LA-UR-97-4430

Title:

LSND Neutrino Oscillation Results and Implications

CONF-9709213--

Author(s):

W. C. Louis

RECEIVED

MAR 25 1997

OST

19980422 050

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Submitted to:

Erice School on Nuclear Physics, 19th Course,
"Neutrinos in Astro, Particle, and Nuclear Physics"
September 16-24, 1997
Erice, Italy

MASTER

DTIC QUALITY INSPECTED 4

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Form No. 836 R5
ST 2629 10/91

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

LSND Neutrino Oscillation Results and Implications

William C. Louis, representing the LSND Collaboration [1]

Los Alamos National Laboratory, Los Alamos, NM 87545, USA

The LSND experiment at Los Alamos has conducted searches for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations using $\bar{\nu}_\mu$ from μ^+ decay at rest and for $\nu_\mu \rightarrow \nu_e$ oscillations using ν_μ from π^+ decay in flight. For the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ 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 $\nu_\mu \rightarrow \nu_e$ 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. For the future, the BoONE experiment at Fermilab could prove that neutrino oscillations occur and make precision measurements of Δm^2 and $\sin^2 2\theta$.

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 $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations. [2] Additional data are reported here that provide stronger evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations [3] as well as evidence for $\nu_\mu \rightarrow \nu_e$ 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 Los Alamos [5] was designed to search with high sensitivity for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations from μ^+ decay at rest. The LANSCE accelerator 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 $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ 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.

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

The signature for a $\bar{\nu}_e$ interaction in the detector is the reaction $\bar{\nu}_e p \rightarrow e^+ n$ followed by $np \rightarrow d\gamma$ (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. As shown in Fig. 1, 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. Fig. 2 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, as shown in Table 1, 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 3 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 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. 4 shows the allowed region (90% and 99% likelihood regions) of $\sin^2 2\theta$ vs Δm^2 from a maximum likelihood

Figure 1: Associated γ distributions in (a) time, (b) PMT hits, and (c) distance distributions for associated (solid) and accidental (dashed) γ s.

Figure 2: 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 3: 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).

Figure 4: 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).

fit to the L/E distribution of the entire data sample. 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]

Six months of additional data have been collected in 1996 and 1997. For this 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 and 1997 data serve as a systematic check. Preliminary results from 1996 and 1997 are given in Tables 2 and 3. Table 2 shows the number of gold-plated events with $R > 30$ from the entire 1993-1997 data sample, while Table 3 shows the total numbers of excess events and the corresponding oscillation probabilities from fits to the R distributions for the running periods 1993-1995, 1996-1997, and 1993-1997. The preliminary oscillation probability for the entire data sample is $(0.31 \pm 0.09 \pm 0.05)\%$.

Figure 5: The energy distribution for the final beam-excess decay-in-flight events. The expectation for backgrounds (dot-dashed histogram), the oscillation signal for large values of Δm^2 (dotted histogram), and the sum of the two (dashed histogram) are shown.

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-flight 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. 5 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. Fig. 6 shows the angular distribution for the beam on-off excess and the expectation from $\nu_e C \rightarrow e^- N$ scattering.

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. 7, which is consistent with the allowed region from the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ search. These two searches have completely different backgrounds and systematic errors, and together they provide strong evidence that the observed event excesses are indeed due to neutrino oscillations.

Figure 6: The angular distribution for the final beam-excess decay-in-flight events. The expectation for neutrino background and an oscillation signal at large values of Δm^2 (solid histogram) is shown.

Figure 7: 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).

Figure 8: The 90% C.L. limit expected from BooNE for $\nu_\mu \rightarrow \nu_e$ appearance after one calendar year of running, including systematic errors, if LSND signal is not observed (solid line). Summary of results from past experiments and expectations for the future MINOS experiment are also shown.

5 The BooNE Experiment at Fermilab

Motivated by the LSND results, a Letter of Intent [12] has been submitted to Fermilab for building a Booster Neutrino Experiment (BooNE) to search for $\nu_\mu \rightarrow \nu_e$ oscillations and ν_μ disappearance in the region of the LSND excess. Figs. 8 and 9 show the expected sensitivities for $\nu_\mu \rightarrow \nu_e$ appearance and ν_μ disappearance after one calendar year of operation. Assuming that the LSND signal is verified, BooNE will be able to measure with precision the Δm^2 and $\sin^2 2\theta$ oscillation parameters and to search for CP violation in the lepton sector by comparing the $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation rates. Fig. 10 shows the number of events expected in 1 calendar year of running with BooNE for the low Δm^2 favored region of LSND (shaded).

Figure 9: Summary of results from past experiments (narrow, dashed and dotted), future approved experiments (wide, dashed) and 90% C.L. limit expected for BooNE (solid) for ν_μ disappearance after one calendar year of running at 0.5 km. Solid region indicates the favored region for the atmospheric neutrino deficit from the Kamioka experiment. A result from Kamiokanda indicating no zenith angle dependence extends the favored region to higher Δm^2 as indicated by the hatched region.

