MiniBooNE: the Booster Neutrino Experiment

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The Booster Neutrino Experiment at Fermilab is preparing to search for $\nu_\mu \to \nu_e$ oscillations. The experiment is designed to make a conclusive statement about LSND's neutrino oscillation evidence. The experimental prospects are outlined in light of the current results from LSND and KARMEN.

I. INTRODUCTION

Currently, the Liquid Scintillator Neutrino Detector (LSND) at the Los Alamos National Laboratory is the only accelerator-based neutrino experiment to have evidence for neutrino oscillations [1].

The Booster Neutrino Experiment (BooNE) at Fermilab is being prepared to conclusively test these results. The experiment will take place at a new neutrino beamline coming off of the FNAL 8 GeV proton Booster. The first phase of BooNE — MiniBooNE — will be a single-detector experiment. MiniBooNE will obtain approximately 1000 events per year if the LSND signal is due to $\nu_\mu \to \nu_e$ oscillations, and will be capable of establishing the signal with greater than 5σ significance. This new experiment expects to be collecting data by the end of 2001.

KARMEN, the Karlsruhe Rutherford Medium Energy Neutrino experiment at the Rutherford Appleton Laboratory, is very similar to LSND, has been running since 1990, and will be completed in early 2001. Therefore we discuss the results of both KARMEN and LSND to highlight the experimental context that MiniBooNE will encounter.

II. LSND AND KARMEN

LSND presented its first evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations in 1995 [2]. In the same year, KARMEN completed its first phase of searching for the same oscillations, but lacked the sensitivity to confirm or refute LSND [3]. After upgrading its cosmic ray veto [4], KARMEN resumed data taking in February 1997 and plans to continue running through 2001. Results based on KARMEN data collected up to April 1998 were available at the time of *DPF'99* [5]. More recently KARMEN has updated results based on data collected through February 1999 [6].

LSND and KARMEN both search for $\bar{\nu}_\mu \to \bar{\nu}_e$. Both experiments are at 800 MeV proton accelerators where muon-antineutrinos are produced from the decay of muons at rest, through the decay chain:

$$\begin{aligned} \pi^+ &\to \mu^+ \nu_\mu \\ &\hookrightarrow e^+ \, \nu_e \, \bar{\nu}_\mu \qquad\qquad \text{endpoint } 52.8 \text{ MeV} \end{aligned}$$

Both experiments employ liquid scintillator detectors. Without being able to directly distinguish e^+ from e^-, the experiments distinguish the appearance of $\bar{\nu}_e$ from the presence of ν_e by correlating the electron-type track in position and time with the photon from an associated neutron capture reaction. Neutrons captured on protons produce 2.2 MeV photons:

$$\begin{aligned} \bar{\nu}_e p &\to e^+ n \\ n\,p &\to d\,\gamma \; (2.2 \text{ MeV}) \end{aligned}$$

There are, of course, differences between the two experiments [7]. The LSND detector is three times the size of the one at KARMEN, 167 tons versus 56 tons; and LSND's proton exposure of more than 25000 C outpaces KARMEN's post-upgrade expectation of 9000 C. LSND is positioned 30 m from the neutrino source, compared with 17.6 m for KARMEN. By being further from the target, LSND gains sensitivity to lower Δm^2 at the expense of reduced neutrino flux. LSND is a single tank whereas KARMEN is segmented into 512 modules, and the concentration of scintillator

in LSND is lower than at KARMEN. KARMEN therefore has better position and energy resolution, whereas LSND can measure the track direction and use Cherenkov rings for particle identification. Finally, because the target at LSND includes a drift space and the detector is positioned downstream, LSND is able to also search for the charge conjugate $\nu_\mu \to \nu_e$ oscillation using neutrinos from π^+ decay in flight [8].

