Tagged nuclear structure functions with $HERMES$

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Abstract: The production of slow nucleons in semi-inclusive deep inelastic electron scattering off nuclei, $A(e, e'N)X$, is analyzed for kinematical conditions accessible at $HERA$ with the $HERMES$ detector. The sensitivity of the semi-inclusive cross section to possible medium-dependent modifications of the nucleon structure function is illustrated.

The investigation of deep inelastic scattering (DIS) of leptons off the nucleon and nuclei is a relevant part of the experimental activity proposed both at present electron facilities, like $HERA$ and $TJNAF$, and at possible future ones, like $ELFE$ and GSI. As is well known, existing inclusive DIS data [1] have provided a wealth of information on quark and gluon distributions in the nucleon and nuclei. However, important questions, concerning, e.g., the mechanism of quark and gluon confinement as well as the origin of the EMC effect, are still awaiting for more clear-cut answers. To this end, the investigation of semi-inclusive DIS processes is expected to be of great relevance. Recently, in [2]-[5] the production of slow nucleons[a] in semi-inclusive DIS processes off nuclei, $A(\ell, \ell' N)X$, has been analyzed within the so-called spectator mechanism, according to which, after lepton interaction with a quark belonging to a nucleon of a correlated nucleon-nucleon (NN) pair, the recoiling nucleon is emitted and detected in coincidence with the scattered lepton. The basic idea is that the momentum of the recoiling nucleon carries information on the momentum of the struck nucleon before lepton interaction, allowing to tag the structure function of a nucleon bound in a nucleus. In Ref. [5] the semi-inclusive reaction $^2H(\ell, \ell' N)X$ has been analyzed, showing that the experimental investigation of this process can be an effective tool to get information on the neutron structure function as well as on the neutron to proton structure function ratio. The aim of this contribution is to show that, at kinematical conditions accessible at $HERA$ with $HERMES$, the semi-inclusive cross section of the process $A(e, e'N)X$, for $A > 2$, exhibits an appreciable sensitivity to possible medium-dependent modifications of the nucleon structure function.

In case of electron scattering the semi-inclusive cross section reads as follows

$$\frac{d^4\sigma}{dE_{e'}\ d\Omega_{e'}\ dE_2\ d\Omega_2} = p_2\ E_2\ \sigma_{Mott} \sum_{i=L,T,LT,TT} V_i(x, Q^2)\ W_i^A(x, Q^2, \vec{p}_2) \tag{1}$$

[a]By slow nucleons we mean nucleons with momentum up to $\sim 0.7\ GeV/c$ in a frame where the target is at rest (lab system).

where $x = Q^2/2M\nu$ is the Bjorken variable; $Q^2 = -q^2 = \vec{q}^2 - \nu^2 > 0$ is the squared four-momentum transfer; V_i is a kinematical factor; W_i^A is the semi-inclusive nuclear response; $\vec{p}_2$ is the momentum of the detected nucleon and $E_2 \equiv \sqrt{M^2 + p_2^2}$ its energy ($p_2 \equiv |\vec{p}_2|$).

Let us consider the process in which a virtual photon interacts with a nucleon of a correlated NN pair, and the recoiling nucleon is emitted and detected in coincidence with the scattered electron. Within the impulse approximation and in the Bjorken limit, the semi-inclusive nuclear structure function $F_2^A(x, \vec{p}_2)$ is given by the following convolution formula (cf. [2])

$$\begin{aligned} F_2^A(x,\vec{p}_2) \;&=\; M \sum_{N_1=n,p} Z_{N_1} \int_x^{\frac{M_A}{M}-z_2} dz_1 \; z_1 \; F_2^{N_1}(\frac{x}{z_1}) \int d\vec{k}_{c.m.} \; dE^{(2)} \\ & P_{N_1N_2}(\vec{k}_{c.m.} - \vec{p}_2, \vec{p}_2, E^{(2)}) \; \delta(M_A - M(z_1+z_2) - M_{A-2}^f z_{A-2}) \end{aligned} \tag{2}$$

