Latest Results from the LSND Experiment

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LATEST RESULTS FROM THE LSND EXPERIMENT

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REPRESENTING THE LSND COLLABORATION

The LSND experiment at Los Alamos has searched for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations using $\bar{\nu}_\mu$ from $\mu^+$ decay at rest and for $\nu_\mu \rightarrow \nu_e$ oscillations using $\nu_\mu$ from $\pi^+$ decay in flight. An excess of events attributable to neutrino oscillations has been observed in both of these channels in data collected in 1993-1995. A recent preliminary analysis of the decay at rest $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ data collected in 1996-1998 with a different $\nu$ source configuration is consistent with the earlier data. The BooNE experiment that is planned to run at FNAL will further test these results.

1 Introduction

The phenomenon of neutrino oscillations, where a neutrino of one type (e.g. $\bar{\nu}_\mu$) spontaneously transforms into a neutrino of another type (e.g. $\bar{\nu}_e$), has important and far-reaching consequences for particle physics and cosmology. For this phenomenon to occur, at least one neutrino must be massive and the heretofore observed lepton flavor conservation law must be violated.

In 1995, the LSND experiment reported the observation of candidate events in a search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations\(^2\). The evidence for oscillations has grown with additional data from the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ channel\(^3\) and with new results on $\nu_\mu \rightarrow \nu_e$ oscillations\(^4\).

2 Experiment

The Liquid Scintillator Neutrino Detector (LSND) experiment\(^5\) at Los Alamos was designed to search with high sensitivity for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations from $\mu^+$ decay at rest. The main concept of the experiment is to create a large flux of $\bar{\nu}_\mu$, with little $\bar{\nu}_e$ background, then to look for $\bar{\nu}_e$ interactions in the detector and compare the rate with that expected from conventional (non-oscillation) sources. An excess may be attributed to neutrino oscillations.

2.1 Neutrino Source

The LANSCE accelerator at Los Alamos National Lab (LANL) is an 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 $\pi^+$ or $\mu^+$ decay — the $\pi^-$ and $\mu^-$ are readily captured in the Fe of the shielding and Cu of the beam stop.\(^6\) This $\pi^+ / \pi^-$ and $\mu^+/ \mu^-$ asymmetry in the beam stop results in a low relative production rate of $\bar{\nu}_e$ as compared to $\nu_\mu$. The $\bar{\nu}_e$ rate is calculated to be $4 \times 10^{-4}$ that of the $\nu_\mu$ in the $36 < E_\nu < 52.8$ MeV energy range. The $\nu_\mu \rightarrow \nu_e$ search utilizes $\nu_\mu$ from $\pi^+$ decay in flight. There are few $\nu_e$ in the beam above 60 MeV because few $\mu^+$ decay in flight and the $\pi^+$ decay to a $\nu_e$ only rarely ($\sim 10^{-4}$).

The energy spectra of the main components of the neutrino flux at the LSND detector are shown in Fig. 1. An important verification of the accuracy of these calculated fluxes are the cross section measurements of $\nu_e C \rightarrow e^- N_{g.s.}$\(^7\) and $\nu_\mu C \rightarrow \mu^- N_{g.s.}$\(^8\), two well-understood reactions.

The neutrino source was reconfigured after the 1995 run to study tritium production. A comparison of the data collected after this change to that collected before allows another important check of the flux calculations and the neutrino oscillation hypothesis.

2.2 The Detector

The LSND detector\(^5\) consists of an approximately cylindrical tank 8.3 m long by 5.7 m in diameter and is located 30 m from the neutrino source. The detector is well-shielded by 9 m steel-equivalent between detector and neutrino source, an 8 m water plug downstream of the detector, and 2 kg/cm\(^2\) overburden. A veto shield\(^9\) with active and passive shielding surrounds the

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Figure 1. Simplified figure showing the main components of the neutrino flux with an arbitrary scale. Note the log scale.
detector tank and tags incoming (or outgoing) charged particles.

The inside surface of the tank is lined with 1220 8-inch Hamamatsu phototubes providing 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. A typical 45 MeV electron created in the detector produces a total of ~1500 photoelectrons, of which ~280 photoelectrons are in the Čerenkov cone.

3 $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Oscillation Search from $\mu^+$ DAR

The signature for a $\bar{\nu}_e$ interaction in the detector is the detection of the $e^+$ from the reaction $\bar{\nu}_e p \rightarrow e^+ n$ followed by the detection of the $\gamma$ from the neutron-capture reaction ($np \rightarrow d\gamma (2.2 \text{ MeV})$). The $e^+$ signature is an event with phototube signals that fit to a non-cosmic $e^+$ hypothesis (small spread in space and time, a good Čerenkov cone, and no sign of cosmic ray correlation). The $e^+$ ID parameter distribution is shown in Fig. 2 for positrons and compared to that for neutrons.

