# Neutrino-nucleus scattering in the QE and $\Delta(1232)$ peak regions

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**Abstract.** Reliable estimates of neutrino-nucleus reactions in the resonance region play an important role in the on-going and planned neutrino oscillation experiments. We report on our recent analysis on the neutrino-nucleus reaction in the delta excitation region with the use of neutrino pion production amplitudes calculated in a dynamical model of electroweak pion production reactions.

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## INTRODUCTION

It is well recognized that the precise knowledge of neutrino nucleus reaction cross section is of importance in analyzing neutrino oscillation experiments. In particular neutrino reaction around incident neutrino energies around 1GeV play a prominent role in many case. To obtain estimates of the relevant cross sections, one must at present rely on theory and much theoretical efforts has been invested to provide estimation of neutrino nucleus cross section. In the neutrino nucleus reaction around 1GeV, the main reaction mechanism is expected to be quasi-elastic scattering and pion production process. For quasi-elastic scattering the relevant transition operator are known and the main theoretical issue is how to incorporate the various nuclear effects. As for the pion production process in addition to the nuclear effects the transition operator for the pion production process needed to be carefully studied. In this paper, we report on our dynamical model of the weak pion production reaction and the application of the model for the quasi-elastic and the delta production region and also the coherent pion production reactions.

## DYNAMICAL MODEL OF PION PRODUCTION REACTION

We start from the effective Hamiltonian of pion-nucleon system with the pion,the nucleon and the delta resonance degrees of freedom.

$$H = H_0 + \Gamma_{JN\to\Delta} + \Gamma_{\pi N\to\Delta} + v_{\pi N,\pi N} + v_{\pi N,JN} + h.c., \quad (1)$$

where $H_0$ is the free Hamiltonian,$v$ represent the non-resonant pion-nucleon and the non-resonant weak pion production interactions, while $\Gamma$ is responsible for the creation and destruction of bare delta resonance. The non-resonant interactions are derived from the meson exchange model and consistent with those from the nonlinear chiral effective Lagrangian. By solving the Lippmann-Schwinger equation based on the above effective Hamiltonian,we obtain the weak pion production amplitude as

$$T_{\pi,J} = t_{\pi,J} + \frac{\bar{\Gamma}_{\Delta\to\pi N}\bar{\Gamma}_{JN\to\Delta}}{E - m_\Delta^0 - \Sigma(E)}. \quad (2)$$

The first term $t_{\pi J}$ is the non-resonant amplitude arising from the interaction $v$, while the second term represents the resonant amplitude involving the dressed vertex $\bar{\Gamma}$.

The parameters of the model for the strong interaction are determined by analysing the pion-nucleon scattering. Then the bare parameters of $\gamma^* N\Delta$ vertex is determined by analysing the extensive data of pion photo and electroproduction reactions. The axial vector $N\Delta$ transition form factor is parametrized as

$$g_A^*(Q^2) = g_A^*(0)R(Q^2)F_D(Q^2), \quad (3)$$

where $F_D(Q^2) = 1/(1+Q^2/M_A^2)^2$ is the axial vector form factor of nucleon with $M_A = 1.02GeV$, $R(Q^2) = (1+aQ^2)e^{-bQ^2}$, which is determined from the analysis of the pion electroproduction reaction and $g_A(Q_0^2) = \sqrt{72/25}g_A(0)$ using SU(6) quark model with $g_A(0) = 1.26$. Further detailed description of the model is given in Ref. [1] for the charged current and in Ref. [2] for the neutral current reaction.

The role of the non-resonant mechanism is significant for the neutrino-nucleon reaction. The energy spectrum of $\nu_e + N \to e^- + \pi + N$ reaction with $E_e = 1GeV$ is shown in Fig. 1, where the full result is shown in the solid curve and the contribution of only the resonant amplitude is shown in dashed curves in Fig. 1.

