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Final-state interaction effects in semi-exclusive DIS off the deuteron

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Abstract. The effects of the final-state interaction (FSI) in semi-exclusive deep inelastic scattering of electrons off the deuteron are analyzed paying particular attention to two extreme kinematical regions: i) the one where FSI effects are minimized, so that the quark distribution of bound nucleons could be investigated, and ii) the one where the re-interaction of the produced hadrons with the spectator nucleon is maximized, which would allow one to study the mechanism of hadronization of highly virtual quarks. It is demonstrated that when the recoiling spectator nucleon is detected in the backward hemisphere with low momentum, the effects from the FSI are negligible, whereas at large transverse momenta of the spectator, FSI effects are rather large. Numerical estimates show that the FSI corrections are sensitive to the theoretical models of the hadronization mechanism.

PACS. 24.85.+p Quarks, gluons, and QCD in nuclei and nuclear processes – 25.10.+s Nuclear reactions involving few-nucleon systems – 25.30.Fj Inelastic electron scattering to continuum

1 Introduction

According to QCD, deep inelastic scattering (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 [1], according to which at world interval of the order of $\simeq 1\,\mathrm{fm}$, 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 [2], 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. In a nucleus, at each hadronization point, one expects re-interactions 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. The theoretical model of hadronization developed in ref. [3], proved to be very effective for the explanation of the leading-hadron multiplicity ratios (nucleus to nucleon) measured at HERMES [4] in semi-inclusive processes. It should however be pointed out that the initial stage of hadronization is difficult to investigate by semi-inclusive processes, where the non-leading hadrons are strongly

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affected by subsequent cascade processes and therefore do not carry information on their formation mechanism. Recently, it has been shown [5] 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, originally proposed to investigate the structure function of bound nucleons [6], could be an effective tool to study the mechanisms of hadronization and the initial stage of hadronization. The simplest of the processes $A(e,e',(A-1))X$, namely that with a deuteron target, viz

$$e + D = e' + X + N \tag{1}$$

has been the object of many theoretical calculations, mainly aimed at studying the neutron structure function [7–9], whereas its experimental investigation is planned to be performed at JLab [10].

Process (1) has many attractive features with respect to the inclusive process ${}^2\mathrm{H}(e,e')X$. As a matter of fact, it should be stressed that, 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 [11]. 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 the 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 bound-nucleon structure functions; 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 both cases, a quantitative estimate of FSI is a prerequisite for obtaining a reliable estimate of either nucleon structure functions or hadronization processes. In view of the planned experiments at JLab, a quantitative calculation of FSI effects in process (1) is called for. It is precisely the aim of the present paper to illustrate the results of the calculations of process (1) in various kinematical conditions taking FSI into account.

Our paper is organized as follows. In sect. 2 the kinematics and the general formula for the cross-section are presented; the theoretical reaction mechanism for the considered process is illustrated in sect. 3 both in the Plane-Wave Impulse Approximation (PWIA) (sect. 3.1) and taking into account FSI effects (sect. 3.2). In the same section the effective cross-section describing the rescattering of the nucleon debris with the spectator nucleons is illustrated (sect. 3.3). Eventually, the results of the numerical calculations are presented and discussed in sect. 4.

2 Kinematics and cross-section

The general theoretical formalism of process (1) can be found in several papers (see, *e.g.*, [7,8], and [6]), therefore only few general aspects of the problem will be recalled here.

In one-photon-exchange approximation, the cross-section for the process (1) can be written as follows:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x dQ^2\, \mathrm{d}^3 p_s} = \frac{4\alpha^2}{Q^4}\frac{\pi\nu}{x}\left[1-y-\frac{Q^2}{4E^2}\right]\widetilde{l}^{\mu\nu}L^D_{\mu\nu} \equiv \tag{2}$$

$$\frac{4\alpha^2}{Q^4}\frac{\pi\nu}{x}\left[1-y-\frac{Q^2}{4E^2}\right]\Big[\tilde{l}_L W_L + \tilde{l}_T W_T + \tilde{l}_{TL} W_{LT}\cos\phi_s + \tilde{l}_{TT} W_{TT}\cos(2\phi_s)\Big]\,, \tag{3}$$