The neutron-capture $\gamma$ is identified via a correlated to accidental likelihood ratio, $R$, that is formed from these distributions: primary to $\gamma$ time.
PMT multiplicity, distance from primary to \( \gamma \). The combination of these quantities serves to separate a correlated \( \gamma \) from an accidental with high efficiency and low background as may be seen by the difference between accidental and correlated \( \gamma \) \( R \) distributions in Fig. 3.

The energy distribution for events passing the \( e^+ \) and stringent \( \gamma \) cuts (\( R > 30 \)) from the entire LSND data set (1993–1998) are shown in Fig. 4. From this sample, with positron energies from 36 to 60 MeV, a preliminary analysis yields 33 oscillation events with 9.5±0.9 background events expected. The favored regions obtained from a likelihood analysis of this data set are shown in Fig. 6.

4 \( \nu_\mu \to \nu_e \) Search from \( \pi^+ \) DIF

The signature for \( \nu_\mu \to \nu_e \) oscillations is an electron from the reaction \( \nu_e C \to e^- X \) in the energy range \( 60 < E_e < 200 \) MeV. Using two different analyses,\(^4\) a total of 40 beam-related events and 175 beam-unrelated events are observed, corresponding to a beam excess of 27.7 ± 6.4 events. The neutrino-induced backgrounds are dominated by \( \mu^+ \to e^+ \bar{\nu}_\mu \nu_e \) and \( \pi^+ \to e^+ \nu_e \) decays-in-flight in the beam-stop and are estimated to be 9.6 ± 1.9 events. Therefore, a total excess of 18.1±6.6±3.5 events is observed above background. The beam excess energy distribution is shown in Fig. 5. If interpreted as \( \nu_\mu \to \nu_e \) oscillations,
Figure 4. The energy distribution for $e^+$ candidates that also have a high $\gamma$-likelihood ($R > 30$) from the 1993-1998 data set. The points show the beam excess data. Also shown are the estimated neutrino background (solid) and the estimated distributions for oscillations at small (dotted) and large (dot-dash) $\Delta m^2$ plus neutrino background (solid).

this data yields an oscillation probability of $(0.26 \pm 0.10 \pm 0.05)\%$. The 95\% confidence region obtained from this data set is shown along with the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ results in Fig. 6.

5 The BooNE Experiment

It is clear that these results from LSND, while convincing evidence for neutrino oscillations, should be verified with followup experiment that is capable of detecting hundreds of events for neutrino oscillations in the parameter space suggested by LSND. The BooNE (Booster Neutrino Experiment) experiment at Fermi National Accelerator Laboratory (Fermilab) is designed for just this purpose. BooNE will search for $\nu_\mu \rightarrow \nu_e$ oscillations in the region of the LSND excess. Fig. 7 shows the expected sensitivities for $\nu_\mu \rightarrow \nu_e$ appearance after one calendar year of operation.

The BooNE detector will consist of a spherical tank, $\sim 12$ m in diameter and covered on the inside by 1280 8-inch phototubes ($\sim$10\% coverage), filled with 800 t of mineral oil, resulting in a $\sim$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 will be located 550 m...
Figure 5. The energy distribution for the $\nu_\mu \rightarrow \nu_e$ oscillation sample. The points show the beam excess data. Also shown are expectation for backgrounds (dotted histogram), the oscillation signal for large values of $\Delta m^2$ (dashed), and the sum of the two (solid).

from the neutrino source.

The neutrino beam will be fed by the 8 GeV proton Booster at Fermilab. The neutrino beam line would consist of a target followed by a focusing system and a $\sim 50$ m long pion decay volume. The low energy, high intensity, and 1 $\mu$s time structure of the Booster neutrino beam will be ideal for this experiment.

The BooNE experiment provides an opportunity to resolve the neutrino oscillation question on a short-time scale. Within the upcoming five years, no existing or approved experiments will be able to test conclusively the LSND signal. Thus BooNE represents an important and unique addition to the Fermilab program. BooNE has received Stage I approval, design is underway, and construction of the detector will begin in the latter part of 1999.

6 Conclusion

The LSND experiment observes excesses of events in both the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ and $\nu_\mu \rightarrow \nu_e$ oscillation searches, corresponding to oscillation probabilities of $(0.31\pm0.12\pm0.05)\%$ and $(0.26\pm0.10\pm0.05)\%$, respectively. These two searches have different backgrounds and systematics and together provide strong evidence for neutrino oscillations in the range $0.2 < \Delta m^2 < 2.0$ $\text{eV}^2$. New data taken in 1996–1998 with a different $\nu$ source configuration strengthens this. In
The near future, the BooNE experiment at Fermilab will definitively confirm or refute these observations.

References

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Figure 7. Expected sensitivity for MiniBooNE for $\nu_\mu \rightarrow \nu_e$ appearance after one year of running, including systematic and statistical errors, if LSND signal is not observed (solid line). Results from past experiments through December, 1997, also are shown.

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