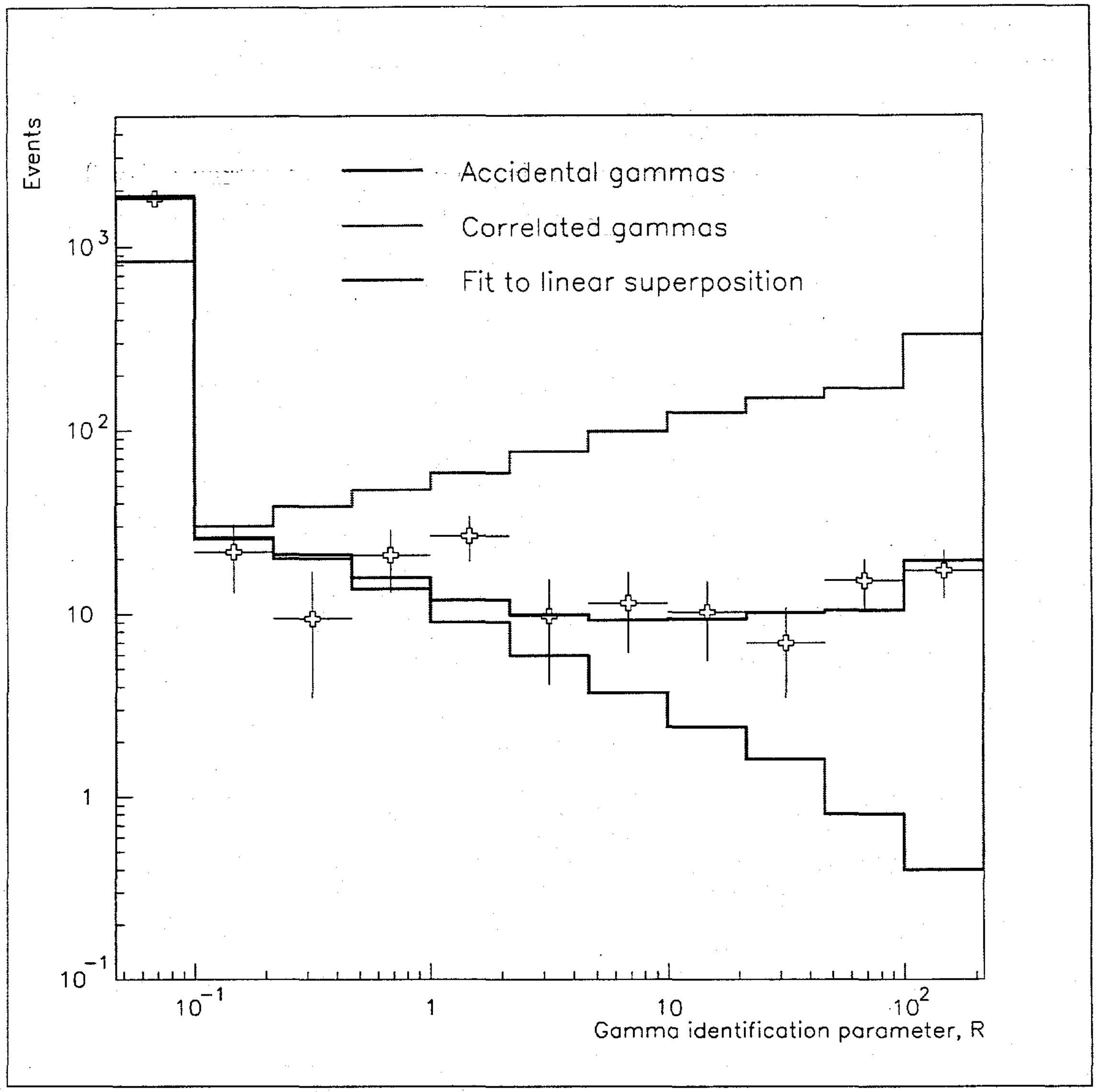

FIGURE 3. The R_γ distribution for events that satisfy the selection criteria for the primary $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation search.

