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Parton Distributions in Nuclei: Overview and Prospect

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Parton Distributions in Nuclei: Overview and Prospect

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Abstract

We give a brief overview of nuclear parton distributions. First, the EMC effect is discussed together with possible interpretations such as nuclear binding and Q^2 rescaling. Next, we explain shadowing descriptions: vector-meson-dominance-type and parton-recombination models. Nuclear dependence of Q^2 evolution should be interesting in testing whether or not DGLAP equations could be applied to nuclear structure functions. Status of nuclear sea-quark and gluon distributions is discussed. The structure function b_1, which will be measured at HERMES and possibly at ELFE, could shed light on a new aspect of high-energy spin physics.

1 Introduction

From the early SLAC experiments on electron scattering, nuclear targets have been used just as a tool for measuring nucleon structure functions. Nuclear corrections are not taken seriously in 1970's except for apparent nucleon-Fermi-motion corrections. Nucleons are bound in a nucleus with average binding energy 8 MeV and typical momentum 200 MeV. These are fairly small compared with reaction energy of several GeV or more in electron or muon scattering. For this reason, nuclear environment was not expected to alter nucleon properties significantly. Even though signature of nuclear modification in the F_2 structure function is found in the SLAC data in 1970's, they are not studied extensively. On the other hand, the European Muon Collaboration (EMC) took the topic rather seriously and published the first paper in 1983 [1]. The nuclear modification of F_2 is now known as the (old) EMC effect.

In the mid 1980's, there are many theoretical publications on this topic, in particular on medium and large x physics. We cannot list all of the ideas in this paper. A conservative one is to interpret it in term of nuclear binding and Fermi motion [2]. On the other hand, there is another extreme model, Q^2 rescaling [3]. In contrast to the binding model in which bound nucleon F_2 is the same as the free one, it is modified due to nuclear environment. The details of these models are discussed in section 2.

From the late 1980's, nuclear F_2 structure functions in the shadowing region ($x < 0.1$) are investigated in detail experimentally and theoretically. In particular, accurate New Muon Collaboration (NMC) data make it possible to test theoretical shadowing models. The traditional idea of describing the shadowing is a vector-meson-dominance

and the phenomenon is called "antishadowing" in contrast with shadowing at small x. The shadowing part is discussed in section 3.

In describing nuclear structure functions, convolution formalism is usually used. A parton distribution in a nucleus is given by a hadron (nucleon, pion, and etc.) momentum distribution convoluted with a parton distribution in the hadron. In terms of light-cone momenta, it is written as

$$f_{a/A}(x_A, Q^2) = \sum_T \int_{x_A}^1 dy_A f_{a/T}(x_A/y_A, Q^2) f_{T/A}(y_A) \quad , \tag{2.2}$$

where x_A is defined by $x_A = Q^2/2M_A\nu$ and y_A is the light-cone momentum fraction $y_A = p_T^+/p_A^+$. In order to explain the modification of the quark distribution in a nucleus $[f_{a/A}(x_A, Q^2)]$, we may ascribe it to modification of the quark distribution in a hadron $[f_{a/T}(x_A/y_A)]$ or to modification of the hadron distribution in the nucleus $[f_{T/A}(y_A)]$.

A standard approach in describing nuclei in the low-energy region is to start from information on nucleon-nucleon interactions, which are obtained by NN scattering experiments and deuteron properties. Then, the knowledge is applied to nuclear structure by taking into account many-body corrections. In this sense, it is a "proper" approach to start from an assumption that the structure function F_2 of a bound nucleon is the same as the free nucleon F_2. This way of interpreting the EMC effect is a nuclear binding model [2]. A nuclear tensor, which appears in calculating a lepton-nucleus cross section, is given by the convolution: $W_{\mu\nu}^A(P,q) = \int d^4p S(p) W_{\mu\nu}^N(p,q)$. The spectral function $S(p)$ is the nucleon momentum distribution in the nucleus. If we consider the simplest case of a shell model, it is given by single particle wave functions and binding energies of nucleons: $S(p) = \sum_i |\phi_i(\vec{p})|^2 \delta(p_0 - m_N - \epsilon_i)$. Recoil energy is neglected in the expression. From these equations, the nuclear F_2 is