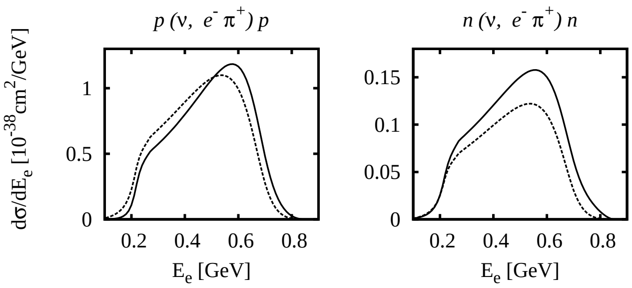


**FIGURE 1.** Neutrino induced pion production reaction

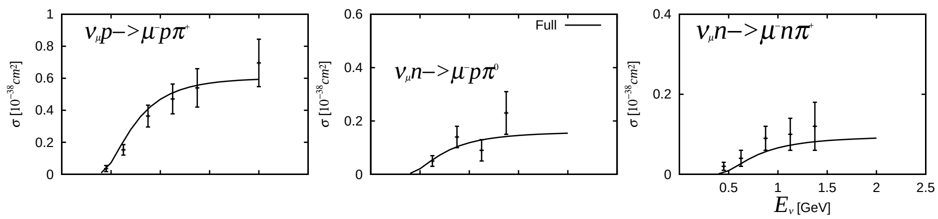


**FIGURE 2.** Total cross sections of $N(\nu_\mu,\mu^-\pi)N$ reactions predicted by the dynamical model.

The prediction of the total cross sections are compared with the data in Fig. 2, which agree reasonably well with the data for three pion channels.

The theoretical model of weak pion production, in particular axial vector $N\Delta$ transition form factor $g_A^*$, cannot be well constrained from the available experimental data of neutrino-nucleon cross sections. One possible opportunity to determine $g_A^*$ is the parity violating asymmetry $A$ of $N(\vec{e},e')$ reaction[2]. The asymmetry is given as

$$\begin{aligned} A &= \frac{d\sigma(h_e=+1)-d\sigma(h_e=-1)}{d\sigma(h_e=+1)+d\sigma(h_e=-1)} \\ &= -\frac{Q^2G_F}{\sqrt{2}4\pi\alpha}[2-4\sin^2\theta_W+\Delta_V+\Delta_A]. \end{aligned} \quad (4)$$

To demonstrate how the asymmetry depends on the axial $N\Delta$ form factor, $Q^2$ dependence of $\Delta_A$ at $W=1.232MeV$ and the scattering angle $\theta=110^o$ is shown in Fig. 3. The non-resonant contribution (dotted curve) is very small and the full results(solid curve) is dominated by the contribution of $g_A^*$.

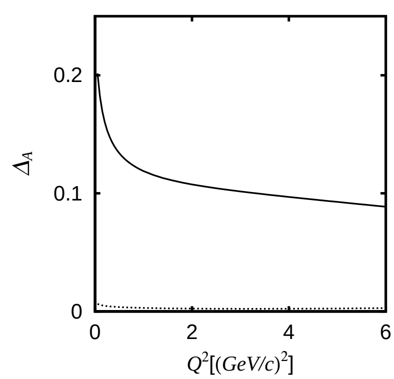


**FIGURE 3.** Parity violating asymmetry term $\Delta_A$

## QE NEUTRINO SCATTERING

We consider the charge-current neutrino nucleus reaction $\nu(p_\nu)+i(P_i)\to l(p_l)+f(P_f)$. The cross section formula for this reaction is given as

$$\frac{d\sigma}{dE_l d\Omega_i} = \frac{p_l}{p_\nu}\frac{G_F^2\cos\theta_c^2}{8\pi^2}L_{\mu\nu}W^{\mu\nu} \quad (5)$$

where $L_{\mu\nu}$ is the lepton tensor. The hadron tensor $W_{\mu\nu}$ is given as

$$\begin{aligned} W^{\mu\nu} &= \sum_{i,f}(2\pi)^3\delta^4(P_f+p_l-P_i-p_\nu) \\ &\times \ < f|J^\mu|i >< f|J^\nu|i >^* . \end{aligned} \quad (6)$$

The hadron tensor is calculated for the single pion production process and the quasi-free nucleon knockout process[3].