where α is the fine-structure constant, $Q^2 = -q^2 = -(k-k')^2 = \mathbf{q}^{\,2} - \nu^2 = 4EE^{'}\sin^2\frac{\theta}{2}$ the four-momentum transfer (with $\mathbf{q} = \mathbf{k} - \mathbf{k}'$, $\nu = E - E^{'}$ and $\theta \equiv \theta_{\widehat{\mathbf{k}\mathbf{k}'}}$), $x = Q^2/2M\nu$ the Bjorken scaling variable, $y = \nu/E$, $\mathbf{p}_s$ the momentum of the detected recoiling nucleon (also called the *spectator* (s) nucleon), $\widetilde{l}_{\mu\nu}$ and $L^D_{\mu\nu}$ the electron and deuteron electromagnetic tensors, respectively; the former has the well-known standard form, whereas the latter can be written as follows:

$$L^D_{\mu\nu} = \sum_X \langle\,\mathbf{P}_D|J_\mu|\mathbf{P}_f\,\rangle\langle\,\mathbf{P}_f|J_\nu|\mathbf{P}_D\,\rangle\delta^{(4)} \times (k + P_D - k' - p_X - p_s)\,\mathrm{d}\boldsymbol{\tau}_X, \tag{4}$$

where J_μ is the operator of the deuteron electromagnetic current, and $\mathbf{P}_D$ and $\mathbf{P}_f = \mathbf{p}_X + \mathbf{p}_s$ denote the three-momentum of the initial deuteron and the final hadron system, respectively, with $\mathbf{p}_X$ being the momentum of the undetected hadronic state created by the DIS process on the active nucleon. In eq. (3) the various W_i represent the nuclear response functions and

$$\tilde{l}_L = \frac{Q^2}{|\mathbf{q}|^2}, \qquad \tilde{l}_T = \frac{Q^2}{2|\mathbf{q}|^2} + \tan^2\left(\frac{\theta}{2}\right),$$

$$\tilde{l}_{LT} = \frac{Q^2}{\sqrt{2}|\mathbf{q}|^2}\sqrt{\tan^2\left(\frac{\theta}{2}\right) + \frac{Q^2}{|\mathbf{q}|^2}}, \qquad \tilde{l}_{TT} = \frac{Q^2}{2|\mathbf{q}|^2}. \tag{5}$$

It is well known that within the PWIA, *i.e.* when FSI effects are disregarded, the four response functions in eq. (3) can be represented only via two independent structure functions, viz W_L and W_T. Moreover, in the DIS kinematics, when the Callan-Gross relation holds, *i.e.* $2xF_1^N(x) = F_2^N(x)$ ($F_{1,2}^N(x)$ are the nucleon DIS structure functions in the Bjorken limit), the semi-inclusive cross-section (3) will depend only upon one DIS structure function, *e.g.* $F_2^N(x)$. In the presence of FSI all four responses contribute to the cross-section (3); however, if FSI effects are not too large, nucleon momenta are sufficiently small and the momentum transfer large enough, one can expect that the additional two structure functions are small corrections, so that the semi-exclusive DIS cross-section can still be described by one effective structure function

$F_{2A}^{\text{s.e.}}(Q^2, x, p_s)$ ([6–8]) (the two structure functions W_{LT} and W_{TT} can exactly be eliminated in the parallel kinematics, *i.e.* by choosing the spectator nucleon along the momentum transfer $\mathbf{q}$, *i.e.* $\theta_s = 0$ or $\theta_s = \pi$, or integrating the cross-section over ϕ_s[1]).

The cross-section (3) can be also represented in terms of the light-cone variable α_s, $p_\parallel$ and p_T, defined as

$$\alpha_s = \frac{E_s - p_\parallel}{m}, \quad p_\parallel = |\mathbf{p}_s|\cos\theta_s, \quad p_T = |\mathbf{p}_s|\sin\theta_s \tag{6}$$

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 terms of the above variables, the cross-section will read as follows:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x\mathrm{d}Q^2\ \mathrm{d}\alpha_s\mathrm{d}{p_T}^2} = \frac{4\alpha^2}{Q^4}\frac{\pi^2 m\nu}{x}\left[1 - y - \frac{Q^2}{4E^2}\right] \times \left[\tilde{l}_L W_L + \tilde{l}_T W_T\right]. \tag{7}$$

