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Parametrization of Nuclear Parton Distributions

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Parametrization of Nuclear Parton Distributions

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Abstract. Optimum nuclear parton distributions are obtained by analyzing available experimental data on electron and muon deep inelastic scattering (DIS). The distributions are given at Q^2=1 GeV^2 with a number of parameters, which are determined by a χ^2 analysis of the data. Valence-quark distributions are relatively well determined at medium x, but they are slightly dependent on the assumed parametrization form particularly at small x. Although antiquark distributions are shadowed at small x, their behavior is not obvious at medium x from the F_2 data. The gluon distributions could not be restricted well by the inclusive DIS data; however, the analysis tends to support the gluon shadowing at small x. We provide analytical expressions and computer subroutines for calculating the nuclear parton distributions, so that other researchers could use them for applications to other high-energy nuclear reactions.

Keywords. parton, distribution, quark, gluon, parametrization

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1. Introduction

Parton distributions in the nucleon are now known accurately by using many experimental data on lepton and hadron reactions. The distributions are expressed by parameters which are determined by a χ^2 analysis of the data. The determination of the distributions is important not only for understanding internal structure of the nucleon but also for calculating other reaction cross sections. If they are precisely known, it becomes possible to find a signature for new physics beyond the current framework by detecting a deviation from theoretical predictions. In the recent years, the parametrization studies have been extended to polarized parton distributions [1]. The situation is not as good as the unpolarized one in the sense that the details of polarized antiquark distributions cannot be determined only by the g_1 measurements. The polarized gluon distribution is also not well determined. We should wait for hadron collider data.

In some sense, the situation of nuclear parton distributions is similar to this polarized case. The antiquark and gluon distributions are not well determined at this stage. In investigating high-energy nuclear reactions, the parton distributions

in the "nucleon" are often used instead of those in a nucleus. Namely, a nucleus is often assumed as a simple collection of nucleons. It is unsatisfactory in the sense, for example, that precise nuclear distributions have to be known in order to find a quark-gluon signature in heavy-ion collisions.

It is recognized that nuclear parton distributions are modified from the ones in the nucleon by the measurements of nuclear F_2 structure functions [2]. According to the data of the nucleus-deuteron ratio F_2^A/F_2^D, the structure functions show shadowing at small x, antishadowing around $x \sim 0.15$, and depletion at $x \sim 0.6$. The ratio tends to increase at large $x > 0.8$. The modification has been also investigated theoretically, and major features are now understood [2]. It is, however, not straightforward to find the details of the modification in each parton distribution because all the distributions contribute to F_2 in principle. Although the determination of the nuclear distributions is important for practical applications, it is unfortunate that there was no χ^2 analysis. Of course, there were some trials to produce the parton distributions from the nuclear data, for example, in a model-dependent way [3] and in a model-independent way by Eskola, Kolhinen, and Ruuskanen [4]. Here, we intend to pioneer the χ^2 analysis of nuclear parton distributions without relying on any theoretical models [5]. We also try to provide analytical expressions and computer subroutines, so that other researchers could use them for their studies. This talk is based on the analysis results in Ref. [5]. The nuclear parton distributions are provided at a fixed Q^2 with a number of parameters, which are then determined by the χ^2 analysis of experimental data. The data are restricted to the inclusive electron and muon deep inelastic data at this stage. We try to include some hadron collider data in a later version.

This paper consists of the following. In Sec. 2, assumed functional forms are explained, and our χ^2 analysis method is explained in Sec. 3. The analysis results are shown in Sec. 4. We explain obtained parton distributions so that other researchers could use them in Sec. 5. The summary is given in Sec. 6.

