Single Pion Production in Low Energy ν-Carbon Interactions

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The MiniBooNE experiment will record a large number of neutrino interactions where single pions are produced. While significant amounts of data exist at MiniBooNE energies for the charged current single pion production channels, there exists very little data for the corresponding neutral current channels. The Gargamelle collaboration is one experiment that has published neutral current pion production event rates. Presented here is a simple re-analysis of Gargamelle results in order to extract absolute cross sections.

1. MiniBooNE

MiniBooNE is a neutrino oscillation experiment at the Fermi National Accelerator Laboratory looking for the appearance of an excess of electron neutrinos in a beam of primarily muon neutrinos. MiniBooNE uses the 8 GeV proton beam from the Fermilab Booster, a beryllium target, a pulsed toroidal field magnet (a horn) and a 50 meter decay region to form a neutrino beam with an average neutrino energy of about 1 GeV. The MiniBooNE detector is located 540 meters downstream of the target. The detector is a 12.2 meter diameter steel sphere filled with pure mineral oil as a neutrino target with a fiducial mass of 445 tons. The detector is instrumented with 1520 photomultiplier tubes, 240 of which are in a 35 cm thick veto region that surrounds the fiducial region of the detector.

2. Single Pion Production

A large number of different types of neutrino interactions will occur in the MiniBooNE detector, as illustrated in Fig. 1. One kind of neutrino interaction that MiniBooNE is especially interested in is neutral current single π^0 production, shown in Eqs. 1 and 3. These kinds of events are sometimes able to mimic electron neutrino charge current quasi-elastic events, which is the channel MiniBooNE will use to look for ν_μ to ν_e oscillations. MiniBooNE will need to understand this background in order to properly search for an oscillation signal in their data.

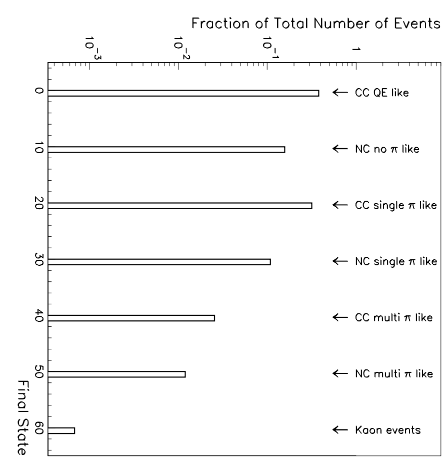

Figure 1. Relative event rates seen in MiniBooNE as predicted by NUANCE using the MiniBooNE neutrino beam Monte Carlo as input. Events are classified by what types of particles are observed in the final state.

An important tool used to better understand processes, such as neutral current π^0 production, is Monte Carlo simulation. To simulate neutrino interactions and the nuclear effects expected in mineral oil, the MiniBooNE collaboration is currently using the NUANCE software package [1] developed by Prof. Dave Casper at the University of California at Irvine.

This software package uses a model developed by Rein and Sehgal [2] to simulate resonant single pion production off free nucleons. NUANCE has additional code to simulate Pauli blocking, Fermi motion, and final state interactions, all three of which are important when simulating neutrino scattering off nuclear targets such as carbon in mineral oil.

As other talks at this conference have shown, there is fair agreement between the Rein and Seghal model and neutrino data for the charged current single pion production channels. Unfortunately very little data exists for the four neutral current single pion production channels

$$\nu_\mu\, p \quad \rightarrow \quad \nu_\mu\, p\, \pi^0 \qquad (1)$$

$$\nu_\mu\, p \quad \rightarrow \quad \nu_\mu\, n\, \pi^+ \qquad (2)$$

$$\nu_\mu\, n \quad \rightarrow \quad \nu_\mu\, n\, \pi^0 \qquad (3)$$

$$\nu_\mu\, n \quad \rightarrow \quad \nu_\mu\, p\, \pi^- \qquad (4)$$

In addition, most of the available experimental data on these pion production channels exists in the form of neutral current to charged current cross section ratios instead of absolute cross sections. While these ratios can be used to verify Monte Carlo simulations to some degree, it would be much more useful to compare to Monte Carlo predictions to absolute cross section results.

3. Gargamelle

One set of published data not in the form of cross section ratios is from an experiment at CERN in the mid 1970s using the Gargamelle bubble chamber [3,4]. In this experiment, the Gargamelle bubble chamber contained mostly propane (C_2H_8) along with 10% (molar) heavy freon (CF_3Br). This type of target is ideal for comparisons with MiniBooNE, since the nuclear effects seen in propane should be very similar to the nuclear effects in the mineral oil used for the MiniBooNE detector.