3 The spectator mechanism

In what follows we will consider the reaction (1) within the so-called *spectator mechanism*, according to which the DIS process occurs on the so-called *active* nucleon, *e.g.* nucleon “1”, and the second nucleon (the *spectator*) recoils and is detected in coincidence with the scattered electron. At high values of the 3-momentum transfer $\mathbf{q}$ the produced hadron debris propagates mostly along the $\mathbf{q}$-direction and re-interacts with the spectator nucleon. The wave function of such a state can be written in the form

$$\Psi_f(\{\xi\}, \mathbf{r}_x, \mathbf{r}_s) = \phi_{\beta_f}(\{\xi\})\psi_{p_x,p_s}(\mathbf{r}_x, \mathbf{r}_s), \tag{8}$$

where $\mathbf{r}_x$ and $\mathbf{r}_s$ are the coordinates of the center-of-mass of system X and the spectator nucleon, respectively, $\{\xi\}$ denotes the set of the internal coordinates of system X, described by the internal wave function $\phi_{\beta_f}(\{\xi\})$, β_f denoting all quantum numbers of the final state X; the wave function $\psi_{p_x,p_s}(\mathbf{r}_x, \mathbf{r}_s)$ describes the relative motion of system X interacting elastically with the spectator s. The matrix elements in eq. (4) can easily be computed, provided the contribution of the two-body part of the deuteron electromagnetic current can be disregarded, which means that the deuteron current can be represented as a sum of electromagnetic currents of individual nucleons, $J_\mu(Q^2, X) = j_\mu^{N_1} + j_\mu^{N_2}$. Introducing complete sets of plane-wave states $|\mathbf{p}_1{}', \mathbf{p}_2{}'\rangle$ and $|\mathbf{p}_1, \mathbf{p}_2\rangle$ in intermediate states, one obtains

$$\begin{aligned}\langle\mathbf{P}_D|j_\mu^N|\beta_f, \mathbf{P}_f = \mathbf{p}_x + \mathbf{p}_s\rangle &= \sum_{\beta,\mathbf{p}_1{}',\mathbf{p}_2{}'}\sum_{\mathbf{p}_1,\mathbf{p}_2}\langle\mathbf{P}_D|\mathbf{p}_1{}', \mathbf{p}_2{}'\rangle \\ &\times\langle\mathbf{p}_1{}', \mathbf{p}_2{}'|j_\mu^{N_1}|\beta, \mathbf{p}_1, \mathbf{p}_2\rangle\langle\beta, \mathbf{p}_1, \mathbf{p}_2|\ \beta_f, \mathbf{p}_x, \mathbf{p}_s\rangle = \\ \int\frac{\mathrm{d}^3p}{(2\pi)^3}\psi_D(\mathbf{p})&\langle\mathbf{p}|j_\mu^{N_1}(Q^2, p\cdot q)|\beta_f, \mathbf{p}+\mathbf{q}\rangle \\ &\times\psi_{\boldsymbol{\kappa}_f}(\mathbf{p}+\mathbf{q}/2),\end{aligned} \tag{9}$$

where $\boldsymbol{\kappa}_f = (\mathbf{p}_x - \mathbf{p}_s)/2$. In eq. (9) the matrix element $\langle\mathbf{p}|j_\mu^{N_1}(Q^2, k\cdot q)|\beta_f, \mathbf{p}+\mathbf{q}\rangle$ describes the electromagnetic transition from a moving nucleon in the initial state to a final hadronic system X in a quantum state β_f. Obviously, the sum over all the final-state β_f of the square of this matrix element, complemented with the corresponding energy conservation δ-function, generates the deep inelastic nucleon hadronic tensor of a moving nucleon.

3.1 The PWIA

In PWIA, γ^* interacts with a quark of the neutron, a nucleon debris is formed and the proton recoils without interacting with the debris. The relative-motion debris proton is thus described by a plane wave

$$\begin{aligned}\psi_{\boldsymbol{\kappa}_f}(\mathbf{p}+\mathbf{q}/2) \sim (2\pi)^3\delta^{(3)}(\mathbf{p}+\mathbf{q}/2-\boldsymbol{\kappa}_f) &= \\ (2\pi)^3\delta^{(3)}(\mathbf{p}-\mathbf{p}_s)&\end{aligned} \tag{10}$$

and the well-known result

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x\mathrm{d}Q^2\ \mathrm{d}\alpha_s\mathrm{d}p_T^2} = K(x, Q^2, p_s)\, n_D(|\mathbf{p}|)\, F_2^{N/A}(Q^2, x, p_s) \tag{11}$$

