Measurement of Charged Current Charged Single Pion Production in SciBooNE

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The SciBooNE experiment is designed to measure neutrino cross sections on carbon around one GeV region. Charged current single charged pion production is a dominant background process for $\nu_\mu$ -- $\nu_x$ oscillation experiments with a few-GeV neutrino beam, and thus a precision measurement of the cross section is essential. This article reports preliminary results on this process from SciBooNE.

1. INTRODUCTION

Neutrino-induced charged current single charged pion production (CC-1$\pi^+$) is dominated by baryonic resonance excitation off a single nucleon bound in a nucleus in the neutrino energy region of a few GeV. The resonance state is followed by its prompt decay into a nucleon and a pion in the final state. The process is written as $\nu_\mu N \rightarrow \mu^- N \pi^+$, where $N$ is proton or neutron. In addition to this reaction, neutrinos can produce pions by interacting coherently with the nucleons forming the target nucleus. The process is expressed as $\nu_\mu A \rightarrow \mu^- A \pi^+$, where $A$ is a nucleus.

Understanding the cross sections of these processes is important to study $\nu_\mu$ -- $\nu_x$ oscillation near one GeV. In such oscillation experiments, a distortion in the $\nu_\mu$ energy spectrum is measured with charged current quasi-elastic (CC-QE) interactions, $\nu_\mu n \rightarrow \mu^- p$, by reconstructing neutrino energy from the measured muon momentum and angle. The background to this channel is dominated by CC-1$\pi^+$ events in which the pion is not observed so that the final state looks like a CC-QE interaction. This mis-identification comes from the lack of the final state $\pi^+$ detection due to low energy as well as pion absorption inside the nucleus. In case of the T2K experiment [1], a next generation long baseline neutrino oscillation experiment, the CC-1$\pi^+$/CC-QE cross section ratio is required to be understood at 5% level to keep the resulting error on the oscillation parameters comparable to that due to statistical uncertainties [2]. However, the current knowledge of the cross section ratio has been limited by low statistics and large systematic uncertainty, and therefore a precision measurement of the cross section is essential.

In addition, 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 [3], 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 [4].

2. SCIBOONE EXPERIMENT

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 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 $4 \times 10^{12}$ protons in a total spill duration of 1.6 $\mu$sec. The target sits at the upstream end of a magnetic focusing horn that is pulsed with approximately 170 kA to focus the mesons, primarily $\pi^+$, produced by the $p$--Be interactions. In a 50 m long decay pipe following the horn, $\pi^+$ 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, $\pi^-$ 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 × 2.5 × 300 cm³. The scintillators are arranged vertically and horizontally to construct a 3 × 3 × 1.7 m³ volume with a total mass of 15 tons. Each strip is read out by a wavelength-shifting (WLS) fiber attached to a 64-channel multi-anode PMT (MA-PMT). Charge and timing information from each MA-PMT is recorded by custom electronics. 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 × 8.2 × 262 cm³, and is read out by two 1” PMTs on both ends. The EC has a thickness of 11X0 along the beam direction to measure π⁰ emitted from neutrino interactions and the intrinsic νe contamination. The energy resolution is 14%/√E[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 cm². 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 × 10²⁰ POT were delivered to the beryllium target during the SciBooNE data run. After beam and detector quality cuts, 2.52 × 10²⁰ POT are usable for physics analyses; 0.99 × 10²⁰ POT for neutrino data and 1.53 × 10²⁰ POT for antineutrino data. Preliminary results from the full neutrino data sample are presented in this paper.

3. CC-1π⁺ EVENT SAMPLE

The experimental signature of CC single charged 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). Even in case of a CC resonant pion event with proton in the final state, νp → μ⁻pπ⁺, the proton is often not reconstructed due to its low energy.

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 matching criteria impose a muon momentum threshold of 350 MeV/c. 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 (FV), 2.6 m × 2.6 m × 1.55 m, a total mass of 10.6 tons. Finally, event timing is required to be within 2 μsec beam timing window. The cosmic-ray background contamination in the beam timing window is only 0.5%, estimated using a beam-off timing window. Approximately 30,000 events are selected as our standard CC sample. According to the MC simulation, the selection efficiency and purity of true νµ CC events are 28% and 93%, respectively.

