ν-Nucleus Cross Section at MiniBooNE Energies

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Introduction

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

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 nucleon inside the nucleus in a local Fermi gas model is written as [2]:

$$\sigma_A(E) = -\frac{{G_F}^2\cos^2\theta_c}{2\pi^2}\int_{r_{min}}^{r_{max}} d\mathbf{r}\int_{k'_{min}}^{k'_{max}} {k'}^2 dk' \times \int_{-1}^{1} dcos\theta\frac{1}{E_{\nu_\mu}E_\mu}L_{\mu\nu}J^{\mu\nu}_{RPA}ImU_N(q_0,\mathbf{q}) \quad (1)$$

where $L_{\mu\nu}$ is the leptonic tensor and $J^{\mu\nu}_{RPA}$ is the hadronic tensor obtained with RPA correlations in nuclei [2]. q is the four momentum transfer, M is nucleon's mass, G_F is the Fermi coupling constant, θ_c is the Cabbibo angle and U_N is the Lindhard function for the particle hole excitation.

The basic reaction for the inelastic pion production in nuclei, for a neutrino interacting with a nucleon N inside a nuclear target is given by $\nu_\mu(k) + N(p) \rightarrow \mu^-(k') + N'(p') + \pi^+(k_\pi)$, where N/$N'$ = n, p. In the local density approximation the expression for the total cross section for the charged current one pion production is written as [2]:

$$\sigma_A(E) = \frac{1}{(4\pi)^5}\int_{r_{min}}^{r_{max}}(\rho_p(r) + \frac{1}{9}\rho_n(r))d\vec{r} \times \int_{Q^2_{min}}^{Q^2_{max}} dQ^2 \int_{k'_{min}}^{k'_{max}} dk' \int_{-1}^{+1} dcos\theta_\pi \int_0^{2\pi} d\phi_\pi \times \frac{1}{E'_p + E_\pi\left(1 - \frac{|\vec{q}|}{|\vec{k_\pi}|}cos\theta_\pi\right)}\frac{\pi|\vec{k}'||\vec{k}_\pi|}{ME^2_\nu E_l}\bar{\Sigma}\Sigma|\mathcal{M}_{fi}|^2 \quad (2)$$

The transition matrix element $\mathcal{M}_{fi}$ is given by [2]

$$\mathcal{M}_{fi} = \sqrt{3}\frac{G_F}{\sqrt{2}}\frac{f_{\pi N\Delta}}{m_\pi}\bar{u}(\mathbf{p}')k^\sigma_\pi\mathcal{P}_{\sigma\lambda}\mathcal{O}^{\lambda\mu}L_\mu u(\mathbf{p}) \quad (3)$$

L_μ is the leptonic current, $\mathcal{O}^{\lambda\mu}$ is the $N-\Delta$ transition current and $\mathcal{P}_{\sigma\lambda}$ is the Δ 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. [3].

The ν_μ induced coherent one pion production on ^{12}C target is given by $\nu_\mu +^{12}_6 C \rightarrow \mu^- +^{12}_6 C + \pi^+$ for which the cross section is given by Eq.(2). However, the matrix element $\mathcal{M}_{fi}$ is now given by

$$\mathcal{M}_{fi} = \frac{G_F}{\sqrt{2}}cos\theta_c L^\mu J_\mu \mathcal{F}(\vec{q} - \vec{k}_\pi) \quad (4)$$

where J_μ is the hadronic current given by [4]

$$J_\mu = \sqrt{3}\frac{f_{\pi N\Delta}}{m_\pi}\sum_{r,s}\bar{u}_s(p)k_{\pi\sigma}\mathcal{P}^{\sigma\lambda}\mathcal{O}_{\lambda\mu}u_r(p) \quad (5)$$

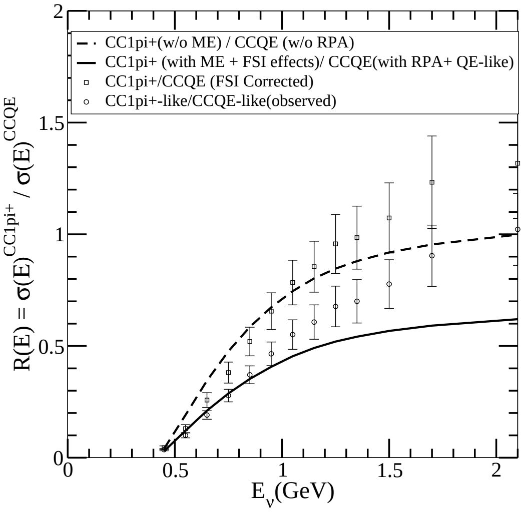

FIG. 1: Ratio R(E) for ν_μ induced reaction in mineral oil. Squares shows the FSI corrected experimental points and circle denotes the ratio of the cross sections for the observed events of $CC1\pi^+$-like/CCQE-like process in the MiniBooNE experiment [1].

$\mathcal{F}(\vec{q}-\vec{k}_\pi)$ is the nuclear form factor which is in the Eikonal approximation given by [4]:

$$\tilde{\mathcal{F}}(\vec{q}-\vec{k}_\pi) = 2\pi \int_0^\infty b\, db \int_{-\infty}^\infty dz\, \rho(\vec{b},z) \times J_0(k_\pi^t b) e^{i(|\vec{q}|-k_\pi^l)z} e^{-if(\vec{b},z)} \quad (6)$$

where $f(\vec{b},z) = \int_z^\infty \frac{1}{2|\vec{k}_\pi|}\Pi(\rho(\vec{b},z'))dz'$, $k_\pi^l(k_\pi^t)$ is the longitudinal(transverse) component of the pion momentum and Π is the self-energy of pion [5].

Results

We have plotted in Fig.(1) the ratio $R(E) = \frac{\sigma^{CC1\pi^+}(E)}{\sigma^{CCQE}(E)}$ of the cross sections for ν_μ induced $CC1\pi^+$ process to the CCQE process. The one pion production includes contributions from incoherent as well as coherent channels. In the ν_μ 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_ν=0.65GeV, 65% at E_ν=0.95GeV, 78% at E_ν=1.15GeV and 86% at E_ν=1.35GeV 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 ν_μ 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 ν_μ 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_ν=0.65GeV, 42% at E_ν=0.95GeV, 50% at E_ν=1.15GeV and 55% at E_ν=1.35GeV 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 ν_μ energy region of E_{ν_μ} <1.2 GeV. Similarly for E_{ν_μ} <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

[1] A. A. Aguilar-Arevalo et al., arXiv:hep-ex/0904.3159 (2009).

[2] M. Sajjad Athar, S. Chauhan and S. K. Singh, arXiv:nucl-th/0908.1443 (2009).

[3] M. J. Vicente Vacas et al., arXiv:nucl-th/9412023 (1994).

[4] S. K. Singh, M. Sajjad Athar and S. Ahmad, Phys. Rev. Lett. **96**, 241807 (2006).

[5] E. Oset and L. L. Salcedo, Nucl. Phys. **A 468**, 631 (1987); C. Garcia Recio et al., Nucl. Phys. **A 526**, 685 (1991).