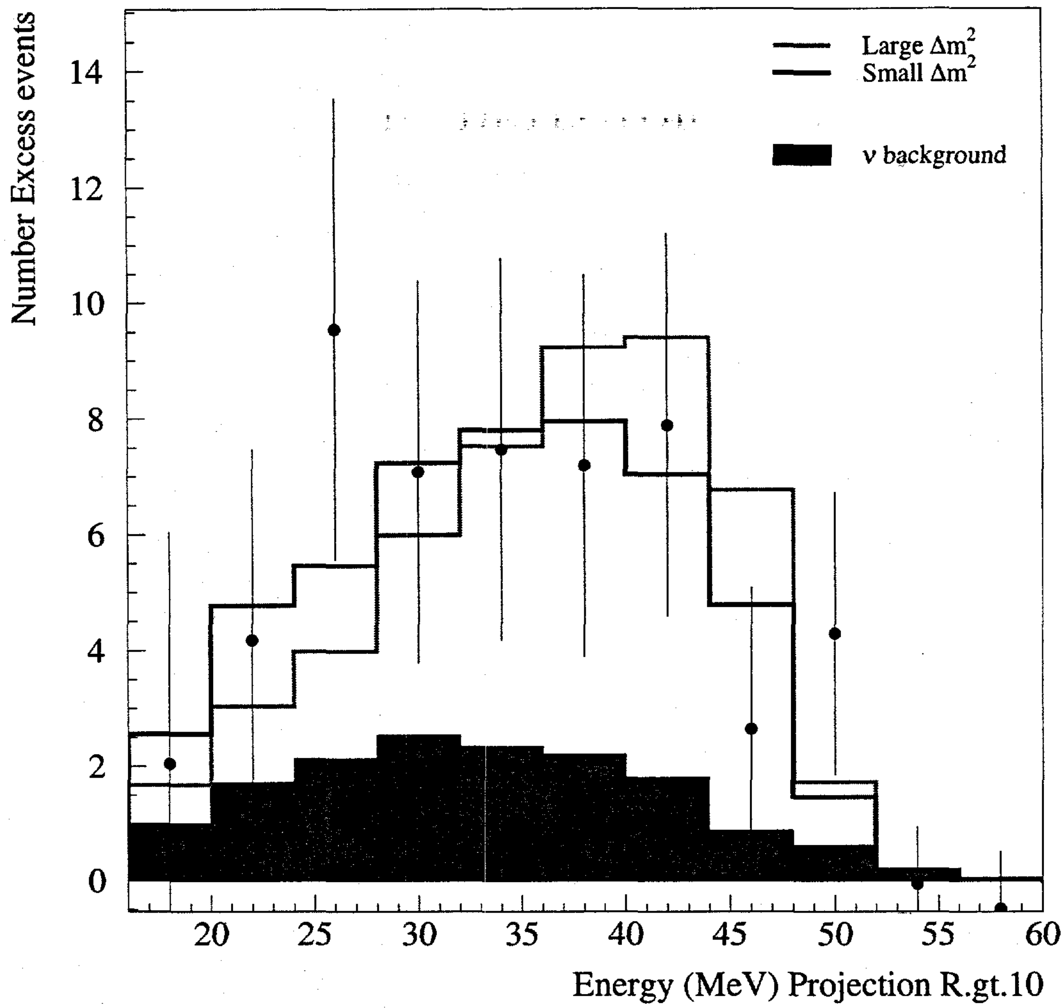

FIGURE 4. The energy distribution of events with $R_\gamma > 10$. The shaded region shows the estimated neutrino background while the curves show the expected distributions from a combination of neutrino background plus neutrino oscillations at high or low Δm^2.

