Neutrino Scattering Studies in MicroBooNE

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A good understanding of the cross sections for neutrino interactions with nucleons and nuclei is crucial for neutrino oscillation studies, in addition to providing a tool for the exploration of nucleon and nuclear structures. The MicroBooNE liquid-argon time-projection-chamber (LArTPC) experiment has been taking neutrino data with the Booster Neutrino Beam at Fermilab since 2015. The LArTPC capabilities in track reconstruction, energy measurement, and particle identification allow us to probe interesting regions of neutrino-argon scattering cross sections and to probe the quark composition of the nucleon and test models of nuclear structure and final-state interactions. We present the current status of several on-going MicroBooNE cross section analyses, as well as plans for future measurements.

PRESENTED AT

Thirteenth Conference on the Intersections of Particle and Nuclear Physics
Palm Springs, CA, May 29 – June 3, 2018

1Supported by the Office of Nuclear Physics in the Office of Science of the Department of Energy.
1 Introduction

The MicroBooNE experiment was designed to explore the “low-energy excess” (LEE) observed \cite{1,2} by the MiniBooNE experiment, recently updated \cite{3} with data from several more years of running. MiniBooNE, a mineral-oil, Cerenkov detector, is observing a signal of events consisting of electron-like, Cerenkov rings almost 5σ above the expectations from all known sources in the (predominantly muon-neutrino) Fermilab Booster Neutrino Beam (BNB). The results may be interpreted as $\nu_\mu \rightarrow \nu_e$ oscillations involving a fourth, sterile type of neutrino; however, the energy-dependence of the signal is not perfectly consistent with oscillations. Alternatively, some unknown source of photons could be responsible for the signal through photon pair conversion, as the Cerenkov detector cannot distinguish between rings from single electrons and from nearly-collinear, $e^+e^-$ pairs, leaving the interpretation in terms of sterile neutrinos in doubt. The technology employed by MicroBooNE, a liquid-argon, time-projection chamber (LArTPC) can separate the two event topologies, considering that an $e^+e^-$ pair will produce twice the amount of ionization per unit length as a single electron track with the same total energy.

Studies of neutrino oscillations require a good understanding of neutrino scattering on nuclear targets. Cross sections and particle-production features in scattering of neutrinos from argon are very poorly known and models used in neutrino generators for Monte Carlo simulations can vary greatly. Among the generators commonly used are GENIE \cite{4} (used as the default by MicroBooNE), NuWro \cite{5}, NEUT \cite{6}, and GiBUU \cite{7}, and various “tunes,” involving different parameters, may be used with any particular generator. These tunes and the generators themselves are constantly evolving as additional data from neutrino experiments become available. MicroBooNE aims to measure cross sections and perform detailed studies of particles produced in $\nu$-Ar interactions which will be of use, not only for this experiment, but also for future experiments of the Short-Baseline Neutrino (SBN) program \cite{8}, as well as the (higher-energy) Long-Baseline Neutrino (LBN) program with the DUNE detector \cite{9}. MicroBooNE has been collecting beam data since October, 2015 and the experimental run is continuing. Both the BNB, with peak neutrino energy at around 800 MeV and, off-axis, the higher-energy, NuMI beam, are seen by the MicroBooNE detector. In the following, some early, mostly preliminary, results from neutrino scattering on argon are presented.

2 The Experiment

The MicroBooNE detector is described in detail in \cite{10}. A cryostat is filled with 170 tons of liquid argon, of which 84 tons are contained within the active volume of the TPC. The TPC is approximately 2.3 m tall by 2.6 m wide (the drift direction) by
10.4 m long (along the beam direction). The anode consists of two induction planes with wires at ±60° and a collection plane with vertical wires, for a total of 8,256 wires. It uses a drift voltage of 70 kV for a field of 273 V/cm, resulting in a maximum drift time of 2.3 ms. A light-collection system [11] comprises 32, 8-inch, photomultiplier tubes with their surfaces coated with tetraphenyl butadiene, in order to convert the VUV, 128-nm, Ar scintillation light into the visible range. The timing provided by the fast, 6-ns component of the scintillation light plays an important role in mitigating the effects of cosmic-ray backgrounds, as the detector is situated just below ground level with no significant overburden for shielding. Fig. 1 presents a partial event display, showing a charged-current event with several cosmic-ray tracks overlaid; between five and ten cosmic rays cross the detector during the 4.8 ms readout window and the scintillation light allows tagging tracks that are coincident with the 1.6-μs beam spill. The light is also used for triggering, as most of the beam spills do not result in any neutrino interaction in the detector.

Figure 1: Charged-current event showing a muon, proton, and pion tracks, with several cosmic-ray tracks superimposed. Tracks are labeled; the direction of the incoming neutrino is also indicated.

