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RESULTS OF THE LSND SEARCH FOR $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ OSCILLATIONS

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A search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations has been conducted at the Los Alamos Meson Physics Facility by using $\bar{\nu}_\mu$ from $\mu^+$ decay at rest. The $\bar{\nu}_e$ are detected via the reaction $\bar{\nu}_e p \rightarrow e^+ n$, correlated with a $\gamma$ from $n p \rightarrow d \gamma$ (2.2 MeV). The use of tight cuts to identify $e^+$ events with correlated $\gamma$ rays yields 22 events with $e^+$ energy between 36 and 60 MeV and only $4.6 \pm 0.6$ background events. The probability that this observation can be explained by statistical fluctuation is less than $10^{-7}$. Assuming these events are due to oscillations, a likelihood fit to all the $e^+$ events between 20 and 60 MeV has been performed to extract the oscillation parameters $\sin^2 2\theta$ and $\Delta m^2$. The favored region resulting from this fit is shown.
We present the results from a search for neutrino oscillations using the Liquid Scintillator Neutrino Detector (LSND) apparatus described in reference [1]. Details of the analysis may be found in reference [2]; this document will present a summary of that analysis and provide details on the extraction of the oscillation parameters.

Protons are accelerated by the LAMPF linac to 800 MeV kinetic energy with a duty factor of 7%. This pulsed beam passes through a series of targets, culminating with the A6 beam stop. The primary neutrino flux comes from $\pi^+$ produced in a 30-cm-long water target in the A6 beam stop [1]. Most of the $\pi^+$ stop and decay at rest (DAR) through the sequence $\pi^+ \rightarrow \mu^+\nu_\mu$, followed by $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$, supplying $\bar{\nu}_\mu$ with a maximum energy of 52.8 MeV. The open space around the target is short compared to the pion decay length, so only 3% of the $\pi^+$ decay in flight (DIF). A much smaller fraction (approximately 0.001%) of the muons DIF, due to the difference in lifetimes and that a $\pi^-$ must first DIF.

A $\bar{\nu}_e$ component in the beam comes from the symmetrical decay chain starting with a $\pi^-$. This background is suppressed by three factors in this experiment. First, $\pi^+$ production is about eight times the $\pi^-$ production in the beam stop. Second, 95% of $\pi^-$ will come to rest and are absorbed before decay in the beam stop. Third, 88% of $\mu^-$ from $\pi^-$ DIF are captured from atomic orbit, a process which does not give a $\bar{\nu}_e$. Thus, the relative yield, compared to the positive channel, is estimated to be $\sim (1/8) \times 0.05 \times 0.12 = 7.5 \times 10^{-4}$. A detailed Monte Carlo simulation [3], gives a value of $7.8 \times 10^{-4}$ for the flux ratio of $\bar{\nu}_e$ to $\nu_\mu$.

The Liquid Scintillator Neutrino Detector is a tank filled with 167 metric tons of dilute liquid scintillator, located 30 m from the neutrino source, and surrounded on all sides except the bottom by a liquid scintillator veto shield. The dilute mixture allows the detection in photomultiplier tubes (PMTs) of both Čerenkov light and isotropic scintillation light, so that reconstruction provides particle identification (PID) for $e^\pm$ along with the $e^\pm$ position and the direction of the event. PID is based on the quality of the position and Čerenkov angle fits, and on the relative amount of early light [1]. LSND detects $\bar{\nu}_e$ via $\bar{\nu}_e p \rightarrow e^+n$, followed by the neutron-capture reaction $np \rightarrow d\gamma(2.2$ MeV). Thus the oscillation event signature consists of an “electron” signal, followed by a 2.2 MeV photon correlated with the electron signal in both position and time. The largest calculated neutrino background (beam-related) with this coincidence signature arises from the conventional production of $\bar{\nu}_e$ through $\mu^-$ DAR. Because the data acquisition and triggering [1] do not depend on whether the beam is on or off, backgrounds from cosmic rays (beam-unrelated) are well measured.

