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Neutrino Oscillation Results from LSND

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The Liquid Scintillator Neutrino Detector took data during the years 1993 through 1998. The results of a final analysis of the data are reported here. In summary, the analysis resulted in a cleaner sample of decay-at-rest oscillation candidates and provided a strong constraint on beam related backgrounds. The oscillation probability is fitted to the correlated photon parameter in the inclusive electron sample. The fit yields an excess of 83.3 ± 21.2 events attributable to neutrino oscillations. This corresponds to an oscillation probability of $(0.25 \pm 0.06 \pm 0.04)\%$ for that detector and beam configuration.

1. Introduction

The Liquid Scintillator Neutrino Detector (LSND) has recorded data over the years 1993 to 1998. LSND searches for μ^+ decay-at-rest $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transitions via the reaction $\bar{\nu}_e p \rightarrow e^+ n$ and for π^+ decay-in-flight $\nu_\mu \rightarrow \nu_e$ transitions via the reaction $^{12}C(\nu_e, e^-)^{12}N$, although the latter transition is statistically much less sensitive. There are two major improvements to the previous analyses [1,2] of this data. The reconstruction accuracy of neutron capture photons and electrons is substantially improved. That results in a much lower accidental background in the decay-at-rest oscillation search. In addition, the decay-at-rest and decay-in-flight interactions are now combined in one analysis. That provides a stronger constraint on the oscillation parameters in certain regions of $(\sin^2 2\theta, \Delta m^2)$.

2. Neutrino Source

The neutrino source has been described elsewhere [3]. An 800 MeV proton beam with nearly one milliamper of current impacts a target. The charged pions thus produced decay and produce neutrinos and muons. The muons subsequently decay producing further neutrinos. The proton beam has a duty ratio of beam-on to beam-off that averages to 6% over the 93-98 running

period. The detector triggers independently of whether the beam is on or off. The beam-off data provides an accurate estimate of the beam-off background, and may be scaled by the duty-ratio and subtracted from the beam-on data. We quote "excess events", or "subtracted data", for our neutrino processes.

The source was run under two major configurations. From 1993 through 1995 the primary target was a water target, and there were two thin upstream targets that provided beams for other experiments. Except for a small period in 1996, the 1996 through 1998 configuration had no upstream targets and had a primary target made mostly of tungsten. The 1996-1998 decay-at-rest neutrino flux per proton-on-target (pot) was reduced by 27% and the decay-in-flight flux was reduced by 37% relative to the 1993-1995 running.

The flux of neutrinos produced by the neutrino source is calculated by using transport code [4] that was calibrated on a small test target. Table 1 shows some of the relevant fluxes that are predicted by the simulation.

3. The Neutrino Detector

The detector is described in detail elsewhere[3]. The LSND detector searches for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transitions in the reaction $\bar{\nu}_e p \rightarrow e^+ n$. Excess events

Table 1

Neutrino fluxes at the center of LSND. Both decay-at-rest (DAR) and decay-in-flight (DIF) are shown in ν/cm^2 .

source	type	93-95 flux	96-98 flux	total flux
μ^+ DAR	$\bar{\nu}_\mu$ and ν_e	7.38×10^{13}	5.02×10^{13}	1.22×10^{14}
μ^- DAR	ν_μ and $\bar{\nu}_e$	5.96×10^{10}	4.87×10^{10}	1.08×10^{11}
π^+ DIF	ν_μ	1.37×10^{12}	8.26×10^{11}	2.20×10^{12}
π^- DIF	$\bar{\nu}_\mu$	1.06×10^{11}	8.36×10^{10}	1.90×10^{11}
π^+ DIF	ν_e	5.56×10^8	5.01×10^8	1.06×10^9
μ^+ DIF	ν_e	4.13×10^9	2.44×10^9	6.57×10^9

in that reaction are evidence for neutrino flavor non-conservation due to neutrino oscillations. It consists of a large tank of mineral oil (167 metric tons) located 30 meters from the beam target area. The tank is viewed by 1220 photo-multiplier tubes which image the light from the event, and allow position and directional information for electron events. The tank is surrounded by a veto system designed to reduce the cosmic ray trigger rate to an acceptable level. The detector was designed to use Čerenkov light as electron particle identification, but with a small admixture of scintillator, it is sensitive to 2.2 MeV gamma rays from the subsequent neutron capture on free protons in the liquid.

