Nucleon-Nucleon Correlations and Six-Quark Cluster Effects in Semi-Inclusive Deep Inelastic Lepton Scattering off Few-Nucleon Systems

C. Ciofi degli Atti\textsuperscript{(a)} and S. Simula\textsuperscript{(b)}

\textsuperscript{(a)}Department of Physics, University of Perugia and Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, Via A. Pascoli, I-06100 Perugia, Italy
\textsuperscript{(b)}Istituto Nazionale di Fisica Nucleare, Sezione Sanitá, Viale Regina Elena 299, I-00161 Roma, Italy

Abstract

Semi-inclusive deep inelastic lepton scattering off few-nucleon systems is investigated assuming that virtual boson absorption occurs on a hadronic cluster which can be either a two-nucleon correlated pair or a six-quark bag. In both cases the relevance of nuclear effects on forward and backward nucleon emissions is illustrated and the differences expected in the energy distribution of the emitted nucleons are analyzed both at $x < 1$ and $x > 1$. 

1
1. Introduction

The investigation of inclusive and exclusive deep inelastic scattering (DIS) of leptons off nuclei can shed light on the origin of nuclear forces and the short range structure of hadronic matter. Inclusive DIS processes off nuclei in the kinematics regions $x < 1$ ($x = Q^2/2M\nu$ being the Bjorken scaling variable) have provided a wealth of information on sea and valence quark distributions in nuclei [1]; however, much work remains to be done in order to unravel the short-range structure of hadronic matter. To this end, two other types of DIS processes would be of great relevance: i) inclusive scattering at $x > 1$, a process forbidden on a free nucleon, and, ii) semi-inclusive processes, in which, besides the scattered lepton, another particle is detected in the final state. As far as the first process is concerned, present experimental data do not reach sufficiently high values of the momentum transfer, so that at $x > 1$ they are mainly due to quasi-elastic scattering and not to DIS [2]; it is only recently that the deep inelastic nuclear structure function has been obtained in a narrow range of $x > 1$ ($x < 1.3$) [3]. As for the semi-inclusive processes, which could provide information on the effects of the nuclear medium on quark and gluon distributions, the relevance of exotic configurations at short nucleon-nucleon (NN) distances, and the mechanism of hadronization, several experiments have been performed [4] - [5], which however still lack of a clear-cut interpretation. In ref. [6] semi-inclusive DIS processes $A(\ell, \ell' N) X$ off complex nuclei have been analyzed within the so-called spectator mechanism according to which, after lepton interaction with a quark belonging to a nucleon of a correlated NN pair, the recoiling nucleon is emitted and detected in coincidence with the scattered lepton. It has been shown that at $x < 1$ the cross section corresponding to such a mechanism represents a valuable tool to detect the momentum and energy dependencies of the nucleon structure function in the nuclear medium, whereas at $x > 1$ it provides information on the short range part of light-cone momentum distributions. In ref. [7] the effects of six-quark ($6q$) cluster configurations upon nucleon emissions in semi-inclusive DIS processes off the deuteron have been investigated by considering that, after lepton interaction with a quark belonging to a $6q$ cluster, nucleons can be formed out of the penta-quark ($5q$)
residuum and emitted forward as well as backward. The aim of this paper is two-fold: i) to extend to few-nucleon systems the analysis of semi-inclusive DIS processes off complex nuclei performed in ref. [6] within the spectator mechanism; ii) to generalize the approach of ref. [6] to the case when the virtual boson is absorbed by a quark belonging to a colorless 6q bag. In case of electron scattering the semi-inclusive cross section reads as follows

$$\frac{d^4\sigma}{dx\,dQ^2\,d\vec{p}_2} = \sigma_{\text{Mott}} \sum_{i=1}^{4} V_i(x, Q^2) W_i^A(x, Q^2, \vec{p}_2)$$