2. Parametrization

Because the parton distributions are well determined in the nucleon and maximum nuclear effects are typically 20% for a medium size nucleus, it is a good idea to parametrize the modification instead of the distributions themselves. There is, however, a disadvantage in this approach although it could be a subtle problem. If the scaling variable x is defined by $x = Q^2/(2m\nu)$ with the nucleon mass m and the energy transfer ν in the electron or muon scattering, there are finite distributions even at $x > 1$. If the nuclear distributions are taken as $w(x, A, Z)\, f(x)$, where $f(x)$ is a parton distribution in the nucleon and $w(x, A, Z)$ is the nuclear modification, there is no way to obtain the large x distributions at $x > 1$ due to $f(x \geq 1) = 0$. In this paper, this issue is neglected because of much more advantages. In any case, even if the large x part ($x > 1$) is included in the initial distributions, there is no reliable theoretical tool to evolve them to larger Q^2 at this stage. In this way, the nuclear distributions are given at a fixed Q^2 ($\equiv Q_0^2$) as

$$f_i^A(x, Q_0^2) = w_i(x, A, Z)\, f_i(x, Q_0^2), \tag{1}$$

where f_i is the type-i parton distribution in the nucleon, and w_i expresses the nuclear modification. Because the distributions in the nucleon (f_i) are well known from other studies, we try to parametrize w_i. Alternatively, we could parametrize the nuclear distributions (f_i^A) themselves. However, it could lead to unphysical results easily because a variety of nuclear data are not available in comparison with the nucleon case. We call w_i a weight function. In the following, we discuss its functional form.

First, we discuss the A dependence of the weight function w_i. In this paper, we do not try to investigate the details of the A dependence. Because our analysis seems to be the first χ^2 trial, we assume the following simple A dependence. According to Ref. [6], any nuclear cross sections could be written in terms of volume and surface contributions: $\sigma_A = A\,\sigma_v + A^{2/3}\sigma_s$. Then, the cross section per nucleon becomes $\sigma_A/A = \sigma_v + A^{-1/3}\sigma_s$. Of course, σ_v and σ_s have nuclear dependence; however, the $1/A^{1/3}$ dependence could be considered as the leading factor. We leave the issue of detailed A dependence as our future topic.

Second, because the nuclear distributions have finite distributions even at $x = 1$ and the distributions vanish in the nucleon, the weight functions should have a property, $w_i(x, A, Z) \to \infty$ as $x \to 1$. In order to explain this x region, we introduce a function $1/(1-x)^{\beta_i}$. The rest of the x dependence is assumed as a polynomial form in our analysis.

In this way, the following quadratic functional form is taken:

$$\text{“quadratic type”:} \quad w_i(x, A, Z) = 1 + \left(1 - \frac{1}{A^{1/3}}\right) \frac{a_i(A, Z) + b_i x + c_i x^2}{(1-x)^{\beta_i}}, \tag{2}$$

as the simplest one which could explain the measured F_2^A data. The parameter a_i is considered to be dependent on the ratio Z/A, and the reason is explained in the end of this section. Because of the quadratic x dependence, there are certain restrictions. For example, the valence-quark distributions show antishadowing at small x if the F_2 depletion at medium x is explained mainly by the valence-quark modification. This is because of a strong restriction due to the baryon-number conservation. On the other hand, this simple parametrization could be sufficient for the antiquark and gluon distributions, where the detailed x dependence at medium and large x is not important at this stage by considering available data.

Because the quadratic form could be too simple to explain the data, we prepare the following second type:

$$\text{“cubic type”:} \quad w_i(x, A, Z) = 1 + \left(1 - \frac{1}{A^{1/3}}\right) \frac{a_i(A, Z) + b_i x + c_i x^2 + d_i x^3}{(1-x)^{\beta_i}}. \tag{3}$$

There is an additional term $d_i x^3$. It is the advantage of this functional form that the distribution shapes become more flexible to explain the experimental data. For example, there is no aforementioned valence-quark problem at small x. Namely, the valence distribution could show either shadowing or antishadowing. However, the drawback is that it takes more computing time in the χ^2 analysis because of the additional freedoms.

As the distribution type i, we take valence up-quark, valence down-quark, antiquark, and gluon distributions. Flavor symmetric antiquark distributions are assumed here due to the lack of data to discriminate the difference, although there are

some predictions on the asymmetry in a nucleus [7]. Furthermore, the valence up- and down-quark weight functions are expected to be similar, so that the parameters are assumed to be the same except for the constants a_{u_v} and a_{d_v}.

