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Weak structure functions in $\nu - N$ and $\nu - A$ scattering with nonperturbative and higher order perturbative QCD effects

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The effect of nonperturbative and higher order perturbative corrections to the free nucleon structure functions in the deep inelastic scattering (DIS) of neutrinos on the free nucleon/nuclear target is studied. The evaluation of the nucleon structure functions have been performed up to next-to-next-to-leading order (NNLO) by using the Martin−Motylinski−Harland−Lang−Thorne 2014 parametrization of the parton distribution functions. The various nucleon and nuclear effects considered in this work are effective in the different regions of x and Q^2, and quite important in the few GeV energy region. The numerical calculations for the $\nu - A$ DIS process have been performed by incorporating the nuclear medium effects like Fermi motion, binding energy, nucleon correlations, mesonic contributions, shadowing, and antishadowing in several nuclear targets such as carbon, polystyrene scintillator, argon, iron and lead which are being used in MINERvA, ArgoNeuT and DUNE experiments.

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1. Introduction

Recently, a lot of continuous efforts both in the theoretical as well as experimental area has been made for a better understanding of the hadronic structure and parton dynamics of nucleons, in a wide range of energy (E) and momentum transfer squared (Q^2). The deep inelastic scattering process with large values of four momentum transfer square has been used to investigate the partonic distribution in the nucleon. Therefore, several researches are available in the perturbative region of high Q^2, however, much emphasis has not been given to the nonperturbative region of low Q^2. In a recent theoretical work [1–3], we have emphasized the effects of perturbative and nonperturbative QCD corrections in the evaluation of electromagnetic and weak nuclear structure functions. In this paper, we have briefly discussed the weak structure functions ($F_1^{WI}(x, Q^2)$, $F_2^{WI}(x, Q^2)$ and $F_3^{WI}(x, Q^2)$) as well as double differential scattering cross sections by considering the QCD corrections in the charged current neutrino induced deep inelastic scattering process off free nucleon and nuclear targets. This study is to understand the effects QCD corrections such as target mass correction (TMC) and perturbative evolution of parton densities, nuclear medium modifications, isoscalarity corrections and the center of mass (CoM) energy cut on the weak nuclear structure functions. This study is important for the development of precision experiments to accurately determine neutrino oscillation parameters, determination of mass hierarchy in the neutrino sector, etc., besides the intrinsic interest of understanding nucleon dynamics in the nuclear medium. For example, the planned DUNE experiment at Fermilab is expected to get more than 50% contribution to the event rates from the intermediate region of DIS and resonance production processes from nuclear targets. The ArgoNeuT collaboration has also measured the inclusive $\nu_l/\bar{\nu}_l -^{40} Ar$ scattering cross section in the low energy mode. As the nucleon structure functions are the basic inputs in the determination of nuclear structure functions and the scattering cross section, therefore, proper understanding of the nucleon structure functions as well as the parton dynamics become quite important.

2. Formalism

The basic reaction for the (anti)neutrino induced charged current deep inelastic scattering process off a nuclear target is given by

$$\nu_l(k)/\bar{\nu}_l(k) + A(p) \longrightarrow l^-(k')/l^+(k') + X(p'), \quad [l = e, \mu \tag{1}$$

where k and k' are the four momenta of incoming and outgoing leptons, p and p' are the four momenta of the target nucleon and the jet of hadrons produced in the final state, respectively. The general expression of double differential scattering cross section (DCX) for the massless lepton limit ($m_l \longrightarrow 0$) corresponding to the reaction given in Eq. 1 in the laboratory frame is expressed as

$$\frac{d^2\sigma_A^{WI}}{dxdy} = \frac{yM_N}{\pi} \frac{E}{E'} \frac{|\mathbf{k}'|}{|\mathbf{k}|} \frac{G_F^2}{2} \left(\frac{M_W^2}{Q^2 + M_W^2}\right)^2 L_{\mu\nu}^{WI} \; W_A^{\mu\nu}, \tag{2}$$

