Tagged Structure Functions of the Deuteron and the Origin of the EMC Effect

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Abstract: We demonstrate how measurement of tagged structure functions of the deuteron in $(e, e'N)$ semi-inclusive reactions at backward kinematics can be used to discriminate between different models of the nuclear EMC effect. A procedure for extracting the large-x neutron to proton structure function ratio from $(e, e'N)$ reactions is also outlined.

1 Objectives and Theoretical Framework

More than a decade after the discovery of the nuclear EMC effect [1] and many fine measurements of the ratios of structure functions of nuclei and deuterium, no consensus has been reached on the origin of the effect. The observed effect is approximately proportional to the nuclear density and the x dependence of the effect, while non-trivial, has the same basic shape for all nuclei, making it easy to fit in a wide range of models with very different underlying assumptions. Proportionality to nuclear density suggests that one should expect a much smaller EMC effect in the deuteron compared to that in heavy nuclei. By virtue of the uncertainty principle, however, one may try to enhance the effect by isolating the configuration where the two nucleons in the deuteron are close together. For example, it is easy to check that the main contributions to the deuteron wave function for nucleon momenta $\mathbf{p} \geq 300$ MeV/c come from distances $\lesssim 1.2$ fm. In order to encounter such a situation, new experiments, which allow control of the inter-nucleon distances in the deuteron, are necessary.

The aim of this discussion is to demonstrate that use of semi-inclusive processes off the deuteron,

$$e + D \rightarrow e + N + X, \tag{1}$$

where a nucleon is detected in the deuteron fragmentation region, could meet the above requirements, and may help to boost our understanding of the origin of the EMC effect. In particular, one may be able to distinguish between models in which the EMC effect arises from hadronic degrees of freedom (nucleons and pions), and models in which the effect is attributed to the explicit deformation of the wave function of the bound nucleon itself. Using heavier nuclei as targets in the reaction (1) may be problematic due to the contribution of secondary interactions, therefore the deuteron is a more ideal target for our purpose.

The cross section for the semi-inclusive $(e, e'N)$ reaction off the deuteron can in general be expressed through four invariant structure functions:

$$\frac{d\sigma}{dx dW^2 (d\alpha_s/\alpha_s) d^2\mathbf{p}_T} = \frac{2\alpha_{em}^2}{Q^4}\left(1 - y - \frac{x^2 y^2 M^2}{Q^2}\right)$$
$$\times \left[F_L^D + \left(\frac{Q^2}{2\mathbf{q}^2} + \tan^2(\theta/2)\right)\frac{\nu}{M}F_T^D + \left(\frac{Q^2}{\mathbf{q}^2} + \tan^2(\theta/2)\right)^{\frac{1}{2}}\cos\phi\ F_{TL}^D + \cos(2\phi)\ F_{TT}^D\right] \tag{2}$$

where the semi-inclusive structure functions $F^D_{L,T,TL,TT}(x,\alpha_s,p_T,Q^2)$ are related to the components of the deuteron electromagnetic tensor $W_D^{\mu\nu}$ by [2]:

$$
\begin{aligned}
F_L^D &= \nu(1+\cos\delta)^2\cdot W_D^{--}, \qquad F_T^D = M(W_D^{xx}+W_D^{yy}),\\
F_{TL}^D &= 2\nu(1+\cos\delta)\cdot W_D^{-x}, \qquad F_{TT}^D = \frac{\nu}{2}\sin^2\delta\cdot(W_D^{xx}-W_D^{yy}).
\end{aligned} \tag{3}
$$

The kinematic variables in Eqs.(2) and (3) are $x = Q^2/2M\nu$, $W^2 = -Q^2+2M\nu+M^2$, where ν is the energy of virtual photon in the target rest frame and M the nucleon mass (we define the photon three-momentum $\mathbf{q}$ to be in the $+z$ direction). The squared four-momentum transferred to the deuteron is $Q^2 = 4E(E-\nu)\sin^2(\theta/2)$, with E the beam energy and $y=\nu/E$. The angles θ and ϕ are the electron scattering and detected nucleon azimuthal angles, respectively, and $\sin^2\delta = Q^2/\mathbf{q^2}$. The spectator nucleon momentum is denoted by $\mathbf{p}_s = (\mathbf{p}_{sT}, p_{sz})$, and the interacting nucleon momentum by $\mathbf{p}$, so that in the deuteron rest frame $\mathbf{p}_s = -\mathbf{p}$. The variable $\alpha_s = 2\left(\sqrt{M^2+\mathbf{p}_s^2}-p_{sz}\right)/M_D$ is the deuteron's light-cone momentum fraction carried by the detected nucleon. The "–" components in Eq.(3) correspond to the projection in the $z-t$ direction on the light-cone.