is obtained, where $\mathbf{p} = -\mathbf{p}_s$ is the momentum of the struck nucleon before interaction, $K(x, Q^2, p_s)$ a kinematical factor (see, *e.g.*, ref. [6]), $F_2^{N/A}(Q^2, x, p_s) = 2xF_1^{N/A}(Q^2, x, p_s)$ the DIS structure function of the active nucleon, and n_D the momentum distribution of the hit nucleon, *i.e.*

$$n_D(|\mathbf{p}|) = \frac{1}{3}\frac{1}{(2\pi)^3}\sum_{\mathcal{M}_D}\left|\int\mathrm{d}^3r\Psi_{1,\mathcal{M}_D}(\mathbf{r})\exp(-i\mathbf{p}\mathbf{r}/2)\right|^2. \tag{12}$$

In general, since the active nucleon inside the deuteron is off-mass shell, its deep inelastic electromagnetic tensor has a more complicate structure [12,13] containing off-mass shell corrections. However, at low values of the 3-momentum of the spectator, *i.e.* at low 3-momenta of the active nucleon before interaction, these corrections are negligible and one can safely express the nucleon tensor only in terms of the DIS structure function $F_2^{N/A}(Q^2, x, p_s)$.

3.2 FSI

Consider now FSI effects within the kinematics when the spectator is slow, and the momentum transfer large

[1] Integration over ϕ_s eliminates from eq. (3) the LT and TT structure functions. Alternatively, the LT and TT structure functions can be eliminated by choosing the reaction plane at, *e.g.*, 45° with respect to the scattering one and performing two measurements of p_s with $\Delta\phi_s = 90°$.

enough so that the rescattering process of the fast system X off the spectator s could be considered as a high-energy soft hadronic interaction. In this case the momentum of the detected spectator $\mathbf{p}_s$ only slightly differs from the momentum $\mathbf{p}$ before rescattering, so that in the matrix element $\langle\,\mathbf{p}|j_\mu^{N_1}(Q^2,p\cdot q)|\beta_f,\mathbf{p}+\mathbf{q}\,\rangle$ one can take $\mathbf{p}\sim-\mathbf{p}_s$, obtaining in coordinate space

$$\langle\,\mathbf{P}_D|j_\mu^N|\mathbf{P}_f\,\rangle \cong j_\mu^N(Q^2,x,\mathbf{p}_s) \times\int \mathrm{d}^3r\psi_D(\mathbf{r})\psi^+_{\boldsymbol{\kappa}_f}(\mathbf{r})\exp(i\mathbf{r}\mathbf{q}/2). \quad (13)$$

The cross-section then becomes

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x\mathrm{d}Q^2\,\mathrm{d}\alpha_s\mathrm{d}p_T^2} = K(x,Q^2,p_s)\,n_D^{\mathrm{FSI}}(\mathbf{p}_s,\mathbf{q})\,F_2^{N/A}(Q^2,x,p_s), \quad (14)$$

where

$$n_D^{\mathrm{FSI}}(\mathbf{p}_s,\mathbf{q})=\frac{1}{3}\frac{1}{(2\pi)^3} \times\sum_{\mathcal{M}_D}\left|\int \mathrm{d}^3r\Psi_{1,\mathcal{M}_D}(\mathbf{r})\psi^+_{\boldsymbol{\kappa}_f}(\mathbf{r})\exp(i\mathbf{r}\mathbf{q}/2)\right|^2, \quad (15)$$

is the distorted momentum distribution, which coincides with the momentum distribution of the hit nucleon (eq. (12)) when $\psi^+_{\boldsymbol{\kappa}_f}(\mathbf{r})\sim\exp(-i\boldsymbol{\kappa}_f\mathbf{r})$.

