RECENT RESULTS FROM SciBooNE*

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SciBooNE is a neutrino experiment measuring the neutrino cross-sections on carbon in the one GeV region. In this paper, we discuss the measurement of charged current coherent pion production on carbon by neutrinos.

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1. Introduction

Neutrino interactions producing single pion form significant backgrounds for neutrino oscillation searches with a few-GeV neutrino beam, and thus understanding those processes is essential. It has been known for years that neutrinos can produce pions by interacting coherently with the nucleons forming the target nucleus. Both charged current (CC) and neutral current (NC) coherent modes are possible, $\nu_\mu A \to \mu^- A \pi^+$ and $\nu_\mu A \to \nu_\mu A \pi^0$, where A is a nucleus. The outgoing lepton and pion tend to go in the forward direction in the lab frame, and no nuclear breakup occurs. Recent results on coherent pion production have induced interest of the neutrino physics community. The non-existence of CC coherent pion production in a 1.3 GeV wide-band neutrino beam has been reported by K2K [1], while there exist CC coherent pion production positive results at higher neutrino energies. On the one hand, evidence for NC coherent pion production in the similar neutrino energy has been recently reported by MiniBooNE [2].

The SciBooNE experiment [3] is designed to measure the neutrino cross-sections on carbon in the one GeV region. In this paper, we report the first measurement of CC coherent pion production on carbon by neutrinos in the SciBooNE experiment, which was recently published in Ref. [4].

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2. The SciBooNE experiment

The experiment uses the Booster Neutrino Beam (BNB) at Fermilab. The primary proton beam, with kinetic energy 8 GeV, is extracted to strike a 71 cm long, 1 cm diameter beryllium target. Each beam spill consists of 81 bunches of protons, containing typically 4×10^{12} protons in a total spill duration of 1.6 μsec. The target sits at the upstream end of a magnetic focusing horn that is pulsed with approximately 170 kA to focus the mesons, primarily π^+, produced by the p–Be interactions. In a 50 m long decay pipe following the horn, π^+ decay and produce neutrinos, before the mesons encounter an absorber. The flux is dominated by muon neutrinos (93% of total), with small contributions from muon antineutrinos (6.4%), and electron neutrinos and antineutrinos (0.6% in total). 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.

The SciBooNE detector is located 100 m downstream from the neutrino production 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 photomultiplier tube (PMT). The minimum length of a reconstructed track is 8 cm which corresponds to a proton with momentum of 450 MeV/c. The EC is installed downstream of SciBar, and consists of 32 vertical and 32 horizontal modules made of scintillating fibers embedded in lead foils. Each module has dimensions of $4.0 \times 8.2 \times 262$ cm^3, and is read out by two 1" PMTs on both ends. The EC has a thickness of 11 radiation lengths along the beam direction to measure π^0 emitted from neutrino interactions and the intrinsic ν_e contamination. The energy resolution is $14\%/\sqrt{E[\mathrm{GeV}]}$. 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 cross-sectional area of each plate is 305×274 cm^2. The horizontal and vertical scintillator planes are arranged alternately, and the total number of scintillators is 362.

The experiment took both neutrino and antineutrino data from June 2007 until August 2008. In total, 2.64×10^{20} POT were delivered to the beryllium 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. Results from the full neutrino data sample are presented in this paper.

3. Event selection

The experimental signature of CC coherent pion production is the existence of two and only two tracks originating from a common vertex, both consistent with minimum ionizing particles (a muon and a charged pion).

To identify CC events, we search for tracks in SciBar matching with a track or hits in the MRD. Such a track is defined as a SciBar-MRD matched track. The most energetic SciBar-MRD matched track in any event is considered as the muon candidate. The neutrino interaction vertex is reconstructed as the upstream edge of the muon candidate. We select events whose vertices are in the SciBar fiducial volume, 2.6 m $\times$ 2.6 m $\times$ 1.55 m, a total mass of 10.6 tons. Finally, event timing is required to be within 2 μsec beam timing window. Approximately 30,000 events are selected as our standard CC sample, which is called SciBar-MRD matched sample. According to the MC simulation, the selection efficiency and purity of true ν_μ CC events are 27.9% and 92.8%, respectively. Two subsamples of the SciBar-MRD matched sample are further defined: the MRD stopped sample and the MRD penetrated sample. Events with the muon stopping in the MRD are classified as MRD stopped events. Events with the muon exiting from the downstream end of the MRD are defined as the MRD penetrated sample, in which we can measure only a part of the muon momentum. The average neutrino beam energy for true CC events in the MRD stopped and MRD penetrated samples is 1.0 GeV and 2.0 GeV, respectively, enabling a measurement of CC coherent pion production at two different mean neutrino energies.