$$F_2^A(x, Q^2) = \sum_i \int dz f_i(z) F_2^N(x/z, Q^2) \quad , \tag{2.3}$$

where x is the Bjorken variable $x = Q^2/2m_N\nu$, and $f_i(z)$ is the light-cone momentum distribution of the nucleon i:

$$f_i(z) = \int d^3p \; z \; \delta\left(z - \frac{p\cdot q}{m_N\nu}\right) |\phi_i(\vec{p})|^2 \quad . \tag{2.4}$$

The momentum fraction z is given by $z = p\cdot q/m_N\nu = 1 - |\epsilon_i|/m_N + \vec{p}\cdot\vec{q}/m_N\nu \approx 1.00 - 0.02 \pm 0.2$ for a typical nucleon. So, the function $f(z)$ is peaked at 0.98. If we replace $f(z)$ by a delta function $\delta(z - 0.98)$ for simplicity, the nuclear F_2 becomes $F_2^A(x, Q^2) \approx F_2^N(x/0.98, Q^2)$. For example at x=0.60, we have $F_2^N(x = 0.61)/F_2^N(x = 0.60) = 0.88$ and the 10% EMC effect can be explained at medium x.

On the other hand, there exist other extreme interpretations in terms of modification of nucleon itself. A well known idea is the Q^2 rescaling model. It seems that the

nucleon modification makes sense if we consider that the average nucleon separation in a nucleus is about 2 fm, which is almost equal to the nucleon diameter. Therefore, it is no wonder that multiquark systems other than the nucleon are formed. If such multiquark hadrons are created, a confinement size for quarks should be changed. Then the quark momentum distributions are modified according to the size change. Using this kind of simple picture at a hadronic scale μ^2, we calculate distributions at large Q^2, where experimental data are taken, by evolving distributions from μ^2. We find that a nuclear F_2 is related to the nucleon one simply by scaling Q^2:

$$F_2^A(x,Q^2) = F_2^N(x,\xi_A Q^2) \quad , \tag{2.5}$$

with the rescaling parameter $\xi_A = (\lambda_A^2/\lambda_N^2)^{\alpha_s(\mu_A^2)/\alpha_s(Q^2)}$, where λ is the confinement radius for a quark.

The binding and rescaling models seem very different interpretations. How shall we understand the situation? A possible explanation is in terms of factorization scale independence [3]. For example in the operator-product-expansion case, the renormalization scale μ separates long-distance physics and short-distance one. However, final results should not depend on the arbitrary human factor μ. Because the bound structure function and the nucleon momentum distribution are *not* separately observables, the same discussion could be valid in our case. The nuclear structure function, which is a physics observable, should not depend on a factorization scale μ which separates it into the quark-distribution part and the hadron-distribution one. Choosing a nuclear-dependent scale $\mu = \mu_A$, we obtain the rescaling model. On the other hand, the binding model corresponds to the nuclear-independent scale. Using this factorization-scale independence, we may relate the two different descriptions. Moments of a nonsinglet distribution are written as $M_n^{q/A} = M_n^{q/N} M_n^{N/A}$ by Mellin-transformation properties. As a simple example of the binding model, a Fermi-gas model is employed. Relations between the two descriptions are found as $\bar{\epsilon}/m_N = -\gamma_2^{NS}\kappa_A/2\beta_0$ and $k_F^2/m_N^2 = 5(2\gamma_2^{NS} - \gamma_3^{NS})\kappa_A/2\beta_0 + O(\bar{\epsilon}^2/m_N^2)$, where κ_A is defined by $1 - \kappa_A = \alpha_s(\xi_A Q^2)/\alpha_s(Q^2)$. The quantities $\bar{\epsilon}$ and k_F are the average binding energy and the Fermi momentum, and γ_n^{NS} is the nonsinglet anomalous dimension. There exists a correspondence between the binding model and the rescaling, so that we may view the rescaling as an effective description of nuclear medium effects. In fact, it is shown in a simple quark model that effects of nucleon interactions could be effectively described by a nucleon size change in the nuclear medium [6], although it is perhaps too simple to explain various nuclear phenomena. Comparison of the rescaling results with the data is discussed in section 3.