All the effects from the FSI in eq. (14) are implicitly generated by the dependence of the distorted momentum distribution (15) upon $\mathbf{q}$, and by the features of the rescattering wave function $\psi^+_{\boldsymbol{\kappa}_f}(\mathbf{r})$; the latter describes the rather complicated many-body system $X+\textit{spectator}$ and can only be generated by model approaches. However, in our particular case, when the relative momentum $\boldsymbol{\kappa}_f\sim\mathbf{q}$ is rather large and the rescattering processes occur with low momentum transfers, the wave function $\psi^+_{\boldsymbol{\kappa}_f}(\mathbf{r})$ can be replaced by its eikonal form describing the propagation of the nucleon debris formed after γ^* absorption by a target quark, followed by hadronization processes and interactions of the newly produced pre-hadrons with the spectator nucleon. This series of soft interactions with the spectator can be characterized by an effective cross-section $\sigma_{\mathrm{eff}}(z,Q^2,x)$ depending upon time (or the distance z traveled by the system X). Thus, the distorted nucleon momentum distribution (eq. 15) becomes

$$n_D^{\mathrm{FSI}}(\mathbf{p}_s,\mathbf{q})=\frac{1}{3}\frac{1}{(2\pi)^3} \times\sum_{\mathcal{M}_D}\left|\int \mathrm{d}\mathbf{r}\Psi_{1,\mathcal{M}_D}(\mathbf{r})S(\mathbf{r},\mathbf{q})\chi_f^+\,\exp(-i\mathbf{p}_s\mathbf{r})\right|^2, \quad (16)$$

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

$$S(\mathbf{r},\mathbf{q})=1-\theta(z)\,\frac{\sigma_{\mathrm{eff}}(z,Q^2,x)(1-i\alpha)}{4\pi b_0^2}\,\exp(-b^2/2b_0^2)\,, \quad (17)$$

where the z-axis is directed along $\mathbf{q}$, *i.e.* $\mathbf{r}=z\dfrac{\mathbf{q}}{|\mathbf{q}|}+\mathbf{b}$.

As previously mentioned, such a treatment of FSI holds if, during the process of hadronization, the FSI occurs as a series of soft, elastic scattering of the produced debris with the spectator nucleon and the kinematics is chosen in such a way that the DIS structure function of the nucleon does not change too rapidly. In this case the factorization assumption holds and the rescattering process is described as the debris-nucleon rescattering via an effective cross-section. Hence, the usual eikonal approximation can be applied. Note that the above expressions can also be used to calculate the effects of FSI in quasi-elastic scattering (QES) by simply replacing the debris-nucleon cross-section with the z-independent nucleon-nucleon cross-section (see, *e.g.*, [14,15]).

3.3 The effective debris-nucleon cross-section

Recently in ref. [5] the final-state interaction in DIS off nuclei due to the propagation of the struck nucleon debris and its hadronization in the nuclear environment, has been considered and applied to the process of the type $A(e,e'(A-1))X$ with $A\geq 4$. This process precisely coincides with the one investigated in the present paper, *i.e.* the process $^2\mathrm{H}(e,e'p)X$. The basic ingredient governing the FSI, *i.e.* the time- and Q^2-dependent effective cross-section σ_{eff} describing the interaction of the debris with a nucleon of the spectator system $(A-1)$, has been obtained in ref. [5] on the basis of a model 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. The general expression has the following form:

$$\sigma_{\mathrm{eff}}(t)=\sigma_{\mathrm{tot}}^{NN}+\sigma_{\mathrm{tot}}^{\pi N}\Big[n_M(t)+n_G(t)\Big]\,, \quad (18)$$

where $\sigma_{\mathrm{tot}}^{NN}$ and $\sigma_{\mathrm{tot}}^{\pi N}$ are the total cross-sections of nucleon-nucleon and meson-nucleon interaction, and $n_M(t)$ and $n_G(t)$ are the effective numbers of created mesons and radiated gluons, respectively, and are explicitly given in ref. [5]. There the color-dipole picture was employed by replacing each radiated gluon by a color-octet $q\bar{q}$ pair.

The cross-section (18) 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 Q^2-dependence of the effective cross-section, calculated with the set of parameters given in ref. [5], is exhibited.

4 Results and discussion

Equation (14) is the basic equation that one has to evaluate in order to provide a quantitative significant description of the semi-exclusive process $A(e,e'(A-1))X$;

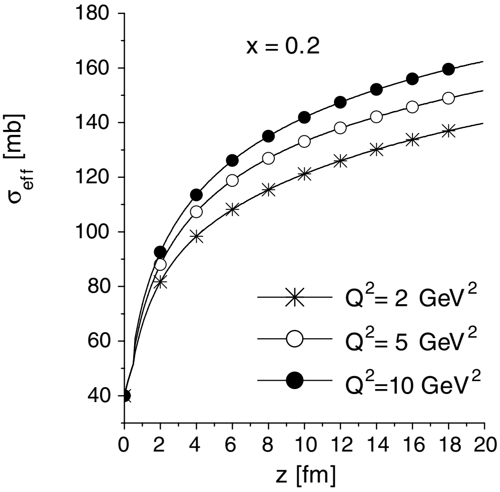

Fig. 1. The debris-nucleon effective cross-section (eq. (18)) plotted *vs.* the distance z for a fixed value of the Bjorken scaling variable x and various values of the four-momentum transfer Q^2 (after ref. [5]).

