Measuring Neutrino Interactions with MiniBooNE

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Abstract. The MiniBooNE neutrino oscillation experiment has collected a large sample of charged- and neutral-current neutrino interaction events. These samples are important to understand the normalization and backgrounds in neutrino oscillation searches. They also reveal insight into the structure of the nucleus and nucleon. The MiniBooNE experiment is briefly described and the neutrino reactions and the underlying physics topics presented.

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INTRODUCTION

The MiniBooNE experiment [1], located at Fermilab and running since 2002, has searched for $\nu_\mu \to \nu_e$ oscillations with mass scale as previously reported by the LSND experiment [2]. For maximum sensitivity to oscillations, the MiniBooNE experiment has been designed for high neutrino interaction rates and good particle identification capability. This also allows for measurements of neutrino interaction cross sections with excellent statistical and systematic precision.

These measurements are important for systematic cross checks of detector efficiencies and background estimations for the MiniBooNE oscillation search. In addition, these measurements are valuable for experiments such as MINOS [3], NOvA [4], and T2K [5] that are running or will run in the same neutrino energy range ($E_\nu \approx 1-5$ GeV) by providing valuable cross section data.

In addition, the physics addressed by these measurements is interesting beyond simple utility for oscillation experiments. The neutrino provides a weak probe of the nucleus and/or nucleon in these processes. Does the neutrino "see" the same nucleus/nucleon as does the proton or electron in the scattering of these particles? In many case neutrino scattering allows for the clearest view of the fundamental physics.

In particular, measurements of interaction rates and kinematic distributions of several processes are crucial to understand in order to measure neutrino oscillations. It is impossible to do this without seeking insight into the underlying nuclear physics as the target is a nucleus (carbon, in the case of MiniBooNE). The following list describes the processes, why they are important to the MiniBooNE oscillation search and what physics they probe.

CCQE A measurement of the ν_μ charged-current quasielastic interaction (CCQE) ($\nu_\mu n \to \mu^- p$) produces the interaction cross section for the ν_e oscillation signal

($\nu_e n \to e^- p$). It also provides a constraint on the ν_μ flux from the production target. This process is sensitive to nucleon form factors (in particular the axial, which is not well-known from other data) and to the nucleon momentum distribution within the carbon nucleus.

NCπ^0 The neutral-current production of π^0 (NCπ^0) by ν_μ is one of the most important background reactions in a ν_e appearance oscillation search. If one of the photons from the π^0 decay is lost in the event reconstruction, the remaining photon is likely to be identified as an electron and thus the event can be misidentified as an oscillation candidate ($\nu_e n \to e^- p$). This process depends on the $N\Delta$ form factors and it may occur via a coherent Z exchange from the nucleus as a whole.

CCπ^+ Charged-current production of π^+ (CCπ^+) provides a measurement of Δ production. This is an important potential background for a ν_e appearance search as the Δ may radiatively decay ($\Delta \to N\gamma$) in NC interaction and mimic the oscillation event signature. The underlying physics of this process depends on the $N\Delta$ form factors, the coherent charged-current process, and the underlying nucleon momentum distribution.

These reactions (among several others) are being studies in the high-statistics MiniBooNE data set.

MINIBOONE EXPERIMENT

The MiniBooNE experiment is located at Fermilab and is shown in the schematic of Figure 1. The neutrino beam is produced with 8 GeV protons (from the Fermilab booster) incident on a beryllium target which creates copious numbers of charged pions. The positive pions are focused by a magnetic horn into a 50 m pipe where they decay, producing ν_μ.

