$\nu_l -^{208} Pb$ deep inelastic scattering at MINERνA energies

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Recently, MINERνA [1] has measured the scattering cross section for $\nu_l - A$ deep inelastic scattering (DIS) process using different nuclear targets like ^{12}C, CH, ^{56}Fe, and ^{208}Pb for the kinematical region of $W > 2\ GeV$ and $Q^2 > 1\ GeV^2$ using beam energy(E_ν) in the range of 5-50 GeV.

We have studied nuclear medium effects in the deep inelastic region for electromagnetic and weak interaction processes [2, 3]. In this work, we have calculated differential scattering cross section(DSC) for ν_l induced reactions on ^{208}Pb target in the DIS region. For the present study, a microscopic model has been used which considers relativistic nucleon spectral function to describe nucleon momentum distribution. Nuclear medium effects like, Fermi motion, binding energy and nucleon correlations are incorporated using nucleon spectral functions that are obtained by using the Lehmann's representation for the relativistic nucleon propagator. While to calculate it in an interacting Fermi sea in the nuclear matter, nuclear many body theory is used. However, to obatin the results for finite nuclei, local density approximation is applied. Furthermore, we have incorporated mesonic cloud contributions which are important at low and intermediate x [4]. Moreover, shadowing and antishadowing effects, have been included following the works of Kulagin and Petti [5]. All the numerical evaluation have been performed at next-to-leading order(NLO). The details of the model are given in Ref. [2, 3]. The double differential scattering cross section for weak interaction(WI) induced DIS process on free nucleon target(neglecting lepton mass) is given by

$$\begin{aligned}\frac{d^2\sigma^N}{dxdy} &= \frac{G_F^2 M_N E_\nu}{\pi}\Big[xy^2 F_{1N}^{WI}(x,Q^2)\\ &+ \left(1 - y - \frac{M_N xy}{2E_\nu}\right) F_{2N}^{WI}(x,Q^2)\\ &\pm\ xy\left(1-\frac{y}{2}\right) F_{3N}^{WI}(x,Q^2)\Big]\ ,\end{aligned}$$

where $F_{iN}^{WI}(x,Q^2)$;$(i = 1-3)$ are the free nucleon structure functions, $(-)+ve$ sign is for (anti)neutrino, G_F is the Fermi coupling constant, M_N is nucleon mass and m_l is the mass of lepton in the final state.

When the scattering takes place inside the nuclear target then the expression of DSC gets modified as

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

where $F_{iA}^{WI}(x,Q^2)$;$(i = 1-3)$ are the weak nuclear structure functions which in the present model are obtained as [3, 6]

$$\begin{aligned}&F_{1A}^{WI}(x_A,Q^2) = 4AM_N\int d^3r\int\frac{d^3p}{(2\pi)^3}\frac{M_N}{E(\vec{p})}\\ &\int_{-\infty}^{\mu} dp_0 S_h(p_0,\vec{p},\rho(\vec{r}))\ \Bigg[\frac{F_{1N}^{WI}(x_N,Q^2)}{M_N}\\ &+\frac{{p_x}^2}{M_N^2}\frac{F_{2N}^{WI}(x_N,Q^2)}{\nu}\Bigg], \qquad (1)\end{aligned}$$

$$\begin{aligned}&F_{2A}^{WI}(x_A,Q^2) = 4\int d^3r\int\frac{d^3p}{(2\pi)^3}\frac{M_N}{E(\vec{p})}\\ &\times\ \int_{-\infty}^{\mu} dp_0 S_h(p_0,\vec{p},\rho(\vec{r}))\times\Bigg[\frac{Q^2}{q_z^2}\left(\frac{|\vec{p}|^2\ -\ p_z^2}{2M_N^2}\right)\\ &+\frac{(p_0\ -\ p_z\ \gamma)^2}{M_N^2}\left(\frac{p_z\ Q^2}{(p_0\ -\ p_z\ \gamma)q_0 q_z}\ +\ 1\right)^2\Bigg]\\ &\frac{M_N}{p_0\ -\ p_z\ \gamma}\ F_{2N}^{WI}(x_N,Q^2), \qquad (2)\end{aligned}$$

