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Low energy cross section measurements in the FNAL Booster beamline: MiniBooNE and SciBooNE

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Until recently, the state of low energy cross section measurements with neutrinos has been limited by low statistics and large flux uncertainties. With new and upcoming results from MiniBooNE and K2K, we already see substantial improvements in what we can measure. The proposed near term future experiment of placing the fine-grained K2K SciBar detector in the Fermilab Booster beamline (SciBooNE) will provide important cross section information for future oscillation experiments, such as T2K.

1. Overview

The rapid advances in neutrino physics, such as oscillation experiments, require advancements in understanding neutrino cross sections. Previous bubble chamber experiments frequently measured neutrinos on light targets (H_2, D_2) only, but the current generation oscillation experiments tend to use heavier targets, and hence require data on carbon, oxygen and iron. It is nontrivial to extrapolate from light to heavy targets; Fermi motion, Pauli blocking, shadowing and coherent production that do not occur on light targets complicate the cross section on heavy targets. Cross section experiments have also often been statistics limited; for example, the world's data on charged current single pion production ($CC\pi^+$) is only 7,000 events total, across all energies. Now, oscillation experiments such as MiniBooNE and K2K are collecting high statistics neutrino samples on heavy targets in the low energy region ($E_\nu \approx$ 1GeV).

Recently, it has been proposed to place one of K2K's near detectors, SciBar, on axis in the Booster Neutrino Beamline (BNB)[2],[3]. This new experiment, SciBooNE, combines a high intensity, independently modeled beam with a fine-grained detector capable of multi-particle final state reconstruction at lower energies.

A next generation oscillation experiment, T2K, will need the cross sections measured by SciBooNE. T2K's mean energy is close to the BNB's. Although T2K will have two near detectors, there is no plan currently for a 40 GeV hadron production experiment. A hadron production experiment has already been run for the BNB; HARP took data with protons on a Be target at the BNB proton energy, and so SciBooNE has an independent measurement of the BNB flux. With precision cross section measurements made at SciBooNE, T2K can use its near detectors to measure their flux on and off axis when they start running, instead of waiting for a concurrent hadron production experiment's flux results.

This new experiment, SciBooNE, complements and improves measurements made by MiniBooNE. These proceedings will detail the cross section measurements that MiniBooNE and SciBooNE will probe.

2. MiniBooNE Beam and Detector

MiniBooNE [1] is a short baseline neutrino oscillation experiment located at Fermilab. 8 GeV protons impinge on a Be target and produce mesons, which subsequently decay to neutrinos with an average energy of 0.7 GeV. The mesons, primarily π^+, are focused by a magnetic horn, increasing the neutrino flux by about a factor of $\sim$ 6. Reversing the horn current means π^-

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will be focused, and an antineutrino beam can be produced. The neutrinos travel ~ 0.5 km before reaching a 12 m diameter, 800 ton mineral oil tank (CH_2 target). The inner wall of the tank is lined with 1280 photomultiplier tubes (PMTs), optically separated from an outer veto region with 240 PMTs. Events produce prompt Cherenkov light, followed by delayed, isotropic scintillation light. "Subevents" are defined to be a cluster of tank activity in time. For example, an "event" could be a muon neutrino interacting in the tank to produce a muon, and a Michel electron, from the muon's decay. The subevents would, then, be the light from the muon, followed at a later time by light from the Michel electron.

3. The SciBar Detector

The SciBar [4] detector is a fully active, fine grained detector which ran in the K2K beamline from October 2003 to November 2004. The K2K 12 GeV protons struck an Al target, and decay mesons were focused by two horns producing neutrinos at an average energy of 1.3 GeV. The SciBar detector consists of three parts: a fully active scintillator bar and fiber tracker, an electromagnetic calorimeter (EC), and a muon range detector (MRD). CC neutrino interactions were observed in the SciBar detector with 94% efficiency. The SciBar detector is capable of 0.08 GeV muon energy resolution and an angular resolution of 1.6 degrees. Recent SciBar detector analyses include a search for CC coherent pion production [5].

4. Cross Sections at the BNB

4.1. Charge Current Quasi-Elastic events (CCQE)

CCQE events, which are 40% of the total event rate at MiniBooNE, can be reconstructed with $\sim 10\%$ energy resolution at $E_\nu = 1$ GeV. To select these events, we look for two subevents (the muon, and its decay electron). The first subevent must be in time with the beam, and have enough tank PMT hits to be considered a muon (tank hits > 200). The first subevent must also be have less than 6 hits in the veto, ensuring it is contained in the inner detector and eliminating contamination from cosmic ray muons. A Fisher discriminant [6] is used to isolate a sample of CCQE interactions with 10 variables including: fraction of light on and off the observed ring, fraction of prompt (Cherenkov) compared to late (scintillation) light, and whether or not the track is consistent with the energy deposited ("μ-like"). The event selection yields an 86% pure CCQE sample according to the NUANCE MiniBooNE detector Monte Carlo [8], with CCπ^+ as the largest background source. MiniBooNE has currently analyzed approximately 60,000 CCQE events after all cuts.

CCQE events serve as a normalization sample for cross sections measurements; commonly, one takes the ratio of a cross section divided by CCQE, to reduce dependencies on the flux. At MiniBooNE, this sample can also be used to constrain the intrinsic ν_e background from beam muon decay.

