Short Baseline Projects

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In a search for $\nu_\mu \to \nu_e$ oscillations, the LSND experiment has observed an excess of events which are consistent with an oscillation signal. The KARMEN experiment, which is the only ongoing experiment which can test the LSND hypothesis, does not observe an excess, but also does not cover the full LSND allowed region. In this report, the results of these two experiments are discussed, together with the expectations of the MiniBooNE experiment which has been approved to run at FNAL in 2001. MiniBooNE's goal is to definitely verify or disprove the LSND oscillation hypothesis. Finally, the implications of the experimental techniques developed for current short baseline experiments for a future short baseline program, assuming the verification of the LSND signal, is also discussed.

1. The LSND signal

In 1995 the LSND experiment at Los Alamos observed an excess of $\bar{\nu}_e$ events in a predominantly $\bar{\nu}_\mu$ beam. The excess events were consistent with $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations [1]. The excess remained as the experiment continued data taking and analysis, and additional results were published consistent with both $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations [2] and $\nu_\mu \bar{\nu}_e$ oscillations[3].

The LSND experiment used the high-intensity, low-energy neutrino source of the LANCE accelerator at LANL. The proton beam had an intensity of 1mA and an energy of 800 MeV. The protons were stopped in a beam stop and neutrinos were produced from the decays of the pions produced during this process. The experiment took data using two different configurations of the beam stop. During 1993-1995 the beam stop consisted of a 30 cm long water target, followed by a water-cooled Cu Beam dump, while during 1996-1997 the water target was replaced by a close-packed high-Z target. The neutrino source was well understood since almost all neutrinos are generated from π^+ or μ^+ decay; π^- and μ^- are readily captured in the Fe of the shielding and Cu of the beam stop. The production of kaons and heavier mesons is negligible at the LSND energies. The $\bar{\nu}_e$ rate was calculated to be 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 could be used as evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations.

The detector was located 30 m from the target and consisted of 167 tons of lightly doped scintillator oil surrounded by 1220 8-inch phototubes, in a cylindrical tank 8.3 m long and 5.7 m in diameter. The phototubes provided 25% photocathode coverage and their time and pulse height information gave resolutions of ~ 30 cm for position, ~ 12 degrees for angular, and $\sim 7\%$ for energy for a typical electron track. The Čerenkov cone is used for particle identification.

LSND performed two oscillation searches, each using neutrinos from a different decay chain. For the high-statistics decay-at-rest (DAR) analysis ($\overline{\nu}_\mu \to \overline{\nu}_e$), the beam was produced by π^+'s which stop and decay in the beam dump, producing muons which then decay to produce $\overline{\nu}_\mu$'s. The signature for oscillations was a $\bar{\nu}_e$ interaction ($\bar{\nu}_e p \to e^+ n$), yielding a positron signal, followed by $np \to d\gamma$, where the 2.2 MeV γ was detected. The ν_μ's from pion decay-in-flight (DIF) were also used for oscillation searches. In this case, 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. The systematic errors and the backgrounds for the two searches are different, thus observation of a signal in both cases strengthens the oscillation hypothesis. Furthermore, the two different beam stop configurations provide a systematic check, since the muon decay-at-rest neutrino flux with the second configuration was 2/3 of the neutrino flux with the first beam stop, and the pion decay-in-flight neutrino flux was 1/2 of the flux with the first beam stop.