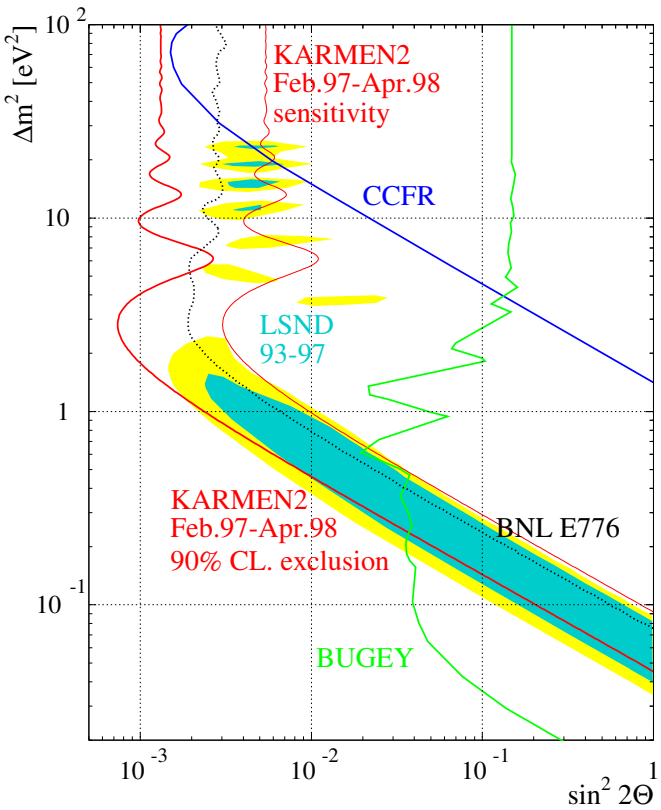

FIG. 1. KARMEN 90% confidence level limit and sensitivity based on data collected through April 1998. The LSND favored region and limits from other experiments are also shown.

Based on analysis of data collected through April 1998, which was a proton exposure of 2900 C, KARMEN observes 0 candidate events while expecting 2.88 ± 0.13 background events. With this data, the KARMEN sensitivity to an LSND-type signal is on the order of 1 event. Figure 1 shows the limit derived from this experimental observation overlaying the LSND favored region. Also shown is KARMEN's sensitivity, the limit if only the background expectation were observed.

Noting that KARMEN expects three times more data, a glance at Figure 1 raises the question, At this rate won't KARMEN soon rule out LSND? Well, not so fast. The difference between KARMEN's sensitivity and limit curves merits scrutiny. The limit here benefits from the non-observation of even the expected background. KARMEN will keep running, and assuming that events are seen in the future, which would be more consistent with the background expectation, KARMEN's limit will necessarily move closer to its sensitivity contour. The sensitivity will improve with more data and with a more sophisticated likelihood analysis. Nevertheless, KARMEN will lack the sensitivity to rule out or confirm LSND.

The situation is illustrated by KARMEN's recently updated results, based on data gathered through February 1999, about half of its ultimate total. With a new analysis, 8 events are observed, while 7.8 ± 0.5 background events are expected. For the favored LSND parameters, KARMEN would expect between 1.5 and 5.5 oscillation events. The limit is now weaker than in Figure 1. These results encroach on LSND's allowed region, but they do not rule out LSND. Another experiment will be needed to make a conclusive statement about LSND, and that is where MiniBooNE comes in.

III. MINIBOONE: EXPERIMENTAL DESIGN

MiniBooNE will use a new neutrino beamline coming off of the FNAL 8 GeV proton Booster. The Booster is a reliable machine, expected to provide 2×10^7 s of running per year, while delivering 5×10^{12} protons per 1 μs pulse at a rate of 5 Hz to MiniBooNE. Furthermore, the Booster will be able to deliver beam to MiniBooNE while also supplying protons for the TeVatron and NuMI programs.

The secondary pion beam will emerge from a two-horn focusing system into a 50 m decay region. The pion decay length will be either 25 m or 50 m depending on the position of a movable steel beam stop (varying the decay length provides a check of experimental systematics). The detector will be positioned 500 m downstream of the decay region.

The detector will consist of a spherical tank 6.1 m (20 feet) in radius filled with 807 tons of pure mineral oil. An inner-tank structure at 5.75 m will support phototubes and form an optical barrier, separating the tank into a central main volume and an outer veto shield. Cherenkov and scintillation light from neutrino interactions in the main volume will be detected by 1280 8-inch phototubes, providing 10% photocathode coverage of the 445 ton fiducial volume. (Undoped mineral oil tends to scintillate modestly from the presence of intrinsic impurities.) The veto shield will be viewed by 240 phototubes mounted on the tank wall.

Typical neutrino energies will be from 0.5 to 1.0 GeV. In one year of running, the experiment will collect approximately 500000 reconstructed ν_μ events. The intrinsic ν_e contamination in the beam will be approximately 0.3% or approximately 1500 reconstructed ν_e background events.

IV. MINIBOONE: ANALYSIS DESCRIPTION

The detector will reconstruct quasielastic ν_e interactions by identifying electrons via their characteristic Cherenkov and scintillation light signatures. Besides the $\nu_e \to e^-$ signal, several backgrounds will contribute. The analysis will come down to accounting for the backgrounds and determining whether or not there is an excess. The background sources will be due to ν_e contamination in the beam and the misidentification of muons and π^0's in the tank as electrons. Because the neutrinos are at higher energies than at LSND and KARMEN, neutrons will not play a role in the signal and will not contribute background.

The detector will record the time of the initial hit and total charge for each phototube. From this information, the track position and direction will be determined. Muon tracks will be distinguished from electron tracks by their Cherenkov rings and scintillation light. Electrons will tend to produce "fuzzy" rings due to multiple scattering and bremsstrahlung, while muon rings will tend to have sharp outer boundaries. Electrons also tend to have a high fraction of prompt (Cherenkov) light compared to late (scintillation) light, whereas muons produce relatively more late light.

