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Hadronization and final state interaction effects in semi-exclusive deep inelastic scattering off nuclei

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Abstract. Recent calculations of the effects of hadronization and final state interaction (FSI) in semi-exclusive deep-inelastic scattering (DIS) $A(e,e'(A-1))X$ processes are reviewed. The basic ingredient underlying these calculations, *viz* the time-dependent effective debris-nucleon cross section is illustrated, and some relevant results on complex nuclei and the deuteron are presented. In the latter case, particular attention is paid to the choice of the kinematics, for such a choice would in principle allow one to investigate both the structure function of a bound nucleon as well as the hadronization mechanisms. It is stressed that a planned experiment at Jlab on the process $D(e,e'p)X$ could be very useful in that respect.

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1 Introduction

To date, information on hadronization mechanisms comes mainly from the measurement of the multiplicity ratio of the lepto-produced hadrons in semi inclusive $A(e,e'h)X$ processes [1], whose interpretation on the basis of the quark re-interaction model of [2] appears to be very convincing. However, it should also be pointed out that the more exclusive processes of $A(e,e'(A-1))X$ (the *semi-exclusive* process) proposed in [3], though difficult to perform, could provide more direct information on quark re-interaction and hadronization mechanisms, as shown recently in [4]. The semi-exclusive reaction $A(e,e'(A-1))X$ represents the process in which an incoming electron undergoes a DIS process off a low-momentum bound nucleon, with the scattered electron and the recoiling $(A-1)$ nucleus detected in coincidence in the final state. Much theoretical attention has been devoted to such process on a deuteron target, i.e. when $A=D$ and $(A-1)=p$ or n (see e.g. [5]-[7]). These calculations (except [6], to be discussed later on) are based upon the *plane wave impulse approximation (PWIA)*, according to which: i) X results from DIS off one of the two nucleons in the deuteron, ii) the second nucleon N recoils without interacting with X and is detected in coincidence with the scattered electron. The process $A(e,e'(A-1))X$ on a complex nucleus was thoroughly investigated in [3] within the PWIA, i.e. by assuming that the nucleon debris created by the virtual photon propagates without re-interacting with the spectator nucleus, which, therefore, always remains intact, an assumption which, at first sight, might appear unjustified.

As a matter of fact, as pointed out in [4], DIS off a bound nucleon results in the production of a multi-particle final state with an effective mass squared equal to

$$\begin{aligned} s' &\simeq m_N^2 - Q^2 + 2\,m_N\,\nu - 2\,\sqrt{\nu^2-Q^2}\,p_L \\ &= Q^2(\frac{1}{x}-1) + m_N^2 - 2|\mathbf{q}|p_L \end{aligned} \quad (1)$$

where $Q^2=\mathbf{q}^2-\nu^2$ is the four- momentum transfer, ν the virtual photon energy in the rest frame of the nucleus, p_L the longitudinal Fermi momentum of the nucleon relative to the direction of the virtual photon ($\mathbf{q} \parallel z$), m_N the nucleon mass, and $x=\frac{Q^2}{2m_N\nu}$ the Bjorken scaling variable (we neglect here the binding energy of the nucleon). At high energies and far from the quasi-elastic region ($x \approx 1$), the effective mass is large, $\sqrt{s'} \gg m_N$, and one expects the production of many particles, which can interact traveling through the nucleus. This would substantially suppress the probability for the spectator nucleus to remain intact. However, the process of multi-particle production has a specific space-time development, and it turns out that not so many particles have a chance to be created inside the nucleus. In order to check such an expectation, in [4] the propagation of the struck nucleon debris and its re-interaction with the nuclear medium, occurring in the semi-exclusive process on complex nuclei $A(e,e'(A-1))X$, has been considered with the aim of also clarifying if and to which extent the process is sensitive to the details of quark hadronization in nuclear environment. To this end an effective time-dependent cross section σ_{eff} (to be called the *debris-nucleon* cross section) has been obtained, which describes the interaction with the nuclear medium of the hadronization products of a highly virtual quark created in a DIS process off a bound nucleon. The main features of the *debris-nucleon* cross section are discussed in the next section.