There are three obvious conditions for the distributions: nuclear charge, baryon number, and momentum. In the parton model, they are expressed as

$$\text{charge} \qquad Z = \int dx\, A \left[\frac{2}{3}(u^A - \bar{u}^A) - \frac{1}{3}(d^A - \bar{d}^A) - \frac{1}{3}(s^A - \bar{s}^A)\right]$$

$$= \int dx\, \frac{A}{3}\left[2\, u_v^A - d_v^A\right], \tag{4}$$

$$\text{baryon number} \qquad A = \int dx\, A \left[\frac{1}{3}(u^A - \bar{u}^A) + \frac{1}{3}(d^A - \bar{d}^A) + \frac{1}{3}(s^A - \bar{s}^A)\right]$$

$$= \int dx\, \frac{A}{3}\left[u_v^A + d_v^A\right], \tag{5}$$

$$\text{momentum} \qquad A = \int dx\, A\, x \left[u^A + \bar{u}^A + d^A + \bar{d}^A + s^A + \bar{s}^A + g^A\right]$$

$$= \int dx\, A\, x \left[u_v^A + d_v^A + 6\, \bar{q}^A + g^A\right]. \tag{6}$$

From these conditions, three parameters can be fixed. In our studies, we decided to determine $a_{u_v}(A, Z)$, $a_{d_v}(A, Z)$, and $a_g(A, Z)$. Although $a_{\bar{q}}$ is still kept as a nuclear independent parameter, these three parameters depend on a nucleus, in particular on the ratio Z/A. Using the three conditions together with the weight functions, we can express the parameters, a_{u_v}, a_{d_v}, and a_g, in terms of nuclear independent constants and the ratio Z/A [5]. Therefore, if the conditions are, for example, satisfied for the deuteron, they are automatically satisfied for all the other isoscalar nuclei. However, we also analyze nuclei with neutron excess. Even if the three conditions are satisfied for the isoscalar nuclei, they are not satisfied for other nuclei with different Z/A factors. In this way, we introduce nuclear dependence in the parameters, a_{u_v}, a_{d_v}, and a_g.

3. χ^2 analysis method

There are many experimental data in lepton and hadron reactions. However, we use only the structure-function F_2 data in our χ^2 fit with the following reasons. First, because this is the first trial of the nuclear χ^2 fit, we would like to simplify the problem. Second, we would like to understand how well the parton distributions are determined only by the inclusive electron and muon scattering. Inclusion of other data such as Drell-Yan measurements is left as our future research topic.

Nuclear F_2 measurements are usually shown by its ratio to the deuteron F_2:

$$R^A_{F_2}(x, Q^2) \equiv \frac{F_2^A(x, Q^2)}{F_2^D(x, Q^2)}. \tag{7}$$

In this paper, the leading order (LO) of α_s is used in the analysis. The structure

function F_2 is then expressed in terms of the parton distributions as

$$F_2^A(x,Q^2) = \sum_q e_q^2\, x\, [q^A(x,Q^2) + \bar{q}^A(x,Q^2)]$$
$$= \frac{x}{9}\, [\, 4\, u_v^A(x,Q^2) + d_v^A(x,Q^2) + 12\, \bar{q}^A(x,Q^2)\,], \tag{8}$$

where the number of flavor is assumed three. Theoretically, the above structure function and the deuteron F_2 can be calculated for a given set of parameters in the weight functions. Then, the theoretical ratios $R_{F_2}^A(x,Q^2)$ are calculated and they are compared with the corresponding experimental data to obtain χ^2:

$$\chi^2 = \sum_j \frac{(R_{F_2,j}^{A,data} - R_{F_2,j}^{A,theo})^2}{(\sigma_j^{data})^2}. \tag{9}$$

It should be noted that the parton distributions are provided in the analytical form at a fixed Q_0^2, and the data are taken, in general, at different Q^2 points. In order to calculate the χ^2, the distributions are evolved to the experimental Q^2 points. This Q^2 evolution is calculated by the ordinary DGLAP (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi) equations in Ref. [8].

