Searching for Physics Beyond the Standard Model with Accelerator Neutrino Experiments

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Abstract. The MiniBooNE experiment at Fermilab was designed to test the LSND evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations [1]. The first MiniBooNE oscillation result in neutrino mode [2] shows no significant excess of events at higher energies ($E_\nu > 475$ MeV), although a sizeable excess is observed at lower energies ($E_\nu < 475$ MeV). The lack of a significant excess at higher energies allows MiniBooNE to rule out simple $2 - \nu$ oscillations as an explanation of the LSND signal. However, the low-energy excess is presently unexplained. Additional antineutrino data and NuMI data may allow the collaboration to determine whether the excess is due, for example, to a neutrino neutral-current radiative interaction [3] or to neutrino oscillations involving sterile neutrinos [4, 5, 6]. If the excess is consistent with being due to sterile neutrinos, then future experiments at FNAL (MicroBooNE & BooNE) or ORNL (OscSNS) could confirm their existence.

1. Introduction
The MiniBooNE experiment was designed to test the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation interpretation of the LSND signal in both neutrino and antineutrino modes. MiniBooNE has approximately the same $L/E_\nu$ as LSND but with an order of magnitude higher baseline and energy. Due to the higher energy and dissimilar event signature, MiniBooNE systematic errors are completely different from LSND. The MiniBooNE detector design has worked very well, and follow-up experiments at FNAL (BooNE) or ORNL (OscSNS) could take advantage of this detector design. BooNE would employ a second detector similar to MiniBooNE at a different distance, while OscSNS would involve a MiniBooNE-like detector at a distance of ~60 m from the SNS beam dump. Another follow-up experiment, MicroBooNE, which was recently approved at FNAL, will consist of a ~70 ton fiducial volume Liquid Argon Time Projection Chamber (LArTPC).

2. MiniBooNE Experiment
A schematic of the MiniBooNE experiment is shown in Fig. 1. The experiment is fed by 8-GeV protons from the Booster that interact in a 71-cm long Be target located at the upstream end of a magnetic focusing horn. The horn pulses with a current of 170 kA and, depending on the polarity, either focuses $\pi^+$ and $K^+$ and defocuses $\pi^-$ and $K^-$ to form a very pure neutrino beam or focuses $\pi^-$ and $K^-$ and defocuses $\pi^+$ and $K^+$ to form a less pure antineutrino beam. The produced pions and kaons then decay in a 50-m decay pipe, and the resulting neutrinos and antineutrinos [7] can then interact in the MiniBooNE detector, which is located 541 m downstream of the Be target. For the MiniBooNE results presented here, a total of $5.58 \times 10^{20}$ protons on target (POT) were collected in neutrino mode.
The MiniBooNE detector [8] consists of a 12.2-m diameter spherical tank filled with approximately 800 tons of mineral oil ($CH_2$). There are a total of 1280 8-inch detector phototubes (covering 10% of the surface area) and 240 veto phototubes. The fiducial volume is a 5-m radius that corresponds to approximately 450 tons. The fraction of bad phototube channels was $<2\%$ over the course of the run.

3. MiniBooNE Results

MiniBooNE has published several interesting results. First, MiniBooNE has made a precision measurement of $\nu_\mu$ charged-current quasi-elastic (CCQE) scattering events [9]. Fig. 2 shows the $\nu_\mu$ CCQE $Q^2$ distribution for data (points with error bars) compared to the Monte Carlo simulation (histograms). A strong disagreement between the data and the original simulation (dashed histogram) was first observed. However, by increasing the axial mass, $M_A$, to $1.23 \pm 0.20$ GeV and by introducing a new variable, $E_{lo} = 1.019 \pm 0.011$, where $E_{lo}$ is the increase in the incident proton threshold, the agreement between data and the simulation (solid histogram) is greatly improved. It is impressive that such good agreement is obtained by adjusting these two variables.

MiniBooNE has also collected the world’s largest sample of neutral-current $\pi^0$ events [10], as shown in Fig. 3. By fitting the $\gamma\gamma$ mass and $E_\pi(1 - \cos \theta_\pi)$ distributions, the fraction of $\pi^0$ produced coherently is determined to be $19.5 \pm 1.1 \pm 2.5\%$. Excellent agreement is obtained between the data and the Monte Carlo simulation.

