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Title: LSND Neutrino Oscillation Results

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LSND NEUTRINO OSCILLATION RESULTS

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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 $51.8^{+18.7}_{-16.9} \pm 8.0$ events is observed with e^+ energy between 20 and 60 MeV, while for the $\nu_\mu \to \nu_e$ search, a total excess of $18.1 \pm 6.6 \pm 4.0$ events is observed with e^- energy between 60 and 200 MeV. If attributed to neutrino oscillations, these excesses correspond to oscillation probabilities (averaged over the experimental energies and spatial acceptances) of $(0.31 \pm 0.12 \pm 0.05)\%$ and $(0.26 \pm 0.10 \pm 0.05)\%$, respectively.

1 Introduction

One of the only ways to probe small neutrino masses is to search for neutrino oscillations, where a neutrino of one type (e.g. $\bar{\nu}_\mu$) spontaneously transforms into a neutrino of another type (e.g. $\bar{\nu}_e$). For this phenomenon to occur, neutrinos must be massive and the apparent conservation law of lepton families must be violated. In 1995 the LSND experiment [1] published data showing candidate events that are consistent with $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations. [2] Additional data are reported here that provide stronger evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations [3] as well as evidence for $\nu_\mu \to \nu_e$ oscillations. [4] The two oscillation searches have completely different backgrounds and systematics from each other.

2 Detector

The Liquid Scintillator Neutrino Detector (LSND) experiment at LAMPF [5] was designed to search with high sensitivity for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations from μ^+ decay at rest. LAMPF is a most intense source of low energy neutrinos due to its 1 mA proton intensity and 800 MeV energy. 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 $\sim$ 1500 photoelectrons, of which $\sim$ 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 $\sim$ 30 cm, an angular resolution of $\sim$ 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.

3 $\bar{\nu}_\mu \to \bar{\nu}_e$ Oscillation Data

The signature for a $\bar{\nu}_e$ interaction in the detector is the reaction $\bar{\nu}_e p \to e^+ n$ followed by $np \to d\gamma$ (2.2 MeV). A likelihood ratio, R, is employed to determine whether a γ is a 2.2 MeV photon correlated with a positron or is from an accidental coincidence. R is the likelihood that the γ is correlated, divided by the likelihood that it is accidental. R depends on the number of hit phototubes for the γ, the reconstructed distance between the positron and the γ, and the relative time between the γ and positron. Figure 1 shows the R distribution, beam on minus beam off, for events with positrons in the $36 < E < 60$ MeV energy range.

The dashed histogram is the result of the R fit for events without a recoil neutron, and the solid histogram is the total fit, including events with a neutron. After subtracting the neutrino background with a recoil neutron there is a total excess of $51.8^{+18.7}_{-16.9} \pm 8.0$ events, which if due to neutrino oscillations corresponds to an oscillation probability of $(0.31 \pm 0.12 \pm 0.05)\%$.

Figure 2 shows the electron energy distribution, beam on minus beam off excess, for events (a) without a γ requirement and (b) events with an associated γ with $R > 30$. For this latter requirement, the total 2.2 MeV γ detection efficiency is 23% and the probability that an event has an accidental γ in coincidence is 0.6%. The dashed histogram shows the background from expected neutrino interactions. There are 22 events beam on in the $36 < E < 60$ MeV energy range and a total estimated background (beam off plus neutrino-induced background) of 4.6 ± 0.6 events. The probability that this excess is a statistical fluctuation is $< 10^{-7}$. The observed average value of $\cos\theta_b$, the angle between the neutrino direction and the reconstructed positron