2 The debris-nucleon cross section

In the derivation of the effective debris-nucleon cross section of [4] use has been made of the color string model [8] and the gluon radiation mechanism [9,2], namely an approach has been adopted which takes into account both the production of hadrons due to the breaking of the color string which is formed after a quark is knocked out off a bound nucleon, as well as the production of hadrons originating from gluon radiation.

According to QCD, DIS is the process in which an incident electron interacts with a target quark by exchanging a gauge boson, making the quark highly virtual. The formation of the final, detectable hadrons, occurs after the space-time propagation of the created nucleon debris, with a sequence of soft and hard production processes. The theoretical description of these processes, which generally cannot be treated within perturbative QCD, requires the use of model approaches. Most of them are based upon the quark color string model [8], according to which at world interval of the order of $\simeq 1fm$, the string, which is formed by the highly virtual leading quark and the remnant target quarks, breaks into a hadron and another, less stretchy string. Further, at longer space-time intervals, this decay process iterates unless the energy of the string is too low for hadron production and all the final hadrons are formed. However, since the hadronization process can also be accompanied by gluon perturbative bremsstrahlung [9], the string model itself is not sufficient for a consistent treatment of hadronization. A reliable model must incorporate both the perturbative and the non-perturbative aspects of the hadron formation process. Note, that the hadronization process starts at extremely short space-time intervals, hence a direct experimental study of these intervals is difficult to undertake in DIS off a free nucleon. As a matter of fact, the final hadrons do not carry much information about their early stage of hadronization, and therefore only nuclear targets, which consist of a number of scattering centers, allow one to probe short times after the hadronization has started. The time-dependent cross section σ_{eff} describing the scattering of the nucleon debris with the surrounding medium turns out to read as follows [4]

$$\sigma_{eff}(t) = \sigma_{tot}^{NN} + \sigma_{tot}^{\pi N}\Big[n_M(t) + n_G(t)\Big] , \qquad (2)$$

where σ_{tot}^{NN} ($\sigma_{tot}^{\pi N}$) are the total cross sections describing nucleon-nucleon (meson-nucleon) interactions, and $n_M(t)$ and $n_G(t)$ are the effective numbers of created mesons and radiated gluons, respectively, and are explicitly given in [4]. It should be pointed out that in obtaining (2) the color-dipole picture was employed by replacing each radiated gluon by a color-octet $q\bar{q}$ pair.

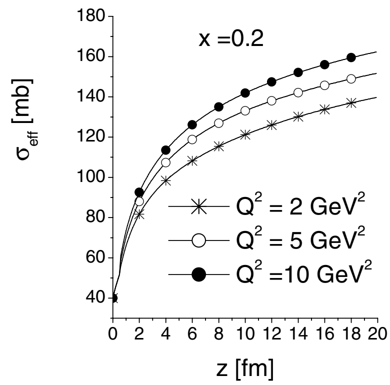

Fig. 1. The debris-nucleon effective cross section (2) plotted vs the distance z for a fixed value of the Bjorken scaling variable x and various values of the four-momentum transfer Q^2 (after [4])

The cross section (2) exhibits a rather complex Q^2- and x-dependence, which, however, asymptotically tends to a simple logarithmical behavior. This is illustrated in Fig. 1, where the dependence of σ_{eff} upon the coordinate z along the propagation direction is shown for different values of the four momentum transfer Q^2 and a fixed value of the Bjorken scaling variable x.

It should be stressed that in [4] it has been shown that the effective cross Sect. (2) can reasonably explain the Fermilab data on the production of protons in semi inclusive Deep Inelastic muon-Xenon scattering at 490 GeV [11]. In this experiment, at a given value of x, *grey tracks* were observed, which have been interpreted as protons in the momentum range $200 < p < 600\ MeV/c$. Using (2) the average number $< n_g >$ of *grey tracks vs* Q^2 has been calculated, obtaining a satisfactory explanation of the experimental data of [11]; this makes us confident in the correctness of the calculation of FSI effects in semi-exclusive processes off nuclear targets, to be discussed in the next section.