The SciBar detector can measure CCQE events with high efficiency. As both the muon and proton tracks are visible in the the SciBar detector, one can isolate CCQE events using QE kinematic constraints on the outgoing proton direction. Additionally, placing another detector on axis will reduce flux errors for MiniBooNE with an independent measurement of the CCQE rate in the BNB.

4.2. Charged Current Single Pion events (CCπ^+)

CCπ^+ is the dominant background to the CCQE events, due to a large cross section and rate (about half of CCQE). It comprises 25% of the total event rate in MiniBooNE. CCπ^+ can help us understand Δ resonance production ($\Delta \to N\gamma$) backgrounds to $\nu_\mu \to \nu_e$ appearance searches as the pion in a CCπ^+ event comes from the decay of a Δ.

CCπ^+ event selection [9] requires 3 subevents (muon and the pion, then the decay electron from the muon, and the decay electron from $\pi^+ \to \mu^+ \to e^+$). The first subevent must be in time with the beam, with greater than 175 tank hits, and veto hits less than 6. The second and third subevents must have tank hits between 20 to 200

hits and less than 6 hits in the veto, to be consistent with Michel electrons.

Though MiniBooNE can't distinguish the charge of the electron and positron directly, it can indirectly. The Michel electron nearest the muon track indicate a different muon lifetime, than the Michel positron far from the muon track, because one is produced from a μ^+ and the other a μ^-. As a μ^- is captured in mineral oil about 8% of the time, its lifetime of 2026 ± 1.5 ns [10] is shorter than that of the μ^+ at 2197 ± 0.04 ns [11].

The CCπ^+ sample is 84% pure according to the NUANCE MiniBooNE detector Monte Carlo, with multi-pion and QE events comprising the dominant backgrounds. Currently, the MiniBooNE sample is 44,000 events, which is 5 times more than the world's dataset. The measurement of the CCπ^+/CCQE cross section[12] is also the world's first measurement at low energies on a nuclear target. Coherent and resonant processes will also be measured as separate results.

T2K estimates they will need to know the CCπ^+ cross section to 5%. With the SciBar detector, one can reconstruct all outgoing tracks and construct the invariant Δ mass, therefore directly constraining Δ production on carbon.

4.3. Neutral Current Single Pion events (NCπ^0)

NCπ^0 is an important background to the oscillation electron neutrino appearance analysis. When a π^0 decays, it produces two photons, and if the photons come out close together, or back to back, then the event can look like a single electron, or a ν_e event. NCπ^0 comprise 7% of the total event rate at MiniBooNE. These events are selected by requiring one subevent, in time with the beam, with greater than 200 tank hits and less than 6 veto hits. The event must have a reconstructed π^0 mass greater than 50 MeV/c^2 and be within a fiducial volume of 500 cm. The π^0 fitter assumes a two ring structure; the rings must have an energy greater than 40 MeV each. The "opening angle" must not be too small or large, that is, the cosine of the angle between the two gammas must be between -0.9 and 0.9. The resulting sample is 55% pure, and if one plots the reconstructed invariant mass, one sees a peak right around the π^0 mass (140 MeV/c^2). One can extract the contribution from π^0 production from this mass peak [13]. The MiniBooNE NCπ^0 sample is also the largest sample to date, at 7,000 events. It will be used to study the cohererent/resonant NCπ^0 ratio.

NCπ^0 is an important background for any ν_e oscillation searches as mentioned in the previous paragraph, and therefore is important for T2K. The SciBar detector, however, can distinguish the two photons from a single electron track, and can identify pions at high momentum, exactly those which are mis-identified as electrons. Although K2K has published a NCπ^0 measurement [14], it is at a higher energy. Placed in the BNB, at a different energy, a second NCπ^0 measurement can help map out the energy dependence of the cross section, at exactly the energies where the cross section is predicted to be changing significantly.

4.4. Antineutrino Cross Sections

MiniBooNE is scheduled to run with antineutrinos with the new year [15], and again SciBooNE could supplement or make otherwise inaccessible measurements with antineutrinos. Currently, few antineutrino cross sections exist in the few GeV range, all with low statistics. Additionally, an antineutrino beam has a significant neutrino contamination (approximately 30% in the BNB). The SciBar detector can observe proton tracks, and therefore can distinguish between $\nu + n \rightarrow \mu^- + p$ and $\overline{\nu} + p \rightarrow \mu^+ + n$ (1 vs 2 track events). SciBooNE can make any of the previous three measurements (CCQE, CCπ^+ and NCπ^0) in antineutrino mode in conjunction with MiniBooNE. As CCπ^+ cannot occur with antineutrinos, a measurement of CCπ^+ constrains the wrong sign background. The exclusive measurement of $\overline{\nu} + p \rightarrow \overline{\nu} + p + \pi^0$ can also be observed in SciBooNE, at the 25% uncertainty level. This would be the first of its kind in the 1 GeV energy range. As T2K plans to run in antineutrino mode, these measurements will be key to understanding signal and background rates in oscillation searches.

5. Conclusion

Large leaps are being made in the low energy region of neutrino cross sections. The combination of intense neutrino beams and fine grain detectors produces unprecedented precision in the near term experiments in this energy region. In the short term, MiniBooNE and K2K have already begun to produce results, such as the $CC\pi^+/CCQE$ cross section ratio and search for CC coherent pion production. The addition of the SciBar detector to the Fermilab BNB offers the potential to perform better or first-time measurements. These measurements are in the energy range useful to a future long baseline experiments, such as T2K, and complement cross sections measurements made at higher energies by MINERνA [16].

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