Lepton mass effect in $\nu_\tau - N$ charged current interactions

A. Fatima,* M. Sajjad Athar, and S. K. Singh
Department of Physics, Aligarh Muslim University, Aligarh - 202002, INDIA

SHiP is a new facility proposed at the CERN SPS accelerator which can be used to study the cross section and the angular distribution of leptons produced in the charged current (CC) induced reactions with tau neutrinos and antineutrinos [1]. The knowledge of the cross sections, angular distributions and the polarization of $\tau^-(\tau^+)$ leptons produced in CC reactions induced by ν_τ and $\bar{\nu}_\tau$ on nucleons and nuclear targets is an important input in the analysis of neutrino oscillation experiments in the $\nu_\mu(\bar{\nu}_\mu) \longrightarrow \nu_\tau(\bar{\nu}_\tau)$ appearence channel with the atmospheric [2] as well as the accelerator neutrinos [3]. In the energy region of the neutrinos relevant for these experiments, the Quasielastic (QE), Inelastic (IE) and Deep Inelastic Scattering (DIS) processes make important contributions. At present there is considerable uncertainty in the theoretical calculations of these processes induced by the tau neutrinos which can be as large as $30-40\%$, coming mainly from the IE and DIS processes [4]. In addition to the uncertainty related with the IE transition form factors and DIS structure functions, the role of the lepton mass terms in the case of $\nu_\tau - N$ scattering is also important. These mass terms are almost negligible in the case of $\nu_e - N$ and $\nu_\mu - N$ scattering in the few GeV energy region. In this paper, we study the role of the lepton mass term in the $\nu_\tau - N$ interactions relevent for the analysis of neutrino oscillation experiments in the $\nu_\mu(\bar{\nu}_\mu) \longrightarrow \nu_\tau(\bar{\nu}_\tau)$ appearence channel.

The general reaction for these processes is given as

$$\nu_l(k) + N(p) \longrightarrow l^-(k') + X(p'), \qquad (1)$$

where X represents the final state particles of the above said processes *i.e.* $X = N(\text{CCQE})$, $X = N + \pi(\text{CC}1\pi)$ and $X =$ jet of hadrons (CCDIS) and the quantities in the brackets represent the four momentum of the corresponding particles.

The general expression for the differential cross section for CCQE and CC1π is given by

$$d\sigma = \frac{(2\pi)^4\delta^4(k+p-k'-p')}{4\sqrt{(k.p)^2 - m_\nu^2 M_N^2}} \frac{d^3\boldsymbol{k'}}{(2\pi)^3 2E_l} \times \prod_{j=1}^{N} \frac{d^3\boldsymbol{p'_j}}{(2\pi)^3 2E_j} \overline{\sum}\sum |\mathcal{M}|^2. \qquad (2)$$

E_l and E_j represent the energies of the outgoing lepton and the final state particles respectively and m_ν and M_N represent the masses of the neutrino and the nucleon respectively. The invariant matrix element squared is given by

$$\overline{\sum}\sum |\mathcal{M}|^2 = \frac{G_F^2}{2}\cos^2\theta_c \, \mathcal{L}_{\mu\nu}\mathcal{J}^{\mu\nu}, \qquad (3)$$

where G_F is the Fermi coupling constant and θ_c is the Cabibbo mixing angle. The leptonic tensor is given by

$$\mathcal{L}_{\mu\nu} = 8[k_\mu k'_\nu + k'_\mu k_\nu - g_{\mu\nu} k.k' + i\epsilon_{\mu\nu\alpha\beta} k'^\alpha k^\beta] \qquad (4)$$

and the hadronic tensor is given as

$$\mathcal{J}^{\mu\nu} = \frac{1}{2}\sum_{spin} J^{\mu\dagger} J^\nu. \qquad (5)$$

The most general expression of the hadronic current J^μ for the CCQE process neglecting the second class currents has the following form:

$$J^\mu = \bar{u}(p')\left[F_1^V(Q^2)\gamma^\mu + F_2^V(Q^2) i\sigma^{\mu\nu}\frac{q_\nu}{2M_N} + F_A(Q^2)\gamma^\mu\gamma^5 + F_P(Q^2)\frac{q^\mu}{M_N}\gamma^5\right] u(p). \qquad (6)$$

*Electronic address: atikafatima1706@gmail.com

$Q^2(=-q^2)\ \geq 0$ is the four momentum transfer square. $F^V_{1,2}(Q^2)$ are the isovector vector form factors and $F_A(Q^2)$, $F_P(Q^2)$ are the axial and pseudoscalar form factors, respectively.