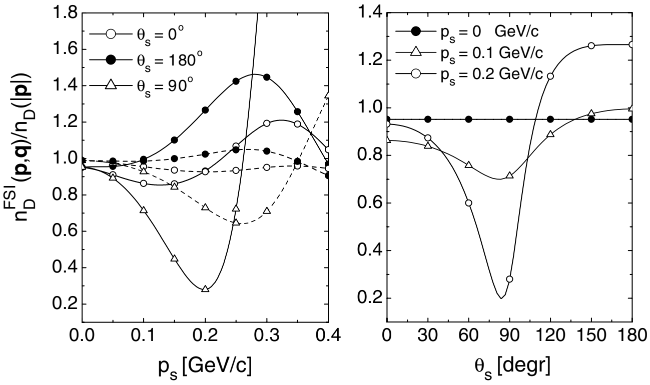

Fig. 2. Left panel: the deep inelastic scattering ratio $n_D^{\rm FSI}/n_D$ with $n_D^{\rm FSI}$ and n_D given, respectively, by eqs. (16) and (12), calculated *vs.* the momentum $p_s \equiv |\mathbf{p}_s|$ of the spectator nucleon emitted at different angles θ_s. The full lines correspond to the Q^2- and z-dependent debris-nucleon effective cross-section $\sigma_{\rm eff}$ shown in fig. 1, whereas the dashed lines correspond to a constant cross-section $\sigma_{\rm eff} = 20\,\rm mb$. Right panel: the same as in the left panel *vs.* the spectator emission angle θ_s for different values of the spectator momentum. Calculations have been performed at $Q^2 = 5\ ({\rm GeV}/c)^2$ and $x = 0.2$.

the latter, as already mentioned, has been originally suggested [6] as a powerful tool to investigate the reaction mechanism of DIS off nuclei and the bound-nucleon structure function; it was however soon realized [5] that it could also be an extremely powerful tool to investigate the hadronization mechanism. In the present paper we will focus on both aspects of the problem, namely we will address the problem of finding two different kinematics, one in which FSI corrections are negligibly small, so that a direct study of the DIS nucleon (neutron) structure functions becomes possible, and another one, where FSI effects are maximized, thus obtaining information on the hadronization mechanism. As can be seen from eq. (14), all of the FSI effects are contained in the distorted momentum distribution $n_D^{\rm FSI}(\mathbf{p}_s, \mathbf{q})$ (eq. (16)), so that the investigation of its deviation from the nucleon momentum distributions ($n_D(|\mathbf{p}|)$)) could provide clear signature on FSI effects. This is illustrated in fig. 2, which shows the ratio $n_D^{\rm FSI}/n_D$, (with $n_D^{\rm FSI}$ and n_D given by eqs. (16) and (12), respectively) calculated using two different models for the effective cross-section $\sigma_{\rm eff}$, representing its upper and lower limits, viz the time- and Q^2- dependent cross-section of ref. [5] (solid lines), and a constant cross-section $\sigma_{\rm eff} = 20\,\rm mb$ (dashed lines) considered in ref. [8]. In our numerical calculations the parameters entering eq. (17), viz the slope b_0 and the ratio α of the real to the imaginary part 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. 2 that the predictions given by the two different models of the effective cross-section are rather different, particularly when the recoiling proton is emitted perpendicularly to $\mathbf{q}$, *i.e.* at $\theta_s \sim 90°$, and with large values of the momentum ($p_s \sim 0.2\,{\rm GeV}/c$). Thus, by investigating this kinematical region one could, in principle, obtain unique information about the magnitude of $\sigma_{\rm eff}$ and, consequently, about the hadronization mechanism.

