Effect of second class currents in the few GeV energy region

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Experiments using a few GeV of (anti) neutrino energies are going to reduce the systematics in order to determine precisely the neutrino oscillation parameters. Most of these experiments are using intermediate and heavier nuclear targets. In the few GeV energy region, the contribution to the cross section mainly comes from the quasielastic, one pion production and deep inelastic scattering processes. To observe the CP violation in the leptonic sector, appreence experiments are being planned which will be looking for $\nu_e \leftrightarrow \nu_\mu$ or $\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$ oscillations. Specially, in the energy region of $E_{\nu/\bar{\nu}} < 1$ GeV, the quasielastic process dominates. Charged current quasielastic(CCQE) scattering process is also important beacuse it allows to deduce the energy of incoming neutrino by observing the charged lepton in the final state.

When (anti)neutrino interacts with a nucleon target, the basic reaction for the charged current quasielastic process is given by: $\nu_l(\bar{\nu}_l) + N \to l^-(l^+) + N'$; $N,\ N' = n,\ p$ and the general expression of the differential scattering cross section is given by

$$d\sigma = \frac{(2\pi)^4 \delta^4(k+p-p'-k')}{4(ME_\nu)} \frac{d^3\vec{k}'}{(2\pi)^3 2E_l} \times \frac{d^3\vec{p}'}{(2\pi)^3 2E_p} \bar{\Sigma}\Sigma|\mathcal{M}|^2, \quad (1)$$

where k, p are the four momenta of initial state particles and k', p' are the four momenta of final state particles, respectively, and $|\mathcal{M}|^2$ is the matrix element square which is given by

$$|\mathcal{M}|^2 = \frac{G_F^2\ cos^2\theta_c}{2} L_{\mu\nu}\ J^{\mu\nu}, \quad (2)$$

where $L_{\mu\nu}(= l_\mu l_\nu^\dagger)$ is the leptonic tensor and $J^{\mu\nu}(= j^\mu j^{\nu\dagger})$ is the hadronic tensor. The leptonic current has V-A form $l_\mu = \bar{u}(k')\gamma_\mu(1 \mp \gamma_5)u(k)$, where $\mp$ sign is for neutrino and antineutrino respectively. The current at the hadronic vertex is given as

$$j^\mu = \bar{u}(p') \Big[F_1^V(Q^2)\gamma^\mu + F_2^V(Q^2) i\sigma^{\mu\nu}\frac{q_\nu}{2M} + F_3^V(Q^2)\frac{q^\mu}{M} + F_A(Q^2)\gamma^\mu\gamma^5 + F_P(Q^2)\frac{q^\mu}{M}\gamma^5 + F_3^A(Q^2)\frac{(p+p')^\mu}{M}\gamma^5 \Big] u(p),$$

where $F_i^V(Q^2);\ i = 1,2,3$ are related to vector current and $F_A(Q^2)$, $F_P(Q^2)$ and $F_3^A(Q^2)$ are associated with axial current. The vector form factors associated with the first class currents are taken from Bradford et al. [1]. Dipole form has been used for the axial form factor $F_A(Q^2)$ and the pseudoscalar form factor $F_P(Q^2)$, is obtained by using Goldberger-Treimann relation [2]. The form factors $F_3^V(Q^2)$ and $F_3^A(Q^2)$ are associated with second class currents(SCC). In the Monte Carlo event generators, the contribution of SCC are not included. However, in the precision era, there is need to understand the contribution of SCC in the lepton event rates. There are uncertainties associated with the SCC form factors and different parameterizations for $F_3^V(Q^2)$ and $F_3^A(Q^2)$ are available in literature. For numerical calculations we have used the following forms for $F_3^V(Q^2)$

$$F_3^V(Q^2) = 4.4\ F_1^V(Q^2)\ [3] \quad (3)$$

Another expression for $F_3^V(Q^2)$ as given in Ref. [4] is

$$F_3^V(Q^2) = \frac{F_3^V(0)}{\left(1 + \frac{Q^2}{M_3^{V2}}\right)^2}. \quad (4)$$

To observe the maximum effect of second class vector current we have taken $F_3^V(0) = 1.6$ and $M_3^V = 1\ GeV$ [4] in our numerical calculations.

