Nuclear Parton Distributions - a DGLAP Analysis

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Abstract

Nuclear parton distributions $f_A(x, Q^2)$ are studied within a framework of the DGLAP evolution. Measurements of $F_A^2/F_D^2$ in deep inelastic $lA$ collisions, and Drell–Yan dilepton cross sections measured in $pA$ collisions are used as constraints. Also conservation of momentum and baryon number is required. It is shown that the calculated $Q^2$ evolution of $F_{2n}^A/F_{2n}^C$ agrees very well with the recent NMC data, and that the ratios $R_f^A = f_A/f$ are only moderately sensitive to the choice of a specific modern set of free parton distributions. For general use, we offer a numerical parametrization of $R_f^A(x, Q^2)$ for all parton flavours $f$ in $A > 2$, and at $10^{-6} \leq x \leq 1$ and $2.25 \text{GeV}^2 \leq Q^2 \leq 10^4 \text{GeV}^2$.

1 Talk given by K.J. Eskola in Quark Matter ’99, 12 May, 1999, Torino, Italy. For the transparencies, see http://www.qm99.to.infn.it/program/qmprogram.html
1 The Framework

The motivation to study nuclear parton distributions are the hard probes of strongly interacting matter [1]. Due to a large momentum (or mass) scale $Q \gg \Lambda_{\text{QCD}}$ involved, these processes take place during the very first fractions of fm/$c$ in the high energy nuclear collisions, acting as probes of the forming quark gluon plasma. Due to the large scale, hard processes are computable within QCD perturbation theory. To a first approximation the cross sections of hard processes in nuclear collisions can be factorized as in hadronic collisions, into parton densities and a hard parton-parton cross section. The parton distributions in bound and free protons, however, are different: $f_A(x, Q^2) \neq f(x, Q^2)$. Typically in hard collisions $x \sim Q/\sqrt{s}$, so quite different regions in $x$ become relevant when moving from the present SPS-energies $\sqrt{s}/A \sim 20$ GeV up to the future LHC energies $\sqrt{s}/A \sim 5.5$ TeV. Thus there is a need for analyses of nuclear parton distributions which consistently cover sufficiently wide ranges in $x$ and $Q^2$. In this talk, I will present the main results from such an analysis [2, 3].

In deeply inelastic $lA$ scatterings (DIS), ratios of measured differential cross sections, 
$$\frac{\frac{1}{A} \frac{d\sigma}{dx dq^2}}{\frac{d\sigma}{2 dx dq^2}},$$
reflect the corresponding ratios of the nuclear structure function $F_2^A$ and that of deuterium $F_2^D$. The ratio $F_2^A/F_2^D$ is observed to deviate clearly from unity [4]. Since
$$F_2(x, Q^2) = \sum_q e_q^2 [xq(x, Q^2) + x\bar{q}(x, Q^2)],$$
parton distributions in bound protons obviously differ from those in the free proton. Often the nuclear modifications are referred to as shadowing ($x \lesssim 0.1$), anti-shadowing ($0.1 \lesssim x \lesssim 0.3$), EMC effect ($0.3 \lesssim x \lesssim 0.7$) and Fermi motion ($x \to 1$ and beyond). The dependence on the Bjorken $x$ has been observed already in the 80’s [4] but the weaker $Q^2$ dependence was detected only fairly recently by the NMC [5].

In Refs. [2, 3] our goal has not been to study the actual origin of the modifications but, rather - because perturbative QCD (pQCD) does not predict the absolute parton distributions - to use the observed effects as input for an analysis in the perturbative region. The basic idea in our study is the same as in the global analyses of parton distributions of the free proton (like in Ref. [1]): we determine the nuclear parton densities at a wide range of $x$ and $Q \geq Q_0 \gg \Lambda_{\text{QCD}}$ through their perturbative QCD (DGLAP [6]) evolution by using available experimental data and conservation of momentum and baryon number as constraints.

Information of the nuclear parton distributions can be obtained from $lA$ DIS and Drell-Yan (DY) measurements in $pA$ collisions. In these measurements, the accessible values of $x$ and $Q^2$ are strongly correlated, as illustrated in Fig. 1. To perform the DGLAP evolution of the parton densities, however, the initial distributions are needed along a fixed scale $Q_0^2$. Therefore, we determine the initial nuclear parton distributions at $Q_0^2$ iteratively through the DGLAP evolution, by using the available data at scales $Q^2 \geq Q_0^2$ as constraints. Note that now the problem is more complicated than in the free proton case because of the additional variable $A$.