In a microscopic description of the process (1) the tensor $W_D^{\mu\nu}$ describes both the deep inelastic scattering (DIS) from a bound nucleon in the deuteron, as well as the dynamics of the nuclear interaction, which are in general not factorizable. However, by considering specific kinematics one can obtain approximate factorization of the two subprocesses, and thus allow for a quantitative treatment of the reaction (1). The kinematics required for factorization are: (I) $Q^2/\mathbf{q}^2 \sim 4Mx/Q^2 \ll 1$, $Q^2 \ll E(E-\nu)$, and (II) $\alpha_s \geq 1-x$, $p_T\approx 0$, $|\mathbf{p}_s| \lesssim 500$ MeV/c. The requirement (I) enhances the contribution of the longitudinal structure function, F_L, which is expressed through the "good" component of the electromagnetic current, Eq.(3). This component is less influenced by effects of final state interactions (FSI), thus allowing a separation of FSI from the dynamics of DIS from a bound nucleon. The conditions (II) suppress contributions from the direct production of nucleons in the $\gamma^* N$ interaction. These restrictions allow one to write [2]: $W_D^{\mu\nu}(x,\alpha_s,p_T,Q^2)\approx \eta S(\alpha_s,p_T)\cdot W_N^{\mu\nu\ eff}(x,\alpha_s,p_T,Q^2)$, where η represents to the factored out FSI effect ($\eta\approx 1$ for the above kinematics), and $S(\alpha_s,p_T)$ is the nucleon spectral function in the deuteron. Note that $W_N^{\mu\nu\ eff}(x,\alpha_s,p_T,Q^2)$ coincidences with the free nucleon tensor $W_N^{\mu\nu}$ in the limit $\alpha_s\to 1$ and $p_T\to 0$.

Using the kinematical constraints (I) and (II) one can express the cross section in Eq.(2) as:

$$
\frac{d\sigma^{eD\to epX}}{dxdW^2d(\log\alpha_s)d^2\mathbf{p}_T} \approx \frac{2\alpha_{em}^2}{Q^4}(1-y)S(\alpha_s,p_T)F_{2N}^{eff}\left(\frac{x}{2-\alpha_s},p_T,Q^2\right). \tag{4}
$$

Though the factorized form in Eq.(4) is quite universal for any self-consistent relativistic approach describing nuclear dynamics and DIS from a bound nucleon, the particular form for the spectral function $S(\alpha_s,p_T)$ or the bound nucleon structure function F_{2N}^{eff} could be very different. Since the goal is primarily to study nuclear effects on F_{2N}^{eff}, one therefore needs to minimize any effects coming from uncertainties in the deuteron wave function (or spectral function) itself. This can be achieved by measuring the ratio of cross sections at large x to that at $x\sim 0.1$–0.2, where the observed EMC effect is small [2, 3, 4]. If both cross sections are measured at the same α_s and p_T, the nuclear effects parameterized by the deuteron spectral function cancel [4]:

$$
G(\alpha_s,p_T,x_1,x_2,Q^2)\equiv\frac{d\sigma(x_1,\alpha_s,p_T,Q^2)/dxdW^2d(\log\alpha_s)d^2\mathbf{p}_T}{d\sigma(x_2,\alpha_s,p_T,Q^2)/dxdW^2d(\log\alpha_s)d^2\mathbf{p}_T} = \frac{F_{2N}^{eff}(x_1/(2-\alpha_s),p_T,Q^2)}{F_{2N}^{eff}(x_2/(2-\alpha_s),p_T,Q^2)}. \tag{5}
$$

This ratio is therefore the ideal experimental quantity to measure since it is not biased by any theoretical normalization of the deuteron wave function.

2 Predictions for $G(\alpha_s, p_T, x_1, x_2, Q^2)$

To assess the expected EMC effect which could be identified in the measurement of G in Eq.(5) we apply several theoretical approaches to the possible modification of the bound nucleon structure functions.

2.1 Binding Models

In the so-called binding models, the bulk of the EMC effect at $x \sim 0.6$ comes from the fact that the typical value for the interacting nucleon light-cone fraction is less than unity, i.e. the average spectator light-cone momentum fraction is $\langle \alpha_s \rangle > 1$. Contributions to the EMC effect from deformation of the bound nucleon structure function in this approach is minimal — indeed, in most versions of this model the explicit dependence on the nucleon virtuality p^2 in F_{2N}^{eff} is ignored, and only recently have the first attempts [5, 6] to account for this possible dependence been made. In any generic quark-parton model, F_{2N}^{eff} can be expressed through the quark spectral function ρ as [5, 6]: $F_{2N}^{eff}(x, p^2, Q^2) = \int dp_q^2\ \rho(p_q^2, p^2, x, Q^2)$, where p_q is the quark four-momentum. A simple microscopic quark–"diquark" model of the nucleon was discussed in Ref.[5], where the quark spectral function was determined from the dynamics contained in the nucleon–quark–spectator "diquark" vertex function, $\Gamma(p, p_q)$. Within the instant-form approximation [5], taking the positive energy nucleon projection,

