Investigation of the neutron structure function via semi-inclusive deep inelastic electron scattering off the deuteron

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Abstract: The production of slow nucleons in semi-inclusive deep inelastic electron scattering off the deuteron is investigated in the region $x \gtrsim 0.3$ for kinematical conditions accessible at $HERA$. Within the spectator mechanism the semi-inclusive cross section exhibits a scaling property, which can be used as a model-independent test of the dominance of the spectator mechanism itself, providing in this way an interesting tool to investigate the neutron structure function. The possibility of extracting model-independent information on the neutron to proton structure function ratio from semi-inclusive experiments is also illustrated.

Untill now, experimental information on the structure function of the neutron has been inferred from nuclear (usually deuteron) deep inelastic scattering (DIS) data [1] by unfolding the neutron contribution from the inclusive nuclear cross section. Such a procedure typically involves the subtraction of both Fermi motion effects and contributions from different nuclear constituents (i.e., nucleons, mesons, isobars, ...), leading to non-trivial ambiguities related to the choice of the model used to describe the structure of the target and the mechanism of the reaction. An interesting way to get information on the neutron structure function could be the investigation of semi-inclusive DIS reactions of leptons off the deuteron. In Ref. [2] the process $^2H(\ell, \ell' N)X$ has been investigated at moderate and large values of the Bjorken variable $x \equiv Q^2/2M\nu$ ($x \gtrsim 0.3$) within the so-called spectator mechanism, according to which, after lepton interaction with a quark of a nucleon in the deuteron, the spectator nucleon is emitted because of recoil and detected in coincidence with the scattered lepton. It has been shown [2] that the semi-inclusive cross section corresponding to such a mechanism exhibits a scaling property (the spectator scaling), which can be used as a model-independent test of the dominance of the spectator mechanism itself. In the spectator-scaling regime the neutron structure function can be investigated from semi-inclusive data and, moreover, the neutron to proton structure function ratio $R^{(n/p)}(x, Q^2) \equiv F_2^n(x, Q^2)/F_2^p(x, Q^2)$ can be obtained directly from the ratio of the semi-inclusive cross sections of the processes $^2H(e, e'p)X$ and $^2H(e, e'n)X$.

The aim of this contribution is to address the issue of the spectator scaling in case of electron kinematical conditions accessible at $HERA$. To this end, let us briefly remind that the semi-inclusive cross section of the process $^2H(e, e'N)X$ reads as follows

$$\frac{d^4\sigma}{dE_{e'}\ d\Omega_{e'}\ dE_2\ d\Omega_2} = \sigma_{Mott}\ p_2\ E_2\ \sum_i\ V_i\ W_i^D(x, Q^2; \vec{p}_2) \tag{1}$$

where E_e ($E_{e'}$) is the initial (final) energy of the electron; $Q^2 \equiv -q^2 = |\vec{q}|^2 - \nu^2$ is the squared four-momentum transfer; $i \equiv \{L, T, LT, TT\}$ identifies the different types of semi-inclusive response functions (W_i^D) of the deuteron; $\vec{p}_2$ is the momentum of the detected nucleon; $E_2 = \sqrt{M^2 + p_2^2}$ its energy ($p_2 \equiv |\vec{p}_2|$) and V_i is a virtual photon flux factor (see [2]). Within the spectator mechanism the virtual photon is absorbed by a quark belonging to the nucleon N_1 in the deuteron and the recoiling nucleon N_2 is emitted and detected in coincidence with the scattered electron. Thus, Eq. (1) can be written in terms of the structure function $F_2^{N_1}(x^*, Q^2)$ of the struck nucleon as [2]

$$\frac{d^4\sigma}{dE_{e'}\ d\Omega_{e'}\ dE_2\ d\Omega_2} = K\ M\ p_2\ n^{(D)}(p_2)\ \frac{F_2^{N_1}(x^*, Q^2)}{x^*}\ D^{N_1}(x, Q^2; \vec{p}_2) \tag{2}$$