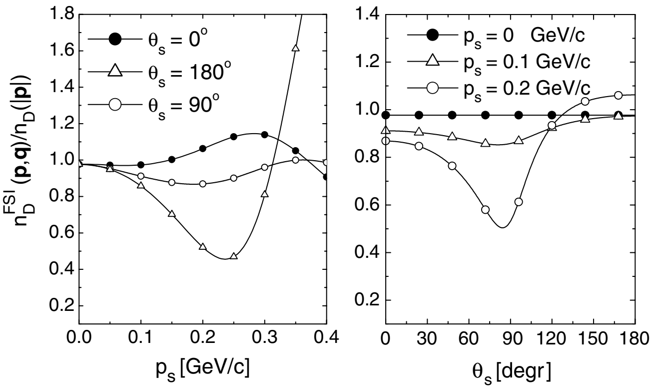

Fig. 3. Left panel: the quasi-elastic scattering ratio $n_D^{\rm FSI}/n_D$ with $n_D^{\rm FSI}$ and n_D given, respectively, by eqs. (16) and (12), calculated with the nucleon-nucleon $\sigma_{\rm eff}$, *i.e.* $\sigma_{\rm eff} = 44\,\rm mb$, *vs.* the momentum $p_s \equiv |\mathbf{p}_s|$ of the spectator nucleon emitted at different angles θ_s. Right panel: the same as in the left panel *vs.* the spectator emission angle θ_s for different values of the spectator momentum. Calculations have been performed at $Q^2 = 5\ ({\rm GeV}/c)^2$ and $x = 0.2$.

In order to illustrate the different role played by the FSI in deep inelastic and quasi-elastic scattering, we show in fig. 3 the ratio $n_D^{\rm FSI}/n_D$ for the QE process $^2{\rm H}(e, e'n)p$, which corresponds to the calculation of $n_D^{\rm FSI}$ using the effective nucleon-nucleon cross-section, *i.e.* $\sigma_{\rm eff} = 44\,\rm mb$. It can be seen, in agreement with the results for heavier nuclei [5], that the survival probability of $(A-1)$ in DIS is less than in QE scattering.

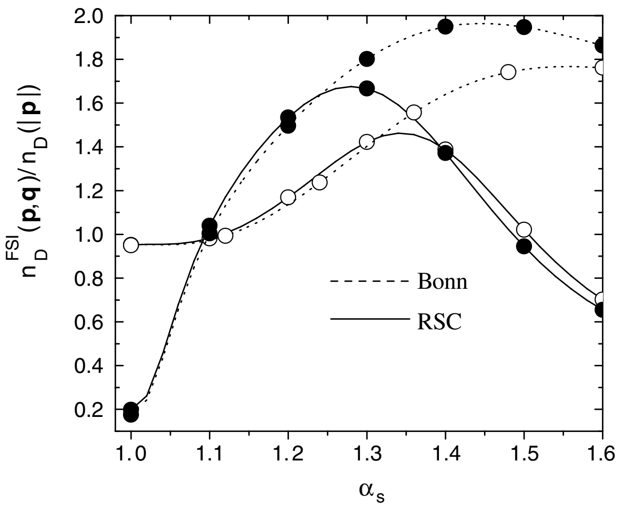

Fig. 4. The deep inelastic scattering ratio n_D^{FSI}/n_D *vs.* the light-cone variable α_s (cf. eq. (6)), calculated at $Q^2 = 5\,\mathrm{GeV}^2/c^2$ and $x = 0.2$ using two different deuteron wave functions: the solid lines correspond to the RSC potential and the dashed lines to the Bonn potential. Calculations have been performed in correspondence of two values of the transverse momentum p_T of the recoiling nucleon (cf. eq. (6)), namely $p_T = 0\,\mathrm{GeV}/c$ (open dots) and $p_T = 0.2\,\mathrm{GeV}/c$ (full dots). The results correspond to the debris-nucleon cross-section shown in fig. 1.