3 Nuclear shadowing

Nuclear modification of F_2 at small x is negative as shown in Fig. 2.1, and it is known as shadowing phenomena. A traditional way of describing the shadowing is in terms

of vector-meson-dominance (VMD) model. The virtual photon transforms into vector meson states, which interact with the target. Because a propagation length of the vector mesons is given by $\lambda = 1/|E_V - E_\gamma| \approx 0.2/\mathrm{x}$ fm, it exceeds 2 fm at $x < 0.1$ and multiple scattering occurs. The vector mesons interact predominantly in the surface region, and internal nucleons are "shadowed" by the surfaces ones. This description is not enough for explaining observed small Q^2 dependence. So various extensions of this model are studied. For example, including $q\bar{q}$ continuum, we have the nuclear F_2 [7]

$$F_2^A(x, Q^2) = \frac{Q^2}{\pi} \int dM^2 \frac{M^2 \Pi(M^2)}{(M^2 + Q^2)^2} \sigma_{VA} \quad , \tag{3.1}$$

where σ_{VA} is the vector-meson nucleus interaction cross section, and $\Pi(M^2)$ is the spectral function $\Pi(M^2) = \sigma(e^+e^- \to hadrons)/\sigma(e^+e^- \to \mu^+\mu^-) = \ vector\ mesons\ + q\bar{q}\ continuum.$

Another interpretation of shadowing is in term of Pomeron exchange [8]. In the case of diffractive scattering, the target is thought to be remain intact so that only vacuum quantum number, "Pomeron", could be exchanged. The Pomeron ($\mathcal{P}$) structure function is defined by the diffractive cross section: $F_{2,\mathcal{P}} = Q^2/(4\pi^2\alpha)\sigma_{\gamma^*\mathcal{P}}$. Pomeron contribution to the nuclear F_2 from double diffractive scattering is given by a convolution of the Pomeron F_2 with its light-cone momentum distribution: $\delta F_2(x) = \int dy f_{\mathcal{P}}(y) F_{2,\mathcal{P}}(x/y)$. The variable y is the momentum fraction carried by the Pomeron $y = k \cdot q / p \cdot q$. The VMD contribution is compared with the Pomeron result in [9]. Both shadowing results are of the same order of magnitude at small x (≈ 0.01) and at Q^2=4 GeV^2.

The above shadowing ideas are in the target rest frame. There is an explanation in an infinite momentum frame in terms of parton recombinations [10, 11]. Both descriptions are supposedly equivalent; however, there is no explicit proof at this stage. The recombinations are parton interactions from different nucleons. They become dominant at small x with the following reason. The average longitudinal nucleon separation in a Lorentz contracted nucleus is $L = (2\ fm) M_A/P_A = (2\ fm) m_N/p_N$. The longitudinal localization size of a parton with momentum xp_N is $\Delta L = 1/xp_N$. In the x region $x < 0.1$, ΔL becomes larger than L, so that partons from different nucleons could interact significantly. For example, a $p_1 p_2 \to p_3(x)$ recombination effect on the p_3 parton distribution is

$$\Delta p_3(x) = \frac{9 A^{1/3} \alpha_s}{2 R_0^2 Q^2} \int dx_1 dx_2 p_1(x_1) p_2(x_2) \Gamma_{p_1 p_2 \to p_3}(x_1, x_2, x) \delta(x - x_1 - x_2) \quad , \tag{3.2}$$