The ν_e contamination in the beam is due to decays of pions and kaons. Monte Carlo simulation constrained by production data will be used to limit the systematic uncertainty in the ν_e background to better than 10%. In addition, it will be possible to measure the pion energy spectrum using the the observed ν_μ events, virtually all (99%) of which will come from pion decay. The technique exploits the classic energy-angle correlation in neutrino beams, which will be enhanced here by the relatively low beam energy and small solid angle subtended by the detector. By measuring the pion spectrum, MiniBooNE expects to reduce the uncertainty in the pion component of the ν_e background to less than 5%.

Ninety two percent of the muons contained in the detector will decay, and they will be relatively easily identified by the presence of a second track. However, the 8% of muons that get captured have a greater chance to be misidentified. The misidentification of muon captures will be estimated by studying the large sample of muons that decay and determining the particle identification algorithm performance while ignoring the decay track. Using this technique, which does not rely on Monte Carlo simulation, the muon misidentification uncertainty is expected to be below 5%.

Most neutral pions will be identified by their two electromagnetic decay tracks. The small fraction (1%) of asymmetric π^0 decays will not yield two resolvable tracks and will therefore be more likely to be misidentified. The

misidentification contribution of these decays will be studied with Monte Carlo simulation, which will be constrained by the large sample of measured π^0's in the experiment. The pion misidentification uncertainty expected to be 5%.

V. MINIBOONE: PROSPECTS

If oscillations occur as indicated by LSND, MiniBooNE will observe an excess of approximately 1000 events in one year of running. Figure 2 shows the number of excess events and their significance for two points in the LSND favored region. The significance is calculated using the systematic uncertainties for the various background sources above.

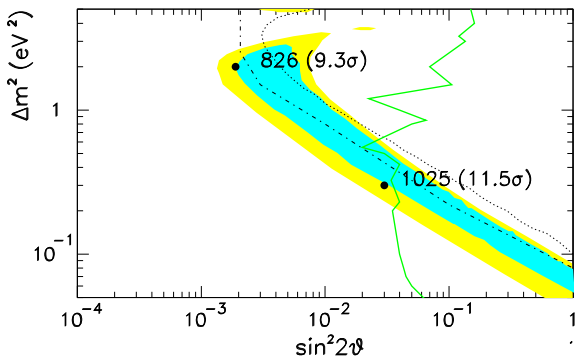

FIG. 2. The expected number of excess events in MiniBooNE (and significance) for two points in the LSND favored region.

MiniBooNE will gain additional sensitivity by measuring the energy dependence of the ν_e events. The oscillation signal has a different energy distribution from the background. Therefore an underestimate of the background will not necessarily lead to a fictitious oscillation signal. Figure 3 shows the exclusion contours for the energy-dependent fit as well as the limit based on using the total number of observed events above background.

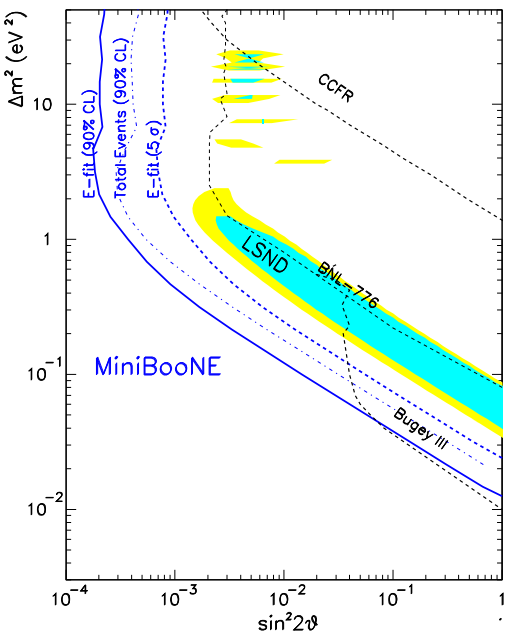

FIG. 3. MiniBooNE 90% confidence level limits using energy-dependent fit (solid), and total event counting (dot-dash). Also shown is the 5σ sensitivity contour of the energy dependent fit (dashed).

VI. CONCLUSIONS

LSND has presented evidence for muon to electron neutrino oscillations. KARMEN is now searching for these oscillations, but KARMEN is unlikely to have the sensitivity to reach a conclusion about LSND. Another experiment will be needed.

MiniBooNE is being prepared to fill this need. The detector and new 8 GeV beam line are being designed at Fermilab, and the experiment is scheduled to start data taking at the end of 2001.

MiniBooNE will either rule out LSND or it will demonstrate the signal and home in on the parameters. Should a single be found, BooNE would be ready to continue its experimental program with a second detector, the position of which determined by the MiniBooNE result.

VII. ACKNOWLEDGEMENTS

It is a pleasure to thank my MiniBooNE colleagues. I thank Eric Church for discussions about LSND and Klaus Eitel for discussions about KARMEN.

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