(1)

where $Q^2 = -q^2 = \vec{q}^2 - \nu^2 > 0$ is the squared four-momentum transfer; $V_i$ is a kinematics factor; $W_i^A$ is the semi-inclusive nuclear response; $\vec{p}_2$ is the momentum of the detected nucleon. Although in this paper calculations will be presented including all four nuclear responses in (1), in what follows only the Bjorken limit of the structure function $F_A^2(x, Q^2, \vec{p}_2) \equiv \nu W_A^2(x, Q^2, \vec{p}_2)$ will formally be considered, since this suffices to illustrate the relevant features of nucleon production mechanisms. Within the above-mentioned multiquark cluster picture, the semi-inclusive nuclear structure function $F_A^2(x, \vec{p}_2)$ can be written as the incoherent sum of the contributions resulting from virtual photon absorption by different multiquark cluster configurations (cf. refs. [8] and [9]); in particular, when 3q and 6q clusters are considered, one has

$$F_A^2(x, \vec{p}_2) = P^{(3q)} F_A^{(3q)}(x, \vec{p}_2) + P^{(6q)} F_A^{(6q)}(x, \vec{p}_2)$$

(2)

where $P^{(3q)}$ (or $P^{(6q)}$) is the probability to have a colorless 3q (6q) bag inside the hadronic cluster absorbing the virtual photon ($P^{(3q)} + P^{(6q)} = 1$). The case $P^{(6q)} = 0$, which corresponds to electron interaction with a quark belonging to a nucleon of a correlated NN pair ($F_A^2(x, \vec{p}_2) = F_A^{(3q)}(x, \vec{p}_2)$), is considered in Section 2, where the 3q cluster contribution is analyzed within the spectator mechanism. The opposite case, $P^{(6q)} = 1$, which corresponds to electron interaction with a quark belonging to a 6q bag ($F_A^2(x, \vec{p}_2) = F_A^{(6q)}(x, \vec{p}_2)$), is presented in Section 3, where the differences in the energy distribution of the emitted nucleons are analyzed both at $x < 1$ and $x > 1$. Nuclear effects on backward and forward nucleon emissions have been taken care of by adopting the extended two-nucleon correlation model [10], which takes into account
the motion of the center of mass (c.m.) of the hadronic cluster interacting with the incoming lepton. Finally, the main conclusions are summarized in Section 4.

2. The cross section for the process $A(e,e'N)X$: spectator mechanism

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 the semi-inclusive nuclear structure function reads as follows (cf. ref. [6])

$$F_{2}^{A,3q}(x,\vec{p}_2) = M \sum_{N_1=n,p} Z_{N_1} \int_{x}^{M_{A}^{z_2}} dz_1 \int d\vec{k}_{c.m.} \int dE^{(2)} P_{N_1N_2}(\vec{k}_{c.m.} - \vec{p}_2, \vec{p}_2, E^{(2)}) \delta(M_{A} - M(z_1 + z_2) - M_{A-2}^{z_{A-2}})$$

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. (3), $x/z_1$ represents the Bjorken variable of the struck nucleon having initial light-cone momentum $z_1 = k^+_1/M$; $z_2 = (\sqrt{M^2 + p_2^2} - p_2 \cos \theta_2)/M$ is the detection angle with respect to $\vec{q}$ and $p_2 \equiv |\vec{p}_2|$; $z_{A-2} = (\sqrt{(M_{A-2}^{f})^2 + k^2_{c.m.}} + (k_{c.m.})))/M_{A-2}^{f}$ 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 (3) is the two-nucleon spectral function, 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 $\delta(E^{(2)} - E^{(2)}_{thr})$, with $E^{(2)}_{thr} = 2M + M_{A-2} - M_A$ 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 [3], [8]. In this work two of these models will be adopted: the first one is the two-nucleon correlation (2NC).
model of ref. [8], based on the assumption that the c.m. of the correlated pair is at rest, which leads to

\[ P_{N_1N_2}(\vec{k}_1, \vec{k}_2, E^{(2)}) = n_{N_1N_2}^{rel}(|\vec{k}_1 - \vec{k}_2|/2) \delta(\vec{k}_1 + \vec{k}_2) \delta(E^{(2)} - E_{thr}^{(2)}) \]  

(4)

where \( n_{N_1N_2}^{rel} \) is the momentum distribution of the relative motion of the two nucleons in a correlated pair; the second model is the extended 2NC model, where the c.m. motion of the correlated pair is properly taken into account (see ref. [10]); it yields