Reference [3] reports on an analysis of the neutral current events that produced a single pion (plus the $\nu_\mu n \rightarrow \mu^- p \pi^0$ channel) in the Gargamelle bubble chamber. This analysis begins with the number of observed events in each channel and then makes corrections for backgrounds and reconstruction efficiencies to give a "Final Corrected Sample" number of events in each of the four neutral current channels (and the single charged current channel) shown in Table 1. Note that these results are off of the propane-freon target mixture so nuclear effects are inherent in these results.

It is believed that the authors did not calculate absolute cross sections because they had not yet calculated the neutrino flux. A slightly later paper [4], cites paper [3] as being the same experiment, but now quotes a total neutrino flux of $4.6 \pm 0.4 \times 10^{15} \nu/\mathrm{m}^2$ and has a plot of neutrino flux as a function of energy.

Absolute raw cross sections per nucleon were calculated for the five channels listed. These raw cross sections have nuclear effects inherent in them, the most important of which are probably the final state interactions between pions and the target nucleus. These raw cross sections were calculated by simply taking the "Final Corrected Sample" number of events in each channel and dividing by the neutrino flux from reference [4] and the number of neutrons (or protons depending on the channel) in the fiducial region. These results are shown in Table 1. Since carbon was a major component of the Gargamelle target, these raw cross sections could be a good indication of what should be seen in MiniBooNE.

Table 1
Single pion production channels. Shown are the results which have inherent nuclear effects.

channel	Final Corrected Sample	raw cross section per nucleon $\times 10^{-38}$ cm^2
$\nu_\mu p \rightarrow \nu_\mu p \pi^0$	248.0 ± 28.5	0.100 ± 0.014
$\nu_\mu n \rightarrow \nu_\mu n \pi^0$	99.2 ± 21.9	0.050 ± 0.012
$\nu_\mu p \rightarrow \nu_\mu n \pi^+$	140.9 ± 23.0	0.056 ± 0.011
$\nu_\mu n \rightarrow \nu_\mu p \pi^-$	134.0 ± 33.0	0.067 ± 0.017
$\nu_\mu n \rightarrow \mu^- p \pi^0$	272.3 ± 33.8	0.136 ± 0.020

The experimental values are from ref. [3].

Further calculations were done in reference [3] to remove the nuclear effects from the "Final Corrected Sample" results. This resulted in a "cross section in arbitrary units" for each channel, as shown in Table 3. As defined in reference [3], these results are related to the absolute cross sections off free nucleons (σ_{free}) by

$$N = \alpha \sum_i w_i \frac{1}{2} \sigma_{free} \qquad (5)$$

where N is the "cross section in arbitrary units", w_i are the weight fractions of each type of nucleus in the Gargamelle target mixture, and α is a normalization that is dependent on neutrino flux and total number of nucleons in the target. When the neutrino flux from reference [4] is used to determine α, then an absolute cross section off free nucleons (σ_{free}) can be computed for each channel. These free nucleon cross section results are shown in Table 2.

Table 2
Single pion production channels. Shown are the results corrected for nuclear effects.

channel	cross section in arbitrary units	cross section per free nucleon $\times 10^{-38}$ cm^2
$\nu_\mu p \to \nu_\mu p \pi^0$	297 ± 37	0.13 ± 0.02
$\nu_\mu n \to \nu_\mu n \pi^0$	177 ± 43	0.08 ± 0.02
$\nu_\mu p \to \nu_\mu n \pi^+$	180 ± 31	0.08 ± 0.02
$\nu_\mu n \to \nu_\mu p \pi^-$	237 ± 59	0.11 ± 0.03
$\nu_\mu n \to \mu^- p \pi^0$	526 ± 65	0.24 ± 0.04

The experimental values are from ref. [3].

4. Comparisons with NUANCE

The calculated results for both the free nucleon cross sections and the raw cross sections can be compared to predictions from NUANCE. In these comparisons the new results shown in Tables 1 and 2 will be plotted at an energy of 2.2 GeV. This energy was determined by calculating the flux weighted average cross section, and then finding the energy where the cross section has that average value. These calculations were done using cross sections from NUANCE and the Gargamelle neutrino flux from reference [4].