The detector triggers on primary events above a threshold of 150 photo-multiplier hits. It then executes a search into the past 52 μs and reads in any past activities above an 18 photo-multiplier hit threshold. This records $^{12}C(\nu_\mu, \mu^-) ^{12}N$ reactions and allows for the rejection of cosmic ray muon induced events.

The trigger also sets a 1 ms time window and waits for any un-vetoed gamma events and records them after primary events. That picks up neutron capture gammas, since they have a 186 μs capture time-constant.

The detector also triggers on the β decays of $^{12}B_{GS}$ and $^{12}N_{GS}$ from μ^- capture and neutrino interactions. These have 30 ms and 15.9 ms decay time-constants, respectively.

The largest number of neutrino events come from interactions on the ^{12}C in the liquid. They are mostly $^{12}C(\nu_e, e^-) ^{12}N$ events from μ^+

decay-at-rest and $^{12}C(\nu_\mu, \mu^-) ^{12}N$ events from π^+ decay-in-flight. The $^{12}C(\nu_e, e^-) ^{12}N_{GS}$ and $^{12}C(\nu_\mu, \mu^-) ^{12}N_{GS}$ exclusive reactions have well known cross sections, and they are used to determine the flux of μ^+ decay-at-rest neutrinos and π^+ decay-in-flight neutrinos. The cross section for the process $\nu e^- \rightarrow \nu e^-$ is also known and provides another measure of the fluxes.

In addition, the $\bar{\nu}_\mu p \rightarrow \mu^+ n$ reaction also has a well determined cross section and is used to measure the $\bar{\nu}_\mu$ flux from π^- decay-in-flight. The number of subsequent μ^- decays is well determined from a knowledge of the distribution of stopped μ^- in the materials in the target area and the knowledge of the μ^- capture rates in these materials. Those have been calculated in the beam simulation[4] for the 37 different configurations of the target area during the running period from 1993 to 1998. The atomic orbital corrections to the μ^- decay spectrum are important and included in the calculation of the flux. It is believed that there is no significant contribution to the μ^- production from π^- decay-at-rest since they are absorbed strongly by the nucleus.

4. Data Analysis

Approximately six tera-bytes of raw LSND data were re-processed in order to take advantage of improved reconstruction algorithms and generate an unbiased sample of primary electron-like events. The efficiency for this process was around 92% over all years, the loss being attributable to old, unreadable data tapes. The hardware trigger efficiencies for primary triggers varied year-

to-year, and they are taken into account in the analysis. On average, the veto holdoff, event latency and deadtime, and veto threshold efficiencies added up to around 75% for primary events, and 98% for past activities.

An offline data reconstruction, selection, and reduction is used to produce a primary electron-like sample for physics purposes. That selection rejected events based on: past activity properties to remove cosmic ray events; particle identification to remove cosmic ray neutron events; a fiducial volume defined by the distance from the nearest surface of photo-multiplier tubes, $dist > 10cm$; and veto system hit requirements on the primary event. The efficiency of this selection was 83% for events inside a surface defined by $dist = 10cm$.

The primary electron-like sample is divided into classes according to whether there are past events or future events associated with the primary electron event.

The inclusive electron class, or *incl. e*, contains electron-like events that have no prior activity within 12 μs , satisfy a stricter particle identification criteria, energy between 20 MeV and 200 MeV and fall inside the $dist > 35cm$ fiducial volume. That class contains dominantly $^{12}C(\nu_e, e^-) ^{12}N$ and $\nu e^- \rightarrow \nu e^-$ interactions. The same particle identification and fiducial volume criteria are also applied to the rest of the event classes.

The μe class additionally requires a prior activity within 10 μs of the primary event. That class contains dominantly ν_μ and $\bar{\nu}_\mu$ interactions.

The future correlated events come in two varieties, neutron-capture gammas and the beta decays of $^{12}N_{GS}$ and $^{12}B_{GS}$. These then yield the $e\beta$, $e\gamma$, $\mu e\beta$, and $\mu e\gamma$ event classes.

For the neutron capture gammas, a correlation likelihood-ratio, R_γ , is used to differentiate random background gammas from true neutron-capture gammas. The probability distributions used in the R_γ likelihood-ratio are the vertex separation, the time separation, and the number of photo-multiplier hits in the gamma event. Due to the improved reconstruction, our correlated gamma efficiency increased to 40% from 23%, while at the same time, the accidental gamma

acceptance dropped from 0.6% to 0.23%. The increase in signal to accidental background is a factor of 4.5.

