SciBooNE and other neutrino cross section measurements

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Recent discovery of neutrino oscillation has renewed interest in the study of neutrino interaction cross-section, especially the interaction with nucleus in the neutrino energy region around one GeV. Among several relevant interaction channels, neutral current π^0 production is of critical importance in the search for $\nu_\mu \to \nu_e$ transition, that is the most important goal of the current neutrino oscillation experiments. We report on the latest result from SciBooNE experiment at Fermilab. Also given is the future outlook of the neutrino cross section measurements.

1 Introduction

Understanding of the neutrino-nucleus interaction cross section, in the neutrino energy region of one GeV, has become increasingly important with the recent discovery of neutrino oscillation and the subsequent success of long baseline oscillation experiments. Over the past decade, new data from neutrino oscillation experiments and, more recently, dedicated neutrino cross-section experiments have been accumulated. In the past few years, new results have been mainly reported by two experiments at Fermilab, MiniBooNE and SciBooNE. Because cross-section measurements by MiniBooNE are presented elsewhere[1], the latest results from SciBooNE experiment is presented in this paper.

2 SciBooNE experiment (FNAL E-954)

The SciBooNE experiment [2] is designed to measure the neutrino cross sections on carbon in the one GeV region. The experiment uses the Booster Neutrino Beam (BNB) at Fermilab. The muon neutrino beam is generated with a conventional beamline with a magnetic focusing horn. The flux-averaged mean neutrino energy is 0.7 GeV. When the horn polarity is reversed, π^- are focused and hence a predominantly antineutrino beam is created. Because the energy spectrum of neutrinos from BNB is well matched with that of T2K long baseline experiment [3], SciBooNE can provide an essential input for the neutrino oscillation studies at T2K. Together with MiniBooNE, SciBooNE can also search for the neutrino oscillation with a short baseline.

The SciBooNE detector is located 100 m downstream from the proton target. The detector complex consists of three sub-detectors: a fully active fine grained scintillator tracking detector (SciBar), an electromagnetic calorimeter (EC) and a muon range detector (MRD). The SciBar detector consists of 14,336 extruded plastic scintillator strips, each $1.3 \times 2.5 \times 300$ cm^3. The scintillators are arranged vertically and horizontally to construct a $3 \times 3 \times 1.7$ m^3 volume with a total mass of 15 tons. Each strip is read out by a wavelength-shifting fiber attached to a

64-channel multi-anode PMT. The EC is installed downstream of SciBar, and consists of 32 vertical and 32 horizontal modules made of scintillating fibers embedded in lead foils. The EC has a thickness of $11X_0$ along the beam direction to measure the electromagnetic component from the neutrino interaction. The MRD is located downstream of the EC in order to measure the momentum of muons up to 1.2 GeV/c with range. It consists of 12 layers of 2"-thick iron plates sandwiched between layers of 6 mm-thick plastic scintillator planes. The experiment was proposed to Fermilab in 2005. After two years of preparation, SciBooNE took both neutrino and antineutrino data from June 2007 until August 2008. In total, 2.64×10^{20} POT were delivered to the target during the SciBooNE data run. After beam and detector quality cuts, 2.52×10^{20} POT are usable for physics analyses; 0.99×10^{20} POT for neutrino data and 1.53×10^{20} POT for antineutrino data.

The physics topics of SciBooNE include all possible interaction channels in relevant energy region, with both charged current (CC) and neutral current (NC) interactions. Preliminary results of many analyses have been shown at conferences [4], and the search for CC coherent pion production in neutrino-carbon scattering has been published as the first result from SciBooNE [5]. We present in this paper the results of neutral current π^0 production measurement that has been recently published [6] including its update on the coherent pion production [7].

3 Neutral current π^0 production

3.1 Motivation

One of the most important topics in the current neutrino physics is the search for oscillaltion from ν_μ to ν_e which is related to the yet-unknown neutrino mixing angle θ_{13}. If the value of θ_{13} is large, we can search for the CP violation in neutrino oscillation with next generation experiments. The precision needed for these searches drives the need for more accurate independent measurements of neutrino cross sections. An understanding of neutral current neutral pion production (NCπ^0) is especially important. NCπ^0 events form the largest ν_μ-induced background to neutrino experiments measuring $\nu_\mu \to \nu_e$ oscillations in the neutrino energy range of a few GeV or less, such as T2K, because NCπ^0 events can mimic ν_e signal events when, for example, one of the two photons associated with $\pi^0 \to \gamma\gamma$ is not detected. The T2K experiment requires less than a 10% uncertainty on NCπ^0 production to maintain high sensitivity for the $\nu_\mu \to \nu_e$ oscillation search.

