\textbf{\nu-}Nucleus Cross Section at MiniBooNE Energies

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\textbf{Introduction}

Recently, MiniBooNE collaboration has reported the results for the observed cross section ratio \( R(E) \) as a function of neutrino energy for the \( \nu_\mu \) induced reaction in mineral oil \((CH_2)\) \cite{1}. In the energy region of MiniBooNE experiment, the contribution to the cross section mainly comes from the charged current quasielastic lepton production (CCQE) and the charged current incoherent and coherent \( \pi^+ \) (CC1\( \pi^+ \)) production processes and therefore the theoretical study of nuclear effect in the calculation of neutrino nucleus cross section becomes important in the \( \nu_\mu \) induced CCQE as well as CC1\( \pi^+ \) processes. In this work, we have studied the nuclear effect in the neutrino nucleus cross sections in the energy region of around 1 GeV and obtained the ratio \( R \).

\textbf{Formalism}

The basic reaction for the quasielastic process is a neutrino interacting with a neutron inside the nucleus i.e. \( \nu_\mu (k) + n(p) \rightarrow \mu^- (k') + p(p') \). The total cross section \( \sigma(E_{\nu}) \) for the charged current neutrino induced reaction on a nucleus inside the nucleus in a local Fermi gas model is written as \cite{2}:

\[ \sigma_A(E) = \frac{1}{(4\pi)^3} \int_{r_{\min}}^{r_{max}} (r_p(r) + \frac{1}{9} r_n(r)) d\vec{r} \times \int_{Q_{\min}^2}^{Q_{max}^2} \int_{k_{min}'}^{k_{max}'} d\vec{k} d\vec{k}' \int_{-1}^{+1} \cos \theta \int_{0}^{2\pi} d\phi \]

\[ \times \frac{1}{E'_p + E_\pi \left( 1 - \frac{\vec{q} \cdot \vec{k}}{|\vec{k}| \cos \theta} \right) ME^p_{\nu} E_l} \pi |\vec{k}'| \Sigma |f_i|^2 \]

The transition matrix element \( f_i \) is given by \cite{2}

\[ f_i = \sqrt{3} \frac{G_F f_{\pi N} \Delta}{\sqrt{2} m_\pi} \bar{u}(p') k'_\pi^2 \mathcal{P}_{\pi \lambda} \mathcal{O}^{\lambda \mu} L_{\mu} u(p) \tag{3} \]

\( L_\mu \) is the leptonic current, \( \mathcal{O}^{\lambda \mu} \) is the \( N - \Delta \) transition current and \( \mathcal{P}_{\pi \lambda} \) is the \( \Delta \) propagator in momentum space. The pions produced in this process are scattered and absorbed in the nuclear medium. This is treated in a Monte Carlo simulation which has been taken from Ref. \cite{3}.

The \( \nu_\mu \) induced coherent one pion production on \( ^{12}\)C target is given by \( \nu_\mu + ^{12}\)C \( \rightarrow \mu^- + ^{12}\)C + \( \pi^+ \) for which the cross section is given by Eq.(2). However, the matrix element \( f_i \) is now given by

\[ f_i = \frac{G_F}{\sqrt{2}} \cos \theta_e L^\mu j_\mu F(q - \vec{k}) \tag{4} \]

where \( j_\mu \) is the hadronic current given by \cite{4}

\[ j_\mu = \sqrt{\frac{3}{2}} f_{\pi N} \Delta \sum_{r,s} \bar{u}_s(p) k_{\pi\sigma} P^{\sigma\lambda} \mathcal{O}_{\lambda\mu} u_r(p) \tag{5} \]
The one pion production includes contributions from incoherent as well as coherent channels. In the $\nu_\mu$ induced lepton production process to the CCQE process. Our final result for the ratio is the one where charged current one pion production cross section is calculated for $\nu_\mu$ induced reaction on free proton as well as from $^{12}$C nucleus with nuclear medium and final state interaction effect and the quasielastic lepton production cross section for $\nu_\mu$ induced reaction in $^{12}$C nucleus is calculated in the local Fermi gas model with RPA effect and this also includes the quasi-like events coming from the inelastic channel when a pion doesn’t appear in the final state and one only observes a lepton. We find the contribution from the inelastic channel is 20% at $E_\nu=0.65\text{GeV}$, 42% at $E_\nu=0.95\text{GeV}$, 50% at $E_\nu=1.15\text{GeV}$ and 55% at $E_\nu=1.35\text{GeV}$ as compared to the contribution from the quasielastic channel. We compare our numerical results with the FSI corrected experimental observations as reported by the MiniBooNE collaboration [1] and find that the theoretical results for the ratio are in agreement with the experimental observation for $\nu_\mu$ energy region of $E_{\nu_\mu}<1.2$ GeV. Similarly for $E_{\nu_\mu}<1.2$ GeV when the results for the ratio $R(E)$ as obtained in our model with nuclear medium effect is compared with the experimentally observed results reported by the MiniBooNE collaboration they are found to be in agreement. Thus, we find that the nuclear medium effect plays an important role in both the CCQE and inelastic processes considered here in obtaining the ratio $R(E)$. 

**Results**

We have plotted in Fig.(1) the ratio $R(E) = \frac{\sigma_{CC1\pi^+}}{\sigma_{CCQE}(E)}$ of the cross sections for $\nu_\mu$ induced $CC1\pi^+$ process to the CCQE process. The one pion production includes contributions from incoherent as well as coherent channels. In the $\nu_\mu$ induced lepton production in $^{12}$C when the cross section for the pion production process is calculated without nuclear medium effect and the cross section for quasielastic lepton production process is calculated in the local Fermi gas model (FGM) without RPA effect the contribution from the inelastic channel is 30% at $E_\nu=0.65\text{GeV}$, 65% at $E_\nu=0.95\text{GeV}$, 78% at $E_\nu=1.15\text{GeV}$ and 86% at $E_\nu=1.35\text{GeV}$ in comparison to the contribution of the lepton events from charged current quasielastic process. Our final result for the ratio is the one where charged current one pion production cross section is calculated for $\nu_\mu$ induced reaction on free proton as well as from $^{12}$C nucleus with nuclear medium and final state interaction effect and the quasielastic lepton production cross section for $\nu_\mu$ induced reaction in $^{12}$C nucleus is calculated in the local Fermi gas model with RPA effect and this also includes the quasi-like events coming from the inelastic channel when a pion doesn’t appear in the final state and one only observes a lepton. We find the contribution from the inelastic channel is 20% at $E_\nu=0.65\text{GeV}$, 42% at $E_\nu=0.95\text{GeV}$, 50% at $E_\nu=1.15\text{GeV}$ and 55% at $E_\nu=1.35\text{GeV}$ as compared to the contribution from the quasielastic channel. We compare our numerical results with the FSI corrected experimental observations as reported by the MiniBooNE collaboration [1] and find that the theoretical results for the ratio are in agreement with the experimental observation for $\nu_\mu$ energy region of $E_{\nu_\mu}<1.2$ GeV. Similarly for $E_{\nu_\mu}<1.2$ GeV when the results for the ratio $R(E)$ as obtained in our model with nuclear medium effect is compared with the experimentally observed results reported by the MiniBooNE collaboration they are found to be in agreement. Thus, we find that the nuclear medium effect plays an important role in both the CCQE and inelastic processes considered here in obtaining the ratio $R(E)$.

**References**