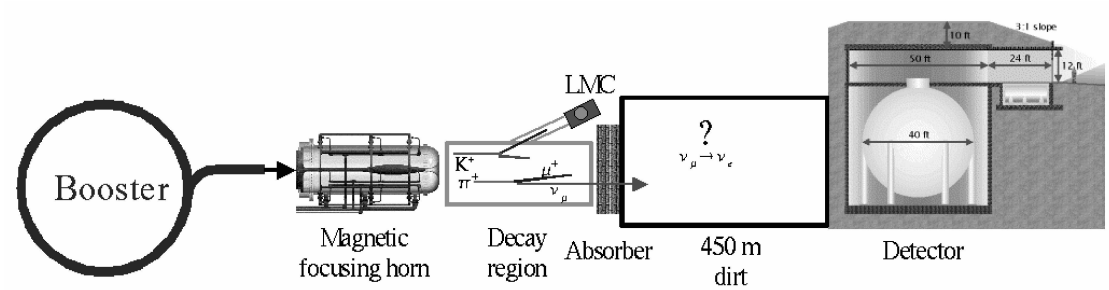

FIGURE 1. Schematic figure of the MiniBooNE experiment showing the arrangement of the ν-production region and detector.

It is important to understand the ν_μ flux in order to make solid measurements of neutrino interactions in the MiniBooNE detector. Pion production has been measured at 8 GeV with the HARP experiment [6]. The kinematic acceptance of the HARP apparatus for charged pions relevant to MiniBooNE is good — approximately 81% of pions that produce neutrinos impinging on the MiniBooNE detector are measured by HARP. These production cross sections are fit to a parameterization (along with other data at several different proton energies). A similar fit is performed with the relevant kaon data. The

results from this procedure are used in the flux Monte Carlo to provide a model, highly constrained by data, for pion (and kaon production). The Monte Carlo also simulates the proton transport (including secondary interactions) through the neutrino production system.

The predicted neutrino flux is 99%-pure ν_μ and of average energy ≈ 0.8 GeV. The energy distribution does not have a large high-energy tail. Approximately 99% of the ν_μ flux is below 2.5 GeV. This is a nice feature of the Fermilab booster neutrino beam. A beam without a high-energy component enables neutrino interaction measurements with lower backgrounds from high-energy reactions (in the detector) "feeding-down" to lower energies. The overall normalization of the neutrino flux is known to approximately 15%. The correlated errors between energy bins are calculated and propagated through the various neutrino interaction measurements.

The detector is located 541 m from the neutrino target and consists of a spherical tank containing 800 tons of mineral oil (CH_2) viewed by 1280 20-cm-diameter photomultiplier (PMT) tubes for 10% photocathode coverage of the surface area of the tank. In addition, a veto region with 240 photomultiplier tubes provides a signal for particles that enter or exit the main tank region. Charged particles created in neutrino reactions create Cerenkov light (for those above Cerenkov threshold in the mineral oil, $\beta_t = 1/n = 1/1.47$) and scintillation light. The mineral oil is not doped with scintillator however intrinsic impurities create scintillation light as a low level. The charge and time of the PMT responses are recorded in a 20 μs window around the 1.6 μs beam spill.

RECONSTRUCTION AND ANALYSIS

The time and charge information recorded by the detector PMTs in response to the Cerenkov radiation and the small amount of scintillation light that is emitted from charged particles enable the reconstruction of neutrino interactions of various types. Both the prompt light from the direct products of the neutrino interactions (μ, e, π) and the delayed light from the decays of subsequent muons are important in the reconstruction and identification of the events.

The prompt Cerenkov light is directed into a cone. As illustrated in Figure 2, muons create a sharp well-directed cone, electrons create a more diffuse pattern due to larger multiple scattering and showering, and neutral pions create two Cerenkov cones due to the two photons. The location and number of the Cerenkov photons allow for the reconstruction of particle location, direction, and energy. The energy (angular) resolution is approximately 7% (5°) for 300 MeV muons.

Because the detector is large, a substantial fraction of the muons range out in the active region. These muons will decay and the decay-electron may be observed and will be reconstructed as a second "sub-event" with a typical time delay of 2 μs. Interactions with this second, delayed, sub-event are likely to be muons and this allows for powerful cut for events with muons. Similarly events with charged pions may be identified as the pions decay in the detector into muons. For example, an event with two delayed sub-events in addition the prompt signal is likely to be a CCπ^+ event.