where $Z_{p(n)}$ is the number of protons (neutrons); $\vec{k}_1$ and $\vec{k}_2$ are initial nucleon momenta in the lab system before interaction with c.m. momentum $\vec{k}_{c.m.} = \vec{k}_1 + \vec{k}_2$; $\vec{p}_1 = \vec{k}_1 + \vec{q}$ and $\vec{p}_2 = \vec{k}_2$ are nucleon momenta in the final state; F_2^N is the structure function of the struck nucleon. In Eq. (2), x/z_1 is the Bjorken variable of the struck nucleon having initial light-cone momentum $z_1 = k_1^+/M$; $z_2 = (E_2 - p_2\cos\theta_2)/M$ is the experimentally measurable light-cone momentum of the detected nucleon (θ_2 is the detection angle with respect to $\vec{q}$); $z_{A-2} = (\sqrt{(M_{A-2}^f)^2 + k_{c.m.}^2} + (k_{c.m.})_{||})/M_{A-2}^f$ is the light-cone momentum of the residual (A-2)-nucleon system with final mass $M_{A-2}^f = M_{A-2} + E_{A-2}^*$ and intrinsic excitation energy E_{A-2}^*. The relevant nuclear quantity in (2) is the two-nucleon spectral function $P_{N_1N_2}$, which represents the joint probability to find in a nucleus two nucleons with momenta $\vec{k}_1$ and $\vec{k}_2$ and removal energy $E^{(2)}$. For deuteron it simply reduces to the nucleon momentum distribution and for ^3He to the square of the wave function in momentum space, times the removal energy delta function $\delta(E^{(2)} - E_{thr}^{(2)})$, with $E_{thr}^{(2)} = 2M + M_{A-2} - M_A$ being the two-nucleon break-up threshold. In case of ^4He and heavier nuclei, the two-nucleon spectral function is not yet available in the exact form; however, realistic models taking into account those features of the two-nucleon spectral function which are relevant in the study of semi-inclusive DIS processes, have been developed [2]-[4]. In this contribution the $2NC$ model of Ref. [6], where the c.m. motion of the correlated pair is properly taken into account, is adopted, viz.

$$P_{N_1N_2}(\vec{k}_1, \vec{k}_2, E^{(2)}) = n_{N_1N_2}^{rel}(|\vec{k}_1 - \vec{k}_2|/2) \; n_{N_1N_2}^{c.m.}(|\vec{k}_1 + \vec{k}_2|) \; \delta(E^{(2)} - E_{thr}^{(2)}) \tag{3}$$

where $n_{N_1N_2}^{rel}$ and $n_{N_1N_2}^{c.m.}$ are the momentum distribution of the relative and c.m. motion of the correlated N_1N_2 pair, respectively. We point out that the $2NC$ model reproduces the high momentum and high removal energy components of the single-nucleon spectral function of ^3He and nuclear matter, calculated using many-body approaches, as well as the high momentum part of the single-nucleon momentum distribution of light and complex nuclei (see [6]). Therefore, in the kinematical region $0.3\ GeV/c \lesssim p_2 \lesssim 0.7\ GeV/c$ for the momentum of the recoiling nucleon, the non-relativistic description (3) of the nuclear structure is expected to be well grounded. Using the $2NC$ model, the nuclear effects on the energy and angular distributions of the nucleons produced in semi-inclusive $A(e, e'N)X$ processes have been extensively investigated [2]-[4], showing that backward emission is strongly enhanced when the effects due to the c.m. motion of the correlated pair are taken into account.

Besides the spectator mechanism, there are other reaction mechanisms which could lead to forward as well as backward nucleon emission, like, e.g., the so-called target fragmentation of the struck nucleon (see [2]) and the hadronization processes following lepton interactions with possible six-quark ($6q$) cluster configurations at short NN separations (see [3, 4]). Furthermore, it should be considered that within the spectator mechanism the virtual boson can be elastically absorbed by the struck nucleon. The contribution from this process, which involves the nucleon form factor instead of the nucleon structure function, vanishes in the Bjorken limit, but it can affect the semi-inclusive cross section at finite values of Q^2 and for $x \to 1$. In what follows, we will refer to such a process as the quasi-elastic (QE) contamination.

The semi-inclusive cross section of the process $^{12}C(e, e'p)X$ has been calculated including in (1) all the nuclear response functions and considering electron kinematical conditions accessible at $HERA$ with $HERMES$ (i.e., $E_e = 30\ GeV$ and Q^2 in the range $5 \div 15\ (GeV/c)^2$). The relative and c.m. momentum distributions adopted in the calculations are taken from [6]. As for the nucleon structure function, the parametrization of the $SLAC$ data of Ref. [7] has been considered. In case of backward proton emission the results obtained for the contributions resulting from the spectator mechanism, the (above-mentioned) hadronization processes and the QE contamination are separately shown in Fig. 1 as a function of the kinetic energy T_2 of the detected nucleon. It can clearly be seen that for $50\ MeV \lesssim T_2 \lesssim 250\ MeV$ (corresponding to $0.3\ GeV/c \lesssim p_2 \lesssim 0.7\ GeV/c$) backward nucleon emission is mainly governed by the spectator mechanism (cf. [2]-[4]). Therefore, in what follows, we will limit ourselves to the case of backward nucleon emission.