Separation of correlated neutron-capture photons from accidental signals is achieved using an approximate likelihood ratio, $R$ for the correlated and accidental hypotheses. $R$ is defined using distributions [2] of the number of hit PMTs for the reconstructed $\gamma$ and of the time and distance between the primary event and that $\gamma$. The $R$ distribution for accidental photons is provided by those $\gamma$ candidates which follow randomly-timed laser calibration events. That for correlated photons is determined in two ways. One method uses the $\gamma$ candidates following cosmic ray neutron events. Another method uses a Monte Carlo simulation of the distance distribution (which could be different for low-energy oscillation neutrons and high-energy cosmic ray neutrons) together with the hit PMT and time distributions determined in the first method.

In the largely background-free region of $36 < E_\gamma < 60$ MeV, we find 22 signal events coincident with a $R > 30 \gamma$. (The probability of an accidental $\gamma$ passing the $R > 30$ selection is 0.0065; its efficiency for a correlated $\gamma$ is 0.23.) The measured beam-unrelated contamination of this sample is $36 \cdot 0.07 = 2.5 \pm 0.4$ events. The calculated beam-related background is $2.1 \pm 0.4$ events. The probability that the 22 events are due to a statistical fluctuation of the $4.6 \pm 0.6$ total background events is $4.1 \times 10^{-8}$. Details of selection criteria and backgrounds considered are presented in Ref. [2].
Table 1: A list of significant backgrounds with the expected number of background events in the $20 < E_\nu < 60$ energy range that satisfy "electron" particle identification cuts. The neutrinos are from either $\pi$ and $\mu$ decay at rest (DAR) or decay in flight (DIF).

<table>
<thead>
<tr>
<th>Background</th>
<th>Neutrino Source</th>
<th>Events with $R \geq 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\nu}_e p \rightarrow e^+ n$</td>
<td>$\mu^+ \rightarrow e^- \nu_\mu \bar{\nu}_e$ DAR</td>
<td>$8.6 \pm 1.7$</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu p \rightarrow \mu^+ n$</td>
<td>$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$ DIF</td>
<td>$3.8 \pm 1.9$</td>
</tr>
<tr>
<td>$\nu_\mu C \rightarrow \mu^- X$</td>
<td>$\pi^+ \rightarrow \mu^+ \nu_\mu$ DIF</td>
<td>$11.3 \pm 5.6$</td>
</tr>
<tr>
<td>$\nu_e^{12} C \rightarrow e^- \ ^{12} N$</td>
<td>$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$ DAR</td>
<td>$666.7 \pm 133.3$</td>
</tr>
<tr>
<td>$\nu_e ^{13} C \rightarrow e^- \ ^{13} N$</td>
<td>$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$ DAR</td>
<td>$44.2 \pm 8.8$</td>
</tr>
<tr>
<td>$e \nu \rightarrow e \nu$</td>
<td>$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$ DAR</td>
<td>$56.7 \pm 5.7$</td>
</tr>
</tbody>
</table>

In the two-generation formalism, the oscillation probability is written as

$$P = \sin^2 2\theta \sin^2\left(1.27 \Delta m^2 L/E_\nu\right),$$

where $\theta$ is the mixing angle, $\Delta m^2$ is the difference of the squares of the two mass eigenstates in eV$^2$, $L$ is the distance from neutrino production in meters, and $E_\nu$ is the neutrino energy in MeV. To extract the maximum constraint on the oscillation parameters, the largest possible energy range was used was used. There are large backgrounds for $E_\nu < 36$ MeV (the dominant source arising from $\nu_e ^{12} C \rightarrow e^- \ ^{12} N$), but these backgrounds are not accompanied by a correlated $\gamma$. For $E_\nu < 20$ MeV, it is energetically possible to produce correlated $e, n$ pairs via $\nu_e ^{12} C \rightarrow e^- n X$; for this reason the energy range used was $20 < E_\nu < 60$ MeV.

There is relatively little background to the oscillation search at either high energy (e.g. $E_\nu > 36$ MeV) or high $R$ (e.g. $R > 30$). To take all this data into account, a likelihood fit was performed on the entire sample of 1763 beam-on events (with no correlated $\gamma$ requirement). The fit binned the oscillation candidates in four dimensions corresponding to four measured quantities. They were $E_\nu$ (the measured energy of the positron), $R$ (the gamma likelihood ratio), $\cos \theta_b$ (the cosine of the angle between the $e$ and $\nu$ directions), and $L$ (the measured distance from the $\bar{\nu}_\mu$ source).