In Figs. 2 to 6, the top Gargamelle point is the cross section per free nucleon while the bottom Gargamelle point is the raw cross section per nucleon with inherent nuclear effects. The two points are slightly offset from 2.2 GeV so that the full error bars can be seen. The solid curves in Figs. 2 to 6 are the free nucleon cross sections computed by NUANCE. The dashed curve in Fig. 2 is the per nucleon cross section for a carbon target, where Pauli blocking and Fermi motion effects were included in the calculation, but final state interactions were not included.

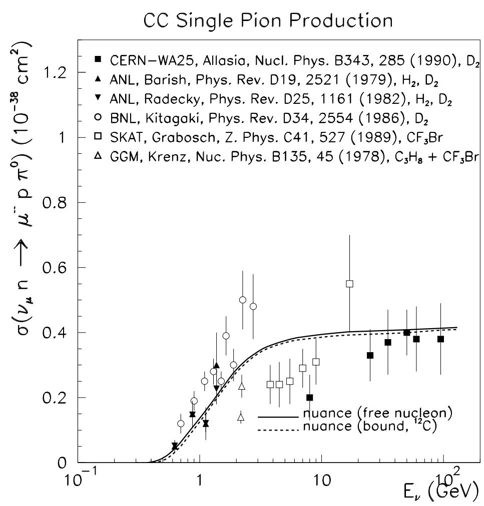

Figure 2. Charged current π^0 production off neutrons. The upper Gargamelle (open triangle) point is the cross section per free nucleon while the lower point is the raw cross section per nucleon with nuclear effects inherent. The solid and dashed curves are the NUANCE predictions for the free and bound nucleon cross sections respectively.

The free nucleon cross sections calculated from the Gargamelle data seem to be in good agreement with the NUANCE predictions with the exception of the $\nu_\mu\, n \to \nu_\mu\, n\, \pi^0$ channel, which is a challenging final state to detect. The raw cross

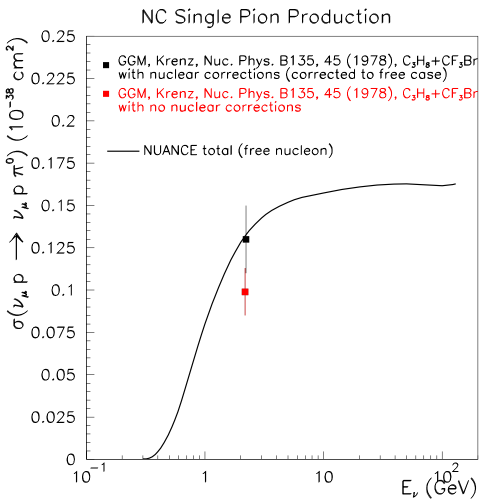

Figure 3. Neutral current π^0 production off protons. The top point is the cross section per free nucleon while the bottom point is the raw cross section per nucleon with nuclear effects folded in. The solid curve is the NUANCE prediction for the free nucleon cross section.

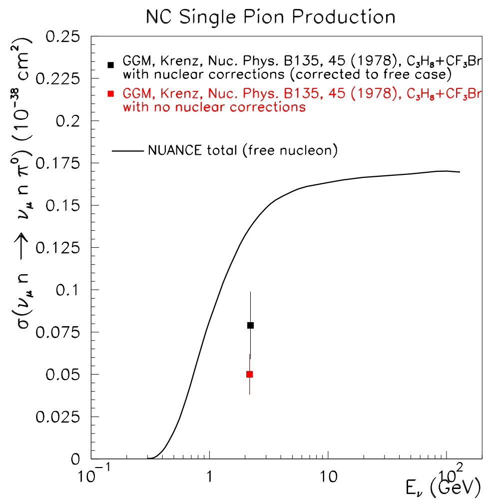

Figure 4. Neutral current π^0 production off neutrons. The top point is the cross section per free nucleon while the bottom point is the raw cross section per nucleon with nuclear effects folded in. The solid curve is the NUANCE prediction for the free nucleon cross section.

section per nucleon results are below the NUANCE predictions as expected since nuclear effects are expected reduce these cross sections.

For each event it generates, the NUANCE code outputs both the initial neutrino interaction channel (i.e. NUANCE channel 1 are charged current quasi-elastic events), and a list of final state particles that exited the target nucleus. To calculate a cross section that includes final state interaction effects, events are classified by what types of particles are observed in the final state. For instance, if NUANCE produces a charged current π^+ event, but the pion is absorbed before it leaves the nucleus, then the event is classified as a charged current quasi-elastic event.