In [2] a ratio of semi-inclusive cross sections, evaluated at different values of x but keeping fixed both Q^2 and the nucleon kinematical variables, has been introduced, viz.

$$R_1(x_0, x; Q^2, \vec{p}_2) \equiv d^4\sigma(x, Q^2, \vec{p}_2) \ / \ d^4\sigma(x_0, Q^2, \vec{p}_2) \tag{4}$$

The ratio R_1 turns out to be almost independent of the effects due to the rescattering of the recoiling nucleon with the residual $(A-2)$-nucleon system (cf. [2]); such an important feature is mainly due to the fact that the nucleon kinematical variables are the same in the numerator and denominator of the cross section ratio R_1. In order to investigate the sensitivity of R_1 to possible medium-dependent modifications of the nucleon structure function, three models available in the literature have been considered. In the first one [8] the valence-quark distributions in the nucleon are expected to be suppressed when the nucleon is bound in a nucleus, since point-like configurations (plc) in the nucleon should interact weaker in the medium with respect to normal-size configurations. In [8] the suppression factor is expected to be a function of the momentum of the struck nucleon. The second and third models are Q^2-rescaling models [9, 10], where the rescaling is driven by nucleon swelling [9] or by the off-shellness of the struck nucleon [10]. The results obtained are reported in Fig. 2 in terms of the ratio of the quantity R_1, evaluated using the medium-modified nucleon structure function, to the quantity R_1, calculated with the free F_2^N. It can clearly be seen that the ratio R_1 is remarkably sensitive to possible deformations of the nucleon structure function.

Another useful cross section ratio can be defined as

$$R_2(Q_0^2, Q^2; x, \vec{p}_2) \equiv d^4\sigma(x, Q^2, \vec{p}_2) \ / \ d^4\sigma(x, Q_0^2, \vec{p}_2) \tag{5}$$

where both x and the nucleon kinematical variables are kept fixed. The ratio R_2 is expected to be mainly dominated by the Q^2 behaviour of the nucleon structure function. As a matter of fact, explicit calculations show that R_2 is almost independent both of p_2 and of the mass number A, when the free nucleon structure function is adopted. Besides the three models