3 The process $A(e, e'(A-1))X$ in complex nuclei

In a nucleus, at each hadronization point one expects reinteractions of the produced hadrons with the nuclear constituents, so that the multiplicity of final particles is predicted to be reduced relative to the case of nucleon targets. Thus, by comparing the same DIS process off a single nucleon and off nuclear targets, information on the space-time structure of the hadronization process could be obtained. As already pointed out, the theoretical model of hadronization developed in [2], proved to be very effective for the explanation of the leading hadron multiplicity ratios (nucleus to nucleon) measured at HERMES [1] in semi-inclusive processes. It should however be pointed out

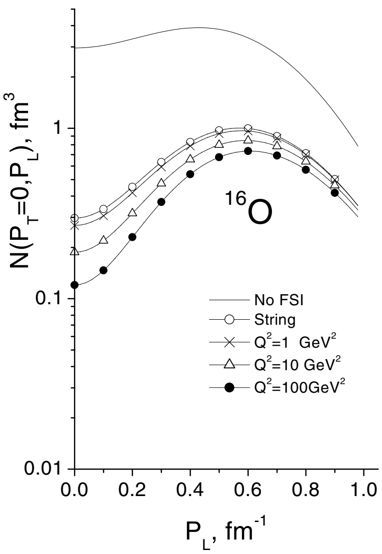

Fig. 2. The proton Momentum Distribution for ^{16}O ((6) – No FSI) compared with the Distorted Momentum Distribution $N(\mathbf{P}_{A-1})$ (3) plotted vs P_L for $P_T = 0$. The curve labeled by open dots has been obtained using the effective cross section for the nucleon debris corresponding to the color string model, whereas the other curves correspond to the cross section which includes also the gluon bremsstrahlung. The stars represent the distorted *proton* momentum distributions calculated in [13] for the semi-inclusive quasi-elastic process $^{16}O(e, e'p)X$ (After [4])

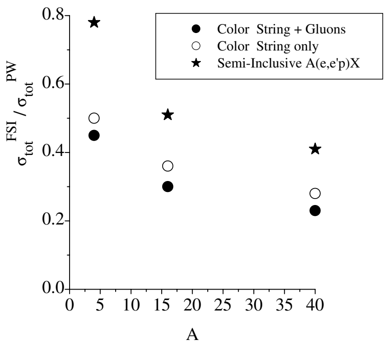

Fig. 3. The nuclear transparency i.e. the ratio between the total cross section σ_{tot}^{FSI}, obtained by integrating (3) over $\mathbf{P}_{A-1}$) and the PWIA total cross section σ_{tot}^{PW}, obtained in the same way but disregarding the Final State Interaction ($S(\mathbf{b}, z) = 0$, $\sigma_{tot} \equiv \sigma_{tot}^{PW}$). The *open dots* correspond to the debris-nucleon effective cross section given by the color string model, whereas the *full dots* correspond to the cross section where the gluon bremsstrahlung has also been considered [(2)] at $Q^2 = 100GeV^2$. The stars represent the *proton* transparency calculated in [12,13] for the reaction $A(e, e'p)X$ (After [4])

that the initial stage of hadronization is difficult to investigate by semi-inclusive processes, where the non leading hadrons are strongly affected by subsequent cascade processes and therefore do not carry information on their formation mechanism.

In [4] it has been shown that the deep inelastic semi-exclusive process $A(e, e', (A-1))X$, where the nucleus $(A-1)$ is detected in coincidence with the scattered electron, could be an effective tool to study the mechanisms and the initial stage of hadronization. The approach of [4] is based on a traditional Glauber-type nuclear structure approach in which the ground state wave function of the initial nucleus $\Psi_A^0(\mathbf{r}, \mathbf{r}_2 \ldots \mathbf{r}_A)$ is written as a product of a function ϕ, describing the motion of the hit nucleon and the wave function $\Psi_{A-1}^f(\mathbf{r}_2 \ldots \mathbf{r}_A)$ of the spectator; moreover $|\Psi_{A-1}^f(\mathbf{r}_2 \ldots \mathbf{r}_A)|^2$ is, as usually, approximated by a product of single particle densities. Within these assumptions, the cross section can be shown to be governed by the *distorted momentum distributions*