As of this writing, the experiment has received 10^{21} protons on target (POT) from the Booster beam, with 97.5% recorded on tape. Fig. 2 shows the weekly and integrated fluxes.
3 Simulations

MicroBooNE uses the GENIE as the default neutrino event generator. Two tunes (sets of parameters) have been used for comparisons with data: the default, with an empirical meson-exchange-current (MEC) model added (the “Dytman Model”), and an alternative model using a theoretical MEC calculation. The main ingredients are shown in Table 1. In one of the analyses presented below, of charged-particle multiplicities, an additional model, based on the default GENIE with the addition of a Transverse-Enhancement Model [12], was also used for comparing with the data. Finally, the NuWro generator will also be used in some future studies as an alternative.

| Tune                | Default + Emp. MEC                  | Alternative                      |
|---------------------|-------------------------------------|----------------------------------|
| Nuclear model       | Relativistic Fermi gas [13]         | Local Fermi gas [14] [15]        |
| Quasielastic model  | Llewellyn-Smith [16]                | Nieves [14] [15]                |
| MEC model           | Empirical [17]                      | Valencia [14] [15]               |
| Resonance model     | Rein-Sehgal [18]                    | Berger-Sehgal [19]              |
| Final-state interactions | hA [20]                          | hA2012 [20]                      |

Table 1: Main GENIE tunes used in simulations. Both are based on GENIE v.2.12.2.
Detector simulation was based on the GEANT4\cite{21, 22} package. The cosmic-ray background is estimated using either the CORSIKA\cite{23, 24} generator or off-beam data to overlay cosmic-ray tracks on Monte-Carlo-generated, neutrino-induced events.

4 Highlights

Here we present a sample of preliminary results on various processes. They are based on a subset of data from the first experimental run (“Run 1”) between October, 2015 and July, 2016, with the Booster beam.

4.1 Charged-Current, Inclusive Cross Sections

This inclusive process is sensitive to not only single-nucleon knockout (one-particle-one-hole, or “1p1h,”) processes, but also to multi-nucleon correlations, such as MEC, mentioned above, and also possible short-range correlations (SRC)\cite{25}. These two-particle-two-hole (“2p2h”) processes may have been responsible for the disagreement between the results of MiniBooNE, which could not detect low-energy, final-state protons below the Cerenkov threshold, and higher-energy neutrino experiments which measured cross sections with the requirement of a single final-state proton\cite{26}. Measurement of the inclusive cross section allows a more direct comparison with predictions based on nuclear models.

Flux-integrated and single-differential cross sections for CC inclusive, nat Ar(νμ,μ−) scattering were measured from six months of data from Run 1, with a total of ∼1.6 × 10^{20} POT\cite{27}. After reconstruction and removal of cosmic-ray tracks, events were selected requiring one muon with any number (including zero) of additional tracks. A spatial match between an optical flash during the 1.6-μs beam window and the tracks in the event was required. Muons were identified using a classifier, a Support Vector Machine algorithm, in the 2D space of track length vs. the average charge deposited per unit length (truncated-mean dQ/dx), corresponding to the average energy loss, making use of the excellent particle-identification capabilities of the detector. A clear separation of muons and protons was observed.Muon momentum was then obtained using a method based on multiple Coulomb scattering (MCS), which can be used for both contained and exiting tracks. For the former, the momentum can also be obtained from the total range, which allows for a cross check for validating the MCS-based method.

Fig. 3 shows the inclusive cross section result from MicroBooNE superimposed on results from neutrino and antineutrino experiments on a variety of targets. We note that only three of these data points, from the ArgoNeuT experiment, are on argon\cite{28, 29}. The cross section used as input in GENIE is also displayed as a
smooth curve. We find

$$\sigma = 0.576 \pm 0.011 \text{ (stat)} \pm 0.185 \text{ (syst)}$$  \hspace{1cm} (1)$$

The result is systematics-limited, with uncertainties in the beam flux and the detector response being the two largest contributors.

Figure 3: Preliminary MicroBooNE result on the charged-current, inclusive, flux-integrated cross section (red dot), compared with the world data as a function of neutrino energy. The only other data on argon are the three points from the ArgoNeuT experiment (open triangles and gray dot). The GENIE input cross section is also shown as a spline (orange curve).

Single-differential cross sections were also measured, as a function of the reconstructed muon momentum and angle. Fig. 4 shows the cross section vs. \(\cos \theta_\mu\) with statistical and systematic errors, compared with the two GENIE models described earlier. Both tunes overpredict the cross section at forward angles, although the “Alternative” model is closer to the data. Work continues on extracting double-differential cross sections in bins of reconstructed \(p_\mu\) and \(\theta_\mu\).

