Light Cone Dynamics and EMC Effects in the Extraction of $F_{2n}$ at Large Bjorken $x$.

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Abstract. We discuss theoretical issues related to the extraction of deep inelastic (DIS) structure function of neutron from inclusive DIS scattering off the deuteron at large Bjorken $x$. Theoretical justification is given to the consideration of only $pn$ component of the deuteron wave function and consistency with both the baryonic number and light-cone momentum conservation sum rules. Next we discuss the EMC type effects and argue that in all cases relevant to the nuclear DIS reactions at large $x$ the main issue is the medium modification of the properties of bound nucleon rather than the non-nucleonic components like pions. We give brief description of the color screening model of EMC and within this model we estimate uncertainties in the extraction of the neutron DIS structure function at large $x$. We emphasize also that these uncertainties are rather "model independent" since any theoretical framework accounting for the medium modification is proportional to the magnitude of the virtuality of bound nucleon which increases with an increase of $x$.

Keywords: deep-inelastic scattering, light-cone dynamics, neutron structure function

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INTRODUCTION

Since the pioneering experiments on deep inelastic electron scattering off the deuteron at SLAC in late 70's[1] the investigation of the partonic distribution functions (PDFs) of the neutron at large $x$ is one of the most important topics in the high $x$ QCD studies.

The main target of the choice for the extraction of the neutron PDFs is the deuteron and as the studies progressed it become more and more clear that several issues purely in nuclear physics nature should be addressed for successful exploration of DIS structure of the neutron.

Historically, due to its simplicity the main reaction considered was the inclusive $d(e,e')X$ scattering of the deuteron. However new generation of semi-inclusive experiments[2, 3, 4] present completely new framework in studies of neutron PDFs[5, 6, 7, 8, 9].

In inclusive DIS scattering several issues pertaining to the deuteron and the nature of the inclusive scattering are important for unambiguous interpretation of the neutron DIS data. These includes appropriate description of the scattering process off the relativistic bound system, effects due to modification of bound nucleon structure as well final state interaction.

In this report we focus on two issues such as light-cone description of the inclusive DIS process involving deuteron and medium modification of neutron PDFs.
Since partons have meaningful interpretation only in the infinite momentum frame or in the light cone[10] the selfconsistent interpretation of DIS scattering off the nuclei in terms of partonic degrees of freedom requires the description of the nuclei in the infinite momentum or light cone reference frame. In this case a bound nucleon is described by light-cone momentum $\alpha$ which is Lorentz invariant quantity boosted in the direction of infinite momentum and has a meaning of the momentum fraction of the nucleus carried by the bound nucleon.

In the case for the deuteron assuming that it consists of only proton and neutron we can express the relative momentum of $pn$ system in the light-cone through the momentum fraction $\alpha$ as follows[11]:

$$k = \sqrt{\frac{m_N^2 + p_t^2}{\alpha(2-\alpha) - m_N^2}}$$

(1)

where momentum fractions are normalized in such a way that for stationary nucleon $\alpha = 1$. The above defined momentum $k$ allows us to estimate the limit at which one can consider the deuteron as consisting of proton and neutron only. For this in Fig.1 we present the Bjorken - $x$ dependence of $k$ for typical DIS scattering kinematics at large $x$ and compare it with the three momentum of the nucleon as it enters in the lab frame description of the deuteron. From the figure we observe that at large $x$ the relative momentum of $pn$ system in the light cone is consistently less than the the one defined in the Lab frame. This situation is important from the point of view of justification of the approximation in which deuteron consists of only proton and neutron. Based on the recent observation[12] that the nucleonic component in the isosinglet $pn$ short range correlation dominates in the wave function till $\sim 650$ MeV/c relative momenta we were able to estimate that for $Q^2 \geq 5 \text{ GeV}^2$ and practically for whole range of large Bjorken $x \leq 1$ the non-nucleonic components can be safely neglected in the ground state wave function of the deuteron.