Fig. 4 shows the reconstructed neutrino energy distribution for candidate $\nu_e$ data events (points with error bars) compared to the Monte Carlo simulation (histogram) [2]. Good agreement between the data and the Monte Carlo simulation is obtained for $E_{\nu_e} > 475$ MeV; however, an unexplained excess of electromagnetic events is observed for $E_{\nu_e} < 475$ MeV. Several improvements have been made to the data analysis since this data was published, including an improved background estimate, an additional fiducial volume cut that greatly reduces the background from events produced outside the tank, and an increase in the data sample from $5.579 \times 10^{20}$ POT to $6.462 \times 10^{20}$ POT. The results of this improved analysis will be available soon.

An excess of $\nu_e$ candidate events is also observed in MiniBooNE from the NuMI beam. The NuMI beam, as shown in Fig. 5, differs from the Booster neutrino beam (BNB) in several respects. First, the NuMI beam is off axis by 110 mrad, whereas the BNB is on axis. Second, neutrinos from NuMI travel $\sim 700$ m, compared to $\sim 500$ m for neutrinos from the BNB. Also, the NuMI beam has a 6% contribution from electron-neutrinos and a 14% contribution from antineutrinos, while the BNB percentages are 0.5% and 2%, respectively. Fig. 6 shows the comparison between data events (points with error bars) and the Monte Carlo simulation (histogram) for $\nu_\mu$ CCQE candidate events (bottom) and $\nu_e$ CCQE candidate events (top). Although the systematic errors are presently very large, the data is observed to be systematically low for $\nu_\mu$ CCQE candidate events and systematically high for $\nu_e$ CCQE candidate events.
Figure 2. The $\nu_\mu$ CCQE $Q^2$ distribution for data (points with error bars) compared to the Monte Carlo simulation (histograms).

Updated results should be available later this year with three times the data sample and with reduced systematic errors by constraining the normalization to the $\nu_\mu$ sample.

4. MiniBooNE Future
MiniBooNE is approved to run for another year in antineutrino mode. So far MiniBooNE has collected $\sim 10^{21}$ POT, corresponding to $\sim 7 \times 10^{20}$ POT in neutrino mode and $\sim 3 \times 10^{20}$ POT in antineutrino mode. For the future, it will be imperative to understand the MiniBooNE low-energy excess. This excess is very interesting in its own right and crucial for future long-baseline experiments such as T2K. T2K will have a very similar neutrino energy distribution to MiniBooNE and will, therefore, be affected by the same low-energy excess. By analysing the MiniBooNE antineutrino data, NuMI data, and SciBooNE data, it may be possible to determine whether any of the published models [3, 4, 5, 6] can provide an explanation for the excess. If the low-energy excess continues to be consistent with a signal, then new experiments at FNAL (BooNE) or ORNL (OscSNS) should be proposed to explore physics beyond the Standard Model.

5. MicroBooNE
The MicroBooNE experiment, which was recently approved at Fermilab, exploits the precise differentiation of photons versus electrons in a detector, as is uniquely available from a Liquid Argon Time Projection Chamber (LArTPC). The detector consists of a $\sim 70$ ton fiducial volume
**Figure 3.** The neutral-current $\pi^0 \gamma\gamma$ mass and $E_\nu(1 - \cos \theta_\nu)$ distributions for data (points with error bars) compared to the Monte Carlo simulation (histograms).

LArTPC. It will run near the MiniBooNE enclosure on the BNB with an expected exposure of $6 \times 10^{20}$ protons on target. The high spatial resolution and energy measurement down to the MeV scale substantially improves on information available from the MiniBooNE detector. The experiment will run in 2011.