Using the calculated background estimates (see Table 1), the distributions of beam-related background events in these variables are calculated. To calculate the beam-unrelated background, the measured beam-off data set is smoothed and scaled by the duty ratio.

A likelihood function, $\mathcal{L}$, is constructed:

$$\mathcal{L}(n_1, n_2, \ldots | \Delta m^2, \sin^2 2\theta) = \prod_{i=1}^{N} \frac{1}{n_i!} \nu_i^{n_i} e^{-\nu_i},$$

where $N$ is the total number of bins, $n_i$ is the number of beam-on events in bin $i$, and $\nu_i$ is the expected number in bin $i$. The expected number in bin $i$ may be written

$$\nu_i = \nu_{i,BUB} + \nu_{i,BRB} + \nu_{i,\text{osc}}(\Delta m^2, \sin^2 2\theta),$$

where $\nu_{i,BUB}$ is the calculated number of events in bin $i$ due to beam-unrelated background, $\nu_{i,BRB}$ is that due to beam-related background, and $\nu_{i,\text{osc}}$ is the expected number of events for a particular pair of $\Delta m^2, \sin^2 2\theta$ values. This likelihood function reaches its maximum at $19eV^2, \sin^2 2\theta = 0.006$. The individual distributions of $E_\nu$, $R$, $\cos \theta_b$, and $L$ for the data are compared with projections of the expected four-dimensional distribution (including oscillations at $19eV^2, \sin^2 2\theta = 0.006$) in Fig. 1. Note that most of the data in Fig. 1 is from beam-unrelated or neutrino-induced background.
Figure 1: Distributions of $E_e$, $R$, $\cos \theta_b$, and $L$ for the beam-on sample compared with the expected distributions (including oscillations at $19eV^2$, $\sin^2 2\theta = 0.006$).
The log of this likelihood function is calculated for a range of $\Delta m^2, \sin^2 2\theta$ values. Regions within 2.3 and 4.5 log-likelihood units of vertical distance from the peak are identified. These regions (called 90% and 99% likelihood regions) are calculated several times while varying inputs to reflect systematic uncertainties. The systematic effects varied included: the method used for smoothing the beam-off data, the method used for calculation of the correlated $R$ distribution, and the normalization of the backgrounds (both beam-related and beam-unrelated are shifted by $\pm 1\sigma$). Also, the product of neutrino flux and detection efficiency was allowed to vary by $\pm 10\%$. Regions which are favored in any of these systematic investigations are shown in Fig. 2, where the darkly-shaded and lightly-shaded regions correspond to 90% and 99% likelihood regions, respectively. After folding in the systematic uncertainties, the no-oscillation hypothesis ($\sin^2 2\theta = 0$) was disfavored by 16.6 log-likelihood units (corresponding to $5.7\sigma$).

Figure 2 shows discrimination against some values of $\Delta m^2$ which would be allowed in an analysis that simply took the size of the oscillation signal into account. This discrimination may be understood from the energy distribution of the oscillation candidates [2]. The presence of relatively high-energy oscillation candidates tends to exclude $\Delta m^2$ near integral multiples of $4.3eV^2$. (These values of $\Delta m^2$ give $\sin^2 (1.27\Delta m^2 L/E_v)$ near 0 for the highest energy $\bar{\nu}_\mu$.)

Some of the favored region is excluded by the ongoing KARMEN experiment [4] at ISIS, E776 at BNL [5], and the Bugey reactor experiment [6] (see section 8.2). However, there remains a region at small values of $\Delta m^2$ and $\sin^2 2\theta$ where our oscillation parameters are not in conflict with any other experiment.

This paper reports the observation of 22 electron events in the $36 < E_e < 60$ MeV energy range that are correlated in time and space with a low-energy $\gamma$ with $R > 30$, and the total estimated background from conventional processes is $4.6 \pm 0.6$ events. The probability that this excess is due to a statistical fluctuation is $4.1 \times 10^{-8}$. These results may be interpreted as evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations within the favored range of Fig. 2.

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References


Figure 2: Plot of the LSND $\Delta m^2$ vs $\sin^2 2\theta$ favored regions. The method used to obtain these contours is described in the text. The darkly-shaded and lightly-shaded regions 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).