where $n^{(D)}$ is the (non-relativistic) nucleon momentum distribution in the deuteron, $x^* \equiv Q^2/(Q^2 + M_1^{*2} - M^2)$ and M_1^* is the invariant mass of the struck nucleon, given through the energy and momentum conservations by: $M_1^* = \sqrt{(\nu + M_D - E_2)^2 - (\vec{q} - \vec{p}_2)^2}$, with M_D being the deuteron mass. In Eq. (2) $K \equiv (2Mx^2 E_e E_{e'}/\pi Q^2)\,(4\pi\alpha^2/Q^4)\ [1 - y + (y^2/2) + (Q^2/4E_e^2)]$, with $y \equiv \nu/E_e$, and the quantity $D^{N_1}(x, Q^2; \vec{p}_2)$ depends both upon kinematical factors and the ratio $R_{L/T}^{N_1}$ of the longitudinal to transverse cross section off the nucleon (see [2]). The relevant quantity, which will be discussed hereafter, is related to the semi-inclusive cross section (1) by

$$\begin{aligned} F^{(s.i.)}(x, Q^2; \vec{p}_2) &\equiv \frac{1}{\tilde{K}}\ \frac{d^4\sigma}{dE_{e'}\ d\Omega_{e'}\ dE_2\ d\Omega_2} \\ &= M\ p_2\ n^{(D)}(p_2)\ \frac{F_2^{N_1}(x^*, Q^2)}{x^*}\ \tilde{D}^{N_1}(x, Q^2; \vec{p}_2) \end{aligned} \tag{3}$$

where $\tilde{K}$ is a kinematical factor given by $\tilde{K} \equiv K\ [D^{N_1}(x, Q^2; \vec{p}_2)]_{R_{L/T}^{N_1}=0}$ and $\tilde{D}^{N_1}(x, Q^2; \vec{p}_2) = D^{N_1}(x, Q^2; \vec{p}_2)\ /\ [D^{N_1}(x, Q^2; \vec{p}_2)]_{R_{L/T}^{N_1}=0}$. Eq. (3) differs from the definition of $F^{(s.i.)}$ given in [2], for $\tilde{K}$, which incorporates kinematical factors depending on $\vec{p}_2$, is used instead of K, which depends only on the electron kinematical variables.

In the Bjorken limit one would expect $R_{L/T}^{N_1} \to_{Bj} 0$, so that $\tilde{D}^{N_1} \to_{Bj} 1$, which implies $F^{(s.i.)}(x, Q^2; \vec{p}_2) \to_{Bj} M\ p_2\ n^{(D)}(p_2)\ F_2^{N_1}(x^*)/x^*$, where $F_2^{N_1}(x^*)$ stands for the nucleon structure function in the Bjorken limit (apart from logarithmic QCD corrections). Therefore, in the Bjorken limit and at fixed values of p_2 the function (3) does not depend separately upon x and the nucleon detection angle θ_2, but only upon the variable $x^* \to_{Bj} x/(2 - z_2)$, with $z_2 = [E_2 - p_2 cos(\theta_2)]/M$ being the light-cone momentum fraction of the detected nucleon. In what follows, we will refer to the function $F^{(sp)}(x^*, Q^2, p_2)$ and variable x^*, given explicitly by

$$F^{(sp)}(x^*, Q^2, p_2) \equiv M\ p_2\ n^{(D)}(p_2)\ F_2^{N_1}(x^*, Q^2)\ /\ x^* \tag{4}$$

$$x^* \equiv \frac{Q^2}{Q^2 + (\nu + M_D - E_2)^2 - (\vec{q} - \vec{p}_2)^2 - M^2} \tag{5}$$

as the spectator-scaling function and variable, respectively. The essence of the spectator scaling relies on the fact that the variable x^* gathers different electron and nucleon kinematical conditions (in x and θ_2), corresponding to the same value of the invariant mass produced on the struck nucleon. The deuteron response will be the same only if the spectator mechanism dominates and, therefore, the experimental observation of the spectator scaling represents a test of the dominance of the spectator mechanism itself.