Once the muon candidate and the neutrino interaction vertex are reconstructed, we search for other tracks originating from the vertex. Most events are reconstructed as either one track or two track events. The two track sample is further divided based on particle identification. The particle identification variable, Muon Confidence Level (MuCL) is related to the probability that a particle is a minimum ionizing particle based on the energy deposition. In a CC resonant pion event, $\nu p \to \mu^- p \pi^+$, the proton is often not reconstructed due to its low energy, and such an event is therefore identified as a two track $\mu + \pi$ event. To separate CC coherent pion events from CC resonant pion events, additional protons with momentum below the tracking threshold are instead detected by their large energy deposition around the vertex, so-called vertex activity. Four sub-samples, the one track events, $\mu + p$ events, $\mu + \pi$ events with vertex activity, and $\mu + \pi$ events without vertex activity are used for constraining systematic uncertainties in the simulation. The MC distributions of the square of the four-momentum transfer (Q^2) are fitted to the distributions of the four aforementioned data samples. The reconstructed Q^2 is calculated by assuming CC quasi-elastic (CC–QE) kinematics. The fitting is described in detail in ref. [4]. Figure 1 shows the reconstructed Q^2 distributions after the fitting.

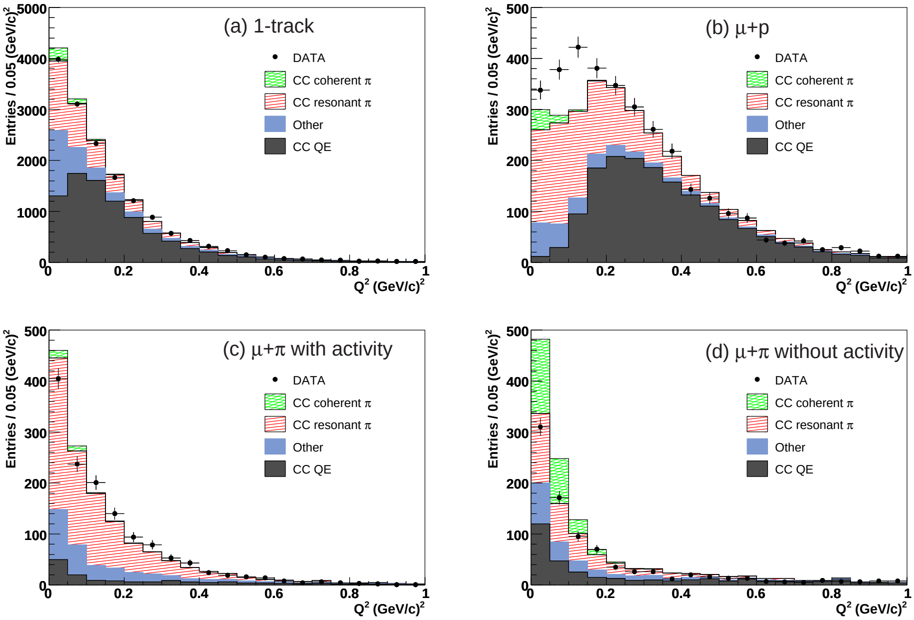

Fig. 1. Reconstructed Q^2 after fitting for (a) the one track, (b) $\mu + p$, (c) $\mu + \pi$ with activity, and (d) $\mu + \pi$ without activity samples.

CC coherent pion candidates are extracted from the $\mu + \pi$ events which do not have vertex activity. The sample still contains CC–QE events in which a proton is misidentified as a minimum ionizing track. We reduce this background by using kinematic information in the event. Since the CC–QE interaction is a two-body interaction, one can predict the proton direction from the measured muon momentum and muon angle. For each two-track event, we define an angle called $\Delta\theta_p$ as the angle between the expected proton track and the observed second track directions. Events with $\Delta\theta_p$ larger than 20 degrees are selected. Further selections are applied in order to separate CC coherent pion events from CC resonant pion events which are the dominant backgrounds for this analysis. In the case of CC coherent pion events, both the muon and pion tracks are directed forward, and therefore events in which the track angle of the pion candidate with respect to the beam direction is less than 90 degrees are selected. Figure 2 (left) shows reconstructed Q^2 for the $\mu + \pi$ events in the MRD stopped sample after the pion track direction cut. Finally, events with reconstructed Q^2 less than 0.1 $(\mathrm{GeV}/c)^2$ are selected. In the signal region, 247 CC coherent pion candidates are observed, while the expected number of background events is 228±12. The error comes from the errors on the fitting parameters. The selection efficiency for the signal is estimated to be 10.4%. The mean neutrino beam energy for true CC coherent pion events in the sample is estimated to be 1.1 GeV after accounting for the effects of the selection efficiency.

