Effect of lepton mass in neutrino induced quasielastic scattering

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Introduction

At the neutrino energies of $\sim 1GeV$ relevant to present and future neutrino oscillation experiments the dominant reaction is charged current quasi elastic process (CCQE):

$$\nu_l + n \longrightarrow l^- + p;\ l = e,\ \mu \qquad (1)$$

The study of CCQE is important because of several reasons. One of them is the simplicity due to the two body process which helps to determine the incident neutrino beam energies. A second reason is its ability to determine the neutrino flavor through the measurement of final leptons. In earlier works the lepton mass was not considered. However, this is important for the neutrino oscillation experiments as they gives direct information of neutrino flavors which could be helpful for the future oscillation experiments like ICARUS [1], LBNE [2], etc. The contribution of lepton mass terms is also relevant for determination of second class currents(F_3^V, F_3^A) which are proportional to $\frac{m_l}{M}$, where m_l is mass of lepton(e/μ) and M is mass of nucleon. Recently, Day and McFarland [3] pointed out the importance of lepton mass effects in the few GeV energy region.

In the present work, we calculate the effect of lepton mass with the inclusion of non vanishing second class currents(F_3^V, F_3^A). The results are presented for ν_l induced reaction on ^{40}Ar given in (1), which are being used in some of the oscillation experiments because of its good tracking ability. For the nuclear medium effects we follow the prescription given in Refs. [4, 5].

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Formalism

The invariant matrix element for the charged current reaction of neutrino, given by Eq.(1) is written as

$$\mathcal{M} = \frac{G_F}{\sqrt{2}} \cos\theta_C\ l_\mu\ J^\mu \qquad (2)$$

where the leptonic current is given by

$$l_\mu \ = \ \bar{u}(k')\gamma_\mu(1-\gamma_5)u(k). \qquad (3)$$

general structure of hadronic current is given as

$$\begin{aligned} J^\mu \ &= \ \bar{u}(p')\Big[F_1^V(q^2)\gamma^\mu + F_2^V(q^2) i\sigma^{\mu\nu}\frac{q_\nu}{2M} \\ &+ \ F_3^V(q^2)\frac{q^\mu}{M} + F_A^V(q^2)\gamma^\mu\gamma^5 + F_P^V(q^2) \\ &\times \ q^\mu\gamma^5 + F_3^A(q^2)\frac{(p+p')^\mu}{M}\gamma^5\Big] u(p) \qquad (4) \end{aligned}$$

where, $q^2 = (k-k')^2$ is the four momentum transfer square and M is the nucleon mass. $F_{1,2}^V(q^2)$ are the isovector form factors and $F_A(q^2)$, $F_P(q^2)$ are respectively the axial vector and pseudoscalar form factors. $F_3^A(q^2)$ and $F_3^V(q^2)$ are the form factors related with second class currents.

The two isovector form factors $F_{1,2}^V(q^2)$ are related with the Dirac and Pauli form factors of proton(neutron) $F_1^{p(n)}(q^2)$ and $F_2^{p(n)}(q^2)$ as,

$$F_{1,2}^V(q^2) = F_{1,2}^p(q^2) - F_{1,2}^n(q^2) \qquad (5)$$

The axial form factor $F_A(q^2)$ is parameterized with the dipole form, $F_A(q^2) = F_A(0)\ \left[1 - \frac{q^2}{M_A^2}\right]^{-2}$, where $F_A(0)$ is obtained from the quasielastic neutrino and antineutrino scattering as well as from pion electroproduction data. We have used axial charge $F_A(0) = -1.267$ and the axial dipole mass