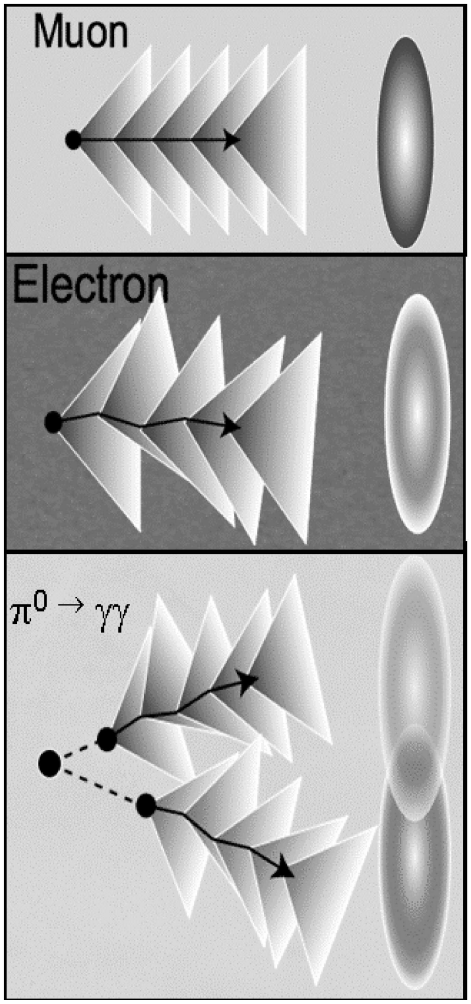

FIGURE 2. Schematic figure of the various event types reconstructed in the MiniBooNE experiment

REACTIONS AND ANALYSES

Both charged- and neutral-current neutrino interactions are observed in the MiniBooNE detector. The rates of these interactions (before efficiency corrections) are estimated via the NUANCE [7] neutrino interaction code. Charged-current quasielastic (CCQE) scattering is the most abundant process, comprising 42% of the total neutrino interaction rate. Charged-current production of a single pions (CC1π) is second-most abundant at 26% of the interaction rate. The neutral-current elastic-scattering process (NC elastic) makes up 18% of the events and neutral-current production of pions is about 10%. The remainder of the events (4%) consist of charged- and neutral-current production of multiple pions and deep-inelastic-scattering processes.

The CCQE reaction is extremely important to identify and understand in MiniBooNE for the neutrino oscillation search. The ν_μ CCQE reaction ($\nu_\mu C \rightarrow \mu^- X$) provides an important cross check of the ν_μ flux. The ν_e CCQE reaction ($\nu_e C \rightarrow e - X$) is the

oscillation signal channel. It is important for MiniBooNE to understand this reaction on carbon for which data does not exist.

A first measurement on the CCQE reaction has recently been published [8, 9]. This result used the entire MiniBooNE data set, collected between 2002–2005 and extracted 194k CCQE candidate events. This is the largest event sample ever collected in this energy range. A fit to this data was performed using a Fermi gas model with two free parameters: M_A, the axial mass and κ, a Pauli blocking parameter. An excellent description to the data was obtained with this procedure in both the Q^2 distribution and in the 2-dimensional muon energy/angle distribution. This description works well down to the lowest Q^2 values including the region were an anomalous suppression has been observed. Work is underway to extract the differential cross section.

The CC1π reaction ($\nu_\mu C \rightarrow \mu^- \pi^+ X$) is the largest background for ν_μ CCQE and provides important information about Δ production which is needed to constrain the $\Delta \rightarrow N\gamma$ background in the oscillation search. In addition, *coherent* CCπ^+ production, is an interesting subject and the K2K experiment has set an upper limit [10]. Work is in progress on this analysis [11].