The axial form factor associated with the second class current $F_3^A(Q^2)$, is taken as [3, 4]

$$F_3^A(Q^2) = 0.15\ F_A(Q^2), \quad (5)$$

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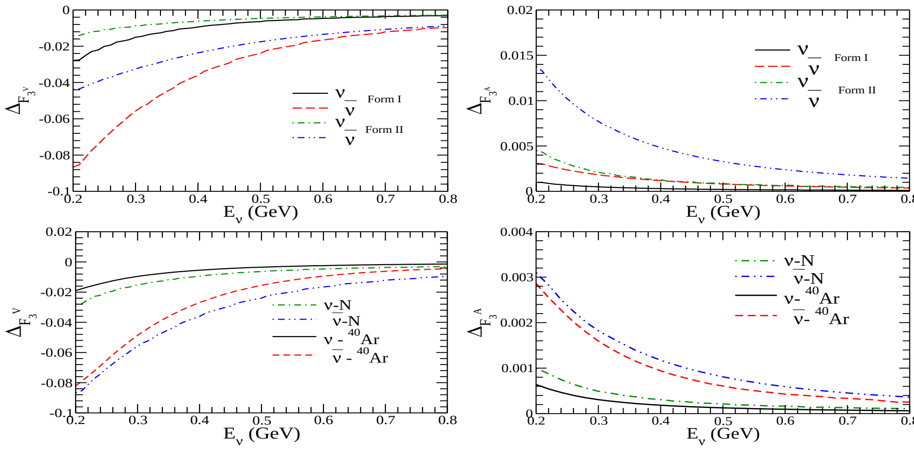

FIG. 1: Results of $\Delta_{F_3^V(Q^2)}$, $\Delta_{F_3^A(Q^2)}$ for $\nu_l/\bar{\nu}_l$ CCQE process, **Top panel:** with form-I(Eqs.3, 5) and form-II(Eqs.3, 6) for free nucleon. **Bottom panel:** on free nucleon and nuclear target ^{40}Ar.

and another form is given by

$$F_3^A(Q^2) = \frac{0.78 \times F_A(0)}{\left(1 + \frac{Q^2}{M_D^2}\right)^2} \quad (6)$$

with axial charge $F_A(0) = -1.267$ and $M_D = 0.5\ GeV$. For the detailed discussion one may look at Ref. [6].

In this work, we have studied the dependence of cross section on the choice of $F_3^V(Q^2)$, $F_3^A(Q^2)$ form factors and the results are shown in Fig.1**(Top panel)** for the free nucleon case. For this purpose we define fractional difference as

$$\Delta_1(E_\nu) = \frac{\sigma_{\nu_\mu}(X \neq 0) - \sigma_{\nu_e}(X \neq 0)}{\sigma_{\nu_e}(X \neq 0)}$$

$$\Delta_2(E_\nu) = \frac{\sigma_{\nu_\mu}(X = 0) - \sigma_{\nu_e}(X = 0)}{\sigma_{\nu_e}(X = 0)}$$

$$\Delta_X(E_\nu) = \Delta_1(E_\nu) - \Delta_2(E_\nu), \quad (7)$$

where $X = F_3^V(Q^2)\ or\ F_3^A(Q^2)$. From the figure, it may be observed that there is a significant difference in the results when the different forms of $F_3^V(Q^2)$ and $F_3^A(Q^2)$ are taken.

In Fig.1**(Bottom panel)**, results show the effect of SCC on (anti)neutrino induced CCQE scattering cross sections for both free nucleon and nuclear target, ^{40}Ar. For the nucleons bound inside the nucleus, nuclear medium effects like Fermi motion, Pauli blocking and nucleon-nucleon correlations should also be taken into account and to incorporate these effects we have performed the calculations in the local density approximation(LDA). In LDA total scattering cross section($\sigma(E_\nu)$) is written as [5]

$$\sigma(E_\nu) = -2{G_F}^2\cos^2\theta_c \int_0^\infty r^2 dr \int_{k'_{min}}^{k'_{max}} k' dk' \times \int_{Q^2_{min}}^{Q^2_{max}} dQ^2 \frac{1}{E^2_{\nu_l} E_l} L_{\mu\nu} J^{\mu\nu} Im U_N[E_{\nu_l} - E_l - Q_r, \vec{q}]$$

From the Fig.1**(Bottom panel)**, it may be noticed that when we perform the calculations for (anti)neutrino induced CCQE processes on target nucleons bound inside the ^{40}Ar then the fractional difference $\Delta_{F_3^V(Q^2)}$, $\Delta_{F_3^A(Q^2)}$ is significant at lower energies and it is almost negligible at higher energies. The fractional difference is more pronounced for $\bar{\nu}_l$ induced processes than to ν_l induced processes. We also find that the effect of $F_3^V(Q^2)$ is more significant as compared to $F_3^A(Q^2)$.

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