The nuclear correlation for the initial state is taken into account by using the spectral function $P(\vec{p},E)$ obtained in Ref. [4] and the Pauli Blocking of the final outgoing nucleon is approximately included with the factor

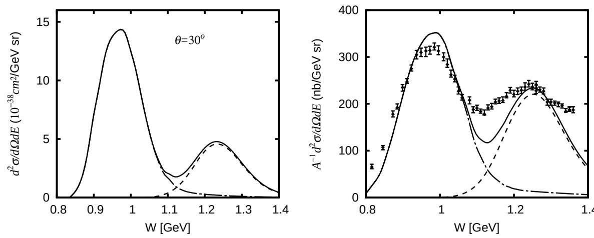


**FIGURE 4.** The differential cross section for the $\nu_e^{12}C \rightarrow e^- + X$ reaction at $E_\nu = 1$GeV and $\theta = 30^o$(left panel) and $e^- + ^{12}C \rightarrow e^- + X$ at $E_e = 1.1$GeV with $\theta_E = 37.5^o$(right panel).

$\theta(|\vec{p}' - p_F)$. The weak pion production amplitude in the Laboratory frame is calculated from the Lorentz transformation of the amplitude in the center of mass system of $\pi N$.

The differential cross section for $\nu_e^{12}C \rightarrow e^- + X$ is shown in the left panel in Fig. 4. The bump at lower energy is due to quasi-elastic nucleon knockout, while the higher energy bump is due to the $\Delta$ resonance excitation. To test the validity of our approach, we apply the same calculational framework to the $e^- + ^{12}C \rightarrow e^- + X$ reaction and compare the results with the experimental data. The general trend of the data is reproduced well in particular the magnitude of the cross section in the delta resonance region. However our calculation gives a dip structure that is somewhat too deep. This feature suggests that we need to go beyond the impulse approximation and/or employ more elaborate treatment of nuclear correlation effects.

## COHERENT PION PRODUCTION

We give a brief report of our study on the coherent pion production reaction in the neutrino nucleus scattering[5]. Our approach is based on the combined use of the dynamical model of the weak pion production reaction given in section 2 and the delta-hole model of pion-nucleus reaction to achieve a unified description of the pion nucleus scattering and the coherent pion production reaction. The analysis are carried out for the case of $^{12}C$ target. All the parameters of the model are fixed by analysing both total and elastic differential cross sections of pion $^{12}C$ scattering. The validity of the model is confirmed by comparing our prediction with the data of coherent pion photoproduction.

To compare our predictions with the data, the cross section of the neutrino induced coherent pion production is obtained by averaging over the neutrino flux. The obtained charge current cross section($\bar{\nu}_\mu + ^{12}C \rightarrow \mu^+ + \pi^- + ^{12}C_{gr}$) $\sigma_{ave}^{CC}$ is compared with the report of K2K[6] experiment $\sigma_{K2K}$ as

$$\sigma_{ave}^{CC} = 6.3 \times 10^{-40} cm^2 \quad (7)$$

$$\sigma_{K2K} < 7.7 \times 10^{-40} cm^2. \quad (8)$$

For NC process, our result $\sigma_{ave}^{NC}$ may be compared with Ref. [7]$\sigma_{MiniBooNE}$,

$$\sigma_{ave}^{NC} = 2.8 \times 10^{-40} \quad (9)$$

$$\sigma_{MiniBooNE} = 7.7 \pm 1.6 \pm 3.6 \times 10^{-40} cm^2 \quad (10)$$

Our results are consistent with the empirical values, although the theoretical value of NC cross section is rather smaller than the empirical central value.

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