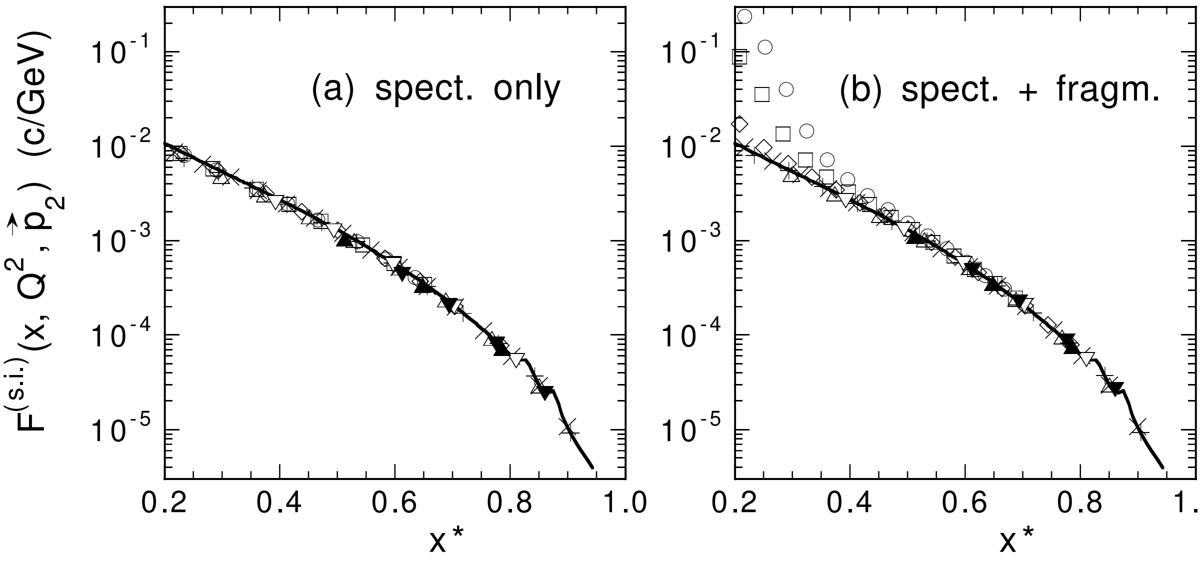

Fig. 1. (a) The function $F^{(s.i.)}(x, Q^2, \vec{p}_2)$ (Eq. (3)) for the process $^2H(e, e'p)X$ plotted versus the spectator-scaling variable x^* (Eq. (5)) at $Q^2 = 10\ (GeV/c)^2$ and $p_2 = 0.5\ GeV/c$. The values of x have been varied in the range $0.20 \div 0.95$, whereas the various markers correspond to different values of the nucleon detection angle θ_2 chosen in the range $10^o \div 150^o$. The solid line is the spectator-scaling function $F^{(sp)}(x^*, Q^2, p_2)$ (Eq. (4)) calculated using the deuteron momentum distribution corresponding to the Paris nucleon-nucleon interaction [5] and to the parametrization of the neutron structure function of Ref. [3]. (b) The same as in (a), but including the effects of the target fragmentation of the struck nucleon, evaluated as in Ref. [6], as well as the contribution of the proton emission arising from virtual photon absorption on 6q cluster configurations in the deuteron, evaluated following Ref. [9] and adopting a 6q bag probability equal to 2%. In particular, the open dots and squares, which exhibit large violations of the spectator scaling, correspond to $\theta_2 = 10^o$ and 30^o, respectively.