$$n_A^{FSI}(\mathbf{P}_{A-1}) \equiv N(\mathbf{P}_{A-1}) = \left|F_{A,A-1}^{FSI}(\mathbf{P}_{A-1})\right|^2 \quad (3)$$

where

$$F_{A,A-1}^{FSI} \simeq \int e^{i\mathbf{P}_{A-1}\,\mathbf{r}}\,\phi(\mathbf{r})\left[1 - \frac{S(\mathbf{b}, z)}{2(A-1)}\right]^{A-1} d\mathbf{r} \quad (4)$$

and

$$S(\mathbf{b}, z) = \int_z^\infty dz'\,\rho_A(\mathbf{b}, z')\,\sigma_{eff}(z' - z) \quad (5)$$

In these equations $\rho_A(\mathbf{b}, z)$ is the nuclear density ($\int d\mathbf{r}\rho_A(\mathbf{r}) = A$), and $\sigma_{eff}(z' - z)$ is given by (2). Note that when FSI are absent, i.e. when $\sigma_{eff} = 0$, the usual nucleon momentum distribution in the nucleus is recovered

$$n_A(|\mathbf{P}_{A-1}|) \simeq \left|\int e^{i\mathbf{P}_{A-1}\,\mathbf{r}}\,\phi(\mathbf{r})\,d\mathbf{r}\right|^2 \quad (6)$$

The distorted momentum distributions for ^{16}O are shown in Fig. 2, whereas the nuclear transparency for the nucleon debris created in a DIS process and for a nucleon knocked out in a quasi-elastic scattering semi-inclusive $A(e, e'p)X$ process, is exhibited in Fig. 3.

4 The process $D(e, e'p)X$

To perform an experiments on semi-exclusive processes $A(e, e'(A-1))X$ off complex nuclei is not easy task; however, in the case of a deuteron target the experiment appears to be feasible [14]. As a matter of fact the process

$$e + D = e' + X + N \quad (7)$$

has been the object of many theoretical calculations, mainly aimed at studying the neutron structure function [5]-[7], and its experimental investigation is planned to be performed at JLab [14].

Process (7) has many attractive features with respect to the inclusive process $^2H(e, e')X$, both for extracting information on the nucleon structure functions and for the investigation of hadronization mechanism. Indeed, in spite of the fact that inclusive DIS processes have provided us in the past with fairly precise knowledge of parton distributions in hadrons, conclusive information about the origin of the EMC effect is still lacking; moreover, important details on the neutron structure function are unknown, which is mostly due the difficulties and ambiguities related to the unfolding of the neutron structure functions from nuclear data [15]. Semi-exclusive processes could provide, on the contrary, unique information on both the origin of the EMC effect, and the details of the neutron structure function; moreover, they can also be used as a unique tool to investigate hadronization processes. Obviously, a reliable treatment of semi-exclusive processes requires a careful treatment of the FSI of the nucleon debris X with the final nuclear system $(A-1)$. Intuitively, one expects, on one hand, that if the proton is detected in the backward hemisphere, FSI effects should not play a relevant role, so that the process could be used to investigate the structure functions of bound nucleons; on the other hand, the effects from FSI are expected to be relevant in the process when the recoiling nucleon is detected in the direction perpendicular to the three-momentum transfer, in which case information on the hadronization mechanism could be obtained. In view of the planned experiments at JLab [14], a detailed quantitative calculation of FSI effects in process (7) has been carried out in [16]. There it has been found that the central quantity describing the process is the distorted momentum distribution

$$n_D^{FSI}(\mathbf{p}_s,\mathbf{q}) = \frac{1}{3}\frac{1}{(2\pi)^3}\sum_{\mathcal{M}_D}\left|\int d\mathbf{r}\Psi_{1,\mathcal{M}_D}(\mathbf{r})S(\mathbf{r},\mathbf{q})\chi_f^+ \exp(-i\mathbf{p}_s\mathbf{r})\right|^2 \tag{8}$$

where χ_f is the spin function of the spectator nucleon and $S(\mathbf{r},\mathbf{q})$ the S-matrix describing the final state interaction between the debris and the spectator, *viz.*

$$S(\mathbf{r},\mathbf{q}) = 1-\theta(z)\,\frac{\sigma_{eff}(z,Q^2,x)(1-i\alpha)}{4\pi b_0^2}\,\exp(-b^2/2b_0^2). \tag{9}$$