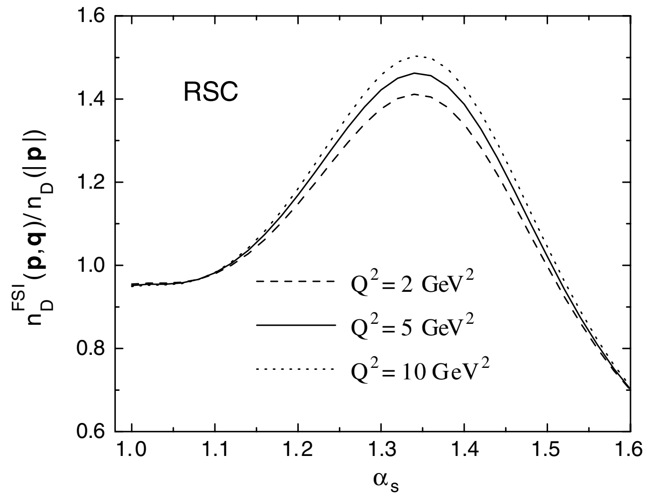

Fig. 5. The deep inelastic scattering ratio n_D^{FSI}/n_D *vs.* the light-cone variable α_s (cf. eq. (6)), calculated at different values of Q^2 and fixed values of $x = 0.2$ and $p_T = 0\,\mathrm{GeV}/c$. The deuteron wave function corresponds to the RSC interaction.

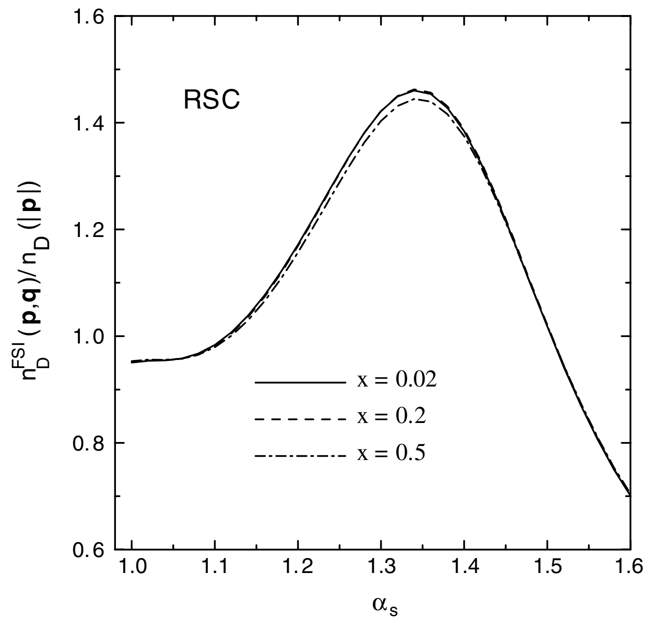

Fig. 6. The same as in fig. 5 for various values of the Bjorken scaling variable x and fixed values of $Q^2 = 5\ (\mathrm{GeV}/c)^2$ and $p_T = 0\,\mathrm{GeV}/c$. The solid and dashed lines practically coincide.

The results exhibited in figs. 2 and 3 also demonstrate that FSI effects are essentially reduced in parallel kinematics ($\theta = 0°, 180°$) and also at small values of p_s. This region is attractive from the experimental point of view since in such a kinematics the structure functions W_{LT} and W_{TT} in eq. (3) vanish exactly and the effective structure function F_2 in eq. (11) exactly coincides with the DIS structure function of a bound nucleon. Thus, in this kinematical region a direct experimental study of the off-mass shell effects in DIS becomes possible. The results exhibited in figs. 2 and 3 have been obtained by using the deuteron wave function corresponding to the Reid soft-core (RSC) potential [16]. At small values of $|\mathbf{p}|$ different potential models provide basically the same deuteron wave function, which is not true, however, at moderate and large values of $|\mathbf{p}|$. Therefore, we have investigated the dependence of the ratio n_D^{FSI}/n_D upon the two-body potential used to generate the deuteron wave function. The results are presented in fig. 4 where the predictions of the Reid and Bonn [17] potentials are compared in correspondence of two different values of the transverse momentum p_T (cf. eq. (6)). It can be seen that, independently of the emission angle of the spectator nucleon, the two potentials provide essentially the same results at relatively small values of the spectator momenta $|\mathbf{p}_s|$, but very different results at large values of $|\mathbf{p}_s|$ ($|\mathbf{p}_s| \geq 0.25\,\mathrm{GeV}/c$).

The dependence of the ratio n_D^{FSI}/n_D upon the electron kinematics (Q^2 and x) is entirely contained in the Q^2- and x-dependence of the effective cross-section σ_{eff} given by eq. (18). Since this dependence is weak (see fig. 1), FSI effects in the quasi-exclusive process ${}^2\mathrm{H}(e, e'p)X$ are practically Q^2- and x-independent (see, *e.g.*, figs. 5 and 6).

To sum up, from the analysis we have exhibited, it can be concluded that FSI effects in the semi-exclusive process (1) are negligible in the backward kinematics with 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.

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