$$\begin{aligned}&F_{3A}^{WI}(x_A,Q^2) = 4\int d^3r\ \int\frac{d^3p}{(2\pi)^3}\ \frac{M_N}{E(\vec{p})}\ \int_{-\infty}^{\mu} dp_0\\ &\times\ S_h(p_0,\vec{p},\rho(\vec{r}))\ \frac{p_0\gamma - p^z}{(p_0 - p_z\gamma)\gamma}\ F_{3N}^{WI}(x_N,Q^2), \qquad (3)\end{aligned}$$

where $\gamma = \frac{q^z}{q^0}$, p_z is the momentum of nucleon along the z-axis and S_h is the hole spectral function. Bjorken variable, $x_A = \frac{Q^2}{2M_A\ q_0}$

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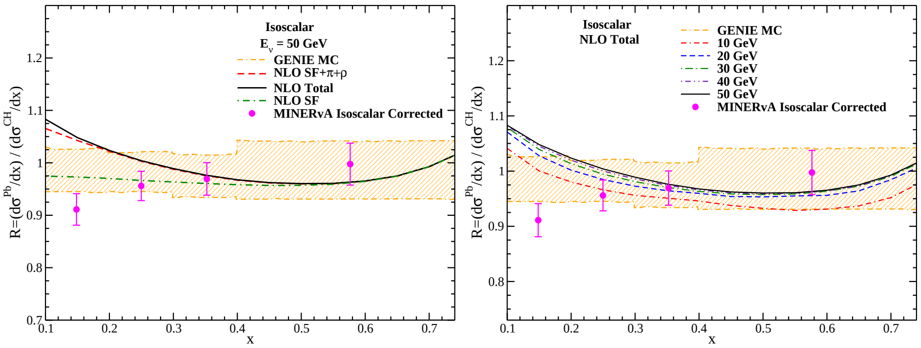

FIG. 1: Results for the ratio of differential scattering cross section in nuclear targets $R = \left(\frac{d\sigma^{Pb}/dx}{d\sigma^{CH}/dx}\right)$ **(i)Left panel:** at 50 GeV showing the effect of nuclear medium, and **(ii)Right panel:** showing energy dependence at different values of E_ν. The results are compared with MINERνA [1] and GENIE MC [7].

corresponds to the nuclear target which is at rest and $x_N = \frac{Q^2}{2(p_0 q_0 - p_z q_z)}$ to the nucleons that are moving inside the nucleus. To evaluate the DSC w.r.t. Bjorken variable x, i.e. $\frac{d\sigma^A}{dx}$, we have integrated Eq.(1) in the limits of $0 < y < 1$ with kinematical cut of $W > 2\ GeV$ and $Q^2 > 1\ GeV^2$ following MINERνA kinematics [1].

We have used parton distribution functions(PDFs) given by CTEQ group [8] for nucleon and PDFs given by Gluck et al. [9] for pion and rho mesons. The results are presented with spectral function(SF) only, including meson cloud contribution(SF+$\pi + \rho$) and further including shadowing effect, i.e. our full model(Total) at NLO in ^{208}Pb and CH nuclei treating ^{208}Pb as isoscalar target. We have compared the numerical results with the recent experimental data of MINERνA [1] as well as with the results obtained from the GENIE Monte Carlo [7] for $5 < E_\nu < 50\ GeV$.

In Fig.(1)(Left panel), the results are presented for the ratio $R = \frac{d\sigma^{Pb}/dx}{d\sigma^{CH}/dx}$ at $E_\nu = 50\ GeV$. From the figure, it may be observed that the ratio obtained with spectral function(SF) only is less than unity because of the nuclear medium effects. However, due to mesonic cloud contribution the ratio increases from unity at low and intermediate x. An additional enhancement in the results is observed at low x when shadowing and antishadowing effects are included with our full model.

In the right panel of Fig.(1), the results of R are shown for the different values of neutrino energies($E_\nu = 10-50,\ GeV$) at NLO with our full model. It may be noticed that the ratio R is energy dependent at low x, i.e., at low x, R increases with the increase in energy but saturates for high x.

We find that our results agree well with the experimental results of MINERνA [1] for mid and high x which is also consistent with the results obtained from GENIE MC [7]. However, at low x the ratio R is suppressed in heavy nuclei which needs further studies. It is important to mention that even at high energies like 50 GeV, nuclear medium effects are important.

References

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