Pions are produced mainly through two distinct mechanisms by neutrinos with energies around 1 GeV. In the dominant mode, resonant pion production, the neutrino interacts with a nucleon in the nucleus and excites it to a baryonic resonance, such as Δ (1232), which subsequently decays to a pion and a nucleon. The other mode, coherent pion production occurs when the neutrino interacts with the whole target nucleus so that no nuclear breakup occurs. There are recent reports from K2K [8] and SciBooNE [5] that the cross section of charged current coherent pion production around 1 GeV is much lower than the prediction of commonly-used model by Rein and Sehgal [9]. On the other hand, MiniBooNE [10] has reported an evidence for the neutral current coherent pion production in the same energy range. It is one of hottest topics in the neutrino interaction physics community to understand the mechanism of the pion production in this energy region. SciBooNE can measure both CC and NC coherent pion production with the same detector, which provides us valuable information.

Resonance production and decay in a nuclear target differs from the case of the free nucleon target. This is due to nuclear effects such as Fermi motion, Pauli blocking, and the nuclear potential. In addition, produced mesons and baryons interact with nuclear matter until they escape from the target nucleus. Due to this final state interaction, the number, momenta, directions and charge states of produced particles can be changed in nuclear matter. Although there are several theoretical models of these processes, their uncertainties are still large. To understand the production mechanism and the nuclear effects, measurements of emitted π^0 kinematics are essential.

3.2 The signal and backgrounds

The signal is defined as a neutral current neutrino interaction where at least one π^0 are emitted in the final state from a nulceus. As long as a π^0 is emitted from the initial target nucleus in an event, the event is treated as a signal even if the $\pi^0$is produced by nuclear effect or other mesons including charged meson are emitted along with π^0. The events where π^0s are produced at the initial target nucleus but all π^0s are absorbed are not included in the signal events.

The clearest feature of the NC π^0production is two gamma rays from π^0s. Both gamma rays are required to convert inside the SciBar detector to be reconstructed. Figure 1 shows a display of NC π^0 event candidate in SciBooNE data. Because SciBar corresponds to approximately four radiation length in the beam direction, about 30% of π^0 has both gamma rays converted inside SciBar. Two tracks, separated from each other, are required as a π^0 candidate.

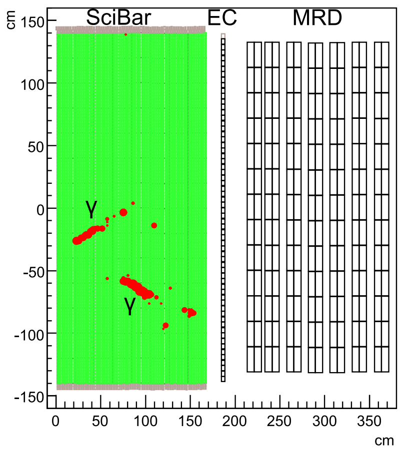

Figure 1: Event display of a typical NCπ^0 event candidate with two electromagnetic shower tracks from γ conversion in SciBooNE data. The neutrino beam runs from left to right in this figure, encountering SciBar, the EC and MRD, in that order. The circles on SciBar indicate ADC hits for which the area of the circle is proportional to the energy deposition in that channel.

The main background events are divided into two categories; the *internal* background and the *external* background. In the *internal* background events, the neutrino interactions other than NCπ^0 interaction in SciBar produce secondary particles. Major part of the internal background comes from the charged current events and can be rejected by finding muons. Energy information from EC and MRD is used to veto particles consistent with muons. Decay electrons are searched for by timing information of SciBar and vetoed. The *external* background is particles coming from the outside of the detectors. Charged particles coming from outside are rejected using outer layers of SciBar. To reduce π^0s produced in the surrounding material and gammas converted inside SciBar, an event is rejected if the reconstructed π^0 vertex, reconstructed from the direction of gamma candidates, is outside of SciBar.