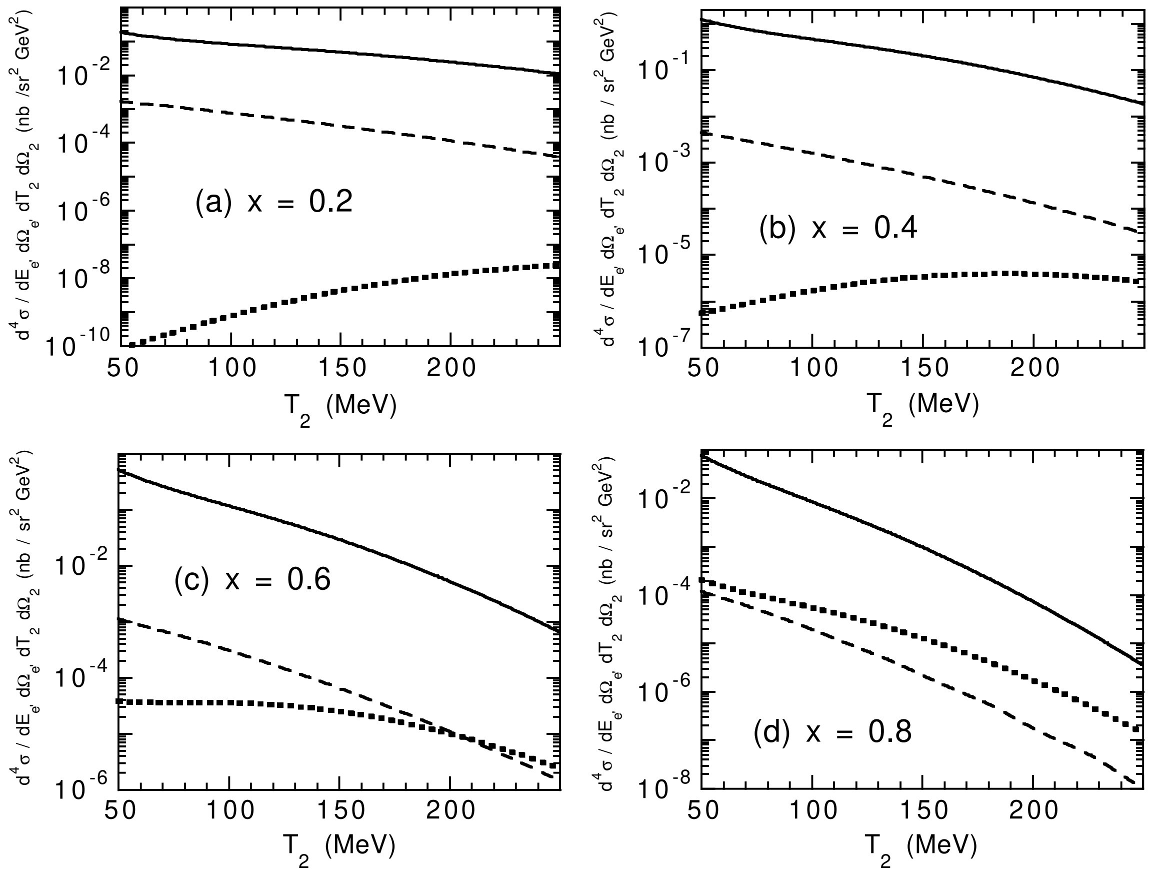

Fig. 1. The semi-inclusive cross section (1) of the process ${}^{12}C(e,e'p)X$, evaluated at $Q^2 = 10\ (GeV/c)^2$ and for backward proton emission at $\theta_2 = 140^o$, versus the kinetic energy T_2 of the detected nucleon at various values of the Bjorken variable x. The solid lines are the results obtained within the spectator mechanism. The dashed lines correspond to the proton emission arising both from the target fragmentation of the struck nucleon, evaluated as in [2], and from virtual photon absorption on 6q cluster configurations, evaluated as in [3, 4]. The dotted lines are the contribution from the QE contamination (see text).

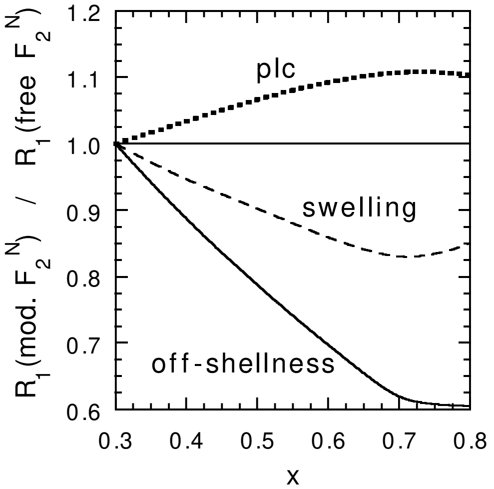

Fig. 2. The ratio of the quantity $R_1(x_0 = 0.3, x; Q^2, \vec{p}_2)$ (Eq. (4)), calculated using medium-modified and free nucleon structure functions. The calculations have been performed in case of the process ${}^{12}C(e,e'p)X$ at $Q^2 = 10\ (GeV/c)^2$, $p_2 = 0.4\ GeV/c$ and for backward proton kinematics ($\theta_2 = 140^o$). The dotted, dashed and solid lines correspond to the models of Refs. [8], [9] and [10], respectively.

employed in the calculations shown in Fig. 2, a further model [11] has been considered. It generates both x- and Q^2-rescaling of F_2^N, driven by binding effects on the energy transferred