For CC1π process along with the spin $3/2^{+(-)}$ resonances like $P_{33}(1232)$, $D_{13}(1520)$ and $P_{13}(1720)$, we have also considered contributions from spin $1/2^{+(-)}$ resonances like $P_{11}(1440)$, $S_{11}(1535)$ and $S_{11}(1650)$ as well as from the nonresonant background (NRB) terms. The hadronic current for the excitation of spin $3/2^{+(-)}$ resonances is given by [5]

$$J^{\frac{3}{2}}_{\mu} = \bar{\psi}^{\nu}(p')\Gamma^{\frac{3}{2}^{+(-)}}_{\nu\mu} u(p), \quad (7)$$

where $\psi^{\mu}(p)$ is the Rarita-Schwinger spinor for spin three-half particle and for the positive and negative parity states $\Gamma^{\frac{3}{2}^{+(-)}}_{\nu\mu}$ has the following form

$$\Gamma^{\frac{3}{2}^+}_{\nu\mu} = \left[V^{\frac{3}{2}}_{\nu\mu} - A^{\frac{3}{2}}_{\nu\mu}\right]\gamma_5,$$
$$\Gamma^{\frac{3}{2}^-}_{\nu\mu} = V^{\frac{3}{2}}_{\nu\mu} - A^{\frac{3}{2}}_{\nu\mu}. \quad (8)$$

The vector and the axial-vector part of the current are given by

$$V^{\frac{3}{2}}_{\nu\mu} = \left[\frac{\tilde{C}^V_3}{M}(g_{\mu\nu}\ \not{q} - q_{\nu}\gamma_{\mu}) + g_{\mu\nu}\tilde{C}^V_6 + \frac{\tilde{C}^V_4}{M^2}(g_{\mu\nu} q\cdot p' - q_{\nu}p'_{\mu}) + \frac{\tilde{C}^V_5}{M^2}(g_{\mu\nu} q\cdot p - q_{\nu}p_{\mu})\right], \quad (9)$$

$$A^{\frac{3}{2}}_{\nu\mu} = -\left[\frac{\tilde{C}^A_3}{M}(g_{\mu\nu}\ \not{q} - q_{\nu}\gamma_{\mu}) + \frac{\tilde{C}^A_6}{M^2}q_{\nu}q_{\mu} + \frac{\tilde{C}^A_4}{M^2}(g_{\mu\nu} q\cdot p' - q_{\nu}p'_{\mu}) + \tilde{C}^A_5 g_{\mu\nu}\right]\gamma_5. \quad (10)$$

The vector and axial-vector form factors ($\tilde{C}^V_i$ and $\tilde{C}^A_i$) are discussed in detail in Ref. [5] and the expression for the hadronic current contributing to spin $1/2^{+(-)}$ resonances and NRB terms are given in Ref. [5].

The expression for the double differential scattering cross section for CCDIS is given by [6]

$$\frac{d^2\sigma}{d\Omega_l dE_l} = \frac{{G_F}^2}{(2\pi)^2}\ \frac{|\mathbf{k}'|}{|\mathbf{k}|}\ \left(\frac{m^2_W}{q^2 - m^2_W}\right)^2 L^{\mu\nu}\ W_{\mu\nu}\,, \quad (11)$$

where m_W is the mass of the W boson and Ω_l, E_l refer to the outgoing lepton and the expression for the hadronic tensor $W_{\mu\nu}$ is given by

$$W_{\mu\nu} = -\frac{1}{M_N}\left[g_{\mu\nu}F_1(x,Q^2) + \frac{p_{\mu}p_{\nu}}{p.q}F_2(x,Q^2) - i\frac{\epsilon_{\mu\nu\alpha\beta}\ p^{\alpha}q^{\beta}}{2p.q}F_3(x,Q^2) + \frac{q_{\mu}q_{\nu}}{p.q}F_4(x,Q^2) + \frac{(p^{\mu}q^{\nu} + p^{\nu}q^{\mu})}{2p.q}F_5(x,Q^2)\right] \quad (12)$$

where x is the Bjorken scaling variable defined as $x = \frac{Q^2}{2p.q}$.

The structure function $F_{1,4,5}(x,Q^2)$ are related to $F_2(x,Q^2)$ by the Callan-Gross and the Albright-Jarlskog relations. The structure function $F_2(x,Q^2)$ and $F_3(x,Q^2)$ are determined in terms of the parton distribution functions (PDF) as discussed in Ref. [6]. For the NLO evolution of the structure functions $F_i(x,Q^2)$ including the charm production and the target mass correction, we have followed the formalism of Ref. [7]. In the present work we have used the CTEQ6 parameterization of the PDFs.

We shall present the results of the differential and the total scattering cross sections for the processes discussed above. These results may be important for the future experiments like DUNE, Hyper-K, SHiP, etc.

References

[1] S. Alekhin *et al.*, Rept. Prog. Phys. **79**, 124201 (2016), A. Buonaura , PoS DIS **2016**, 260 (2016).

[2] K. Abe *et al.* , Phys. Rev. Lett. **110**, 181802 (2013).

[3] R. Acciarri *et al.* , arXiv:1601.02984 [physics.ins-det].

[4] J. Conrad *et al.*, Phys. Rev. D **82**, 093012 (2010).

[5] M. Rafi Alam *et al.*, Int. J. Mod. Phys. E **25**, 1650010 (2016).

[6] H. Haider, I. Ruiz Simo and M. Sajjad Athar, Phys. Rev. C **85**, 055201 (2012); ibid **87**, 035502 (2013).

[7] S. Kretzer and M. H. Reno, Phys. Rev. D **66**, 113007 (2002).