The initial Q^2 point is taken as Q_0^2=1 GeV^2 with the following reason. In order to accommodate many data, a small Q^2 point is desirable. However, it should be large enough to be within the perturbative QCD range. As a compromise of these conditions, Q_0^2=1 GeV^2 is chosen. Because we do not investigate the distributions in the nucleon, it is necessary to employ a set of LO distributions. There are three major groups in the nucleon parametrization: CTEQ, GRV (Glück, Reya, and Vogt), and MRS (Martin, Roberts, and Stirling). Among them, we decided to use the LO version of MRST-central gluon in 1998 [9] because analytical expressions are available at Q^2=1 GeV^2 in the LO.

Before the actual analysis, we need to clarify the valence up- and down-quark distributions in a nucleus in comparison with those in the nucleon. If a nucleus consists of a simple collection of nucleons, namely if there is no nuclear modification, nuclear parton distributions are given by the summation of proton and neutron contributions: $Af_i^A(x,Q^2)_{\text{no-mod}} = Zf_i^p(x,Q^2) + Nf_i^n(x,Q^2)$. Here, the nuclear parton distributions are defined by the ones per nucleon. Isospin symmetry is assumed in discussing the relation between the distributions in the neutron and the ones in the proton. Then, the deviation from this simple summation is expressed by the weight functions:

$$u_v^A(x,Q_0^2) = w_{u_v}(x,A,Z)\, \frac{Zu_v(x,Q_0^2) + Nd_v(x,Q_0^2)}{A},$$
$$d_v^A(x,Q_0^2) = w_{d_v}(x,A,Z)\, \frac{Zd_v(x,Q_0^2) + Nu_v(x,Q_0^2)}{A},$$
$$\bar{q}^A(x,Q_0^2) = w_{\bar{q}}(x,A,Z)\, \bar{q}(x,Q_0^2),$$
$$g^A(x,Q_0^2) = w_g(x,A,Z)\, g(x,Q_0^2). \tag{10}$$

The technical part of the χ^2 analysis is now ready, but we should also specify used experimental data. As already mentioned, nuclear F_2^A/F_2^D data are considered.

Because of the DGLAP evolution equations, the used data should be taken in a perturbative QCD region. Therefore, the only data with $Q^2 \geq 1$ GeV^2 are used in the analysis. We collected all the available data [10] by the European Muon Collaboration (EMC) at CERN, the E49, E87, E139, and E140 Collaborations at SLAC, the Bologna-CERN-Dubna-Munich-Saclay (BCDMS) Collaboration at CERN, the New Muon Collaboration (NMC) at CERN, and the E665 Collaboration at Fermilab.

Kinematical range of the experimental data is shown in Fig. 1. The small x data are taken by EMC, NMC, and E665, and they have rather small Q^2 values in a restricted Q^2 range. This fact suggests that it should be rather difficult to pin down the nuclear gluon distributions from the scaling violation at small x. A significant number of data are taken by the SLAC groups at large x with relatively small Q^2 values. On the contrary, the BCDMS data are in the larger Q^2 range. The data exist for the following nuclei: helium (He), lithium (Li), beryllium (Be), carbon (C), nitrogen (N), aluminum (Al), calcium (Ca), iron (Fe), copper (Cu), silver (Ag), tin (Sn), xenon (Xe), gold (Au), and lead (Pb). The total number of the data is 309. Theoretically, these nuclei are assumed as ^{4}He, ^{7}Li, ^{9}Be, ^{12}C, ^{14}N, ^{27}Al, ^{40}Ca, ^{56}Fe, ^{63}Cu, ^{107}Ag, ^{118}Sn, ^{131}Xe, ^{197}Au, and ^{208}Pb in calculating the parton distributions.

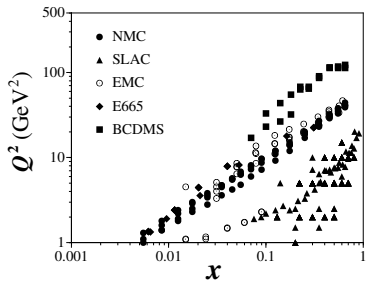

Figure 1. x and Q^2 values of the used data.