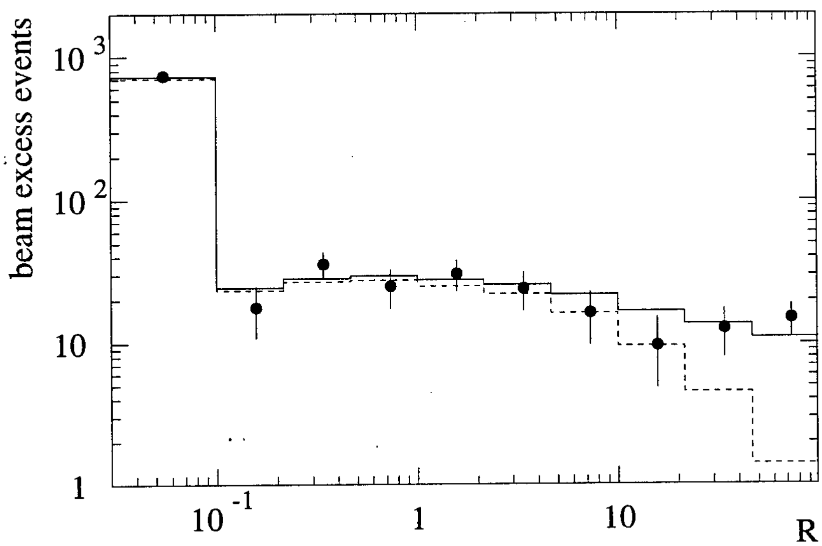

Figure 1: The R distribution, beam on minus beam off excess, for events that have energies in the range $20 < E_e < 60$ MeV. The solid curve is the best fit to the data, while the dashed curve is the component of the fit with an uncorrelated γ.

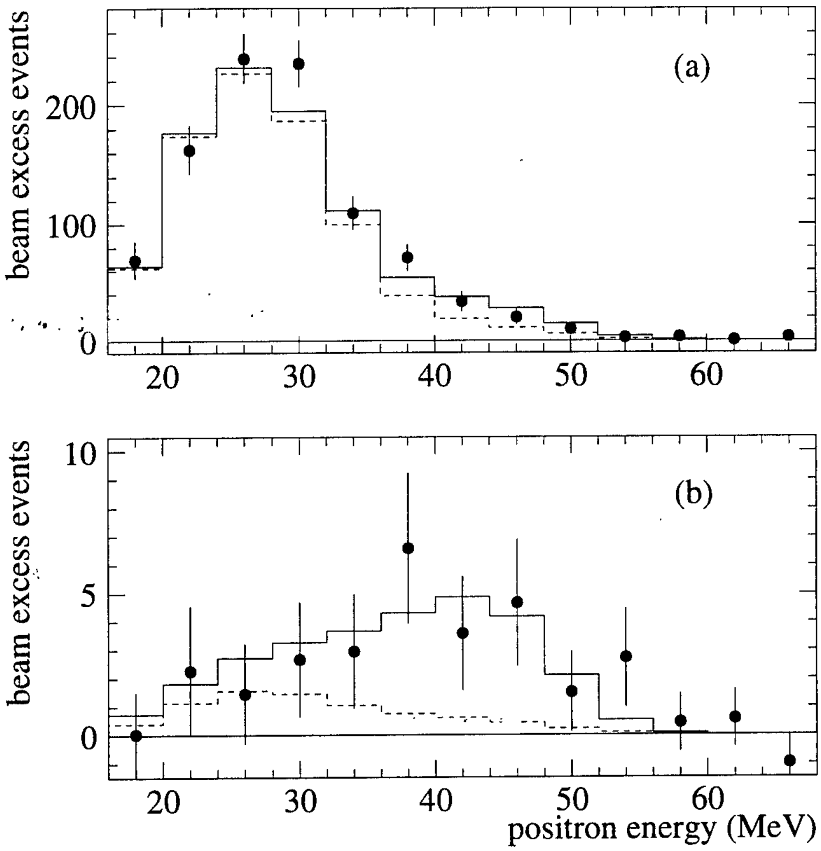

Figure 2: The energy distribution for events with (a) $R \geq 0$ and (b) $R > 30$. Shown in the figure are the beam-excess data, estimated neutrino background (dashed), and expected distribution for neutrino oscillations at large Δm^2 plus estimated neutrino background (solid).

direction, is 0.20 ± 0.13, in agreement with the expected value of 0.16 for $\bar{\nu}_e p$ interactions. If the observed excess is due to neutrino oscillations, Fig. 3 shows the allowed region (90% and 99% likelihood regions) of $\sin^2 2\theta$ vs Δm^2 from a maximum likelihood fit to the L/E distribution of the 22 beam on events. Some of the allowed region is excluded by the ongoing KARMEN experiment at ISIS,[9] the E776 experiment at BNL,[10] and the Bugey reactor experiment.[11]