Constraining ourselves only by two-nucleon component of the deuteron wave function within LC approximation for the DIS structure function of the deuteron we obtain[13, 14]

$$F_2^A(x,Q^2) = \sum_{N=1}^2 \int \frac{d\alpha}{\alpha^2} d^2 p_\perp \rho_{N}^{LC} (\alpha, p_\perp) F_2^N (\tilde{x}, Q^2) \frac{\nu}{\bar{\nu}}$$

$$\times \left[ \left( \frac{M_d}{2m_N} \right)^2 (1+\cos\delta)^2 (z + \alpha_q \frac{m_N v'}{Q^2})^2 + \frac{p_\perp^2}{2m_N^2} \sin^2\delta \right],$$

(2)

where

$$\tilde{x} = \frac{Q^2}{2m_N \nu}, \quad \bar{\nu} = \frac{w_N^2 + Q^2 - m_N^2}{2m_N},$$

$$w_N^2 = Q^2 + \frac{M_d}{2} (p_+ \alpha_q + zq_+) + \frac{M_d}{2} p_+ z - p_\perp^2,$$
FIGURE 1. The dependence of minimal light-cone \( k \) (solid line) and lab frame \( p \) (dashed line) relative momenta of the pn system in the deuteron on the Bjorken \( x \). Calculations are done for \( Q^2 = 5 \) GeV\(^2\) and \( w_N = 2 \) GeV.

\[
\nu' = \frac{1}{2m_N} (p_+ + q_+ + p_- + q_-) = \frac{M_d}{2m_N} [p_+ + \alpha q + q_+ z],
\]

and \( p_\pm = E \pm p_z \) where \( z \) axis is defined in the direction of \( \vec{q} \). The light-cone density matrix \( \rho_{\alpha}(\alpha, p_\perp) \) can be expressed through the deuteron wave function as follows\[11\]:

\[
\rho_{\alpha}^{LC}(\alpha, p_\perp) = \frac{E_k |\Psi_d(k)|^2}{2 - \alpha}
\]

where \( E_k = \sqrt{m_N^2 + k^2} \) and the momentum \( k \) is defined according to Eq.(1). The light-cone density matrix defined above satisfies two sum rules: From baryon charge conservation one has

\[
\int \frac{d\alpha}{\alpha} d^2 p_\perp \rho_N^{LC}(\alpha, p_\perp) = 1,
\]

while the momentum sum rule requires

\[
\int \frac{d\alpha}{\alpha} d^2 p_\perp \alpha \rho_N^{LC}(\alpha, p_\perp) = 1.
\]

The above two relations are necessary conditions for self-consistency if one excludes any non-nucleonic component in the deuteron wave function. In this respect it is interesting that within approximations in which the struck nucleon is treated as virtual in the lab frame of the scattering process (generally referred as virtual nucleon (VN) approximation) (see e.g.\[16, 17, 18, 19, 8, 9\]) the momentum sum rule of Eq.(6) is not satisfied and:

\[
\int \frac{d\alpha}{\alpha} d^2 p_\perp \alpha \rho_N^{VN}(\alpha, p_\perp) < 1.
\]
Such a result can be interpreted as missing momentum fraction being distributed to the unaccounted degrees of freedom such as pions. Note that the last sum rule is not directly satisfied in the VN model, but it can be restored if mesonic degrees of freedom are introduced explicitly (see e.g. Ref.[20].

The account of both sum rules, given above, within light-cone approximation leads to a prediction for the \( F_2^A/F_2^N \) ratio which qualitatively contradicts the EMC effect for \( x \gtrsim 0.5 \) (Fig.2). This situation however indicates that the next step in the description of DIS scattering off the nucleus should be the account of nuclear medium modifications of the structure functions of bound nucleon.

**MEDIUM MODIFICATION EFFECTS**

The discovery of the EMC effect at large \( x \) has triggered a huge theoretical effort which has led to the development of a large number of models (see, e.g., Refs. [21, 22, 23, 24, 25, 26]). One can divide these models in two groups: one in which the effect is due to the missed non-nucleonic component (such as pion degrees of freedom) and the other group in which EMC effects are due to modification of the properties of bound nucleons. According to our discussion above we believe that the first group contributes little in the DIS kinematics at large \( x \). Moreover it can be shown that in the LC approximation even if pions will carry sizable light cone momentum fraction it will not be accessible in DIS measurement[27].

The important characteristics of the models in the second group is that the extent of modification depends on the magnitude of virtuality of the bound nucleon. In this case as it follows from Fig.1 one expects that with an increase of \( x \) the medium modification of the DIS structure function will be more and more important.

To estimate the expected magnitude of the effects in the extraction of large \( x \) neutron structure function from inclusive DIS scattering off the deuteron we calculate the medium modification based on one of "second group" models: the color screening model of Ref.[23, 13].