where $x = \frac{Q^2}{2M_N \nu}$ is the Bjorken scaling variable, $y = \frac{p.q}{p.k} (= \frac{\nu}{E}$ in the lab frame) is the inelasticity, $\nu = E - E'$ is the energy transfer, M_N is the nucleon mass, $E(E')$ is the energy of the incoming(outgoing) lepton with $Q^2 = -q^2 \geq 0$. $L_{\mu\nu}^{WI}$ and $W_A^{\mu\nu}$ are the leptonic and nuclear hadronic tensor respectively.

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Further simplifying Eq.2, the differential scattering cross section is obtained as

$$\begin{aligned}\frac{d^2\sigma_A^{WI}}{dxdy} &= \frac{G_F^2 M_N E}{\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2\left[xy^2 F_{1A}^{WI}(x,Q^2)+\left(1-y-\frac{M_N xy}{2E}\right)F_{2A}^{WI}(x,Q^2)\right.\\ &\left.\pm xy\left(1-\frac{y}{2}\right)F_{3A}^{WI}(x,Q^2)\right]\ . \end{aligned} \tag{3}$$

The expressions for the nuclear structure functions $F_{iA}^{WI}(x,Q^2)$; $(i = 1-3)$ are obtained in terms of the hole spectral function and the free nucleon structure functions. For details, please see Ref. [1–3]. For example, in the case of a nonisoscalar nuclear target, the expressions of $F_{iA}^{WI}(x,Q^2)$; $(i = 1-3)$ are given by

$$\begin{aligned}F_{1A,N}^{WI}(x_A,Q^2) &= 2\sum_{\tau=p,n} AM_N \int d^3r \int \frac{d^3p}{(2\pi)^3}\frac{M_N}{E_N(\mathbf{p})}\int_{-\infty}^{\mu_\tau} dp^0\ S_h^\tau(p^0,\mathbf{p},\rho_\tau(r))\\ &\times\left[\frac{F_{1\tau}^{WI}(x_N,Q^2)}{M_N}+\left(\frac{p^x}{M_N}\right)^2\frac{F_{2\tau}^{WI}(x_N,Q^2)}{\nu_N}\right],\end{aligned} \tag{4}$$

where $\nu_N = \frac{p\cdot q}{M_N} = \frac{p^0q^0-p^zq^z}{M_N}$. We must point out that the evaluation of $F_{1A,N}^{WI}(x_A,Q^2)$ has been performed independently, i.e., without using the Callan-Gross relation at the nuclear level.

$$\begin{aligned}F_{2A,N}^{WI}(x_A,Q^2) &= 2\sum_{\tau=p,n}\int d^3r \int \frac{d^3p}{(2\pi)^3}\frac{M_N}{E_N(\mathbf{p})}\int_{-\infty}^{\mu_\tau} dp^0\ S_h^\tau(p^0,\mathbf{p},\rho_\tau(r))\\ &\times\left[\left(\frac{Q}{q^z}\right)^2\left(\frac{|\mathbf{p}|^2-(p^z)^2}{2M_N^2}\right)+\frac{(p^0-p^z\gamma)^2}{M_N^2}\left(\frac{p^z\,Q^2}{(p^0-p^z\gamma)q^0q^z}+1\right)^2\right]\\ &\times\left(\frac{M_N}{p^0-p^z\gamma}\right)\times F_{2\tau}^{WI}(x_N,Q^2),\end{aligned} \tag{5}$$

with $\gamma = \frac{q^0}{q^z}$.