When FSI are absent ($\sigma_{eff}=0$) the usual deuteron momentum distributions are recovered, *viz.*

$$n_D(|\mathbf{p}_s|,) = \frac{1}{3}\frac{1}{(2\pi)^3}\sum_{\mathcal{M}_D}\left|\int d\mathbf{r}\Psi_{1,\mathcal{M}_D}(\mathbf{r})\chi_f^+ \exp(-i\mathbf{p}_s\mathbf{r})\right|^2 \tag{10}$$

In what follows, the momentum distributions are expressed in terms of the light cone variable α_s, $p_{\|}$ and p_T, defined as

$$\alpha_s = \frac{E_s - p_{\|}}{m}, \quad p_{\|} = |\mathbf{p}_s|\cos\theta_s, \quad p_T = |\mathbf{p}_s|\sin\theta_s \tag{11}$$

where θ_s is the angle between $\mathbf{p}_s$ and $\mathbf{q}$, and the spectator four-momentum is $p_s \equiv (E_s, \mathbf{p}_s)$ (note, that in the DIS kinematics the light cone z-axis is directed opposite to the vector $\mathbf{q}$). In [16] the problem was addressed of finding proper kinematics which would allow the investigation of both the nucleon structure function and the hadronization mechanism; in the first case FSI effects should be minimized, whereas in the second case they have to be maximized. Since all of the FSI effects are contained in the distorted momentum distribution $n_D^{FSI}(\mathbf{p}_s,\mathbf{q})$, its deviation from the nucleon momentum distributions $n_D(|\mathbf{p}_s|)$ could provides clear signature of FSI effects. This is illustrated in Fig. 4, which shows the ratio n_D^{FSI}/n_D, calculated using two different models for the effective cross section σ_{eff}, representing its upper and lower limits, *viz* the time- and Q^2- dependent cross section of [4] (solid lines), and a constant cross section $\sigma_{eff} = 20\ mb$ (dashed lines) considered in [6]. In our numerical calculations the parameters entering (10), *viz* the slope b_0 and the ratio α of the real to the imaginary parts of the forward amplitude, have been taken from NN scattering data at high energies. It should be pointed out, in this respect, that our results, in the range of considered momenta, are not very sensitive to the value of α; whereas the values of the latter is known in the case of *nucleon-nucleon* scattering, the value for *debris-nucleon* scattering should rely on some theoretical models. This point is under investigations and the results will be presented elsewhere. It can be seen from Fig. 4 that the predictions given by the two different models of the effective cross section ere rather different, particularly when the recoiling proton is emitted perpendicularly to $\mathbf{q}$,