In Figs. 7 to 11 the raw cross sections per nucleon listed in Table 1 are plotted along with cross section curves computed using NUANCE with a CH_2 (mineral oil) target. The curves labeled "no nuclear corrections" have Pauli blocking and Fermi motion effects included in the calculation, but not final state interaction effects. The curves labeled "only channels.lt.10" and "all channels" have Pauli blocking, Fermi motion, and final state interaction effects included in the calculation. For the "only channels.lt.10" curves, only events with a NUANCE initial interaction channel number less than 10 contribute to the cross sections. These NUANCE channels correspond to charged current quasi-elastic, neutral current elastic, and resonant single pion neutrino interactions. The curves labeled "all channels" can have events from any NUANCE channel contribute to the cross sections, including the DIS and coherent channels.

It is noted that in Figs. 7 to 11 the comparisons between the calculated raw cross sections and the NUANCE predictions are not strictly the correct comparisons to make. The nuclear effects inherent in the NUANCE curves come only from interactions with carbon nuclei, however in the Gargamelle data a significant number of in-

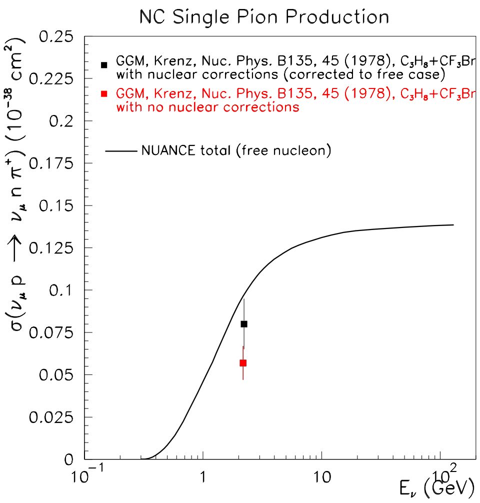

Figure 5. Neutral current π^+ production off protons. The top point is the cross section per free nucleon while the bottom point is the raw cross section per nucleon with nuclear effects folded in. The solid curve is the NUANCE prediction for the free nucleon cross section.

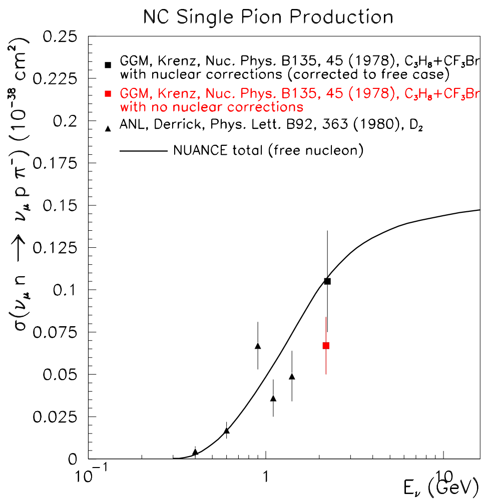

Figure 6. Neutral current π^- production off neutrons. The top square point is the Gargamelle cross section per free nucleon while the bottom square point is the Gargamelle raw cross section per nucleon with nuclear effects folded in. The solid curve is the NUANCE prediction for the free nucleon cross section.

teractions would be with fluorine or bromine nuclei, where the nuclear effects are expected to be larger. Because of this discrepancy the calculated raw cross sections are expected to be lower than the NUANCE predictions, which is what is seen in Figs. 7 to 11.

5. Conclusions

Absolute raw cross sections per nucleon and absolute free nucleon cross sections have been calculated from previously published Gargamelle data. The Rein and Sehgal model, as implemented in NUANCE, has been shown to be in good agreement with the calculated free nucleon results, with the exception of the $\nu_\mu n \to \nu_\mu n \pi^0$ channel which appears to be low by about three standard deviations. More work is needed to make an accurate comparison between the calculated raw cross sections and Monte Carlo predictions. However, the comparisons shown here are encouraging since they show what is qualitatively expected.

6. Acknowledgments

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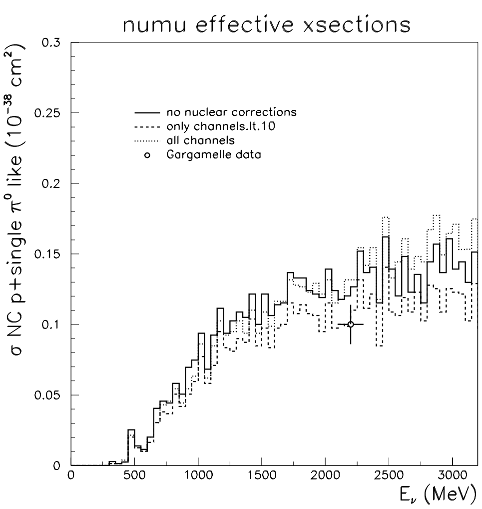

Figure 7. Neutral current π^0 production off protons. The curves shown are NUANCE cross section predictions with (dashed and dotted) and without (solid) final state interaction effects. The data point is the raw cross section result from Table 1.