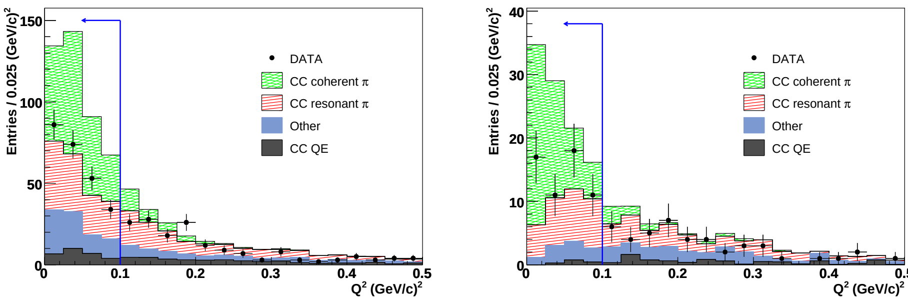

Fig. 2. Reconstructed Q^2 for the MRD stopped CC coherent pion sample (left), and the MRD penetrated CC coherent pion sample (right).

The same selection is applied to the MRD penetrated sample to extract CC coherent pion candidates at higher energy. Figure 2 (right) shows reconstructed Q^2 for the MRD penetrated CC coherent pion sample. In the signal region, 57 CC coherent pion candidates are observed, while the expected number of background events is 40±2.2. The selection efficiency for the signal is estimated to be 3.1%. The mean neutrino beam energy for true CC coherent pion events in the sample is estimated to be 2.2 GeV.

4. σ(CC coherent π)/σ(CC) cross-section ratio

We measure the cross-section ratios of CC coherent pion production to total CC interaction with two distinct data samples. With the MRD stopped sample, the ratio of the CC coherent pion production to total CC cross-sections is measured to be $(0.16 \pm 0.17(\mathrm{stat})^{+0.30}_{-0.27}(\mathrm{sys})) \times 10^{-2}$. The result is consistent with the nonexistence of CC coherent pion production, and hence we set an upper limit on the cross-section ratio by using the likelihood distribution ($\mathcal{L}$) which is convolved with the systematic error. We calculate the 90% confidence level (C.L.) upper limit (UL) using the relation $\int_0^{\mathrm{UL}} \mathcal{L}dx / \int_0^{\infty} \mathcal{L}dx = 0.9$ to be

$$\sigma(\mathrm{CC\ coherent}\ \pi)/\sigma(\mathrm{CC}) < 0.67 \times 10^{-2} \tag{1}$$

at a mean neutrino energy of 1.1 GeV.

With the MRD penetrated sample, the cross-section ratio is measured to be $(0.68 \pm 0.32(\mathrm{stat})^{+0.39}_{-0.25}(\mathrm{sys})) \times 10^{-2}$. No significant evidence for CC coherent pion production is observed, and hence we set an upper limit on the cross-section ratio at 90% C.L.:

$$\sigma(\text{CC coherent } \pi)/\sigma(\text{CC}) < 1.36 \times 10^{-2} \quad (2)$$

at a mean neutrino energy of 2.2 GeV.

According to the Rein–Sehgal model [5,6] implemented in our simulation, the cross-section ratio of CC coherent pion production to total CC interactions is expected to be 2.04×10^{-2}. Our limits correspond to 33% and 67% of the prediction at 1.1 GeV and 2.2 GeV, respectively. Our results are consistent with the K2K result [1]: $\sigma(\text{CC coherent } \pi)/\sigma(\text{CC}) < 0.60 \times 10^{-2}$ at 90% C.L. measured in a 1.3 GeV wideband neutrino beam.

5. Summary

In summary, we have searched for muon neutrino CC coherent pion production on carbon in the few-GeV region using the full SciBooNE neutrino data set of 0.99×10^{20} POT. No evidence of CC coherent pion production is found, and hence we set 90% C.L. upper limits on the cross-section ratio of CC coherent pion production to total CC cross-sections at 0.67×10^{-2} and 1.36×10^{-2}, at mean neutrino energies of 1.1 GeV and 2.2 GeV, respectively.

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