Evidence for oscillations has been observed in both search-modes. For the $\bar{\nu}_\mu \to \bar{\nu}_e$ search, a total excess of 82.8 $\pm$ 23.7 $\pm$ 12.0 events was 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 was observed with e^- energy between 60 and 200 MeV. Recently, LSND presented its final results on the muon to electron flavor oscillation search using a combined fit for both the DAR and DIF results (see ref. [4]). The strategy for this combined analysis can be summarized in the following: *(i)* search for $\bar{\nu}_\mu \to \bar{\nu}_e$ DAR events in the energy range of 20-60 MeV *(ii)* search for $\nu_\mu \to \nu_e$ DIF events in the energy range of 20-200 MeV *(iii)* use the same primary electron selection for all processes *(iv)* simultaneously fit all observed neutrino processes to constrain flux and background *(v)* use combined fit for both DAR and DIF signals in the range of 20-200 MeV to obtain the best oscillation parameters. For the DAR analysis, a likelihood ratio was employed to determine whether a γ was a 2.2 MeV photon correlated with a positron or was from an accidental coincidence. The ratio was formed from the likelihood that the γ was correlated, divided by the likelihood that it was an accidental. This final analysis achieved a better position resolution, resulting in a higher accidental rejection. The efficiency to detect a correlated γ increased from 23% to 40%, while the accidental backgrounds dropped from 0.6% to 0.23%. The results of the DAR analysis are shown in Table 1. The final conclusion from the LSND experiment is that the excess of events which they observe is not consistent with conventional neutrino physics and that if the source of this excess is electron flavor appearance then the overall oscillation probability is (0.25$\pm$0.06$\pm$0.04)% with $\Delta\ m^2 > 0.2$ eV^2.

Table 1
Final LSND results in the 20-60 MeV range.

R>10 cut			
Beam on	Beam off	ν background	excess
83	(-)33.7	(-)16.6	32.7$\pm$9.2
Fit to R distribution			
Event Excess		Oscillation Excess	
83.3$\pm$21.2		(0.25$\pm$0.06$\pm$0.04)%	

2. Testing the LSND hypothesis

Several accelerator experiments have excluded the high Δm^2 solution to the LSND excess [5,6], while the very low Δm^2 region has been ruled out by the Bugey [7] reactor experiment. The only ongoing experiment which could test the LSND question is KARMEN [8] at the ISIS facility in Rutherford Laboratory. KARMEN also uses a neutrino beam produced by pion decay-at-rest, but the experimental technique is complementary to LSND; since the neutrino source has a well defined time structure the experiment heavily uses timing information for its analysis. The KARMEN detector is smaller and closer to the source than LSND ($\sim$ 18 m vs 30 m), and the beam is less intense than at LAMPF, resulting in reduced sensitivity compared to LSND for the same parameter space. The experiment has had two data runs. The KARMEN 1 experiment took data through 1995. The KARMEN 2 experiment [9], which has an improved cosmic-muon veto shield is ongoing. The new, improved, shield is expected to reduce the main background to the $\bar{\nu}_\mu \to \bar{\nu}_e$ search by a factor of 40 compared to KARMEN 1.

KARMEN 1 had presented results quoting a limit for oscillations, although in principle their results were not inconsistent with the LSND hypothesis in the low Δm^2 region. In this region, the expected signal for KARMEN 1 was 4 events, assuming oscillations for the LSND excess.

The KARMEN 2 run is in progress and the data taken from February 1997 to March 2000, corresponding to 7160 C of protons on target, have been analyzed (see also ref. [10]). This analysis also uses a revised procedure, based on maximum likelihood, which makes direct comparison to the LSND maximum likelihood result more straightforward. The total background expectation for the analyzed data sample was 12.3±0.6 events, and 11 candidate events were observed passing all the analysis cuts. KARMEN 2 extracts limits at 90% and 95% confidence level (CL), as shown in figure 2 (the figure is from ref. [9]). The KARMEN 2 limit, even at 95% CL excludes the LSND allowed region for large Δm^2 (greater than 20 eV^2), but it does not fully cover (at 90% CL) the region below 1 eV^2. Using a frequentist approach, the 90% CL upper limit for high Δm^2 is 3.1 events and for $\Delta m^2 < 1$ eV^2 is 3.8 events, while the expectation from the LSND oscillation hypothesis is on the order of 8 events and 2-5 events respectively. In the future,