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

(5)

where \( n_{N_1N_2}^{c.m.} \) represents the momentum distribution of the c.m. of the correlated pair. It can be seen that in both models the (A-2)-nucleon system is assumed to be in its ground-state; such an assumption is justified by the fact that only soft components of the c.m. motion distribution are considered in (5). As a matter of facts, it can be demonstrated that the excited states of the residual (A-2)-nucleon system contribute only to the high momentum tail of \( n_{N_1N_2}^{c.m.} \) (cf. refs. [11] and [12]). It should be pointed out that the extended 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 [10], [13]. The relative and c.m. momentum distributions are normalized according to

\[ \sum_{N_1, N_2 = n,p} Z_N \int d\tilde{k}_{rel} n_{N_1N_2}^{rel}(|\tilde{k}_{rel}|) \int d\tilde{k}_{c.m.} n_{N_1N_2}^{c.m.}(|\tilde{k}_{c.m.}|) = S_1 \cdot A \]  

(6)

where \( S_1 \) is the probability of finding a nucleon in a correlated NN pair or, more precisely, the probability that, after the removal of a nucleon from a nucleus, the residual (A-1)-nucleon system is in any state of its continuum.

Let us first analyze the semi-inclusive process within the 2NC model, i.e. let us assume that the correlated NN pair is at rest with respect to the (A-2)-nucleon system \((\vec{k}_{c.m.} = \vec{k}_1 + \vec{k}_2 = 0)\). Inserting (4) in (3), one obtains the well-known result [8] that the semi-inclusive nuclear structure function is directly proportional to the one of the struck nucleon, viz.

\[ F_2^{A,3q}(x, \vec{p}_2) = \sum_{N_1 = n,p} Z_{N_1} n_{N_1N_2}^{rel}(p_2) \bar{z}_1 F_2^{N_1}(x/\bar{z}_1) \]  

(7)
where

\[ \bar{z}_1 = 2 - z_2 - E_{thr}^{(2)}/M \]  

(8)

is the light-cone momentum of the struck nucleon. Thus, within the 2NC model (i.e., the correlated NN pair at rest) the semi-inclusive nuclear structure function factorises into a momentum-dependent nucleon structure function \( F_2^N(x/\bar{z}_1) \) and a nuclear quantity related to the relative momentum distribution of the correlated pair; more important, the light-cone momentum \( \bar{z}_1 \) of the struck nucleon is linked to the measured value of \( z_2 \) by the simple relation given by (8) and, if the free nucleon structure function is used in (7), nuclear effects reduce to a momentum dependent rescaling of the argument of \( F_2^N \). It should be pointed out that at \( x > 1 \) backward nucleon emission is kinematically forbidden within the 2NC model, because the condition \( \bar{z}_1 \geq x > 1 \) implies \( z_2 < 1 \) only (cf. (8)).

Let us now consider the two-nucleon spectral function given by (5). By allowing the correlated pair to share its c.m. momentum with the residual (A-2)-nucleon system, the semi-inclusive nuclear structure function is no longer proportional to the nucleon structure function \( F_2^N \), but is given by the following convolution integral

\[
F_{A,3q}^{A,3q}(x, \vec{p}_2) = M \sum_{N_1=n,p} Z_{N_1} \int_M^{\frac{M}{M(z_1+z_2)}} \frac{x}{M} z_1 z_2 F_2^N \left( \frac{x}{z_1} \right) \int d\vec{k}_{c.m.} \, n_{N_1,N_2}^{rel}(|\vec{k}_{c.m.}|) \delta(M_A - M(z_1+z_2) - M_{A-2}z_{A-2})
\]

(9)

It can be seen that not only the motion of the c.m. of the pair destroys the factorization generated by the 2NC model (cf. (7)), but, moreover, the light-cone momentum \( z_1 \) of the struck nucleon depends both upon \( z_2 \) and \( z_{A-2} \) and, consequently, it cannot be directly related to measurable quantities.

Within the extended 2NC model nuclear effects on backward and forward nucleon emissions in the semi-inclusive DIS process \( ^4He(e,e'p)X \) have been investigated. Calculations have been performed including all nuclear responses in (1) and using the free nucleon structure function of ref. \[14\]; the relative and c.m. momentum distributions have been taken from ref. \[12\]. Before presenting the results, let us remind that at \( x < 1 \) both backward \( (z_2 > 1) \) and forward \( (z_2 < 1) \) nucleon emissions are possible,
whereas at $x > 1$ the spectator nucleon is mainly emitted in the forward hemisphere ($z_2 < 1$); as a matter of fact, at $x > 1$ backward nucleon production is kinematically forbidden within the 2NC model (i.e., $\vec{k}_{c.m.} = 0$) and is strongly suppressed within the extended 2NC one (i.e., $\vec{k}_{c.m.} \neq 0$), because only soft components of $n_{c.m.}^{N_1 N_2}$ contribute to the semi-inclusive nuclear structure function given by (9). It should also be pointed out that in order to minimize nucleon emission from quasi-elastic scattering processes on a correlated NN pair sufficiently high values of $Q^2$ have to be considered.