Figure 10: If the LSND signal is observed, this plot shows the number of events expected in 1 calendar year of running with BooNE for the low Δm^2 favored region of LSND (shaded). Lines indicate regions excluded by past experiments.

The BooNE experiment (phase 1) would begin taking data in 2001. By using phototubes and electronics from the LSND experiment, the BooNE Detector is relatively inexpensive, $\sim \$2M$, and able to be constructed on a short time scale. The detector, as shown in Fig. 11, would consist of a spherical tank which is 12 m in diameter and covered on the inside by 1220 8-inch phototubes (10% coverage) and filled with 750 t of mineral oil, resulting in a 450 t fiducial volume. The volume outside of the phototubes would serve as a veto shield for identifying particles both entering and leaving the detector. The detector would be located 500 m from the neutrino source. The second phase of the experiment would be to add an additional detector, that is identical to the first, at a distance of 1000 m from the neutrino source. The ratio of $\nu_e C \rightarrow e^- N$ events in the two detectors as a function of energy would allow the unambiguous determination of the oscillation parameters with much reduced systematic uncertainties.

The neutrino beam would be fed by the 8 GeV proton Booster at FNAL and would service both phases of the experiment. The neutrino beam line would consist of a target followed by a focusing system and a ~ 30 m long pion decay volume. The low energy, high intensity, and 1 μs time-structure of the Booster neutrino beam would be ideal for this experiment. The sensitivities shown in Figs. 8 and 9 assume the experiment receives 5 Hz of protons over one calendar year (2×10^7 s). The cost of this beam line is expected to be $\sim \$4$ M.

This Booster experiment is compatible with the Fermilab collider or the fixed-target MI programs. The FNAL Booster is capable of running at 15 Hz (5×10^{12} protons per pulse), or 30 Booster batches per 2 s Main Injector Cycle. The antiproton stacking requires only 6 Booster batches at the start of the Main Injector cycle. In principle, this means the BooNE beam line could receive 12 Hz, well above

Figure 11: Schematic of the proposed BooNE detector.

the expectation on which the sensitivities are based.

The BooNE experiments represent an opportunity to resolve two outstanding neutrino oscillation questions on a short-time scale. Within the upcoming five years, no existing or approved experiments will be able to address conclusively the LSND signal region. Thus BooNE represents an important and unique addition to the Fermilab program, and a formal proposal for this experiment will be submitted to the Fermilab Physics Advisory Committee in December of 1997.

6 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 $0.2 < \Delta m^2 < 2.0 \text{ eV}^2$. This implies that at least one neutrino has a mass greater than 0.4 eV. For the future, the BooNE experiment at Fermilab is capable of making precision measurements of the Δm^2 and $\sin^2 2\theta$ oscillation parameters. 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

References

- [1] The LSND Collaboration consists of the following people and institutions: E. D. Church, K. McIlhany, I. Stancu, W. Strossman, G.J. VanDalen (Univ. of California, Riverside); W. Vernon (Univ. of California, San Diego); D.O. Caldwell, M. Gray, S. Yellin (Univ. of California, Santa Barbara); D. Smith, J. Waltz (Embry-Riddle Aeronautical Univ.); I. Cohen (Linfield College); R.L. Burman, J.B. Donahue, F.J. Federspiel, G.T. Garvey, W.C. Louis, G.B. Mills, V. Sandberg, R. Tayloe, D.H. White (Los Alamos National Laboratory); R.M. Gunasingha, R. Imlay, H.J. Kim, W. Metcalf, N. Wadia (Louisiana State Univ.); K. Johnston (Louisiana Tech Univ.); R. A. Reeder (Univ. of New Mexico); A. Fazely (Southern Univ); C. Athanassopoulos, L.B. Auerbach, R. Majkic, D. Works, Y. Xiao (Temple Univ.).
- [2] C. Athanassopoulos *et al.*, *Phys. Rev. Lett.* **75**, 2650 (1995).
- [3] C. Athanassopoulos *et al.*, *Phys. Rev. C* **54**, 2685 (1996); C. Athanassopoulos *et al.*, *Phys. Rev. Lett.* **77**, 3082 (1996).
- [4] C. Athanassopoulos *et al.*, LA-UR-97-1998, submitted to *Phys. Rev. C*.
- [5] C. Athanassopoulos *et al.*, *Nucl. Instrum. Methods A* **388**, 149 (1997).
- [6] R.L. Burman, M.E. Potter, and E.S. Smith, *Nucl. Instrum. Methods A* **291**, 621 (1990); R.L. Burman, A.C. Dodd, and P. Plischke, *Nucl. Instrum. Methods in Phys. Res. A* **368**, 416 (1996).
- [7] R.A. Reeder *et al.*, *Nucl. Instrum. Methods A* **334**, 353 (1993).
- [8] J.J. Napolitano *et al.*, *Nucl. Instrum. Methods A* **274**, 152 (1989).
- [9] B. Bodmann *et al.*, *Phys. Lett. B* **267**, 321 (1991), B. Bodmann *et al.*, *Phys. Lett. B* **280**, 198 (1992), B. Zeitnitz *et al.*, *Prog. Part. Nucl. Phys.* **32** 351 (1994).
- [10] L. Borodovsky *et al.*, *Phys. Rev. Lett.* **68**, 274 (1992).
- [11] B. Achkar *et al.*, *Nucl. Phys.* **B434**, 503 (1995).
- [12] E. Church *et al.*, "A letter of intent for an experiment to measure $\nu_\mu \rightarrow \nu_e$ oscillations and ν_μ disappearance at the Fermilab Booster", LA-UR-97-2120.