This model is based on the observation that the most significant EMC effect is observed in the range of \( x \) corresponding to high momentum components of the quark distribution in the nucleon and therefore the EMC effect is expected to be mostly sensitive to the nucleon wave function configurations where three quarks are likely to be close together. Such small size configurations are referred as point-like configurations (PLC). It is then assumed that for large \( x \) the dominant contribution to \( F_2^N(x, Q^2) \) is given by PLC of partons which, due to color screening, interact weakly with the other nucleons. Because of this the optimally bound configuration of nucleons will have suppressed contribution from the PLC component of nucleon wave function. The suppression of PLC in a bound nucleon is assumed to be the main source of the EMC effect in inclusive DIS and the suppression factor is calculated in perturbation series of the parameter:

\[
\kappa = \frac{\langle U_A \rangle}{\Delta E_A}
\]
FIGURE 2. The $x$ dependence of EMC ratios. Solid line light-cone approximation without medium modifications. Dashed area corresponds to LC calculations with EMC effects calculated according to color screening model. Largest effect corresponds to $\Delta E_A = 0.6$ GeV and smallest - $\Delta E = 1$ GeV. The data are from Refs.[29, 30].

where $\langle U_A \rangle$ is the average potential energy per nucleon and $\Delta E_A \approx M^* - M \sim 0.6 \div 1$ GeV is the typical energy for nucleon excitations within the nucleus.

To calculate the deformation of the quark wave function in the bound nucleon due to suppression of the probability of PLC in the bound nucleon and then to account for it in the calculation of $F_A^2(x, Q^2)$ one needs to introduce the nuclear potential with explicit quark degrees of freedom in it: $V(R_{ij}, y_i, y_j)$. Then using this potential to reevaluate the potential energy $U$ that enters into Schrödinger equation for the nuclear ground state wave function in the form:

$$U(R_{ij}) = \sum_{y_i, y_j, \tilde{y}_i, \tilde{y}_j} \langle \phi_N(y_i)\phi_N(y_j) | V(R_{ij}, y_i, y_j, \tilde{y}_i, \tilde{y}_j) | \phi_N(\tilde{y}_i)\phi_N(\tilde{y}_j) \rangle,$$

where $\phi_N(y_i)$ is the free nucleon wave function. Using for the unperturbed nuclear wave function the solution of the Schrödinger equation with $U(R_{ij})$, one can treat $(U - V)/\Delta E_A$ as a small parameter to calculate the dependence of the probability to find a nucleon in a PLC on the momentum of the nucleon inside the nucleus. Such a calculation allows to estimate the suppression of the probability to find a PLC in a bound nucleon as compared to the similar probability for a free nucleon. In the DIS cross section the PLC suppression can be represented as a suppression factor $\delta_A(k^2)$ which is multiplicative to the nucleon structure function $F_2^N(\tilde{x}, Q^2)$ in the LC convolution formula of Eq.(2)[23]

$$\delta_A(p^2) = \frac{1}{(1 + \kappa)^2} = \frac{1}{\left[1 + (p^2/M + 2\varepsilon_A)/\Delta E_A\right]^2},$$

(10)
where $k$ is the momentum of the bound nucleon in the light cone. Finally the $x$ dependence of the suppression effect is based on the assumption that the PLC contribution in the nucleon wave function is negligible at $x \lesssim 0.3$, and gives the dominant contribution at $x \gtrsim 0.5$. We use a simple linear fit to describe the $x$ dependence between these two values of $x$ [28].

Using the above estimate of the suppression factor we present in Fig.2 the comparison of our calculations for $\Delta E_A \approx M^* - M \sim 0.6 \div 1 \text{GeV}$ with the old SLAC[29] and new JLab[30] data. These comparisons also demonstrate that the LC calculation without medium modification disagrees strongly with the measured EMC ratios.

**EXTRACTION OF THE NEUTRON DIS STRUCTURE FUNCTION**

Within the above described theoretical model we perform the extraction of neutron DIS structure function $F_{2n}(x)$ with the similar procedure used in Ref.[1]. In the estimates in which EMC effects are taken into account we first modify the proton structure function, smear it by Fermi motion and then subtract from the deuteron data. After correcting by nucleon motion effects we modify back the extracted neutron structure functions to reconstruct "free" $F_{2n}$ for neutron. The results are presented in Fig.3, which indicates that larger is $x$ more important are nuclear modification effects due to large virtuality of nucleons (see Fig.1) involved in DIS scattering.

**CONCLUSION AND OUTLOOK**

It can be shown that other models of EMC based on the modification of structure function of nucleon exhibit similar dependence on the momentum (virtuality) of bound nucleon[14, 15]. As a result one expects that the uncertainty in the extraction of large $x$
DIS structure functions of the neutron from inclusive scattering off the deuteron to be rather "model independent". This emphasizes further the urgency of understanding the origin and extent of EMC effects relevant to large $x$ kinematics.

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