Eq. (3) has been calculated considering electron kinematical conditions accessible at $HERA$ (i.e., $E_e = 30\ GeV$ and $Q^2 = 10\ (GeV/c)^2$) and $p_2 = 0.1,\ 0.3,\ 0.5\ GeV/c$. The Bjorken variable x and the nucleon detection angle θ_2 have been varied in the range $0.20 \div 0.95$ and $10^o \div 150^o$, respectively (for sake of simplicity, the polar angle ϕ_2 has been chosen equal to 0). As for the nucleon structure function, the parametrization of the $SLAC$ data of Ref. [3], containing $R_{L/T}^{N_1} \simeq 0.18$, has been adopted. The results of the calculations, performed at $p_2 = 0.5\ GeV/c$, are shown in Fig. 1(a) and compared with the spectator-scaling function (4). It can clearly be seen that at $Q^2 = 10\ (GeV/c)^2$ the spectator scaling is almost completely fulfilled (within 10%) in the whole x-range, including the region at $x^* \gtrsim 0.8$, where (small) contributions from nucleon resonances are still visible. Using the new definition (3), the spectator scaling is fulfilled not only at $p_2 \lesssim 0.3\ GeV/c$, as shown in [2], but also at higher values of p_2.

In the spectator-scaling regime the measurement of the semi-inclusive cross section both for the $^2H(e, e'p)X$ and $^2H(e, e'n)X$ processes would allow the investigation of two spectator-scaling functions, involving the same nuclear part, $Mp_2n^{(D)}(p_2)$, and the neutron and proton structure functions, respectively. Therefore, assuming $R_{L/T}^n = R_{L/T}^p$ (as it is suggested by recent $SLAC$ data analyses [4]), both the nuclear part and the factor $\tilde{D}^{N_1}(x, Q^2; \vec{p}_2)$ cancel out in the ratio $R^{(s.i.)}(x, Q^2, \vec{p}_2) \equiv d^4\sigma[^2H(e, e'p)X]/d^4\sigma[^2H(e, e'n)X]$, which provides in this way directly the neutron to proton structure function ratio $R^{(n/p)}(x^*, Q^2)$. With respect to the function $F^{(s.i.)}(x, Q^2, \vec{p}_2)$, the ratio $R^{(s.i.)}(x, Q^2, \vec{p}_2)$ exhibits a more general scaling property, for