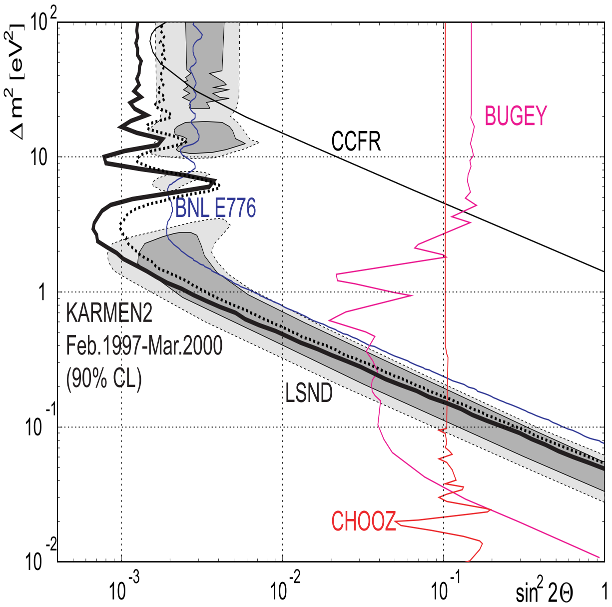

Figure 1. Summary of the results of various experiments relevant to the LSND hypothesis.

the KARMEN 2 exclusion region at low Δm^2 is not expected to change substantially with continued running, since improvements in sensitivity go as the fourth root of the number of events.

3. Future tests of the LSND hypothesis

In order to definitively verify or disprove the hypothesis that the observed event excess by LSND is due to neutrino oscillations, next generation experiments should *(i)* have high-statistical power, *(ii)* be able to show a many-σ effect (more than the 4σ LSND DAR result), for the case of LSND oscillations, and *(ii)* have different experimental and beam systematics than LSND. In addition, if a signal is found, the experiment should be able to make a precise measurement of the oscillation parameters.

3.1. The BooNE experiment at FNAL

The BooNE (Booster Neutrino Experiment), which has been approved at FNAL, is in a unique position to verify or disprove the LSND oscillation hypothesis. BooNE will be capable of observing both $\nu_\mu \rightarrow \nu_e$ appearance and ν_μ disappearance. The first phase of BooNE, MiniBooNE [11], is a single detector experiment designed to search for $\nu_\mu \rightarrow \nu_e$ oscillations. MiniBooNE is expected to obtain $\sim$ 1000 events per year if the LSND signal is due to $\nu_\mu \rightarrow \nu_e$ oscillations. Assuming that an oscillation signal is observed, the second phase of the experiment is aiming to accurately measure the Δm^2 and $\sin^2 2\theta$ parameters of the oscillations, by introducing a second detector. The MiniBooNE experiment (phase 1 of BooNE), which is currently being constructed at FNAL, together with the BooNE beamline, will begin taking data in December 2001.

3.2. MiniBooNE Overview

The BooNE beamline uses a primary proton beam from the FNAL Booster. The Booster is a high-intensity source of 8 GeV protons. MiniBooNE will run at an average rate of 5 Hz with 5×10^{12} protons per pulse for at least 2×10^7 seconds of Booster running (66% of one calendar year). Providing beam for BooNE is compatible with the Booster beam needs of the other FNAL collider and fixed-target programs. Each Booster pulse is 1.6 μs, and this low duty factor will substantially reduce backgrounds due to cosmic rays.

The BooNE neutrino beam is produced from the decays of secondary hadrons. Protons from the primary beam strike a beryllium target, producing short lived hadrons. The positively charged mesons which decay to neutrinos are focussed into a 50 m decay channel using a magnetic horn. The target is located within the magnetic focusing horn. Note that this horn configuration is different than the one described in the proposal, which called for a two-horn system. The sign selection of the horn can be reversed, to provide a check of systematics. In addition, the decay region is designed so that decay lengths of both 50 m and 25 m are possible, by placing a movable steel and concrete absorber in the middle of the channel (the total length of the channel is defined by a similar absorber, permanently positioned at a length of 50 m). Changing the decay pipe length provides a useful check on the oscillation signal, for systematics associated with the intrinsic beam ν_e component. The neutrino beam produced by the meson decays in this channel will have an energy range of 0.5 - 1.0 GeV and consists of mostly ν_μ, with a small (less than 0.3%) ν_e component.