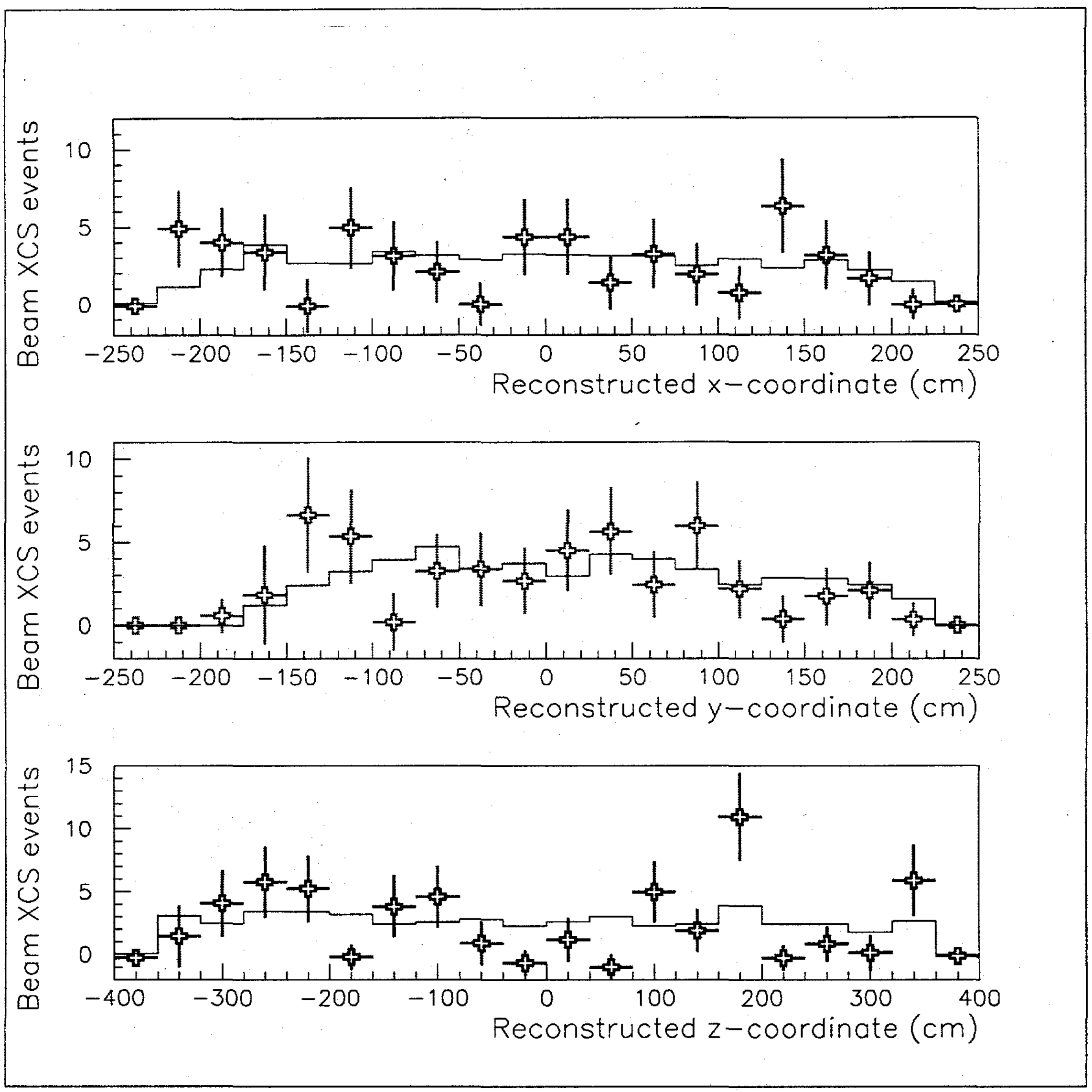

FIGURE 5. The spatial distributions for events with $R_\gamma > 10$. The data agree well with the distributions from $\nu_e C \rightarrow e^- N_{gs}$ scattering (solid histogram), where the reaction is identified by the N_{gs} beta decay.

TABLE 2. Number of beam on-off excess events that satisfy the selection criteria for the primary $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation search with one $R_\gamma > 10$ associated γ and with > 1 $R_\gamma > 10$ associated γ. The excess of events with > 1 correlated γ is approximately zero, which is what is expected for the reaction $\bar{\nu}_e p \to e^+ n$.

Energy Selection	1 Associated γ	> 1 Associated γ
$20 < E_e < 60$ MeV	49.2 ± 9.1	-2.8 ± 1.7
$36 < E_e < 60$ MeV	20.8 ± 5.8	-2.8 ± 1.0

A Δm^2 vs. $\sin^2 2\theta$ oscillation parameter fit for the entire data sample, $20 < E_e < 200$ MeV, is shown in Fig. 6. The fit includes both $\bar{\nu}_\mu \to \bar{\nu}_e$ and $\nu_\mu \to \nu_e$ oscillations, as well as all known neutrino backgrounds. The red and blue regions correspond to 90% and 99% CL allowed regions, while the curves are 90% CL limits from the Bugey reactor experiment, [11] the CCFR experiment at Fermilab, [12] the NOMAD experiment at CERN, [13] and the KARMEN experiment at ISIS. [14] The most favored allowed region is the band from 0.2 to 2.0 eV^2, although a region around 7 eV^2 is also possible. Note that a fit to the $60 < E_e < 200$ MeV data sample, involving secondary $\nu_\mu \to \nu_e$ oscillations only, results in a total excess of 8.3 ± 5.5 oscillation events or an oscillation probability of $(0.09 \pm 0.06 \pm 0.04)\%$, which is consistent with what is expected at low Δm^2 ($\Delta m^2 < 2$ eV^2).

V CONCLUSIONS

The LSND experiment provides evidence for neutrino oscillations from both the primary $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation search and the secondary $\nu_\mu \to \nu_e$ oscillation search. At present, this remains the only evidence for appearance neutrino oscillations and implies that at least one neutrino has a mass greater than 0.4 eV/c^2 and that neutrinos comprise more than 1% of the mass of the universe. The MiniBooNE experiment at Fermilab, [15] which is presently under construction, will provide a definitive test of the LSND results, and if the neutrino oscillation results are confirmed, will make a precision measurement of the oscillation parameters.