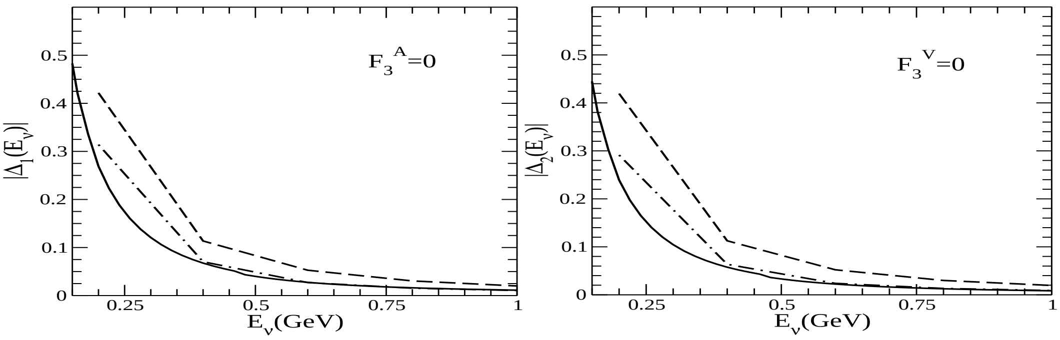

FIG. 1: $\Delta_1(E_\nu)$ & $\Delta_2(E_\nu)$ vs E_ν for $F_3^A = 0$(left panel) and $F_3^V = 0$(right panel), free case(solid line), Local Fermi gas model[4](dashed line) and Llewellyn Smith(LS)[6] Fermi gas model(dashed-dotted line).

M_A=1.05GeV. The Goldberger-Treiman relation connect the pseudoscalar form factor $F_p^V(q^2)$ with the axial form factor $F_A^V(q^2)$, $F_p^V(q^2) = \frac{2MF_A^V(q^2)}{m_\pi^2 - q^2}$. For numerical calculation we have chosen the parameterization given in Ref. [3] for second class currents $F_3^V(q^2)$ and $F_3^A(q^2)$. The vector second class current $F_3^V(q^2)$ is related to $F_1^V(q^2)$ as $F_3^V(q^2) = 4.4F_1^V(q^2)$ which is constrained by beta decay and muon capture experiments. The beta decay experiments also give a constraint for $F_3^A(q^2)$ and assuming the dipole form, parameterized it as $F_3^A(q^2) = 0.15F_A(q^2)$.

In the local density approximation, the scattering cross section($\sigma(E_\nu)$) is written as [4]

$$\sigma(E_\nu) = -2{G_F}^2 \cos^2\theta_c \int_0^\infty r^2 dr \int_{k'_{min}}^{k'_{max}} k' dk' \times \int_{Q^2_{min}}^{Q^2_{max}} dQ^2 \frac{1}{E_{\nu_l}^2 E_l} L_{\mu\nu} J^{\mu\nu} \times ImU_N[E_{\nu_l} - E_l - Q_r, \vec{q}]. \quad (6)$$

Results and Discussion

Using Eq. 2 in Eq. 6 we calculate the ratio

$$\Delta_1(E_\nu) = \frac{\sigma_{\nu\mu}(F_3^A = 0) - \sigma_{\nu e}(F_3^A = 0)}{\sigma_{\nu e}(F_3^A = 0)} \quad (7)$$

$$\Delta_2(E_\nu) = \frac{\sigma_{\nu\mu}(F_3^V = 0) - \sigma_{\nu e}(F_3^V = 0)}{\sigma_{\nu e}(F_3^V = 0)}, \quad (8)$$

in ^{40}Ar with nuclear medium effects like Fermi motion, Pauli blocking and Coulomb effect, by keeping all the form factors given in Eq. 4 except F_3^A in Δ_1 (Eq. 7) and F_3^V in Δ_2 (Eq. 8). In Fig.1 we have plotted $\Delta_1(E_\nu)$ & $\Delta_2(E_\nu)$ defined in Eqs.7 and 8 vs E_ν, for free as well as for bound nucleons in Local Fermi gas model[4] and Llewellyn Smith(LS)[6] Fermi gas model. In the left panel the contribution of F_3^V is plotted which may be important to set the limits for G-invariance and $SU(3)$ breaking effects and in right panel the contribution of F_3^A is plotted which also gives limit for $SU(3)$ breaking effects and non-conservation of CVC hypothesis. It can be seen from these figures that the ratio is modified inside the nucleus as we go from free to bound nucleons and also it is model dependent. However, the effect of lepton mass at high energies is negligible.

References

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