# THE PARTON TRANSVERSE MOMENTUM DISTRIBUTION IN THE NUCLEAR DEEP-INELASTIC REGION* **

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We show with the model for the parton distribution in nuclei, that nuclear Fermi motion fully accounts for the collective motion of partons in nuclear medium. The sea parton distributions are described by additional virtual pions in interacting nucleon in such a way as to reproduce the nuclear lepton pair production data and saturate the energy-momentum sum rule. The influence of Fermi motion changes the nucleon rest energy and consequently the transverse momentum square of partons inside bound nucleons.

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In the frame of properly formulated covariant parton model [1], we calculated the nuclear modifications of the transverse momentum distribution in the nucleon inside nucleus. The modifications concern the nucleon rest energy which changes the Bjorken $x$ in the nuclear medium giving the good agreement [2, 3] with the experimental data (the EMC effect for $x > 0.15$ and the nuclear lepton-pair production). In the model we discuss a connection between the average value of the parton transverse momentum square and the Bjorken variable $x$ for bound nucleons which interact inside nuclear medium. In this way we introduce a final state interaction between the scattered nucleon and the rest of the nucleus. It is known [2], that in the deeply inelastic electron nucleon (nucleus) scattering, the hit quark can propagate freely the distance $z = 1/M_N x$ in the nucleon with mass $M_N$. For large $x$ $z = 1/M_N x$ is small (see Fig. 1), in the Bjorken limit (large $Q^2$ momentum

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transfer) the final state nucleon–nucleon interaction is negligible and we will see that the average transverse parton momentum in the bound nucleon will be smaller than in the free one. Contrary, for $x < 0.3$ the influence of the nuclear medium on the transverse momentum parton distribution (PD) is strongly reduced due to the presence of nuclear interaction.

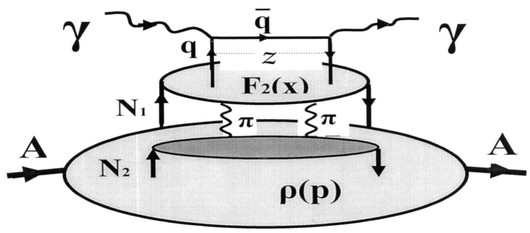


Fig. 1. The graphical representation of the convolution model for the deep inelastic electron nucleus scattering with $2\pi$ Final State Interaction (FSI) between the active nucleon $N_1$ (with hit quark $q$) and the spectator $N_2$.

## 1. Convolution with nuclear medium

In the convolution model [4] (CM) (see Fig. 1), deep inelastic scattering is described as a two step process. Electrons interact with partons (quarks) which make up a nucleon, a constituent of a nucleus. Other components of a nuclear wave function like pions will be also discussed. Thus two compound objects will be dealt with: the nucleon and the nucleus. The main goal is to show how the relativistic treatment of the single quark degrees of freedom in the nucleus makes it possible to accommodate the results of CM. The nuclear quark structure function (SF) $F_2^A$ in a nucleus with the mass number $A$ will be constructed from the free nucleon SF $F_2^N(x)$ in the nucleon and the nucleon distribution function $\rho^A(y_A)$ in the nucleus. The usual convolution formula has the following form:

$$\frac{F_2^A(x_A)}{x_A} = A \int\int dy_A dx \ \delta(x_A - y_A x)\rho^A(y_A) \ \frac{F_2^N(x)}{x} \, . \tag{1}$$

### *1.1. Monte Carlo modeling with pure Fermi motion.*

Now we proposed for illustration a simple Monte Carlo method for calculating parton distribution in nuclei (including the EMC effect). Our approach is based on the model where valence parton momenta in hadron at rest are calculated from a spherically symmetric Gaussian distribution with a width derived from the Heisenberg uncertainty relation whereas the sea parton contributions result from similar Gaussian distribution but with a width dictated by the presence of virtual pions in hadron [5]. When going to the nuclear case these initial Gaussian momentum distributions are changed accordingly in order to account for the presence of nuclear medium (like rescattering effects or changes in the virtual pion clouds in the nuclear matter). The energy momentum conservation is strictly imposed. The nuclear parton density distributions are then obtained by generating initial parton momenta of nucleons and calculating the corresponding light-cone longitudinal momentum fractions (Bjorken $x$). Only events satisfying the exact kinematical constrains of the corresponding deep-inelastic reaction probing our nuclear distribution are selected to form the final distribution we are looking for.