4.2 Charged-Particle Multiplicity Distributions

Further comparisons with GENIE predictions were made possible using events with one, fully-contained, final-state muon and any number of additional, charged tracks \cite{30}.
Figure 4: Preliminary MicroBooNE results on the charged-current, inclusive, differential cross section $d\sigma/d\cos\theta_{\mu}$ (black dots) with statistical and total errors (inner and outer error bars, respectively). The two GENIE tunes described in the text are also shown with statistical uncertainties, from Monte Carlo statistics, as the green (“Default + Emp. MEC”) and blue (“Alternative”) bands.

The charged-particle multiplicity distributions were compared with predictions from three GENIE models: the default; the default with the empirical MEC as above; and an additional model with the GENIE default augmented by a Transverse Enhancement Model (TEM). The last two implement $2p2h$ final-state excitations not included in the default GENIE. In addition to the multiplicity distributions, detailed data-Monte Carlo comparisons were made of distributions in terms of a number of kinematic variables for fixed multiplicity. Both multiplicity and kinematic-variable distributions are sensitive to not only the nuclear model but also the model for final-state interactions.

Kinematic-variable distributions at fixed multiplicity were in general in good agreement with Monte-Carlo predictions; however, the data showed lower average multiplicities overall compared to the simulations. Fig. 5 shows the charged-track, multiplicity distribution from data acquired with an integrated beam flux corresponding to $5 \times 10^{19}$ POT, compared to the three GENIE models. Cosmic-ray subtraction, after event selection, was based on a CORSIKA simulation. A larger fraction of events have observed multiplicity one, while the fractions with multiplicities two or higher are all lower than predictions from GENIE.
Figure 5: Charged-particle multiplicities in charged-current events compared to the default GENIE model and two models where the default was supplemented with either empirical MEC or the TEM (see text); in linear (left) or logarithmic (right) vertical scale.

4.3 Charged-Current $\pi^0$ Production

Neutral-pion production in neutral-current interactions can be a significant background to the oscillation searches. Showers from the two photons from the $\pi^0$ decay can be merged and be reconstructed as a single photon, which in some cases may be mistaken for an electron. This can cause a ($\nu_\mu$, $\nu_\mu\pi^0$) event to be misreconstructed as ($\nu_e$, e), where the $\nu_e$ is interpreted as signature of an oscillation signal.

The performance of the shower-reconstruction algorithms can be studied and a quantitative estimate of the above background can be obtained using the more easily identifiable charged-current, neutral-pion production: events with a muon and electromagnetic showers in the final state as the signature. The shower-energy resolution can be obtained as well. Fig. 6 shows preliminary results on the reconstructed diphoton mass, after background subtraction, from data corresponding to $5 \times 10^{19}$ POT [31]. A peak consistent with the $\pi^0$ mass is clearly visible. The mass resolution is very competitive with the projected resolution for DUNE, based on the design energy and angular resolution [9], also shown on the plot. The total, flux-integrated cross section for this process is measured to be $\sigma^{\nu\mu CC\pi^0} = [1.94 \pm 0.16\text{(stat)} \pm 0.60\text{(syst)}] \times 10^{-38}\text{cm}^2$.

4.4 Neutral-Current, Elastic Scattering

The neutral-current, elastic (NCE) scattering process Ar($\nu$, $\nu p$) is also very useful for oscillation studies, as it can be employed in searches for sterile neutrinos through flux disappearance: the process is insensitive to (active) neutrino flavor. In addition, it is an important, complementary tool for studies of the nucleon structure. In particular, it can serve as a probe of the contribution of the strange quarks to the spin of the nucleon [32], usually denoted as $\Delta s$ and measured, with various model-dependent
assumptions, in deep-inelastic, lepton-nucleon scattering (DIS). Experiments over the last thirty years point to a (surprisingly) negative $\Delta s$ [33]. However, this has not been confirmed by studies of semi-inclusive DIS production and the overall model-dependence demands an independent probe of this quantity, which affects predictions in searches for certain types of dark matter [34], as well as being one of the major unknown quantities of the nucleon structure.

The NCE cross section is sensitive to $\Delta s$ and can help extract it when combined with data from CC neutrino scattering and charged-lepton elastic scattering. Measurements at low $Q^2$, (four-momentum transfer squared), are needed. The signature for the NCE events is a single, proton track and at low $Q^2$ the track will be short.

A method has been devised to identify proton tracks based on a machine-learning algorithm, gradient-boosting decision trees, using a number of reconstructed event variables. Then a logistic-regression model is used to combine the information from the decision trees with other event features to obtain an enriched sample of NCE events. The final step involves a comparison with the GENIE prediction for this process and a fit that will optimize the form factor that GENIE uses as input; a Markov Chain Monte Carlo has been written for this purpose. This work is in progress [35].
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