The results of calculations at $x < 1$ are presented in figs. 1 and 2 in the kinematics region $0.3 \text{ GeV/c} < p_2 < 0.7 \text{ GeV/c}$, where the use of a non relativistic description of nuclear structure is well grounded. The behaviour of the cross section as a function of the kinetic energy $T_2$ of the detected nucleon, is governed by the relative and c.m. momentum distributions of the correlated pair (particularly at low values of $x$) and by the nucleon structure function (particularly at high values of $x$). From fig. 1 it can be seen that forward emission is not sensitive to the two-nucleon spectral function, whereas such a sensitivity is present for backward emission. This is due to the fact that the condition $z_1 \simeq 2 - z_2 - (k_{c.m.})_{\parallel}/M \geq x$ can be satisfied for forward nucleon emission ($z_2 < 1$) at any values of $p_2$ both with $k_{c.m.} = 0$ and $k_{c.m.} \neq 0$, whereas for backward nucleon emission ($z_2 > 1$) and sufficiently large values of $p_2$ it requires that $k_{c.m.} \neq 0$. In order to obtain reliable information on the structure function of a bound nucleon the following ratio has been defined (cf. ref. [6])

$$R^{s.i.}(x, x'; \vec{p}_2) = \frac{F_2^A(x, \vec{p}_2)}{F_2^A(x', \vec{p}_2)} \cdot \frac{\bar{F}_2^N(x')}{\bar{F}_2^N(x)} \quad (10)$$

with $\bar{F}_2^N = (F_2^p + F_2^n)/2$ and $F_2^A(x, \vec{p}_2) = F_2^{A,3q}(x, \vec{p}_2)$ given by (9). It turns out that the ratio $R^{s.i.}$ is almost completely independent on the particular behaviour of the relative and c.m. momentum distributions and, therefore, it is governed by the behaviour of the structure function of a bound nucleon. The ratio, calculated using the free nucleon structure function in (9), is shown in fig. 2 for backward and forward nucleon emission and $x \geq x' = 0.3$. The $x$ dependence of the calculated ratio sharply reflects the behaviour of the rescaling of the nucleon structure function: as a matter of fact, for forward nucleon emission ($z_2 < 1$), $x/z_1$ is always less than $x$ and decreases with
increasing $p_2$, so that the ratio is almost constant for small values of $x$ and increases with increasing $p_2$; vice versa, for backward nucleon emission ($z_2 > 1$), $x/z_1$ is always larger than $x$ and increases with increasing $p_2$, so that the ratio is less than one and decreases with increasing $p_2$. From fig. 2 it can be seen that the ratio $R_s^{s.i.}$ exhibits an appreciable sensitivity upon the value of $p_2$; therefore, it is clear that any medium-dependent momentum effect on quark distributions in nuclei can be investigated at forward and backward nucleon emissions. To sum up, the measurement of the semi-inclusive cross section at $x < 1$ can represent a valuable tool to detect any binding and momentum dependencies of the nucleon structure function in the medium, and, consequently, such a measurement can provide non-trivial information on the origin of the EMC effect (cf. ref. [15]).

The results presented show that quantitative predictions for backward nucleon emissions require a careful treatment of nuclear effects.

At $x > 1 + k_F/M \sim 1.3$ (where $k_F$ is the Fermi momentum) the semi-inclusive DIS cross section strongly depends upon nuclear effects. This is illustrated in fig. 3, where the results obtained with the Spectral Functions given by (4) and (5), are compared at $x = 1.2$ and $x = 1.5$. It can be seen that with increasing $T_2$ the cross section drops out by orders of magnitude; this is a typical nuclear effect: as a matter of fact, for $T_2 > 250 \, MeV$ ($p_2 > 0.7 \, GeV/c$) the cross section mainly follows the behaviour of the light-cone momentum distributions in the medium rather than the behaviour of the nucleon structure function; it appears therefore that the cross section at $x > 1$ and $0.3 \, GeV/c < p_2 < 0.7 \, GeV/c$ can be used to investigate quark distributions in nuclei, whereas at higher values of $p_2$ it provides information on the short range structure of the two-nucleon system interacting with the incoming lepton. It should be pointed out that the results presented have been obtained using the free nucleon structure function; therefore, any deviation from the behaviour shown in figs. 1-3, could be ascribed to medium effects on the quark distributions of a bound nucleon.