3.3 Results

After rejecting background and reconstructing the events, a clear peak at the expected π^0 mass is seen in the invariant mass of two gamma candidates. Figure 2 shows the invariant mass distribution of the reconstructed π^0 candidates. The final sample is selected by requiring the invariant mass $M^{\rm rec}_{\pi^0}$ to be $50 < M^{\rm rec}_{\pi^0} < 200$ MeV. After all the selection, 657 events remain as

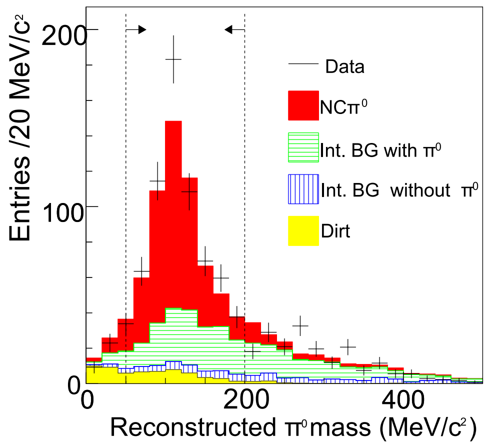

Figure 2: The reconstructed mass of π^0s after all other selections.

the signal candidates. The background for this sample, estimated using a Monte Carlo (MC) simulation using NEUT neutrino interaction simulation package [11] and GEANT4 library, is 240 (202 internal and 38 external). The number of events from the MC simulation is normalized to data using inclusive charged current events, in which a track is required to reach and stop inside MRD to tag muons. The purity and efficiency of NC π^0 production after all event selection is estimated to be 61% and 5.3%, respectively.

We measure the ratio of the NCπ^0 production to the total CC interaction cross sections, in order to avoid a large uncertainty arising from the estimate of absolute neutrino flux. The inclusive CC candidates are selected using MRD and 21,702 events are selected with 19% efficiency. The ratio of the NC π^0 production to the total CC cross section is measured to be

$$\frac{\sigma(\mathrm{NC}\pi^0)}{\sigma(\mathrm{CC})} = (7.7 \pm 0.5(\mathrm{stat.}) \pm 0.5(\mathrm{sys.})) \times 10^{-2}$$

at the mean neutrino energy of 1.14 GeV. The largest contribution to the systematic uncertainty comes from the understanding of the detector response. The MC expectation based on the NEUT program using the Rein and Sehgal model is 6.8×10^{-2}.

Figure 3 shows the π^0 momentum and direction distributions, after background subtractions, conversions to the true π^0 kinematics and efficiency corrections. To compare the shapes of the distributions, the total numbers of entries in the distributions are normalized to unity both for the measurement and the MC expectation. The shapes of these two distributions agree with the MC expectation.

In NC coherent pion production, there is no recoil nucleon in the final state since the π^0 is produced by the neutrino interacting with the whole nucleus. Conversely, a recoiling nucleon should be present in a resonant pion event. To separate the NC coherent π^0 events from the NC resonant π^0 events, recoil protons in the final state are used. The recoil protons are detected by their large energy deposition near the neutrino interaction vertex. This is a unique feature to SciBooNE utilizing its fully active detector design. The absence of a recoil nucleon provides a clear and less model-dependent signal of coherent pion production, in addition to the kinematic distribution of π^0 used in the previous analyses from MiniBooNE and SciBooNE.

To identify the coherent pion production, the kinematic variable of reconstructed π^0 $E^{\rm rec}_{\pi^0}(1-\cos\theta^{\rm rec}_{\pi^0})$, where $E^{\rm rec}_{\pi^0}$ is the reconstructed π^0 energy calculated as the sum of the reconstructed