$$\rho(p_q^2, p^2, x, Q^2) \quad \rightarrow \quad \mathrm{Tr}\left[(\not p + M)\ \overline{\Gamma}(p, p_q)\ (\not p_q - m_q)^{-1}\ \not q\ (\not p_q - m_q)^{-1}\ \Gamma(p, p_q) \right], \qquad (6)$$

where m_q is the quark mass. The simplest approximation is to assume that the vertex function is independent of the nucleon virtuality. The momentum dependence of the vertex function can then be parameterized as $\Gamma(p, p_q) \propto (m_q^2 - p_q^2)/(\Lambda^2 - p_q^2)^n$, which allows one to account for the bound nature of the nucleon state [5]. The parameters Λ and n are then fixed by comparing with the quark distribution data, with the overall normalization fixed by baryon number conservation [5]. The result for the α_s dependence of G is shown in Fig.1 by the dot-dashed curve. The values of x_1 and x_2 are selected to fulfill the condition $x_1/(2 - \alpha_s) = 0.6$ (large EMC effect in inclusive measurements) and $x_2/(2 - \alpha_s) = 0.2$ (essentially no EMC effect in inclusive measurements). The relatively weak α_s dependence reflects the assumption that the vertex function Γ is independent of p^2 — including such dependence would lead to a steeper slope.

2.2 Suppression of Point-like Configurations in Bound Nucleons

A significant EMC effect in inclusive (e, e') reactions occurs for $x \sim 0.5$–0.6, which corresponds to the high-momentum component of the quark distribution in the nucleon where 3 quarks are likely to be close together [3, 4]. It is assumed in this model that for large x the dominant contribution to $F_{2N}(x, Q^2)$ is given by the weakly interacting point-like configurations (PLC) of partons. The suppression of this component in a bound nucleon is predicted to be the main source of the EMC effect. To calculate this suppression one can use a perturbation series over a small parameter, $\kappa = \mid \langle U_A \rangle / \Delta E_A \mid$, which controls corrections to the description of a nucleus as a system of undeformed nucleons. Here $\langle U_A \rangle \sim -40$ MeV is the average potential energy per nucleon, and $\Delta E_A \approx M^*$–$M \sim 0.6$–0.7 GeV is the typical energy for nucleon excitations within the nucleus. The estimation of the deformation of the bound nucleon wave

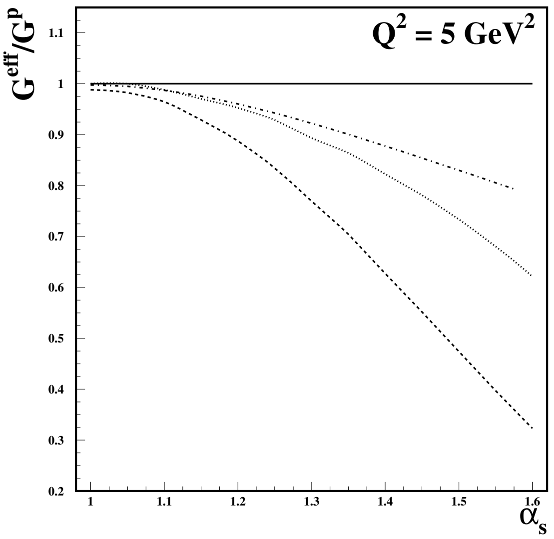

Figure 1 The α_s dependence of $G(\alpha_s, p_T, x_1, x_2, Q^2)$. G^{eff} is normalized to G calculated with the free proton structure function. Dashed, dot-dashed and doted curves represent the PLC suppression, binding and delocalization models, respectively.

function by a Schrödinger equation with a potential which explicitly takes into account the internal structure of the bound nucleon [3] gives the following suppression factor:

$$\delta_A(\mathbf{k}^2) = (1+z)^{-2}, \qquad z = (\mathbf{k}^2/M + 2\epsilon_D)/\Delta E_D, \quad |\mathbf{k}| = \sqrt{\frac{M^2+p_T^2}{\alpha_s(2-\alpha_s)} - M^2}, \tag{7}$$

where $F_{2N}^{eff}(x, Q^2, \alpha_s, p_T) \approx \delta(k)F_{2N}(x/(2-\alpha_s), Q^2)$. The x dependence of the suppression effect is based on the assumption that the PLC contribution in the nucleon wave function is negligible at $x \le 0.3$, but gives the dominant contribution at $x \ge 0.5$ [4, 7]. The result for G is illustrated by the dashed curve in Fig.1, which in this model has a somewhat larger magnitude for the slope compared with the binding model.