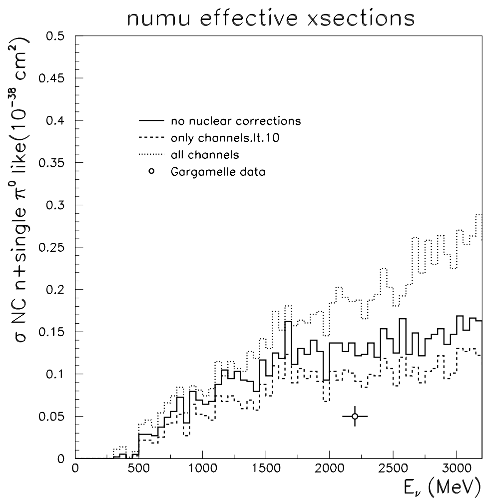

Figure 8. Neutral current π^0 production off neutrons. The curves shown are NUANCE cross section predictions with (dashed and dotted) and without (solid) final state interaction effects. The data point is the raw cross section result from Table 1.

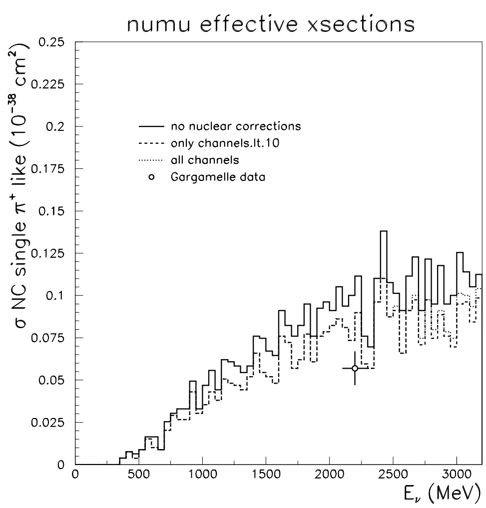

Figure 9. Neutral current π^+ production. The curves shown are NUANCE cross section predictions with (dashed and dotted) and without (solid) final state interaction effects. The data point is the raw cross section result from Table 1.

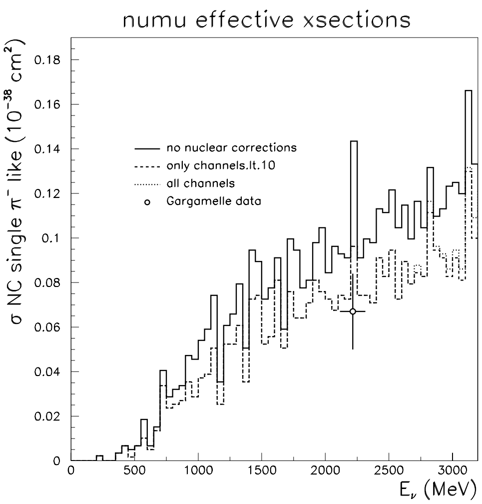

Figure 10. Neutral current π^- production. The curves shown are NUANCE cross section predictions with (dashed and dotted) and without (solid) final state interaction effects. The data point is the raw cross section result from Table 1.

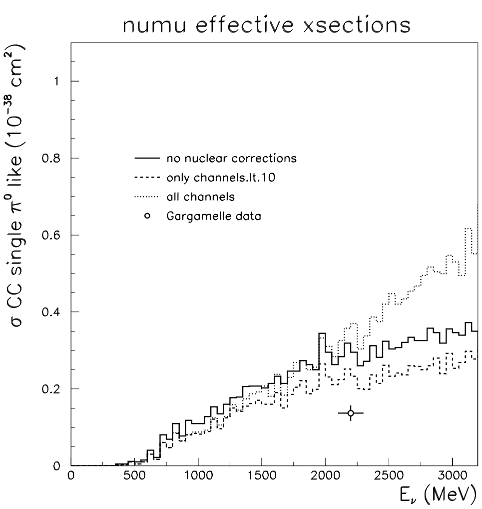

Figure 11. Charged current π^0 production. The curves shown are NUANCE cross section predictions with (dashed and dotted) and without (solid) final state interaction effects. The data point is the raw cross section result from Table 1.