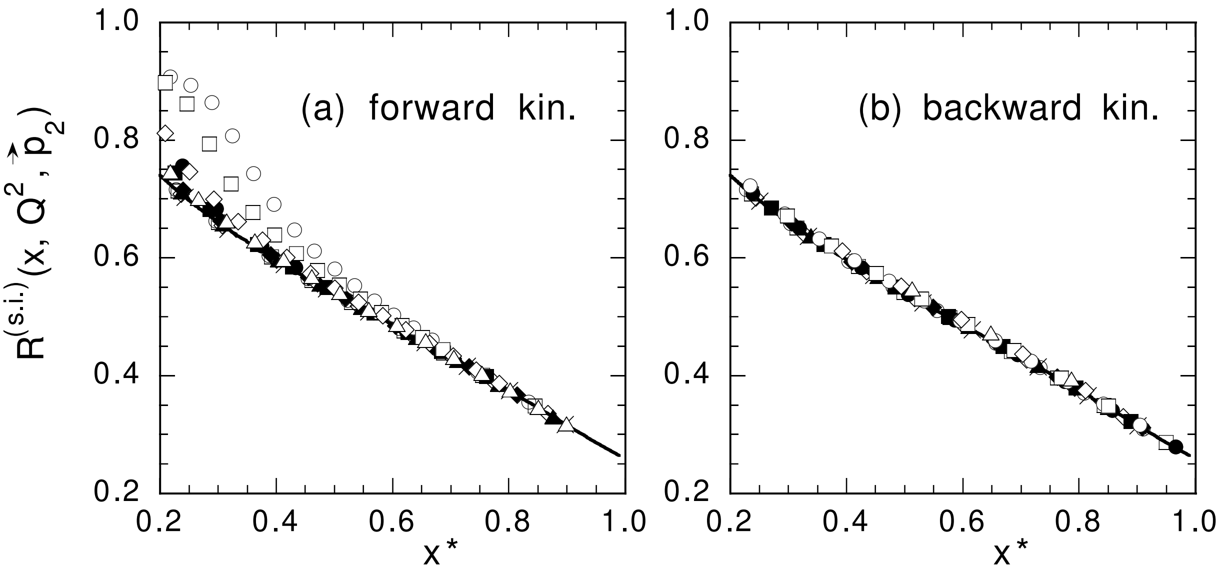

Fig. 2. The ratio $R^{(s.i.)}(x, Q^2, \vec{p}_2)$ of the semi-inclusive cross sections for the processes $^2H(e,e'p)X$ and $^2H(e,e'n)X$, calculated at $Q^2 = 10$ $(GeV/c)^2$ and $p_2 = 0.1, 0.3, 0.5$ GeV/c. The values of x have been varied in the range $0.20 \div 0.95$. Forward ($\theta_2 < 90^o$) and backward ($\theta_2 > 90^o$) nucleon emissions are shown in (a) and (b), respectively. The solid line is the neutron to proton structure function ratio $R^{(n/p)}(x^*, Q^2)$ calculated using the parametrization of the nucleon structure function of Ref. [3].

at fixed Q^2 it does not depend separately upon x, p_2 and θ_2, but only on x^*. This means that any p_2-dependence of the ratio $R^{(s.i.)}$ would allow to investigate off-shell deformations of the nucleon structure functions (see below).

The results presented and, in particular, the spectator-scaling properties of $F^{(s.i.)}$ and $R^{(s.i.)}$ could in principle be modified by the effects of mechanisms different from the spectator one, like, e.g., the fragmentation of the struck nucleon, or by the breakdown of the impulse approximation. In order to estimate the effects of the so-called target fragmentation of the struck nucleon (which is thought to be responsible for the production of slow hadrons in DIS processes), we adopt the approach of Ref. [6], where the hadronization mechanism has been parametrized through the use of fragmentation functions, whose explicit form has been chosen according to the prescription of Ref. [7], elaborated to describe the production of slow protons in DIS of (anti)neutrinos off hydrogen and deuterium targets. Furthermore, the effects arising from possible six-quark ($6q$) cluster configurations at short internucleon separations, are explicitly considered. According to the mechanism first proposed in Ref. [8], after lepton interaction with a quark belonging to a $6q$ cluster, nucleons can be formed out of the penta-quark residuum and emitted forward as well as backward. The details of the calculations can be easily inferred from Ref. [9], where $6q$ bag effects in semi-inclusive DIS of leptons off light and complex nuclei have been investigated. The estimate of the nucleon production, arising from the above-mentioned target fragmentation processes, is shown in Fig. 1(b) for the function $F^{(s.i.)}$ and in Fig. 2 for the ratio $R^{(s.i.)}$. It can clearly be seen that: i) only at $x^* \lesssim 0.4$ the fragmentation processes can produce relevant violations of the spectator scaling (see Figs. 1(b) and 2(a)); ii) backward kinematics (see Fig. 2(b)) appear to be the most appropriate conditions to extract the neutron to proton ratio $R^{(n/p)}$. Moreover, explicit calculations show that the relevance of the fragmentation processes drastically decreases when $p_2 < 0.5$ GeV/c.