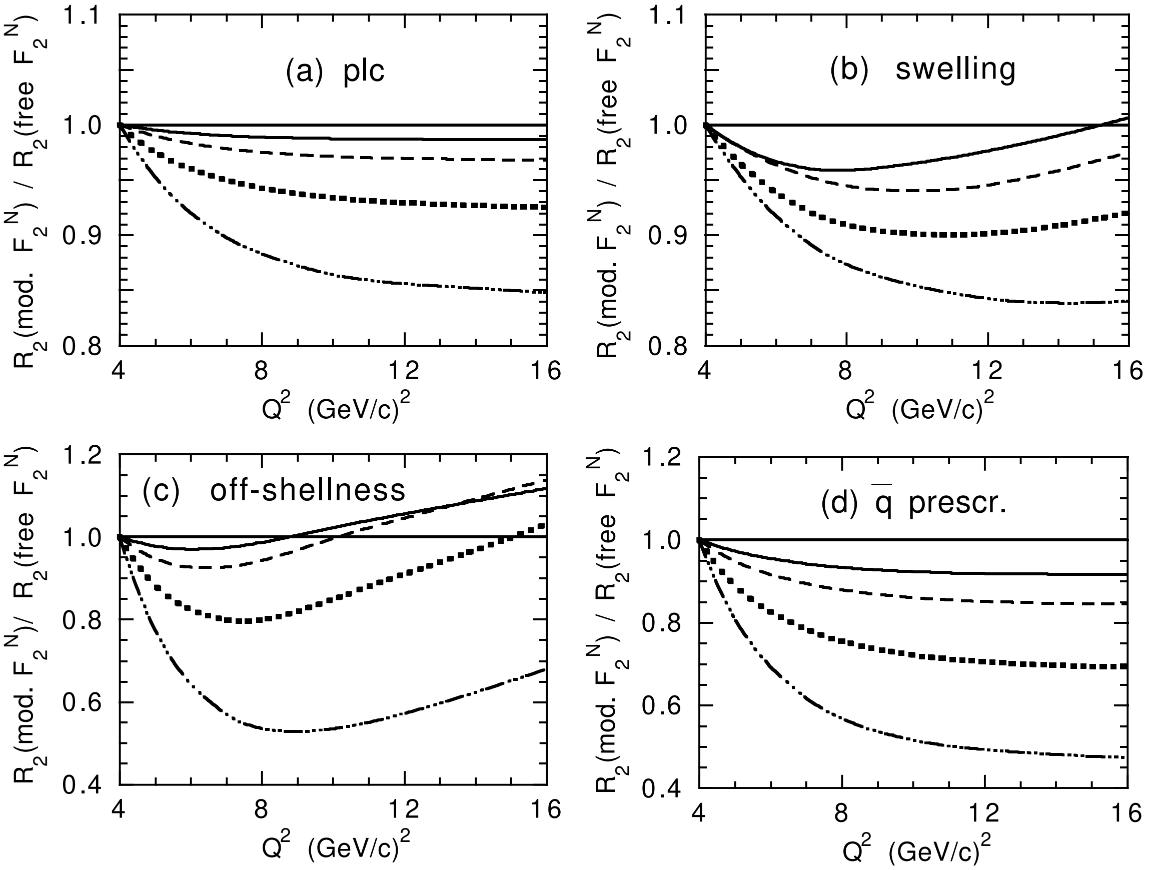

Fig. 3. The ratio of the quantity $R_2(Q_0^2 = 4\ (GeV/c)^2, Q^2; x, \vec{p}_2)$ (Eq. (5)), calculated using medium-modified and free nucleon structure functions. The calculations have been performed in case of the process $^{12}C(e,e'p)X$ at $x = 0.6$ and for backward nucleon kinematics ($\theta_2 = 140^o$). The solid, dashed, dotted and dot-dashed lines correspond to $p_2 = 0.3, 0.4, 0.5$ and 0.6 GeV/c, respectively. The models adopted for the description of the medium-dependent modifications of F_2^N are from [8] (a), [9] (b), [10] (c) and [11] (d), respectively.

to the struck nucleon. The results are shown in Fig. 3. It can be seen that also the ratio R_2 is appreciably affected by possible deformations of the nucleon structure function and, moreover, the p_2-dependence of the deviations with respect to the predictions obtained using free F_2^N, could provide relevant information on the type of medium effects on F_2^N.

Before closing, 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 [12], 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 (cf. [13]), and the effects due to the final state interactions of the fragments are expected to cancel out (at least partially) in the cross section ratios R_1 and R_2.

In conclusion, the production of slow nucleons in semi-inclusive deep inelastic electron scattering off nuclei, $A(e,e'N)X$, has been investigated in kinematical regions accessible at $HERA$ with the $HERMES$ detector. It has been shown that backward nucleon production is mainly governed by the spectator mechanism, provided the Bjorken variable x and the kinetic energy of the detected nucleon are in the range $0.2 \div 0.8$ and $50 \div 250$ MeV, respectively. The ratios (4) and (5) of the semi-inclusive cross sections, evaluated at different electron kinematics keeping fixed the nucleon ones, exhibit an appreciable sensitivity to possible medium-dependent modifications of the nucleon structure function.

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