In order to reconstruct muon momentum from its range, the muon candidate is required to stop in the MRD. Once the muon candidate and the neutrino interaction vertex are reconstructed, we search for other tracks originating from the vertex. Events with two and only two vertex-matched tracks are selected. The SciBar detector has the capability to distinguish protons from muons and pions using dE/dx. The particle identification variable, Muon Confidence Level (MuCL) is related to the probability that a particle is a minimum ionizing particle (MIP) based on the energy deposition. The confidence level at each plane is first defined as the fraction of events in the expected dE/dx distribution of muons above the observed value. The expected dE/dx distribution of muons is obtained by using cosmic-ray muons. Each plane’s confidence level is combined to form a total confidence level, assuming the confidence level at each layer is independent. The particle identification is applied to both tracks to select events with two MIP-like tracks (μ + π). The probability of mis-identification is estimated to be 1.1% for muons and 12% for protons.

After selecting μ + π events, the sample still contains CC-QE events in which a proton is mis-identified as a MIP-like track. We reduce CC-QE background by using kinematic information. Since the CC-QE interaction is a two-body interaction, one can predict the proton direction from the measured muon momentum and muon angle. We define an
angle called $\Delta \theta_p$ as the angle between the expected proton track direction and the observed second track direction. In CC-QE events, the angle $\Delta \theta_p$ is expected to be small, and therefore we select events in which $\Delta \theta_p$ is greater than 20 degrees to reject CC-QE background. With this selection, 48% of CC-QE events in the $\mu^+\pi^+$ sample are rejected.

We select approximately 2,000 CC-$1\pi^+$ candidates. Figure 1 shows reconstructed muon momentum and angle with respect to the neutrino beam direction for CC-$1\pi^+$ sample. For the MC simulation, the contributions from each interaction mode are shown separately. According to the MC simulation, the fraction of CC resonant pion production ($\nu_\mu p \rightarrow \mu^- p \pi^+$ and $\nu_\mu n \rightarrow \mu^- n \pi^+$) and CC coherent pion production in the sample is 34%, 11%, and 15%, respectively. As seen in the figure, the deficit of data in the small muon angle region is found. Further investigation has been performed by extracting CC coherent pion events.

4. EXTRACTION OF CC COHERENT PION EVENTS

CC coherent pion events are separated from CC resonant pion events by using their characteristic kinematic information. Because of the small momentum transfer to the target nucleus, both the muon and pion go in the forward direction. Events in which a pion candidate goes forward are selected. The additional protons with momentum below the tracking threshold are detected by their large energy deposition around the vertex, so-called vertex activity. We search for the maximum deposited energy in a strip around the vertex, an area of $12.5 \text{ cm} \times 12.5 \text{ cm}$ in both views. Events with the energy deposition less than 10 MeV are considered to have no vertex activity and selected.

Figure 2 shows reconstructed $Q^2$ assuming CC-QE kinematics for the CC coherent pion sample. Although a CC-QE interaction is assumed, the $Q^2$ of CC coherent pion events is reconstructed with a resolution of 0.02 (GeV/c)$^2$ and a shift of -0.02 (GeV/c)$^2$ according to the MC simulation. Finally, events with reconstructed $Q^2$ less than 0.1 (GeV/c)$^2$ are selected as CC coherent pion candidates. The selection efficiency of CC coherent pion production is 11%, and the mean neutrino energy after accounting for the selection efficiency is 1.1 GeV, both estimated with the MC simulation. The observed CC coherent pion sample contains fewer events than our MC prediction which is based on the Rein-Sehgal model with lepton mass correction. Our 90% C.L. sensitivity on the cross section ratio of CC coherent pion production to total CC interaction is estimated to be 0.004, which corresponds to 20% of the MC prediction.
5. SUMMARY

In summary, we present preliminary results on charged current single charged pion production, analyzing the full neutrino data corresponding to $0.99 \times 10^{20}$ POT. Observed CC coherent pion sample contains fewer events than our MC prediction which is based on the Rein and Sehgal model. Our 90% C.L. sensitivity on the cross section ratio of CC coherent pion production to total CC interaction is 0.004 at the mean neutrino energy of 1.1 GeV. After measuring CC coherent pion production, the measurement on CC resonant pion production will be performed.

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