The predictions of the 2NC and extended 2NC models are compared in fig. 4 with the analysis [4] of the existing experimental data on single proton backward production in (anti)neutrino charged current interaction with neon target (Big European Bubble Chamber WA59 collaboration). It can be seen that, according to (7) the 2NC model
predicts for the mean value $<z_1>$ of the light-cone momentum of the struck nucleon a value $\sim 2 - z_2$, whereas the extended 2NC model predicts a mean value $<z_1>$ larger than $2 - z_2$, in better agreement with the experimental data. The larger value of $<z_1>$ can be explained as follows: within the 2NC model (i.e., the correlated NN pair at rest) only $|\vec{k}_1| = |\vec{k}_2|$ is possible, whereas within the extended 2NC model one can have both $|\vec{k}_1| < |\vec{k}_2|$ and $|\vec{k}_1| > |\vec{k}_2|$. The former case is favored, because it corresponds to smaller values of the initial relative momentum of the correlated pair and of the argument of the nucleon structure function. From fig. 4 it can be seen that the difference between the values $<z_1>$ predicted by the two models is not larger than $\sim 0.25$; such a difference corresponds to values of $k_{c.m.} \sim \sqrt{<k_{c.m.}^2>_{soft}} \sim k_F \sim 0.25 \text{ GeV}/c$. It should be pointed out that in single proton backward production nuclear effects arising from the Fermi motion of the c.m. of the correlated NN pair would reduce the role of competitive mechanisms, like, e.g., intranuclear cascade and few-nucleon correlations advocated in refs. [4] and [8], respectively.

The results presented could in principle be modified by mechanisms different from the spectator one or by the breakdown of the impulse approximation. In ref. [8] the sensitivity of backward and forward nucleon emissions to the effects of the so-called target fragmentation of the struck nucleon and the final state interaction of the recoiling nucleon with the residual (A-2)-nucleon system, has been analyzed; it has been found that for $0.3 \text{ GeV}/c < p_2 < 0.7 \text{ GeV}/c$ (i.e., in the kinematics region of interest for the spectator mechanism)  

i) the effects from target fragmentation of the struck nucleon play a negligible role and do not affect at all backward nucleon production, and  
ii) the contributions from the rescattering of the recoiling nucleon can modify the magnitude of the cross section without changing in a significant way its dependence upon the kinetic energy of the detected nucleon.

3. The cross section for the process $A(e,e'N)X$: six-quark clusters

Let us now consider the possibility that the nucleons of a correlated NN pair can lose their identity at short separations; in particular, let us consider the extreme case in which the short-range structure of the hadronic cluster interacting with the incoming
electron is entirely given by a 6q bag (i.e., $P^{(6q)} = 1$). Within a convolution approach the semi-inclusive nuclear structure function can be written as

$$F_{2}^{A,6q}(x,\vec{p}_{2}) = \frac{A}{2} S_{1} \sum_{\beta} \int_{z_{c.m.}}^{M_{A}} d\vec{q}_{2} \ F_{2}^{A}(\vec{q}_{2},\vec{p}_{2}) \ 5\beta_{\gamma}(\vec{q}_{2},\vec{p}_{2})$$

where $\beta = (u^{2}d^{4}, u^{3}d^{3}, u^{4}d^{2}) = ([nn], [np], [pp])$ identifies the type of 6q cluster, $f_{\beta}(z_{c.m.})$ is the light-cone momentum distribution describing the c.m. motion of the 6q cluster in the medium, $\tilde{F}_{2}^{\beta(N_{2})}(\xi,\varsigma,\vec{p}_{2}^{2})$ is the fragmentation structure function of the struck 6q cluster producing a nucleon $N_{2}$, $\vec{p}_{2}^{2}$ is the transverse component of the momentum $\vec{p}_{2}$ of the detected nucleon with respect to $\vec{q}$ (note that in (11) the mass of the 6q cluster has been assumed to be 2M). Following ref. [7] it is assumed that $\tilde{F}_{2}^{\beta(N_{2})}(\xi,\varsigma,\vec{p}_{2}^{2})$ factorises into the structure function of the 6q bag, $F_{2}^{\beta}(\xi)$, and a fragmentation function $D_{1}^{(N_{2})}(\varsigma,\vec{p}_{2}^{2})$ describing the hadronization of the resulting intermediate 5q state. However, since $D_{1}^{(N_{2})}(\varsigma,\vec{p}_{2}^{2})$ is poorly known, a simplified form suggested by quark counting rules [14] will be adopted; thus, the final expression of the fragmentation structure function $\tilde{F}_{2}^{\beta(N_{2})}(\xi,\varsigma,\vec{p}_{2}^{2})$ reads as follows