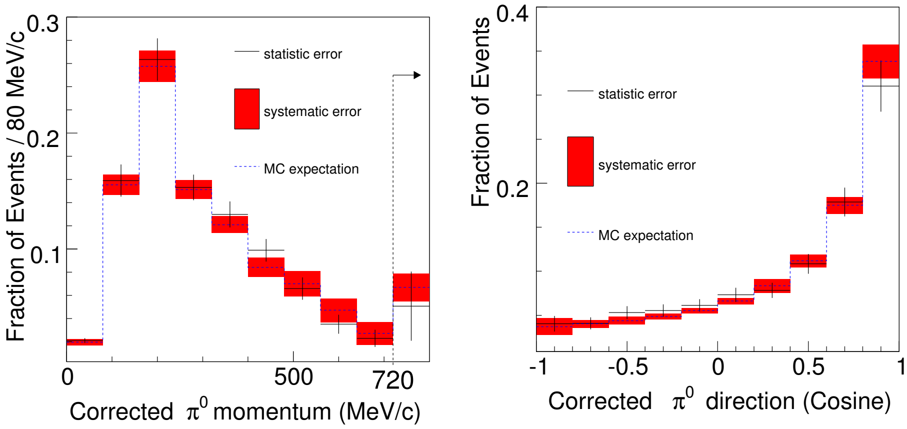

Figure 3: The π^0 kinatic distributions after subtracting the background, unfolding the detector effects, and correcting for the efficiency. Error bars and boxes show statistical and systematic uncertainties, respectively. Left and right plot shows the distribution of momentum and cosine of angle with respect to the beam axis, respectively. The dashed line shows the Monte Carlo expectation based on the Rein and Sehgal model.

energies of two gamma ray candidates and $\theta_{\pi^0}^{\rm rec}$ is the reconstructed π^0 direction with respect to the neutrino beam axis, is used. Two $E_{\pi^0}^{\rm rec}(1-\cos\theta_{\pi^0}^{\rm rec})$ distributions, with and without the vertex activity, are fitted with three templates made by dividing the final MC sample into NC coherent π^0, NC resonant π^0 and background samples. Figure 4 shows the $E_{\pi^0}^{\rm rec}(1-\cos\theta_{\pi^0}^{\rm rec})$

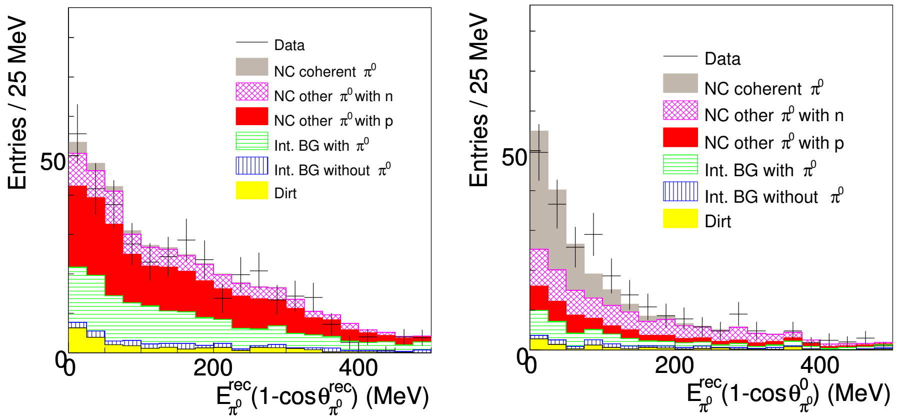

Figure 4: The $E_{\pi^0}^{\rm rec}(1-\cos\theta_{\pi^0}^{\rm rec})$ distributions after fitting with (left) and without (right) vertex activity.

distributions after fitting. Clear evidence of coherent pion production is seen.

The ratio of the NC coherent π^0 production to the total CC cross sections from the MC prediction based on the Rein and Sehgal model is 1.21 $\times 10^{-2}$. From SciBooNE data, the cross section ratios are measured to be

$$\frac{\sigma(\mathrm{NCcoh}\pi^0)}{\sigma(\mathrm{CC})} = (1.16 \pm 0.24) \times 10^{-2}.$$

This result is in agreement with MiniBooNE result with the same neutrino energy and also with the model prediction. However, there is no model which can accommodate the measurement of the CC/NC coherent pion production ratio at these energies, although the measurement of the ratio at higher energies is consistent with model expectation.

4 Future prospects

While both SciBooNE and MiniBooNE collaborations are actively analyzing their data, there are also more experiments coming into the field. MINERνA experiment at Fermilab is an experiment dedicated to the precise measurement of neutrino cross section and has just started taking data. There will be precise measurements of neutrino cross section from the near detectors of long baseline experiment such as T2K. Also experiments based on a new technology, such as the liquid argon TPC, are proposed. ArgoNEUT at Fermilab has recently took data at NuMI beamline and analyzing the data.

The future, precision neutrino oscillation experiments require improved understanding of neutrino-nucleus interaction in the energy region of 1 GeV. Although uncertainties in neutrino flux, energy spectrum, nuclear effects, as well as the cross section itself, make it a difficult task, there have been much progress in the past decade with the new data and theory. On the other hand, we encounter new puzzles as we gain more data and analysis experience, which we hope to solve with new experiments and more data. The understanding of neutrino interaction will become even more important, and it will continue to be one of exciting fields of research in the next decade.

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