2.3 QCD Radiation, Quark Delocalization

It was observed in Refs.[8, 9] that the original EMC data could be roughly fitted as: $F_{2A}(x, Q^2)/A = F_{2D}\left(x, Q^2\xi_A(Q^2)\right)/2$, with $\xi_{Fe}(Q^2) \approx 2$ for $Q^2 \approx 20$ GeV^2, the so-called dynamical rescaling. The observation has been interpreted as an indication that gluon radiation occurs more efficiently in a nucleus than in a free nucleon due to quark delocalization, either in a bound nucleon (or in two nearby nucleons), or in the nucleus as a whole. The Q^2 dependence of $\xi(Q^2)$ follows from QCD evolution equations. In the leading logarithmic approximation one has: $\xi_A(Q^2) = \xi_A(Q_0^2)^{\alpha_{QCD}(Q_0^2)/\alpha_{QCD}(Q^2)}$. If the confinement size in a nucleus, λ_A, is larger than that in a free nucleon, one may expect that the Q^2 evolution may start at $Q_0^2(A) < Q_0^2(N)$, i.e. $Q_0^2(A)/Q_0^2(N) = 1/\xi(Q_0^2(A))$. On dimensional grounds $Q_0^2(A)\lambda_A^2 = Q_0^2(N)\lambda_N^2$, thus $\lambda_A/\lambda_N \approx \sqrt{\xi(Q_0^2(A))}$.

Since in this model the delocalization is approximately proportional to the nuclear density, one can expect that the effect is also proportional to the $\mathbf{k}^2$ of a bound nucleon. Fixing the parameters of the model to fit the Fe data, and assuming $\lambda(\mathbf{k}^2)/\lambda = 1 + a\mathbf{k}^2$ we obtain $a \approx 0.4/<\mathbf{k}^2>_{Fe}$, where $<\mathbf{k}^2>_{Fe} \sim 0.08$ GeV^2/c^2. Using this expression for $\lambda(\mathbf{k}^2)$ one can calculate the $\xi_D(Q^2, \mathbf{k}^2)$, and express the effective structure function of a bound nucleon as:

$$F_{2N}^{eff}(x, \alpha_s, p_T, Q^2) = F_{2N}\left(x, Q^2\xi(Q^2, \mathbf{k}^2)\right), \tag{8}$$

where $\mathbf{k}$ is defined through α_s and p_T according to Eq.(7).

In Fig.1 the predictions of the delocalization model for the α_s dependence of G are denoted by the dotted curve. The predictions are noticeably different for the various models, which suggests that measurement of this ratio for the reaction (1) will be valuable for understanding the origin of the EMC effect.

3 Extraction of the n/p Structure Function Ratio

Aside from providing insight into the origin of the nuclear EMC effect per se, the measurements of tagged events may also be useful in connection with the problem of extracting the neutron structure function from deuteron data. A large ambiguity exists in the asymptotic value of F_{2n}/F_{2p} as $x \to 1$ extracted from inclusive ep and eD data: inclusion of the EMC effect in the deuteron when extracting F_{2n} leads to significantly larger values for F_{2n}/F_{2p} than the 1/4 value obtained in analyses in which only Fermi motion is accounted for [10]. Unlike in inclusive measurements, where the nucleon structure function in the deuteron is smeared by a nucleon momentum distribution in the deuteron, semi-inclusive reactions allow one to select specific values of α_s and p_T in the spectral function $S(\alpha_s, p_T)$, thereby giving the opportunity to minimize the nuclear effects in the deuteron. By selecting backward produced nucleons with $\alpha_s \approx 1$ and $p_T \approx 0$, one can approximately determine the free neutron to proton ratio,

$$\frac{F_{2n}(x,Q^2)}{F_{2p}(x,Q^2)} \approx \left.\frac{F_{2n}^{eff}(x/(2-\alpha_s),p_T,Q^2)}{F_{2p}^{eff}(x/(2-\alpha_s),p_T,Q^2)}\right|_{\alpha_s\approx 1, p_T\approx 0}. \tag{9}$$

For non-zero p_T, deviations of this ratio from the free limit are proportional to p^2 with a good accuracy [2]. Hence, if one samples the data as a function of p^2, interpolation to the pole $p^2 - M^2 = 2M\epsilon$, where ϵ is the deuteron binding energy, should be smooth as long as the momentum of the spectator nucleon is $\lesssim$ 100–200 MeV/c.

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