4 $\nu_\mu \rightarrow \nu_e$ Oscillation Data

The signature for $\nu_\mu \rightarrow \nu_e$ oscillations is an electron from the reaction $\nu_e C \rightarrow e^- X$ in the energy range $60 < E_e < 200$ MeV. Using two independent analyses,[4] a total of 40 beam-related events and 175 beam-unrelated events are observed, corresponding to a beam on-off excess of 27.7 ± 6.4 events. The neutrino-induced backgrounds are dominated by $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$ and $\pi^+ \rightarrow e^+ \nu_e$ decays in the beam-stop and are estimated to be 9.6 ± 1.9 events. Therefore, a total excess of $18.1 \pm 6.6 \pm 3.5$ events is observed above background. Fig. 4 shows the energy distribution of the beam on-off excess along with the expectation for the backgrounds, for an oscillation signal at large Δm^2, and for the sum of the two.

The excess events are consistent with $\nu_\mu \rightarrow \nu_e$ oscillations with an oscillation probability of $(0.26 \pm 0.10 \pm 0.05)\%$. A fit to the event distributions yields the allowed region in the $(\sin^2 2\theta, \Delta m^2)$ parameter space shown in Fig. 5, which is consistent with the allowed region from the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ search.

5 Conclusion

In summary, the LSND experiment observes excesses of events for both the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ and $\nu_\mu \rightarrow \nu_e$ oscillation searches, corresponding to oscillation probabilities of $(0.31 \pm 0.12 \pm 0.05\%)$ and $(0.26 \pm 0.10 \pm 0.05\%)$, respectively. These two searches have completely different backgrounds and systematics and together provide strong evidence for neutrino oscillations in the range $0.2 < \Delta m^2 < 2.0$ eV^2. If neutrino oscillations have in fact been observed, then the minimal standard model would need to be modified and neutrinos would have mass sufficient to influence cosmology and the evolution of the universe.

References

1. The LSND Collaboration consists of the following people and institutions: E. D. Church, K. McIlhany, I. Stancu, W. Strossman, G.J. Van-