4. Results

The χ^2 analyses are done for both the quadratic and cubic parametrization forms by the CERN subroutine Minuit [11]. The following simplifications are introduced in the parameters. First, the parameter β controls the large x behavior. Because the antiquark and gluon distributions do not contribute to F_2 significantly at large x, the detailed values of $\beta_{\bar{q}}$ and β_g are not important. They are fixed at $\beta_{\bar{q}} = \beta_g = 1$. Furthermore, the relation between b_g and c_g is also fixed at $b_g = -2c_g$ because the gluon shape in the medium and large x regions could not be determined reliably. Because of the same reason, the gluon distribution is kept in the quadratic form even in the cubic type analysis. The possible additional term $d_g x^3$ is associated with the distribution shape at large x; however, such a term is almost irrelevant in the present analysis.

The analysis results are shown for some of the used nuclei in Figs. 2−7, where the dashed and solid curves are the quadratic and cubic type results, respectively, at Q^2=5 GeV^2. We should be careful in comparing the theoretical curves with the data because the data are taken in various Q^2 points, which are in general different from Q^2=5 GeV^2. Considering even the Q^2 differences, there are some deviations from the experimental data, for example, in the medium-x region of the carbon figure. However, if we try to fit these data in this x region, it is obvious that the medium-x

depletion of the beryllium and gold is overestimated. Therefore, this kind of small deviations seem to be inevitable in the present χ^2 analysis. Nevertheless, the figures indicate that our analyses are reasonable in explaining the existing experimental data. The obtained χ^2_{min} is 583.7 and 546.6 in the quadratic and cubic analyses, respectively.

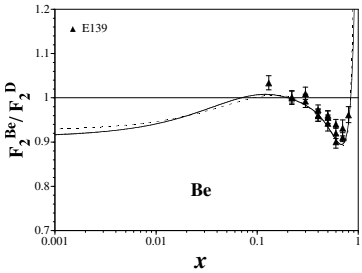

Figure 2. The dashed and solid curves are fitting results for the beryllium in the quadratic and cubic analyses, respectively, at Q^2=5 GeV^2. They are compared with the data.

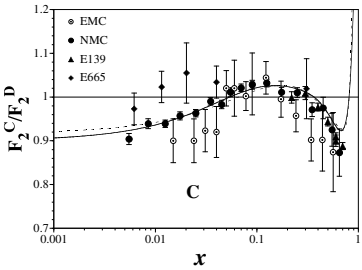

Figure 3. Comparison with the carbon data.

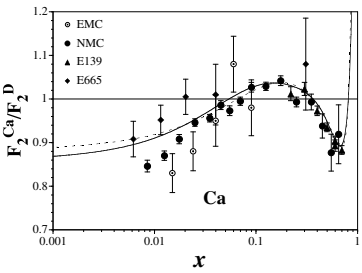

Figure 4. Comparison with the calcium data.

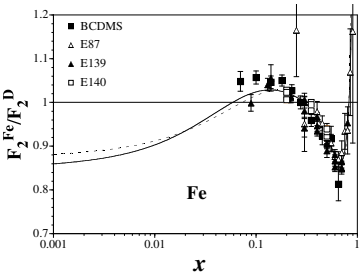

Figure 5. Comparison with the iron data.

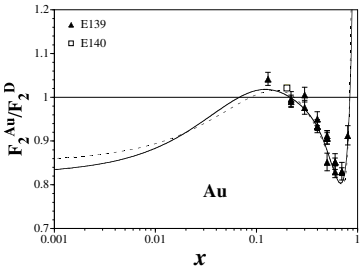

Figure 6.Comparison with the gold data.

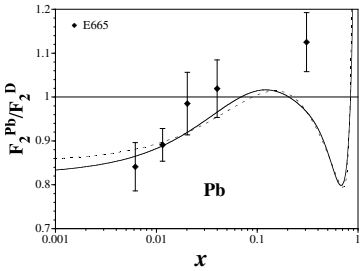

Figure 7. Comparison with the lead data.