Let $j$ denote four-momentum of the struck parton (probed by current with virtuality $Q_0^2$) selected (for valence quarks) from Gaussian PD with width 0.172 GeV, $r$ the respective four-momentum of hadronic remnants and $W$ and $W'$ their respective invariant masses. Only events satisfying the exact kinematical constraints of the corresponding deep-inelastic reaction probing our nuclear distribution

$$0 \leq j^2 \leq W^2, \qquad\qquad 0 \leq r^2 \leq W'^2 \tag{2}$$

are accepted and selected to form the final distribution we are looking for. Calculating the momentum distribution of partons inside bound nucleons, with the assumption that primordial parton distribution in the nuclear medium remains the same as in free nucleon we have to subtract the effect the Fermi motion on parton energies in the nucleon rest frame. This mechanism works similarly to the decreasing of the size of the valence parton momentum distribution used in [3] and produces both the minimum for $x$ around $x \sim 0.6$ and the maximum around $x \sim 0.1$. It can be interpreted as increasing de-confinement region in the configuration space. Similarly to statistical models, the subtraction of the Fermi average energy changes the energy width of parton by 7%. The corresponding results are presented in Fig. 2 as full triangles (which practically follow the solid line representing results of the previous approach showing, therefore, their equivalence). The sea parton distribution is given here by the convolution of the pionic component of the nucleon, $f_\pi(x; Q_0^2)$, and the parton structure of pion, $f_{\text{pion}}(x; Q_0^2)$, obtained from the same Gaussian PD as used for valence partons. Notice that the influence of Fermi motion is strong but the agreement for small $x$ is lost.

### *1.2. Full Monte Carlo modeling*

We shall, therefore, improve the treatment of sea quarks. In the presented model the sea parton distribution is generated directly from distribution of the pionic cloud which surrounds the nucleon core constituted by the valence quarks. Because part of these pions is responsible for mediating nucleon–nucleon interactions, the corresponding part of the sea quarks must be connected rather to whole nuclear medium and not to the individual nucleons. For small $x$ the crucial factor turns out to be the change of the nuclear virtual pion cloud connected with the exchanged mesons responsible for the nuclear forces [3]. In order to be able to fit data in this region we have, therefore, to adjust the value of the parameter which determines the relative number of the (effective) intermediate pions (which are assumed to mediate the nucleon–nucleon interaction). It turns out [3] that the proportion leading to good results is to assign 93% of virtual pions to contribute to the sea quark structure function of the nucleon and let the rest to be responsible for the nucleon–nucleon interaction. Full calculation in which the width of the energy-momentum PD was changed by 10% (from 0.18 GeV to 0.165 GeV) result in very good fit to experimental data including the small $x$ region (see Fig. 2 full squares).

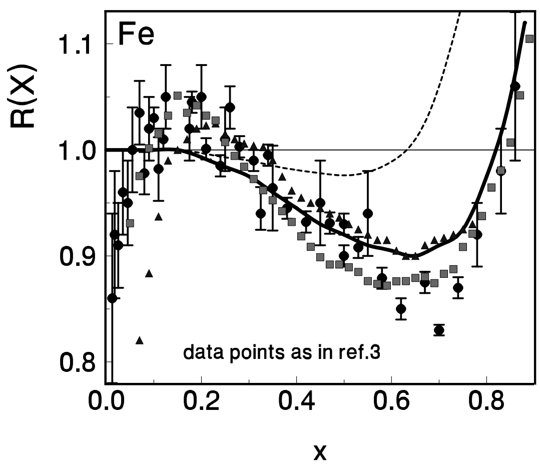


Fig. 2. $R(x)$ — the ratio of nuclear structure functions (iron to deuterium).

We conclude that Fermi motion of nucleons provides very big contribution to the nucleon PD in the nuclear medium (at least in the examples considered here). Therefore, contrary to some previous calculations and conclusions to the opposite opinions including recent work [6], it affects strongly the observed EMC ratio in the broad range of variable $x > 0.1$.

## 2. The nuclear deep inelastic limit

Now we show that there exist a simpler treatment of modified Fermi motion which gives even better results. We will start from the large $x$ regime where the parton mean free path $z$ is much shorter than the average distance between nucleons inside the nucleus. It means then that we can treat nucleons as noninteracting objects remaining on the energy shell:

$$\sqrt{p^2} \equiv M_B \xrightarrow[\text{rest}]{} p^+ \,, \tag{3}$$

where $M_B$ denotes now the nucleon mass in the DIS (identified here with the $p^+$ component in the nucleon rest frame). To calculate $M_B$ we shall consider the nuclear longitudinal $P_A^+$ component as given by the sum of all parton momenta $k_{Ai}^+$. For $A$ nucleons we have:

$$\frac{1}{A}\sum_{i=1}^{lA} k_{Ai}^+ = \frac{M_A}{A} \equiv M_N + \varepsilon = \int n(\vec{p}^{\,2})\sqrt{{M_B}^2 + \vec{p}^{\,2}}\; d^3p \,, \tag{4}$$

where $\varepsilon \simeq -8\,\mathrm{MeV}$ is the usual nuclear mass defect, $n(\vec{p}^{\,2})$ is the nucleon momentum distribution normalized to 1 and $l$ denotes number of partons inside nucleon. We will calculate the effect for nuclei with $A > 50$, where we assume the average uniform momentum distribution for nucleons with the Fermi momentum $p_{\mathrm{F}}$. We introduce the nucleon average energy, $E_{\mathrm{Fermi}} \simeq 0.6\,\left(\vec{p}_{\mathrm{F}}^{\,2}/(2M_B)\right)$ in the nuclear matter. In terms of it we have the following nonrelativistic reduction of equation (4) for $x > 0.6$:

$$M_B \cong M_N + \varepsilon - E_{\mathrm{Fermi}} \cong M_N + \varepsilon - \frac{0.6\,\vec{p}_{\mathrm{F}}^{\,2}}{2\left(M_N + \varepsilon - 0.6\,\frac{\vec{p}_{\mathrm{F}}^{\,2}}{2M_N}\right)} \,. \tag{5}$$

Therefore, in the nuclear medium, characterized by $\varepsilon$ and $E_{\mathrm{Fermi}}$, the rest energy of the nucleon $M_B = \sum_i k_{Ni}^+$, in the Bjorken on shell limit, takes effectively different value than its free nucleon mass $M_N$. It can be thought as the sum of the corresponding partonic energies $k_{Ni}^0$ expressed in the rest frame of nucleon (notice that they differ from $k_{Ai}^0$). Such $M_B$ accounts, therefore, effectively for the Fermi motion of nucleons inside the nucleus. This is, in addition to the standard Fermi smearing on a nuclear level, the influence of the Fermi motion emerging from a nucleonic ($x$) level.

## 3. $k_{\mathrm{T}}^2$ distribution

The distribution of the transverse momentum of partons inside nucleons calculated in a simple model on the light-cone depends on $x, Q^2$ and parton boost invariant variable $\xi = k^+/P^+$. Integrating $k_{\mathrm{T}}^2$ over $\xi = k^+/P^+$ with the normalized distribution function we get [1] for large $Q^2 \gg M_N^2$:

$$\left\langle k_{\mathrm{T}}^2 \right\rangle \sim \gamma M_N^2 \left\langle \frac{1}{N} \right\rangle . \tag{6}$$

For $\gamma = 3/2$ $M_x = M_N$ and $\langle(1/N)\rangle = 1/3$ (naive quark counting) one obtains $\langle k_{\mathrm{T}}^2\rangle = (0.44\,\mathrm{GeV})^2$. The effective nucleon mass $M_x$ in DIS inside nuclear medium depends [2] on $x$ (see Fig. 3) due to incremental switching of final state interaction shown in Fig. 2. Eqs. (5) and (6) give together the influence of nuclear medium on transverse momentum distribution $k_{\mathrm{T}}^B$ for bound nucleon for large $x > 0.6$:

$$\frac{\langle {k_{\mathrm{T}}^{B}}^2\rangle}{\langle {k_{\mathrm{T}}^{N}}^2\rangle} = \frac{M_B^2}{M_N^2}\,. \tag{7}$$

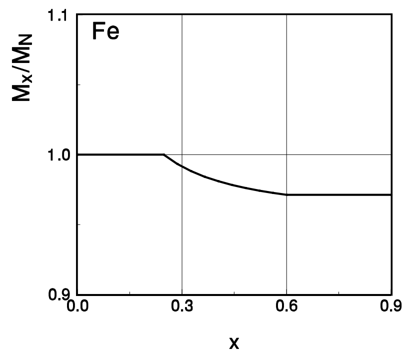


Fig. 3. The $M_x/M_N$ ratio.

Systematic study [7] of high $p_{\mathrm{T}}$ hadron spectra in proton–proton ($pp$), $pA$ and $AA$ collisions which depend on initial $k_{\mathrm{T}}$ distribution supports the fact that effective nuclear $\langle {k_{\mathrm{T}}^{A}}^2\rangle$ remains unchanged for large $x$. It will be great challenge to measure the possible $x$ dependence (Fig. 3) in future.

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