The MicroBooNE detector can separate electron showers from photon showers using the energy deposited in the first 2.4 cm of the track. For an electron efficiency of 80%, $\gamma$ contamination is expected to be < 5%, based on Monte Carlo studies. Given the excellent $e/\gamma$ separation, MicroBooNE can identify the source of the low energy events observed in MiniBooNE. MicroBooNE’s sensitivity to the low energy excess is $\sim 5\sigma$ if the signal is electron-like and $\sim 3\sigma$ if the signal is photon-like, in a strictly counting-based experiment. Fits to shape-signatures may increase the significance.

**6. BooNE**

The BooNE experiment would involve building a second detector at a cost of $\sim 8M along the BNB at FNAL at a different distance. With two detectors, many of the systematic errors would cancel, as the neutrino flux varies as $1/r^2$ to good approximation, so that a simple ratio of events in the two detectors would provide a sensitive search for $\nu_e$ appearance and $\nu_\mu$ disappearance. Furthermore, by comparing the rates for a neutral-current reaction, such as neutral-current $\pi^0$ scattering, a sensitive search for sterile neutrinos can be made.
Figure 4. The reconstructed neutrino energy distribution for candidate $\nu_e$ data events (points with error bars) compared to the Monte Carlo simulation (histogram) [2].

7. OscSNS

The OscSNS experiment would involve building a MiniBooNE-like detector at a distance of $\sim 60$ m from the SNS beam dump at ORNL. The detector would be the same as MiniBooNE except with a higher phototube coverage of 25% and the addition of $\sim 0.031$ g/l of b-PBD scintillator. Due to the higher phototube coverage, the estimated cost is $\sim$ $12M. Fig. 7 shows the layout of the SNS, which is running with a proton energy of 1 GeV and will eventually reach a beam intensity of $\sim 1.4$ MW. The great advantage of the SNS is that the neutrino flux is extremely intense and known almost perfectly, and the neutrino cross sections are known very well. The right plot of Fig. 8 shows the neutrino flux energy distribution, which includes a monoenergetic 30 MeV $\nu_\mu$ from $\pi^+$ decay at rest and $\nu_e$ and $\bar{\nu}_\mu$ from $\mu^+$ decay at rest. Furthermore, as shown in the left plot of Fig. 8, the monoenergetic $\nu_\mu$ can be identified by timing.

With the SNS neutrino flux, OscSNS would be capable of making precision measurements of $\nu_e$ and $\bar{\nu}_e$ appearance and $\nu_\mu$ disappearance and proving the existence of sterile neutrinos via the neutral-current reaction $\nu_\mu C \rightarrow \nu_\mu C^*$ (15.11). Any observed reduction of this cross section would be evidence for active-sterile neutrino oscillations. Fig. 9 shows the expected active-sterile neutrino oscillation sensitivity as a function of $\Delta m^2$ and $\sin^2 2\theta$ [11]. Other physics goals include precision measurements of $\nu e \rightarrow \nu e$ elastic scattering (and the world’s best sensitivity for the $\nu_\mu$ magnetic moment) and $\nu_e C \rightarrow e^- N$ charged-current scattering.
8. Conclusions
The MiniBooNE experiment observes an unexplained excess of electromagnetic events at low energies, which may be due, for example, to either a neutral current radiative interaction [3] or to neutrino oscillations involving sterile neutrinos [4, 5, 6]. If the excess is consistent with being due to sterile neutrinos, then future experiments at FNAL (MicroBooNE & BooNE) or ORNL (OscSNS) would confirm their existence.

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Figure 5. The NuMI beam.
Figure 6. The comparison between data events (points with error bars) and the Monte Carlo simulation (histogram) for $\nu_\mu$ CCQE candidate events (bottom) and $\nu_e$ CCQE candidate events (top).

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Figure 7. The layout of the SNS.
Figure 8. The right plot shows the neutrino flux energy distribution, which includes a monoenergetic 30 MeV $\nu_\mu$ from $\pi^+$ decay at rest and $\nu_e$ and $\bar{\nu}_\mu$ from $\mu^+$ decay at rest. The left plot shows the neutrino time distribution. The monoenergetic $\nu_\mu$ can be identified by timing.

Figure 9. The expected OscSNS active-sterile neutrino oscillation sensitivity as a function of $\Delta m^2$ and $\sin^2 2\theta$ [11]. The stars represent the best fit of a 3+2 model [12].