$$\tilde{F}_{2}^{\beta(N_{2})}(\xi,\varsigma,\vec{p}_{2}^{2}) = F_{2}^{\beta}(\xi) \ \frac{\rho_{\perp}(\vec{p}_{2}^{2})}{E_{2}} \ \gamma_{(5q)} \ \varsigma(1-\varsigma)^{3} \ \Theta(1-\varsigma) (12)$$

where $\rho_{\perp}$ is the transverse momentum distribution of the fragments. In (12) $\gamma_{(5q)}$ is a constant not known from quark counting rules, whose value governs the probability (given by $\gamma_{(5q)} \int_{0}^{1} d\varsigma (1-\varsigma)^{3}$) of the break-up of the 5q system into mesons or baryons. In the calculations a 50% probability for the break-up (i.e., $\gamma_{(5q)} \int_{0}^{1} d\varsigma (1-\varsigma)^{3} = 0.5$), which implies $\gamma_{(5q)} = 2$, has been assumed on the analogy of the corresponding break-up probability of the diquark responsible of the target fragmentation of the struck nucleon (cf. ref. [17]). It should be pointed out that the value of $\gamma_{(5q)}$ affects only the absolute value of the cross section. The 6q structure function $F_{2}^{\beta}(\xi)$ contains both valence and sea quark distributions, for which the parametrizations of ref. [18] have been adopted. Scaling violation at finite values of $Q^{2}$ has been accounted for by using the Natchmann variable [19] instead of the Bjorken one, as suggested in ref. [1]. Finally, for the transverse momentum distribution $\rho_{\perp}$ appearing in (12) the parametrization of ref. [20] has been used.
The relevant nuclear quantity in (11) is the light-cone c.m. momentum distribution 
\( f_\beta(z_{c.m.}) \) of the 6\( q \) cluster. For its evaluation the 2NC and the extended 2NC models 
have been considered; in the first model the 6\( q \) cluster is considered to be at rest with 
respect to the \((A-2)\)-nucleon system, leading to 
\[ f_\beta(z_{c.m.}) = \delta(z_{c.m.} - 1) \]; in the second 
one the c.m. momentum distribution of a 6\( q \) cluster is assumed to be the same as the 
one of a correlated NN pair; this means that a 6\( q \) cluster and a correlated NN pair differ 
only in their short-range intrinsic structure. Thus, the extended 2NC model yields 
\[ f_\beta=[N_1N_2](z_{c.m.}) = \int d\vec{k}_{c.m.} \ n_{N_1N_2}^{cm}(k_{c.m.}) \ \delta(z_{c.m.} - k_{c.m.}^+ / 2M) \] (13)

The semi-inclusive nuclear structure function \( F_{2}^{A,6q}(x, \vec{p}_2) \) (see (11)) becomes 
\[ F_{2}^{A,6q}(x, \vec{p}_2) = A \frac{1}{2} S_1 z_2 E_2 \rho_{\perp}(\vec{p}_2) \gamma(5q) \left(1 - \frac{z_2}{2 - x}\right)^3 \Theta(2 - x - z_2) \frac{1}{2 - x} \sum_\beta F_2^\beta(x) \] (14)

within the 2NC model (i.e., the 6\( q \) cluster at rest), whereas one has 
\[ F_{2}^{A,6q}(x, \vec{p}_2) = A \frac{1}{2} S_1 z_2 E_2 \rho_{\perp}(\vec{p}_2) \gamma(5q) \int_{\frac{z_2}{2 - x}}^{\frac{M_A}{2z_{c.m.}}} \frac{dz_{c.m.}}{2z_{c.m.} - x} \left(1 - \frac{z_2}{2z_{c.m.} - x}\right)^3 \sum_\beta F_2^\beta(\frac{x}{2z_{c.m.}}) \] (15)

within the extended 2NC model.