where the factor $A^{1/3}$ is the number of nucleons in the longitudinal direction, $p_1 p_2 \to p_3$ cross section is proportional to α_s/Q^2, and R_0 is given by $R_0 \approx 1$ fm. The parton-fusion function $\Gamma_{p_1 p_2 \to p_3}$ indicates a probability of the fusion process $p_1 p_2 \to p_3$. Because it is opposite to the splitting, $\Gamma_{p_1 p_2 \to p_3}$ is related to the Altarelli-Parisi splitting function by $\Gamma_{p_1 p_2 \to p_3}(x_1, x_2, x_3) = (x_1 x_2 / x_3^2) P_{p_1 \leftarrow p_3}(x_1/x_3) C_{p_1 p_2 \to p_3}$, where $C_{p_1 p_2 \to p_3}$ is the

where $\delta q_i = [q_i^0 - (q_i^{+1} + q_i^{-1})/2]/2 = \frac{1}{2}[q_i^0(x) - q_i^{+1}(x)]$ with the flavor-i quark distribution $q_i^H(x)$ in z component of the target spin (H). Because quark spin does not appear in the above expression, b_1 probes very different spin structure.

We discuss a sum rule for b_1 [18]. The integral of Eq. (5.1) over x is related to a tensor combination of elastic amplitudes by using the parton picture in an infinite momentum frame. Next, the elastic helicity amplitudes are written by charge and quadrupole form factors of the spin-one hadron. In the case of tensor combination, the charge form factor cancels out and the remaining term is the quadrupole one:

$$\int dx\ b_1(x) = \lim_{t\to 0} -\frac{5}{3}\frac{t}{4M^2}F_Q(t) + \frac{1}{9}\delta Q_{sea} \quad , \tag{5.2}$$

where the sea-quark tensor polarization is defined by $\delta Q_{sea} = \int dx[8\delta\bar{u} + 2\delta\bar{d} + \delta s + \delta\bar{s}]$, and $F_Q(t)$ is the quadrupole form factor in the unit of e/M^2. Equation (5.2) is analogous to the Gottfried integral $\int dx\ [F_2^p(x) - F_2^n(x)] = 1/3 + (2/3)\int dx[\bar{u}(x) - \bar{d}(x)]$. As the Gottfried sum $1/3$ is obtained by assuming the flavor symmetry $\bar{u} = \bar{d}$, the b_1 sum

$$\int dx\ b_1(x) = \lim_{t\to 0} -\frac{5}{3}\frac{t}{4M^2}F_Q(t) = 0 \quad , \tag{5.3}$$

is obtained if there is no sea-quark tensor polarization. Because of this assumption on the tensor polarization, the b_1 sum rule is considered as one of the sum rules in a naive parton model. It is similar to the Gottfried sum rule in this sense. At this stage, all model calculations for $b_1(x)$ satisfy the sum rule $\int dx\ b_1(x) = 0$. As the breaking of the Gottfried sum rule became an interesting topic recently, it is worth while investigating a possible mechanism to produce the tensor polarization δQ_{sea}, which breaks the sum rule.

Even though the sum-rule value is expected to be zero for the b_1, it does not mean that b_1 itself is zero. In fact, b_1 can be negative in a certain x region. For example, the deuteron b_1 is given by a helicity amplitude for the nucleon convoluted with a light-like momentum distribution of the nucleon [17, 19]:

$$b_1^D(x) = \int_x^2 \frac{dy}{y}F_1(x/y)\int d^3p \left[-\frac{3}{4\pi\sqrt{2}}\sin\alpha\cos\alpha u_s(p)u_d(p) + \frac{3}{16\pi}\sin^2\alpha u_d^2(p)\right]$$
$$\times\ (3\cos^2\theta - 1)\left[1 + \frac{p\cos\theta}{M} + \frac{p^2}{4M^2}\right]\delta\left[y - \frac{p\cos\theta + E(p)}{M}\right] \quad , \tag{5.4}$$

where $sin\alpha$ is the D-state admixture, and $u_{s,d}$ are S and D-wave deuteron wave functions. The first term is due to the S-D interference and the second to the D-state. This is just an example of nuclear structure aspects. Measured deuteron b_1 does not have to agree with the above estimate. If a deviation from nuclear contributions is found, b_1 provides important clues to physics of non-nucleonic components in nuclei and to new tensor structure on the parton level.

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