The MiniBooNE detector is located 500 m from the target. The detector consists of a spherical tank, 12.2 m in diameter. The vessel will be filled with 800 tons of pure mineral oil. An inner structure will support 1280 8-inch phototubes (10% coverage) pointed inward and optically isolated from the outer region of the tank. This structure also optically isolates the outer most 35 cm of the contained oil. This outer volume will serve as a veto shield for identifying particles both entering and leaving the detector, with 240 phototubes mounted on the support structure facing outwards. The resulting fiducial volume for the inner region corresponds to 445 tons of oil.

3.3. MiniBooNE Analysis and Sensitivity

In order to search for $\nu_\mu \rightarrow \nu_e$ oscillations in a predominantly ν_μ beam, MiniBooNE utilizes the detection of quasi-elastic ν_e interactions by identifying electrons via their Cerenkov and scintillation light signatures. The backgrounds to the oscillation signal come from the intrinsic ν_e beam component and the misidentification of captured muons and π^0 events in the detector as electrons.

The detector records the time and total charge for each phototube and from this information the vertex position and direction for the event will be determined. Muon events will be distinguished from electrons by their Cerenkov rings and scintillation light. Electrons tend to produce "fuzzy" rings due to multiple scattering and bremsstrahlung, while muon rings have sharper outer boundaries. In addition, electrons tend to have a higher fraction of prompt (Cerenkov) light compared to late (scintillation) light. The performance of the muon pattern recognition algorithm will be constrained by the data. Ninety two percent of the muons contained in the detector will decay, and they will be tagged by the presence of a second track from the decay electron. The misidentification of muon captures, which will be estimated from the large sample of decayed muons by applying the particle identification algorithm while ignoring the decay track is expected to be below 5%. Most π^0 events will be identified by their two electromagnetic decay tracks. A small fraction (1%) of asymmetric π^0 decays will not yield two resolvable tracks and therefore could be misidentified as electrons. This misidentification contribution, which is expected to be $\sim$ 5%, will be studied with Monte Carlo simulation, constrained by the large sample of measured π^0's in the experiment.

The intrinsic ν_e component of the beam is either produced by muon decays in the decay channel or by kaon decays. MiniBooNE's secondary (π^+)'s have energies around 2 GeV, thus the muons from their decay have relatively long lifetimes and most of them will travel to the end of the decay channel and stop in the absorber or the dirt. To constrain the ν_e's from the muons which decay, the observed ν_μ interactions at the detector will be used. Since both the muon and the ν_μ emerge from the same two-body pion decay, the measurement of one of the decay particles constrains the other. MiniBooNE is expected to record about 0.5 million ν_μ events in a year of running. These events will be used to reduce the uncertainty in the muon component of the ν_e background to less than 5%, since the 2-body kinematics, low beam energy, and small angle subtended by the detector produce a very tight correlation between π^+ and ν_μ energies, thus constraining the $\pi^+ \rightarrow \mu^+ \rightarrow \nu_e$ chain. In addition, the variable decay pipe length, L, provides a solid systematic check for the muon decay contribution, since ν_e production from this decay is proportional to L^2, while the ν_e rate from oscillations is proportional to L.

The overall kaon contribution to ν_e contamination is expected to be about one third of that due to the muons. Charged kaons decay via $K^+ \rightarrow \pi^0 e^+ \nu_e$ 4.8% of the time, and neutral kaons decay via $K_L \rightarrow \pi^\pm e^\mp \nu_e$ 38.8% of the time, but because the K^+'s are focused by the horn and the K_L's are not, the K^+ ν_e component will be about twice that of the K_L. The systematic uncertainty in the kaon component of the ν_e background will be limited to ~10% from Monte Carlo simulation constrained by production data. In addition, a monitoring system is designed with the objective to directly measure the kaon content of our secondary beam and further constrain this background source.