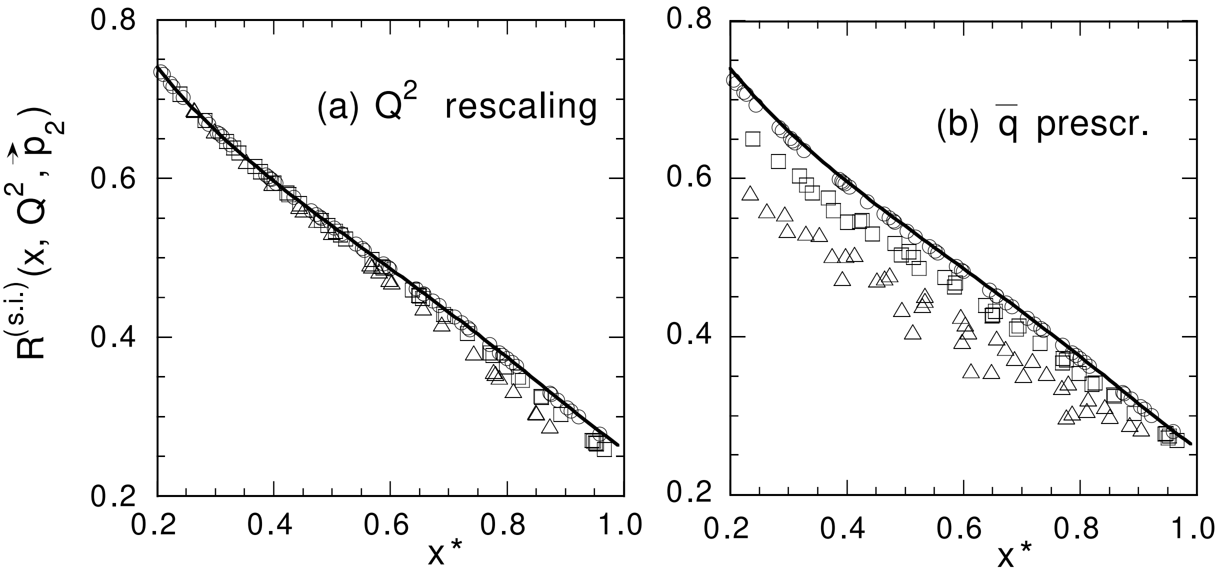

Fig. 3. The ratio $R^{(s.i.)}(x, Q^2, \vec{p}_2)$ of the semi-inclusive cross sections for the processes $^2H(e, e'p)X$ and $^2H(e, e'n)X$, calculated considering the off-shell effects proposed in Refs. [13] (a) and [14] (b), respectively. Backward nucleon kinematics only ($\theta_2 > 90^o$) have been considered. The dots, squares and triangles correspond to $p_2 = 0.1,\ 0.3,\ 0.5\ GeV/c$, respectively. The solid line is the same as in Fig. 2.

As far as the impulse approximation is concerned, it should be reminded that our calculations have been performed within the assumption that the debris produced by the fragmentation of the struck nucleon does not interact with the recoiling spectator nucleon. Estimates of the final state interactions of the fragments in semi-inclusive processes off the deuteron have been obtained in [10], suggesting that rescattering effects should play a minor role thanks to the finite formation time of the dressed hadrons. Moreover, backward nucleon emission is not expected to be sensitively affected by forward-produced hadrons (see [11]), and final state interaction effects are expected to cancel out (at least partially) in the cross section ratio $R^{(s.i.)}(x, Q^2, \vec{p}_2)$. Besides fragmentation processes and final state interactions, also nucleon off-shell effects [12] might produce violations of the spectator scaling, in particular at high values of p_2 ($\gtrsim 0.3\ GeV/c$). The results of the calculations of the ratio $R^{(s.i.)}(x, Q^2, \vec{p}_2)$, obtained considering the off-shell effects suggested in Refs. [13] and [14], are shown in Fig. 3(a) and 3(b), respectively. It can be seen that the measurement of the ratio $R^{(s.i.)}(x, Q^2, \vec{p}_2)$ represents an interesting tool both to investigate the ratio of free neutron to proton structure function, provided $p_2 \sim 0.1 \div 0.2\ GeV/c$, and to get information on the possible off-shell behaviour of the nucleon structure function when $p_2 \gtrsim 0.3\ GeV/c$.

In conclusion, the production of slow nucleons in semi-inclusive deep inelastic electron scattering off the deuteron has been investigated in kinematical regions accessible at $HERA$. Within the spectator mechanism the semi-inclusive cross section exhibits the spectator-scaling property, which can be used as a model-independent test of the dominance of the spectator mechanism itself. In the spectator-scaling regime both the neutron structure function and the neutron to proton structure function ratio can be obtained directly from semi-inclusive DIS data off the deuteron. Finally, the pattern of possible spectator-scaling violations could provide relevant information on the off-shell behaviour of the nucleon structure function in the medium.

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