The NC elastic reaction ($\nu_\mu n, p \rightarrow \nu n, p$) is a unique weak-neutral-current probe of the nucleon. Unlike the CC channel, it is sensitive to the isoscalar content of the nucleon and may show the effects of strange quarks. The NC elastic reaction is identified in MiniBooNE by selecting for low-energy events with a small fraction of prompt light (the signature for proton/neutron scintillation only) and no associated muon decay. A NC elastic event sample has been extracted from approximately 10% of the total MB data sample. This sample consists of approximately 4000 events with an expected background of approximately 20%. Preliminary results on this analysis have been reported [12].

The NC π^0 production reaction ($\nu_\mu C \rightarrow \nu \pi^0 X$) is a crucial channel for MiniBooNE as it contributes substantially to the $\nu_\mu \rightarrow \nu_e$ oscillation search. Both resonant and coherent channels contribute to the process. The coherent channel — predicted to compose $\approx 5-20\%$ of the total rate — is dominated by the axial current and, therefore, is unconstrained by any electron-scattering data. The existing data on the coherent process is extremely sparse and requires better measurements. The resonant and coherent rates may be separately extracted from the data via the different pion angular distributions in each process. The NC π^0 reaction is extracted from the MiniBooNE event sample by selecting events with no muon decays and and a "2-ring" event topology consistent with the prompt decay of a π^0 ($\pi^0 \rightarrow \gamma\gamma$). Preliminary results on a rate measurement of this process as a function of π^0 momentum and the fraction of NC π^0 coherent have been reported [13].

ANTINEUTRINO DATA

MiniBooNE finished with the first neutrino run at the end of 2005. In January 2006, the polarity of the neutrino horn was changed so as to focus negatively charged pions and thus create an antineutrino beam. Measurements of the analogous reactions to those described above is a very important test of our understanding of these processes and effectively no data exists with antineutrinos below 1 GeV.

Some of the topics that will be studied with antineutrino data are:

- Extraction of the axial mass, M_A from $\bar{\nu}_\mu$ CCQE events. Preliminary results show that the model developed to fit the neutrino data works well for the antineutrino data [9].
- A measurement of the vector-axial vector interference term via a joint analysis of the neutrino and antineutrino CCQE data.
- Investigation of the coherent NC π^0 fraction and the NC π^0 differential cross section with antineutrino data. [14].
- A measurement of the "wrong-sign" (neutrino) contribution to the CCπ^+ reaction in the antineutrino data. [11].

CONCLUSIONS

The MiniBooNE experiment has collected large samples of both charged-current and neutral-current neutrino-carbon interactions. The experiment is currently running to collect antineutrino data. These data are enabling precise measurements of the cross sections and greater insight into the underlying physics. This are important for future precision measurements of neutrino oscillations.

REFERENCES

1. A. A. Aguilar-Arevalo *et al.* [MiniBooNE Collaboration], Phys. Rev. Lett. **98**, 231801 (2007).
2. A. A. Aguilar-Arevalo *et al.* [LSND Collaboration], Phys. Rev. **D64**, 112007 (2001).
3. D. G. Michael *et al.* [MINOS Collaboration], Phys. Rev. Lett. **97**, 191801 (2006) [arXiv:hep-ex/0607088].
4. D. S. Ayres *et al.* [NOvA Collaboration], [arXiv:hep-ex/0503053].
5. Y. Itow *et al.* [T2K Collaboration], [arXiv:hep-ex/0106019].
6. Eur. Phys. J. C **52**, 29 (2007) [arXiv:hep-ex/0702024].
7. D. Casper, Nucl. Phys. Proc. Suppl. **112**, 161 (2002).
8. A. A. Aguilar-Arevalo *et al.*), arXiv:0706.0926 [hep-ex], submitted to Phys. Rev. Lett
9. T. Katori, *these proceedings*.
10. M. Hasegawa *et al.* [K2K Collaboration], Phys. Rev. Lett. **95**, 252301 (2005).
11. B. Fleming, *these proceedings*.
12. D. Cox, *these proceedings*.
13. J. Link, *these proceedings*.
14. V. Nguyen, *these proceedings*.