There are systematic differences between the dashed and solid curves in Figs. 2−7 at small x, where there are not many experimental data. The quadratic results are in general above the cubic ones at $x < 0.01$, and they are below in the region, $0.03 < x < 0.14$. Because of the additional parameters, the cubic analysis has more freedoms to readjust the distributions. This fact results in such differences. In the medium and large x regions, both results are almost the same. Of course, the cubic results are better than the quadratic ones because of smaller χ^2_{min}. However, as far as we see in the figures, there are not so much differences between both curves in comparison with the data, so that both results could be taken as possible nuclear parton distributions.

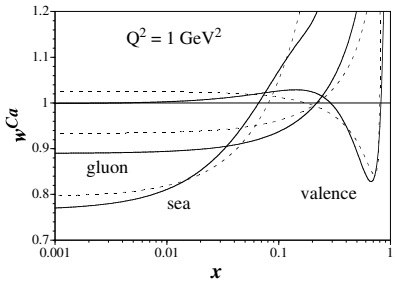

Figure 8. Weight functions are shown for the calcium nucleus. The dashed and solid curves are the results for the quadratic and cubic analyses, respectively.

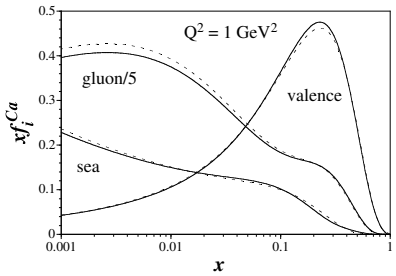

Figure 9. Obtained parton distributions are shown for the calcium nucleus. The dashed and solid curves are the results for the quadratic and cubic analyses, respectively.

Using the obtained parameters, we plot the weight functions for the calcium nucleus at Q^2=1 GeV^2 in Fig. 8. The quadratic and cubic analysis results are shown by the dashed and solid curves, respectively. The valence-quark distributions are relatively well determined from the F_2 data. However, we notice that the small-x behavior is slightly dependent on the assumed functional form by comparing the dashed and solid curves. In the quadratic fit, it shows antishadowing as expected from the baryon-number conservation. However, it indicates slight shadowing at very small x (~ 0.001) in the cubic fit. This kind of issue cannot be solved only by the F_2 data, and future neutrino factory data for F_3 [12] should clarify the problem.

The antiquark distributions are determined well at small x; however their shapes are difficult to be determined at medium and large x. Even if the cubic functional form is taken for the antiquark distribution, the obtained weight function is similar to the quadratic one according to Fig. 8. The antiquark functions monotonically increase as x becomes larger. The gluon functional shapes are similar to the antiquark functions. The gluon distributions tend to be shadowed at small x; however, its determination is not easy in the larger x region.

Using the weight functions in Fig. 8 and the MRST distributions, we obtain the parton distributions in the calcium nucleus in Fig. 9. The dashed and solid curves indicate the distributions at Q^2=1 GeV^2 in the quadratic and cubic analyses, respectively. The quark distributions are well constrained by the F_2 measurements; however, the gluon distributions are not reliably determined particularly at large

x. The details of the obtained distributions are explained in the next section, so that one could use them for one's applications.

We should also mention the effects of our studies on the parton distributions in the nucleon. Because the nuclear data are partially used in determining the distributions in the nucleon without the nuclear corrections, the existing nucleon parametrizations should be modified, particularly in the valence-quark part.

5. Parton distributions for practical usage

We provide both distributions obtained by the quadratic and cubic analyses because the χ^2_{min} values are not much different. However, the cubic type distributions are preferred because the χ^2_{min} is smaller. We call the cubic and quadratic distributions type I and type II, respectively. The obtained distributions are provided in two different ways: analytical expressions and computer codes for numerical calculations.