The results of calculations for forward and backward proton emissions in case of the 
process \(^4He(e,e'p)X\) are presented in fig. 5 at \( x < 1 \) and in fig. 6 at \( x > 1 \). It can 
be seen that, as in the case of the spectator mechanism (see figs. 1 and 3), backward 
emission at \( x < 1 \) and forward emission at \( x > 1 \) are largely affected by the c.m. motion 
of the hadronic cluster, whereas forward nucleon emission at \( x < 1 \) is insensitive to 
nuclear effects. It should be pointed out that, forward nucleon emission both at \( x < 1 \) 
and \( x > 1 \) is mainly governed by the short-range structure of the hadronic cluster 
interacting with the incoming lepton; as a matter of fact, the differences in the energy 
distribution of emitted nucleons due to 3\( q \) or 6\( q \) clusters can be ascribed to the different 
short-range structure of the multiquark cluster absorbing the virtual photon (as it is 
clearly visible by comparing the results of figs. 5(a) and 6 with those reported in figs. 
1(a) and 3, respectively). On the contrary, backward nucleon production at \( x < 1 \) is
dominated by the c.m. momentum distribution of the hadronic cluster interacting with
the incoming electron, so that in this case the $T_2$ dependence of the cross section is
expected to be quite similar when the virtual photon is absorbed by 3$q$ or 6$q$ clusters,
as it can be seen by comparing the results of fig. 5(b) with those of fig. 1(b). The
effects of virtual photon absorption on 3$q$ and 6$q$ clusters upon forward and backward
proton emissions are compared in figs. 7 and 8 (note that the contributions from the
target fragmentation of the struck nucleon, estimated as in ref. [6], are also reported
when the virtual photon absorption occurs on a nucleon of a correlated NN pair). It
can clearly be seen that the effects from 6$q$ clusters are not expected to sharply modify
the $T_2$ dependence of the cross section when $50 \text{ MeV} < T_2 < 250 \text{ MeV}$ (i.e., in the
kinematics region of interest for the spectator mechanism); on the contrary, at higher
values of $T_2$ the presence of 6$q$ bags may strongly affect the cross section both at $x < 1$
and $x > 1$.

4. Summary and Conclusions

Forward and backward nucleon emissions in semi-inclusive DIS process $A(\ell, \ell'N)X$
have been investigated assuming that virtual boson absorption occurs on a hadronic
cluster which can be either a two-nucleon correlated pair or a six-quark bag. Nuclear
effects have been taken care of by adopting the extended two-nucleon correlation model
[3], [10], which takes into account the binding and the motion of the center of mass of
the hadronic cluster interacting with the incoming lepton. As for the effects of virtual
photon absorption on a nucleon of a correlated NN pair, the main results of the analysis
can be listed as follows: i) backward emission at $x < 1$ and forward emission at $x > 1$
are sensitive to nuclear effects, whereas forward emission at $x < 1$ is not (cf. fig. 1
and fig. 3); as a matter of fact, a large part of the discrepancy between the predictions
of ref. [8] and the experimental data on single proton backward production observed
in neutrino and antineutrino charged current interactions with neon nuclei [4], can be
ascribed to nuclear effects arising from the c.m. motion of the correlated NN pair (cf.
fig. 4), rather than to intranuclear cascade or few-nucleon correlation effects; ii) at
$x < 1$ the momentum and energy dependencies of quark distributions in nuclei can
be investigated (cf. fig. 2), providing relevant information on the EMC effect; iii) at $x > 1$ the cross section is mainly governed by the high momentum components of nucleon light-cone momentum distributions, i.e., by the short-range structure of the correlated NN pair (cf. fig. 3). As for the effects from six-quark clusters, the main conclusions are as follows: i) nuclear effects are not important in forward emission at $x < 1$ (cf. fig. 5(a)) but become relevant in backward emission at $x < 1$ (cf. fig. 5(b)) and forward emission at $x > 1$ (cf. fig. 6); ii) forward emission both at $x < 1$ and $x > 1$ appears to be the appropriate kinematics condition for studying multiquark configurations in nuclei provided $p_2 > 1 \text{ (GeV/c)}$ (cf. figs. 7 and 8).