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1. The LSND Collaboration presently consists of the following people and institutions: E. D. Church, I. Stancu, W. Strossman, G.J. VanDalen (Univ. of California, Riverside); W. Vernon (Univ. of California, San Diego); D.O. Caldwell, S. Yellin (Univ. of California, Santa Barbara); D. Smith (Embry-Riddle Aeronautical Univ.); R.L. Burman, J.B. Donahue, G.T. Garvey, W.C. Louis, G.B. Mills, V. Sandberg, R. Tayloe, D.H. White (Los Alamos National Laboratory);R. Imlay, H.J. Kim, A. Malik,

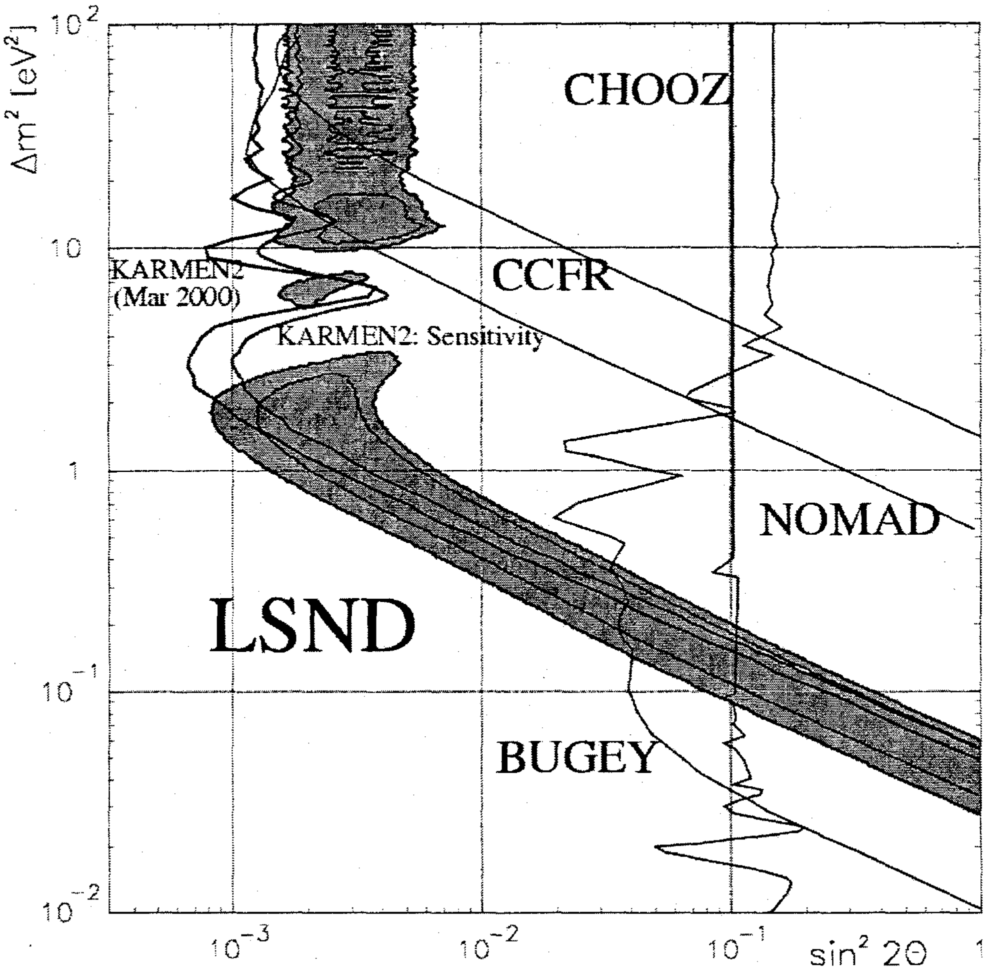

FIGURE 6. A Δm^2 vs. $\sin^2 2\theta$ oscillation parameter fit for the entire data sample, $20 < E_e < 200$ MeV. The fit includes primary $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations and secondary $\nu_\mu \to \nu_e$ oscillations, as well as all known neutrino backgrounds. The red and blue regions correspond to 90% and 99% CL allowed regions, while the red curves are 90% CL limits from the Bugey reactor experiment, the CCFR experiment at Fermilab, the NOMAD experiment at CERN, and the KARMEN experiment at ISIS.

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