5.1 Analytical expressions

First, analytical expressions are useful if one has own Q^2 evolution program or if the Q^2 dependence could be neglected. The nuclear parton distributions are given by the weight functions and MRST-LO (central gluon) distributions [9]. Here, we provide the expressions for the weight functions. One should note that these functions are given at Q^2=1 GeV^2:

Type I: cubic fit

$$\begin{aligned}
w_{u_v} &= 1 + \left(1 - \frac{1}{A^{1/3}}\right) \frac{a_{u_v}(A,Z) + 0.6222x - 2.858x^2 + 2.557x^3}{(1-x)^{0.8107}}, \\
w_{d_v} &= 1 + \left(1 - \frac{1}{A^{1/3}}\right) \frac{a_{d_v}(A,Z) + 0.6222x - 2.858x^2 + 2.557x^3}{(1-x)^{0.8107}}, \\
w_{\bar{q}} &= 1 + \left(1 - \frac{1}{A^{1/3}}\right) \frac{-0.3313 + 6.995x - 34.17x^2 + 62.54x^3}{1-x}, \\
w_g &= 1 + \left(1 - \frac{1}{A^{1/3}}\right) \frac{a_g(A,Z) + 0.8008x - 0.4004x^2}{1-x},
\end{aligned} \tag{11}$$

Type II: quadratic fit

$$\begin{aligned}
w_{u_v} &= 1 + \left(1 - \frac{1}{A^{1/3}}\right) \frac{a_{u_v}(A,Z) - 0.2593\,x + 0.2586\,x^2}{(1-x)^{2.108}}, \\
w_{d_v} &= 1 + \left(1 - \frac{1}{A^{1/3}}\right) \frac{a_{d_v}(A,Z) - 0.2593\,x + 0.2586\,x^2}{(1-x)^{2.108}}, \\
w_{\bar{q}} &= 1 + \left(1 - \frac{1}{A^{1/3}}\right) \frac{-0.2900 + 3.774\,x - 2.236\,x^2}{1-x}, \\
w_g &= 1 + \left(1 - \frac{1}{A^{1/3}}\right) \frac{a_g(A,Z) + 0.4798\,x - 0.2399\,x^2}{1-x}.
\end{aligned} \tag{12}$$

The actual values of a_{u_v}, a_{d_v}, and a_g are not provided here. One may determine them by one's effort so as to satisfy the conditions in Eqs. (4), (5), and (6). If one is considering a nucleus which is one of the analyzed nuclei (D, He, Li, ..., Pb) in this paper, one may simply take the tabulated values in Ref. [5]. For other nucleus, one is asked to follow the instructions in Appendix of Ref. [5]. However, the requested nucleus should not be too far away from the analyzed nuclei. Because the distributions are given at Q^2=1 GeV^2, one should evolve them to the appropriate Q^2 point in one's project.

5.2 Computer subroutines

If one thinks that it is tedious to evolve the analytical expressions, one had better use computer subroutines, which are prepared to calculate the nuclear parton distribution at any given x and Q^2 points. The variables x and Q^2 are divided into small steps, and a grid data is prepared for each nucleus at these x and Q^2 points. The linear interpolation is used for $log\, Q^2$ because the Q^2 dependence is small, and the cubic Spline interpolation is used for the x part. Suggested kinematical ranges are $10^{-9} \leq x \leq 1$ and 1 GeV^2 $\leq Q^2 \leq 10^5$ GeV^2. Our codes could be used for calculating the distributions in other nuclei than the analyzed ones. The detailed instructions are found in the web page of Ref. [13].

6. Summary

We have done χ^2 analyses of nuclear structure-function ratios F_2^A/F_2^D by collecting existing electron and muon deep inelastic experimental data. Assuming simple $1/A^{1/3}$ dependence in the nuclear modification part, we parametrized the initial nuclear parton distributions at Q^2=1 GeV^2. They are taken as the quadratic or cubic functional form with a number of parameters, which are then determined by the χ^2 analysis. We have obtained reasonable fit to the data. As a result, the valence-quark distributions are reasonably well determined except for the small x region. The obtained antiquark distributions indicate shadowing at small x. However, the antiquark and gluon distributions are not well fixed by the F_2 data in the medium and large x regions. In particular, it is difficult to determine the gluon distributions in the whole x region. However, the results indicate the gluon shadowing at small x.

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