Table 1: A list of all backgrounds with the expected number of background events in the $36 < E_e < 60$ MeV energy range for $R \geq 0$ and $R > 30$. The neutrinos are from either π and μ decay at rest (DAR) or decay in flight (DIF). Also shown are the number of events expected for 100% $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transmutation.

Background	Source	$R \geq 0$	$R > 30$
Beam off		146.5 ± 3.2	2.52 ± 0.42
Beam neutrons		< 0.7	< 0.1
DAR			
$\bar{\nu}_e p \rightarrow e^+ n$	$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$	4.8 ± 1.0	1.10 ± 0.22
DIF			
$\bar{\nu}_\mu p \rightarrow \mu^+ n$	$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$	2.7 ± 1.3	0.62 ± 0.31
$\bar{\nu}_e p \rightarrow e^+ n$	$\pi \rightarrow e \nu$ and $\mu \rightarrow e \nu \bar{\nu}$	0.1 ± 0.1	0
Total		7.6 ± 1.6	1.72 ± 0.38
DAR			
$\nu_e {}^{12}\text{C} \rightarrow e^- {}^{12}\text{N}$	$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$	20.1 ± 4.0	0.12 ± 0.02
$\nu_e {}^{13}\text{C} \rightarrow e^- {}^{13}\text{N}$	$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$	22.5 ± 4.5	0.14 ± 0.03
$\nu e \rightarrow \nu e$	$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$	12.0 ± 1.2	0.07 ± 0.01
$\nu_e \text{C} \rightarrow e^- X$	$\pi \rightarrow e \nu_e$	3.6 ± 0.7	0.02 ± 0.01
DIF			
$\nu_\mu \text{C} \rightarrow \mu^- X$	$\pi^+ \rightarrow \mu^+ \nu_\mu$	8.1 ± 4.0	0.05 ± 0.02
$\nu e \rightarrow \nu e$	$\pi \rightarrow \mu \nu_\mu$	1.5 ± 0.3	0.01 ± 0.01
$\nu_\mu \text{C} \rightarrow \pi X$	$\pi \rightarrow \mu \nu_\mu$	0.2 ± 0.1	0
$\nu_e \text{C} \rightarrow e^- X$	$\pi \rightarrow e \nu$ and $\mu \rightarrow e \nu \bar{\nu}$	0.6 ± 0.1	0
Total		68.6 ± 7.4	0.41 ± 0.04
Grand Total		222.7 ± 8.2	4.65 ± 0.57
100% Transmutation	$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$	12500 ± 1250	2875 ± 345

Table 2: Preliminary numbers of gold-plated events with $R > 30$ from the entire 1993-1997 data sample.

e^+ Energy	Events Beam On	Events Beam Off	ν Background	Total Excess
$20 < E_e < 60$ MeV	61	15.6 ± 1.0	11.5 ± 1.5	33.9 ± 8.0
$36 < E_e < 60$ MeV	29	5.2 ± 0.6	3.0 ± 0.6	20.8 ± 5.4

Table 3: Preliminary numbers of excess events and the corresponding oscillation probabilities from fits to the R distributions for the running periods 1993-1995, 1996-1997, and 1993-1997.

Data Sample	Fitted Excess	ν Background	Total Excess	Oscillation Probability
1993-1995	63.5 ± 20.0	12.5 ± 2.9	51.0 ± 20.2	$(0.31 \pm 0.12 \pm 0.05)\%$
1996-1997	35.1 ± 14.7	4.8 ± 1.1	30.3 ± 14.8	$(0.32 \pm 0.15 \pm 0.05)\%$
1993-1997	100.1 ± 23.4	17.3 ± 4.0	82.8 ± 23.7	$(0.31 \pm 0.09 \pm 0.05)\%$

M98003362

Report Number (14) LA-UR--97-4430
CONF-9709213

Publ. Date (11) 199803
Sponsor Code (18) DOE/ER, XF
UC Category (19) UC-413, DOE/ER

DOE