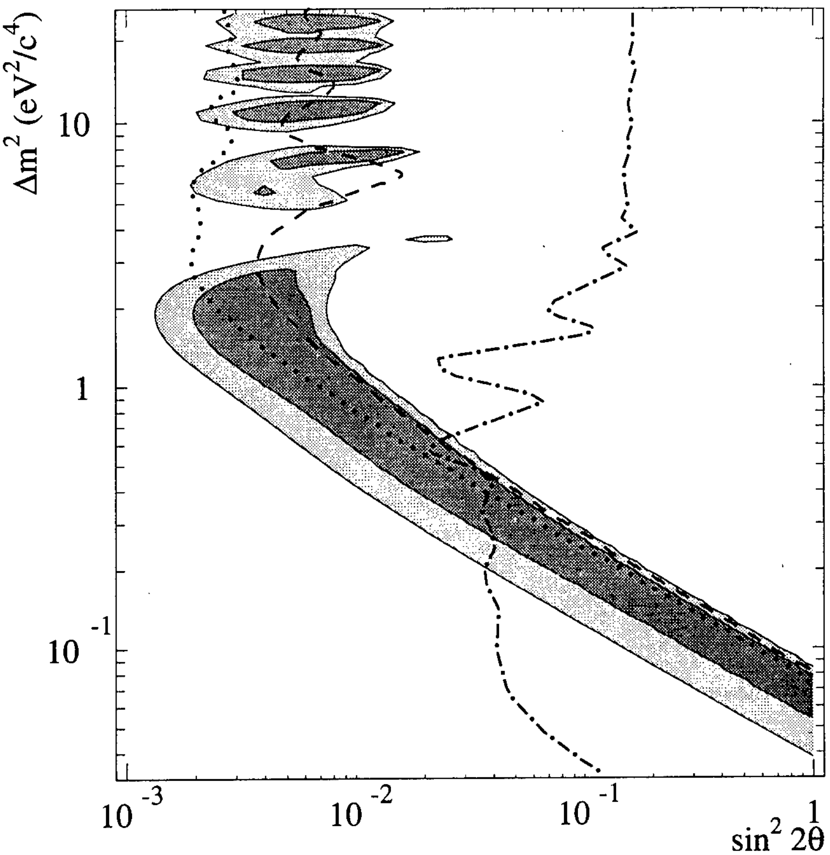

Figure 3: Plot of the LSND Δm^2 *vs* $\sin^2 2\theta$ favored regions. They correspond to 90% and 99% likelihood regions after the inclusion of the effects of systematic errors. Also shown are 90% C.L. limits from KARMEN at ISIS (dashed curve), E776 at BNL (dotted curve), and the Bugey reactor experiment (dot-dashed curve).

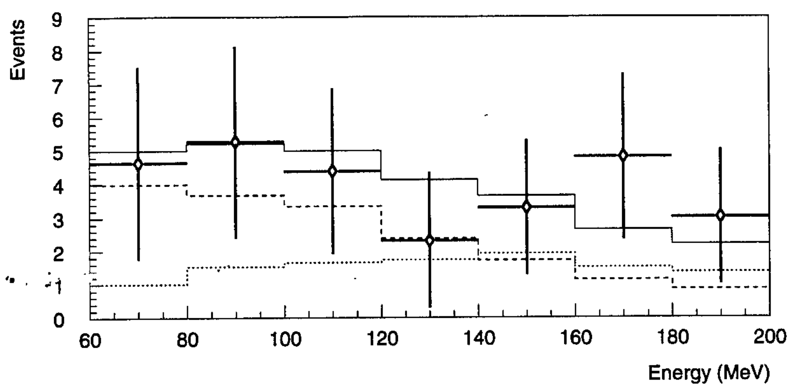

Figure 4: The energy distribution for the final beam-excess decay-in-flight events. The expectation for backgrounds (dotted histogram), the oscillation signal for large values of Δm^2 (dashed histogram), and the sum of the two (solid histogram) are shown.

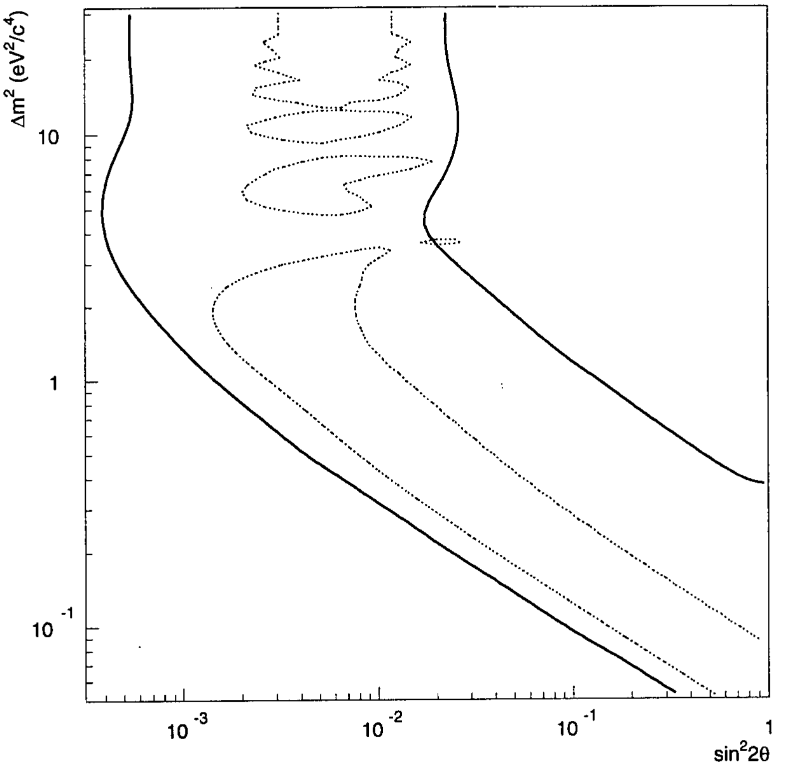

Figure 5: The 95% confidence region for $\nu_\mu \rightarrow \nu_e$ oscillations (solid curve) along with the favored regions for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations (dotted curve).

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