We take the parton distributions of the free proton as accurately known. We choose $Q_0^2 = 2.25$ GeV$^2$ which is the $c$-quark mass threshold in the set GRVLO [12] we are using as the basis. We first parametrize the ratio $R_{F_2}^A(x, Q_0^2)$ for (isoscalar) $A$ and $x$. The potential but small nuclear effects in deuterium, and the small tails at $x > 1$ are neglected here. At the initial scale $Q_0^2$ (but only at $Q_0^2$), we assume that the nuclear sea quarks and antiquarks are modified approximately with the same profile, and similarly for the valence quarks. The ratio
Figure 1: The correlation of $x$ and $\langle Q^2 \rangle$ in the measurements of DIS [8, 10] in $pA$ and DY ($x = x_2$) [11] in $pA$. Our choice for the initial scale $Q_0^2$ is also indicated.

$F_A^2/F_D^2$ can then be simply written as a linear combination of a sea quark ratio $R_A^S = S_A/S$ and a valence quark ratio $R_A^V = V_A/V$, where $S(V)$ are the total sea (valence) distributions. The ratios $R_A^S$ and $R_A^V$ at $Q_0^2$ in turn are constrained by the DIS data [8, 9, 10] and DY data in $pA$ collisions [11] (see Fig. 1) at higher scales. $R_A^V$ is also further constrained by baryon number conservation. Momentum conservation gives an overall constraint for the gluon distributions at $Q_0^2$. In lack of any direct constraints for the nuclear gluons from the data, we assume that initially $g_A/g \approx R_A^S$ at very small values of $x$. The value of $x$ where $R_A^G(x, Q_0^2) = 1$ is estimated on the basis of Ref. [13]. For more details, please see Ref. [4]. Once the initial distributions for all parton flavours have been determined like this, the DGLAP evolution to larger scales can be performed, and comparison with the data can be made (see Fig.1). The initial ratios $R_A^S(x), R_A^V(x), R_A^G(x)$ at $Q_0^2$ are then iterated until a "best" initial condition is found.

Fig. 2a shows the scale evolution of the nuclear effects in parton distributions for an isoscalar nucleus $A=208$. The ratios $g_A/g, S_A/S, V_A/V$ and $F_A^2/F_D^2$ are shown as functions of $x$ at fixed values of $Q^2 = 2.25$ GeV$^2$ (solid lines), 5.39 GeV$^2$ (dotted), 14.7 GeV$^2$ (dashed), 39.9 GeV$^2$ (dotted-dashed), 108 GeV$^2$ (double-dashed), equidistant in log $Q^2$, and 10000 GeV$^2$ (dashed). For $R_A^S$ only the first and last ones are shown.

In Fig. 2b we plot the calculated lowest order, leading twist pQCD evolution for the ratio $F_A^{2n}/F_D^{2C}$ at different fixed values of $x$, and compare the results directly with the corresponding data of NMC [3]. The agreement is very good. Note that in order to reduce the potential gluon fusion [14] effects in the evolution as much as possible, we have chosen the initial scale above 1 GeV but below the $m_c$-threshold in order to make the treatment of the initial state as simple as possible. The log $Q^2$ slopes of $F_2$, and also of the ratio $F_A^2/F_D^2$, can be used to constrain the gluon distributions [13]. Unfortunately, however, the values of $x$ of the NMC data [5] are not quite small enough to get a firm handle on the initial nuclear shadowing of gluons.
Figure 2: (a) The scale evolution of the ratios $xg_A/xg$, $xS_A/xS$, $xV_A/xV$ and $F_A^2/F_D^2$ for an isoscalar nucleus $A = 208$. (b) The calculated $Q^2$ dependence of $F_{Sn}^2/F_C^2$ compared with the NMC data [5].

2  The EKS98-parametrization

We have also repeated the analysis by using the CTEQ4L parton distributions [3] as the basis [3]. Note that in CTEQ4L the sea is more flavour-asymmetric than in GRVLO, and that there are less gluons in CTEQ4L at very small values of $x$. The nuclear ratios $R_f^A \equiv f_A/f$ for each flavour of partons were, however, found to deviate at most a few per cents relative to those computed with GRVLO. We therefore conclude that to a good first approximation $f_A(x, Q^2)_{\text{set}} = R_f^A(x, Q^2)f(x, Q^2)_{\text{set}}$, where “set” refers to any modern lowest order set of parton distributions for the free proton, and where $R_f^A$ does not depend on the set.

For practical applications of computing hard cross sections in high energy nuclear collisions, we have also prepared a parametrization of the nuclear ratios $R_f^A(x, Q^2)$ for each
parton flavour $f$ in any nucleus $A > 2$, at $10^{-6} \leq x \leq 1$ and $2.25 \text{GeV}^2 \leq Q^2 \leq 10^4 \text{GeV}^2$. The parametrization is intended for general use, and it is available from us via email, or from [http://fpaxp1.usc.es/phenom](http://fpaxp1.usc.es/phenom) or from http://www.urhic.phy.jyu.fi/.

Finally, we note that our analysis can be improved in obvious ways: more quantitative error analysis must be implemented, next-to-leading order DGLAP evolution must be done, the initial gluon distributions and gluon fusion corrections [14] must be studied in more detail.

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