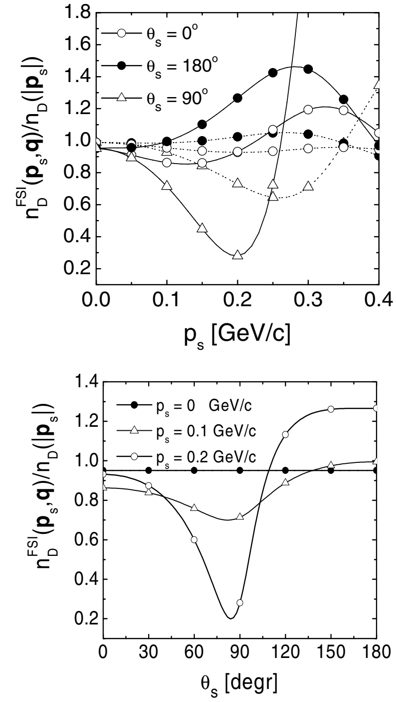

Fig. 4. *Upper panel*: the Deep Inelastic Scattering ratio n_D^{FSI}/n_D for the process $D(e,e'p)X$ with n_D^{FSI} and n_D (given, respectively, by (8) and (10)), calculated vs the momentum $p_s \equiv |\mathbf{p}_s|$ of the spectator nucleon emitted at different angles θ_s. The *full lines* correspond to the Q^2- and z-dependent debris-nucleon effective cross section σ_{eff} shown in Fig. 1, whereas the *dashed lines* correspond to a constant cross section $\sigma_{eff} = 20\ mb$. *Lower panel:* the same as in the upper panel, vs the emission angle θ_s of the spectator, for different values of the spectator momentum. Calculations have been performed at $Q^2 = 5\ (GeV/c)^2$ and $x = 0.2$ (After [16])

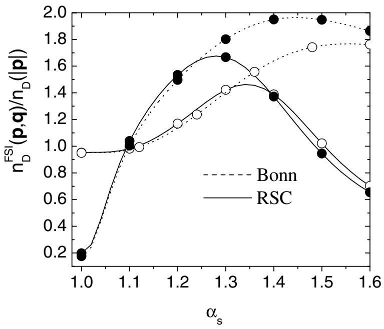

Fig. 5. The Deep Inelastic Scattering ratio n_D^{FSI}/n_D for the process $D(e,e'p)X$ *vs* the light cone variable α_s, calculated at $Q^2 = 5\ GeV^2/c^2$ and $x = 0.2$ using two different deuteron wave functions: the *solid lines* correspond to the RSC potential and the *dashed lines* to the Bonn potential. Calculations have performed in correspondence of two values of the transverse momentum p_T of the recoiling nucleon (cf. 11), namely $p_T = 0\,GeV/c$ (*open dots*) and $p_T = 0.2\ GeV/c$ (*full dots*). The results correspond to the debris-nucleon cross section shown in Fig. 1 (After [16])

i.e. at $\theta_s \sim 90^o$, and with large values of the momentum ($p_s \sim 0.2\ GeV/c$). Thus, by investigating this kinematical region one could, in principle, obtain unique information about the magnitude of σ_{eff} and, consequently, about the hadronization mechanism.

The results exhibited in Figs. 4 also demonstrate that FSI effects are essentially reduced in parallel kinematics ($\theta = 0^o, 180^o$) and also at small values of p_s. It can be shown that in this region the cross section provides direct information on the structure function F_2 of a bound nucleon, so that a reliable investigation of off-mass shell effects [18,19] in DIS could be possible. The results exhibited in Figs. 4 have been obtained by using the deuteron wave function corresponding to the Reid Soft Core (RSC) potential [20]. Calculations have been repeated with the Bonn interaction [21]. As shown in Fig. 5, at small values of α_s different potential models yield basically the same results; however at moderate and large values of α_s the predictions by different deuteron wave functions appreciably differ.

To sum up, from the analysis exhibited in [16], it can be concluded that FSI effects in the semi-exclusive process (7) are negligible in the backward kinematics and slow momenta of the detected nucleon, which would allow one to investigate the nucleon structure function of bound nucleons, in particular the neutron one; if, on the contrary, the spectator nucleon is emitted perpendicularly to the momentum transfer, FSI effects are enhanced and different models for the hadronization process could be investigated.

5 Summary and conclusions

We have reviewed recent calculations of FSI effects which occur in the semi-exclusive deep inelastic $A(e,e'(A-1))X$ process. The FSI is generated by the rescattering with the medium of the nucleon debris formed by the deep inelastic scattering of the virtual photon. These calculations are based upon the effective time-dependent debris-nucleon cross section obtained in [4] on the basis of the color string [8] and the gluon radiation [9] models. The detailed calculation [16] of the reaction $D(e,e'p)X$, shows that the planned experiment at Jlab [14], aimed at investigating such a reaction, may provide unique information on the hadronization mechanisms.

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