The $e\beta$ class is almost purely $^{12}C(\nu_e, e^-) ^{12}N_{GS}$ reactions that constrain the ν_e decay-at-rest flux. The $e\gamma$ class is the channel for the decay-at-rest oscillation search. The $\mu e\beta$ is largely $^{12}C(\nu_\mu, \mu^-) ^{12}N_{GS}$ and constrains the ν_μ flux. The $\mu e\gamma$ class is important because it is dominated by $\bar{\nu}_\mu p \rightarrow \mu^+ n$ with some $^{12}C(\nu_\mu, \mu^-) ^{12}N$. The $\mu e\gamma$ class provides a source of neutrino induced neutrons that test the gamma correlation parameter R_γ and constrain the π^- production and decay level in the beam target area.

Energy, time difference, R_γ , and $\frac{L_\nu}{E_\nu}$ distributions from these event classes are simultaneously fit in order to obtain the best values for the fluxes, efficiencies, and event numbers for the different neutrino processes involved. Only the 1994-1998 data is used in this fit. The 1993 data is only 8% of the total and the fit results are corrected accordingly.

Table 2 shows the results of the fit. The χ^2 of the fit is 265 for 269 degrees of freedom.

The decay-at-rest oscillation reaction, $\bar{\nu}_e p \rightarrow e^+ n$, shows up in the $e\gamma$ ($R_\gamma > 10$) class of events. The reaction is two-body and thus the initial neutrino energy can be determined from the out-going electron energy. That allows an accurate determination of the oscillation phase of the neutrino, $\frac{L_\nu}{E_\nu}$, on an event-by-event basis. Figure 1 shows the electron energy distributions and Figure 2 shows the $\frac{L_\nu}{E_\nu}$ excess events for the $e\gamma$ ($R_\gamma > 10$) class. In Figure 2, the neutrino energy is determined by the incident neutrino direction, and by the outgoing electron energy and direction. The expectation for the most likely oscillation parameters is shown also, including beam related backgrounds.

In order to determine the oscillation parameters, a fit to the R_γ distribution of the *incl. e* events is also made. The result is that (83.3 ± 21.2) events with correlated gammas are needed to account for the observed excess. This corresponds to an overall oscillation probability of $(0.25 \pm 0.06 \pm 0.04)\%$ for the LSND beam and detector configuration.

Table 2

The best fit values for numbers of events in different event classes for the 1994-1998 data.

event class	Excess data events	Best fit number
<i>incl. e</i>	1818	1885
<i>eβ</i>	910	894
<i>μe</i>	2096	2033
<i>$\mu e\beta$</i>	78.4	73.8
<i>$\mu e\beta$</i>	78.4	73.8
<i>$\mu e\gamma$ ($R_\gamma > 1$)</i>	182	176
<i>$e\gamma$ ($R_\gamma > 10$)</i>	43.6	43.7

A four-dimensional fit in $(E, R_\gamma, L, \cos\theta_\nu)$ was performed to determine the allowed region in the two-dimensional $(\sin^2 2\theta, \Delta m^2)$ space. The results are shown in Figure 3.

4.1. Summary

A new analysis of the 1993-1998 LSND data has been performed with improved event reconstruction and oscillation fit algorithms. The data show a strong excess of $\bar{\nu}_e p \rightarrow e^+ n$ events above standard model expectations. A natural explanation of this excess is the flavor oscillation of $\bar{\nu}_\mu$ into $\bar{\nu}_e$. That would imply the existence of a Δm^2 above 0.2 eV^2 . An experiment to test that oscillation hypothesis, MiniBooNE[5], is under construction at Fermilab. MiniBooNE will search for $\nu_\mu \rightarrow \nu_e$ transitions in a π decay-in-flight beam and should be in operation at the end of the year 2001.

iment to measure $\nu_\mu \rightarrow \nu_e$ oscillations and ν_μ disappearance at the Fermilab Booster: BooNE", LA-UR-98-352, Fermilab experiment 898. See also A. Bazarko, these proceedings. The MiniBooNE proposal is available at www.neutrino.lanl.gov/BooNE/boone_proposal.ps.

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Figure 1. The electron energy distribution for $R_\gamma > 10$ incl. e events.

Figure 2. The $\frac{L}{E_\nu}$ distribution for $R_\gamma > 10$ *incl. e* events.

Figure 3. Allowed region for the *incl. e* sample with energies from 20 MeV to 200 MeV.