In closing, it should be pointed out that our calculations were performed within the impulse approximation based on the assumption that the debris produced by the fragmentation of the hit nucleon do not interact with the nuclear medium. The problem of the final state interaction (FSI) of the fragments in inclusive scattering at $x < 1$ has been recently addressed by various groups [21] - [23]. Estimates of FSI effects in semi-inclusive processes have also been recently obtained [24], which suggest that for light nuclei, which is the case considered in the present paper, FSI should play a minor role thanks to the finite formation time of the dressed hadrons. Moreover, it should be stressed that backward nucleon emission is not expected to be affected by forward-produced hadrons [25].
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**Figure Captions**

Fig. 1. The semi-inclusive DIS cross section for the process $^4He(e, e'p)X$ within the spectator mechanism, in which the virtual photon is absorbed by a quark belonging to a nucleon of a correlated NN pair and the recoiling nucleon is emitted and detected in coincidence with the scattered electron. $T_2$ is the kinetic energy of the detected proton, emitted forward ($\theta_2 = 25^o$ (a)) and backward ($\theta_2 = 140^o$ (b)), $x$ is the Bjorken scaling variable. The curves with and without full dots represent the results obtained within the 2NC (cf. (7)) and the extended 2NC (cf. (9)) models, respectively. Note that for $T_2 > 50$ $MeV$ backward proton emissions at $x = 0.6$ and $x = 0.8$ are kinematically forbidden within the 2NC model. Calculations have been performed assuming the following values for the incident electron energy and scattering angle: $E_e = 20$ $GeV$ and $\theta_{e'} = 15^o$. The values of the four-momentum transfer $Q^2$ are 6, 10, 12, 14 $(GeV/c)^2$ for $x = 0.2, 0.4, 0.6, 0.8$, respectively.

Fig. 2. The ratio of the semi-inclusive nuclear structure function $R^{s.i.}(x, x' = 0.3; p_2)$ (see (11)) for the process $^4He(e, e'p)X$ versus the Bjorken variable $x$, within the spectator mechanism. Protons are emitted forward at $\theta_2 = 25^o$ (a) and backward at $\theta_2 = 140^o$ (b). The solid, dashed, dotted and dot-dashed curves correspond to $p_2 = 0.3, 0.4, 0.5$ and 0.6 $GeV/c$, respectively. Calculations have been performed assuming $E_e = 30$ $GeV$ and $Q^2 = 10$ $(GeV/c)^2$.

Fig. 3. The same as in fig. 1, but for protons emitted forward at $\theta_2 = 25^o$ and $x > 1$.

Fig. 4. Mean value $< z_1 >$ of the light-cone momentum of the struck nucleon versus the light-cone momentum $z_2$ of the detected proton. Open and full dots represent the experimental data [4] on single proton backward production from antineutrino and neutrino charged current interaction with neon target, respectively. Dashed and solid lines are the predictions of the 2NC (cf. (4)) and extended 2NC (cf. (5)) models, respectively.
Fig. 5. The same as in fig. 1, but assuming that the virtual photon is absorbed by a quark belonging to a 6q bag. The curves with and without full dots represent the results obtained within the 2NC (cf. (14)) and the extended 2NC (cf. (15)) models, respectively.

Fig. 6. The same as in fig. 5, but for protons emitted forward at $\theta_2 = 25^\circ$ and $x > 1$. The kinematics conditions are the same as in fig. 3.

Fig. 7. The semi-inclusive DIS cross section for the process $^4He(e,e'p)X$ versus the kinetic energy $T_2$ of the detected proton, emitted forward at $\theta_2 = 50^\circ$ (a) and backward at $\theta_2 = 120^\circ$ (b), when $x = 0.6$. The solid line is the contribution due to virtual photon absorption on a nucleon of a correlated NN pair (cf. (9)), whereas the solid line with full dots includes also the effects from the target fragmentation of the struck nucleon, estimated as in ref. [6]. The dashed line is the contribution resulting from virtual photon absorption on a quark belonging to a 6q bag (cf. (15)). The kinematics conditions are the same as in figs. 1 and 5.

Fig. 8. The same as in fig. 7, but for protons emitted forward at $\theta_2 = 25^\circ$ and $x = 1.5$. The kinematics conditions are the same as in figs. 3 and 6.
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