The most conservative estimate of the MiniBooNE sensitivity is based on using the total number of observed events compared to background. This method is a conservative estimate of the experiment's sensitive region since it does not depend on knowing the energy distributions of the various background sources. Fig. 2 shows the resulting 90% CL sensitivity. An analysis using information from the shape of the energy distributions for both signal and backgrounds increases the MiniBooNE sensitivity. This type of analysis takes full advantage of the background constraints from measured event distributions (see discussion above). Thus, only the contribution of the ν_e background from K decay, which is not tied directly to MiniBooNE data, is not reduced in this analysis. The significance of an observed excess, assuming that the LSND signal is due to oscillations, will be at the 8-10σ level.

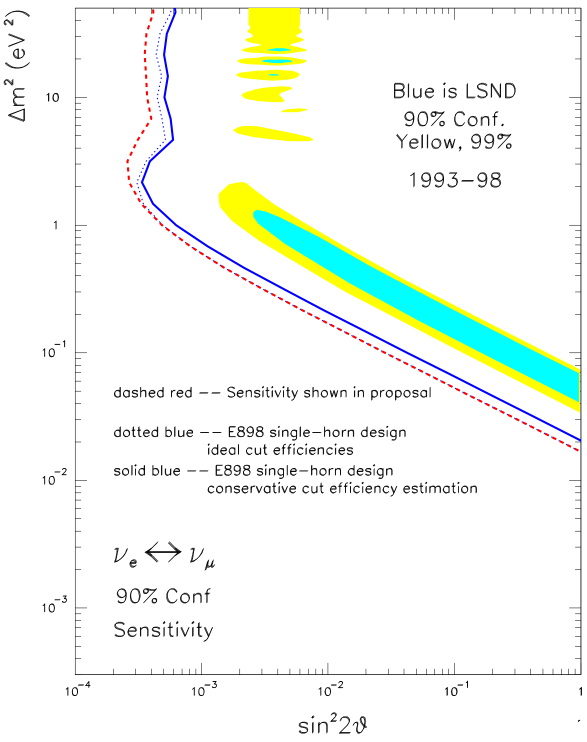

Figure 2. MiniBooNE expected 90% confidence level sensitivity limits from event counting. The solid curve is the expectation for the final single horn design and an analysis with conservative efficiency assumptions. The dotted curve is for the single horn and ideal efficiency. The dashed curve shows the sensitivity from the two-horn design described in the experiment's proposal.

3.4. Summary

From the discussion above, it is clear that the MiniBooNE experiment can establish a signal in the LSND region. MiniBooNE has statistical power, good handles on potential backgrounds, and systematics (and background sources) which are different from those of the LSND experiment. The construction of the MiniBooNE detector and beamline is well underway and the experiment is expected to start taking data in December 2001. If a signal is observed, Δm^2 will be determined with sufficient accuracy $\left(\approx 0.1\mathrm{eV}^2\right)$ to indicate where a second detector should be placed for the follow-up two detector BooNE experiment, which is aiming in a precise determination of the oscillation parameters.

4. Prospects for a future short baseline program

If the LSND oscillation hypothesis is confirmed, a short baseline program with future neutrino sources like the neutrino factory [12] will be of great importance in order to determine the oscillation parameter space. In the case of a three flavor scenario (no solar oscillations) measuring the $\nu_e \to \nu_\tau$ transition will be needed to complete the measurement of oscillation parameters, while CP violation could be reached with either $\nu_e \to \nu_\mu$ or $\nu_\mu \to \nu_\tau$ short baseline measurements. In the case of a four flavor scenario, measurements of $\nu_\mu \to \nu_\tau$, $\nu_e \to \nu_\mu$, and $\nu_\mu \to \nu_\tau$, with both neutrinos and anti-neutrinos would be necessary [13]. These measurements require the use of very challenging experimental techniques in order to efficiently identify electron and τ interactions. The analysis techniques employed for the ongoing searches for $\nu_\mu \to \nu_\tau$ oscillations provide useful guidelines on the physics reach of such a short baseline program. Both CHORUS [14], using emulsion, and NOMAD [15], using an electronic detector and elaborate kinematic criteria, obtain sensitivities which are very close to their design values. These analysis techniques could be the starting point for a comprehensive study of the physics reach of a short baseline program with a neutrino factory (or any other future neutrino source), which will be necessary in order to fully determine the oscillation parameter space if the LSND signal is verified.

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