$$\begin{aligned}F_{3A,N}^{WI}(x_A,Q^2) &= 2A\sum_{\tau=p,n}\int d^3r \int \frac{d^3p}{(2\pi)^3}\frac{M_N}{E_N(\mathbf{p})}\int_{-\infty}^{\mu_\tau} dp^0 S_h^\tau(p^0,\mathbf{p},\rho_\tau(r))\times\frac{q^0}{q^z}\\ &\times\left(\frac{p^0q^z-p^zq^0}{p\cdot q}\right)F_{3\tau}^{WI}(x_N,Q^2).\end{aligned} \tag{6}$$

Using these expressions, we have incorporated the effects like Fermi motion, binding energy and nucleon correlations through the use of hole spectral function. The proton/neutron structure functions $F_{i\tau}^{WI}(x_N,Q^2)$; $(i = 1-3)$ are evaluated incorporating the QCD corrections such as evolution of parton densities at NNLO and target mass corrections (TMC). However, we have obtained the nucleon structure functions with the dynamical higher twist corrections(not shown here) at NLO and find no difference compared to the NNLO calculations [2]. Moreover, we have studied the modifications of the nuclear structure functions due to the effect of mesonic cloud contributions which is significant in the low and intermediate region of x as well as the effect of shadowing and antishadowing corrections.

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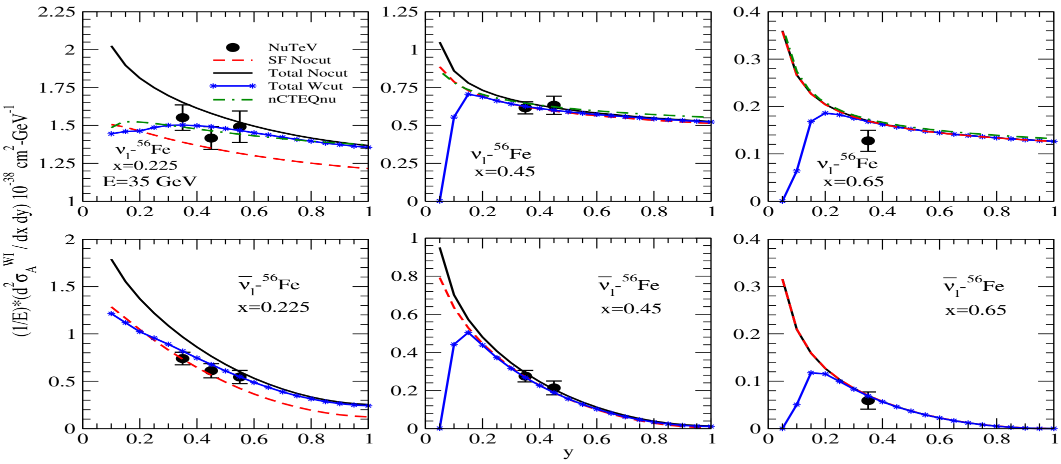

Figure 1: $\frac{1}{E}\frac{d^2\sigma_A^{WI}}{dxdy}$ vs y are shown at the different values of x for $E = 35$ GeV.

3. Results and Discussion

In Fig.1, the results are shown for $\frac{1}{E}\frac{d^2\sigma_A^{WI}}{dxdy}$ vs y for $\nu_l - A$, $(A =^{56} Fe,)$ (top panel) and $\bar{\nu}_l - A$, $(A =^{56} Fe)$ (bottom panel) scattering processes at NNLO. The numerical results are obtained for a beam energy of 35 GeV at the different values of x. Furthermore, we have compared these results with the phenomenological results of nCTEQnu (evaluated by using $\nu_l - A$ scattering experimental data). One may notice that the present theoretical results differ from the results of nCTEQnu PDFs parameterization in the region of low x and y while at high x and y they are in good agreement.

4. Conclusion

From the present theoretical results we conclude about the energy dependence, effect of CoM energy cut, medium modifications and isoscalarity correction effects on the nuclear structure functions and cross sections for the deep inelastic scattering of (anti)neutrino from various nuclei. This study will be helpful to understand the present and future experimental results from MINERvA, ArgoNeuT, and DUNE experiments.

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