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Quark distributions in nuclei and nuclear effects on nucleon structure functions*

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Abstract Extended quark distribution functions are presented obtained by fitting a large amount of experimental data of the l-A DIS process on the basis of an improved nuclear density model. The experimental data of l-A DIS processes with $A\geqslant 3$ in the region $0.0010\leqslant x\leqslant 0.9500$ are quite satisfactorily described by using the extended formulae. Our knowledge of the influence of nuclear matter on the quark distributions is deepened.

Key words improved nuclear density model, quark distributions in nuclei, nuclear effects on nucleon structure functions

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1 Introduction

Since the discovery of the EMC effect[1], physicists have proposed several models giving a more or less satisfactory explanation for it[2—7]. Among these models, the nuclear density model proposed by Frankfurt and Strikman is such a model that explains the EMC effect[8]. It can explain the nuclear effect in l-A DIS processes (lepton-nucleus (A) deep inelastic scattering) for medium range x values[9]. However, the function $R^{A_1/A_2}(x,Q^2)$ obtained from the nuclear density model is used to describe the influence of the nuclear medium on the valence quark distribution and the sea quark distribution, which does not reflect their corresponding variations[10—12]. In 2006, Gao et al. presented an improved nuclear density model and obtained formulae for $R^A_V(x,Q^2)$, $R^A_S(x,Q^2)$ describing the valence quark distribution and the sea quark distribution within the region of $0.0010\leqslant x\leqslant 0.6000$ for a bound nucleon. These functions depending on phenomenological parameters were obtained by fitting experimental data on deep inelastic scattering. With these formulae, containing now a description of the nuclear effects in parametric form, the experimental data of the l-A DIS processes (for $A\geqslant 12$) and the nuclear Drell-Yan processes (E772 Collaboration experimental data) could be well described[13, 14]. Due to the restriction of the nuclear momentum conservation condition, a gloun distribution formula depending on a corresponding parameter was also proposed. With this also, the nuclear effect on the J/ψ process could be explained satisfactorily[15].

Although several nuclear effects were explained satisfactorily by these parametric formulae for the parton distributions, we think that the original quark distribution formulae have two shortcomings. First, they are obtained by using only a limited set of experimental data, therefore some uncertainties exist. Second, the original formulae do not include values of the phenomenological parameters for the region $x\geqslant 0.6000$, i.e., they cannot describe the distributions of the valence and sea quarks in the large x

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region. This is true for the l-A DIS processes and also for the prediction of other nuclear processes, such as the nuclear Drell-Yan process in the large x region. Therefore we refitted the quark distribution functions taking into account a larger experimental data for the l-A DIS processes and extended the x region. In this paper we obtain the phenomenological valence and sea quark distribution functions for the range $0.0010 \leqslant x \leqslant 0.9500$. The experimental data of the l-A DIS processes for $A \geqslant 3$ in this region is then quite satisfactorily explained. The paper is organized as follows. In Sec. 2, the extended parametric quark distribution functions are presented refitting an enlarged experimental data set for the l-A DIS processes based on an improved nuclear density model. The results are shown and discussed in Sec. 3. In the last section some conclusions are drawn.

2 Improved nuclear density model and quark distributions in nuclei

Frankfurt and Strikman suggested the following form for the structure functions:

$$[F_2^A/F_2^N-1]/[F_2^D/F_2^N-1]=\rho(A)/\rho(D), \tag{1}$$

where $F_2^N=(F_2^{\mathrm{p}}+F_2^{\mathrm{n}})/2$ is the structure function of the free nucleon, F_2^A and F_2^D are the isoscalar nuclear and deuteron structure functions. They assumed that the nuclear effect on the nucleon structure has its origin in the differences of the nuclear densities $\rho(A)$ (in units of nucleon/fm^3). Thus Eq. (1) can be written as follows

$$[F_2^A/F_2^N-1]=\beta(x)\rho(A)\ , \tag{2}$$

where $\beta(x)$ is for all kinds of nuclei the same, the nuclear effect being described by $\rho(A)$. The function describing the effect of nuclear medium on the structure function of a bound nucleon in a nucleus A is then given by

$$R^{A_1/A_2}(x,Q^2)=F_2^{A_1}(x,Q^2)/F_2^{A_2}(x,Q^2)= \\ [1+\beta(x)\rho(A_1)]\,/\,[1+\beta(x)\rho(A_2)]\,. \tag{3}$$

The ratio $R^{A_1/A_2}(x,Q^2)$ of Eq. (3) describes the result for a parton distribution under the influence of the nuclear medium. However, it does not reflect the respective change of the valence and sea quark distributions in nucleus. If in Eq. (3) A_2 is a deuteron with a very small density of $\rho(D)=0.0244$, we can write Eq. (3) in the form

$$R^{A_1/D}(x,Q^2)\approx 1+\beta(x)\rho(A_1). \tag{4}$$

That Eq. (4) is reasonable can be tested by using effective field theory (see Ref. [16]).

The influence of the nuclear medium experienced by the valence quark and the sea quark momentum distributions is not necessarily the same and different descriptions should be used. Explicit forms for $R_V^A(x,Q^2)$ and $R_S^A(x,Q^2)$ (for the valence quark and the sea quark distributions) for the range $0.0010 \leqslant x \leqslant 0.6000$ have been obtained in Ref. [13]. They are given by

$$R_V^A(x,Q^2)=1+\frac{K_V(A)\beta_V(x)-1}{0.107}\rho(A), \tag{5}$$

$$R_S^A(x,Q^2)=1+\frac{K_S(A)\beta_S(x)-1}{0.107}\rho(A), \tag{6}$$

where $\beta_V(x)$, $\beta_S(x)$ and $K_V(A)$, $K_S(A)$ are phenomenological parameters to determine the valence quark distributions and the sea quark distributions in bound nucleon and have been obtained by fitting a limited set of experimental data of the l-A DIS process. The number of phenomenological parameters in Eqs. (5,6) has now increased and the expressions are more complicated. In order to put Eqs. (5,6) into a more compact form, we write

$$R_V^A(x,Q^2)\ =\ 1+\beta_V^*(x)\rho(A), \tag{7}$$

$$R_S^A(x,Q^2)\ =\ 1+\beta_S^*(x)\rho(A). \tag{8}$$

The phenomenological parameters $\beta_V^*(x)$, $\beta_S^*(x)$ in Eqs. (7,8) have been by fitting an extended experimental data set of the l-A DIS process. A value of $Q^2=40$ GeV^2 has been taken for the fitting procedure. The obtained phenomenological parameter values are listed in Table 1.

The nuclear density $\rho(A)$ used in Eqs. (7,8) has been taken from an empirical formula used to describe the average properties of nuclei[17].

$$\rho(A)=0.01\epsilon^{1/2}+0.02\ln A \tag{9}$$

where ε is the mean binding energy in the nucleus of mass number A. The mean binding energies have been taken from Ref. [18].

For a nucleus A the momentum distribution functions of the valence and the sea quarks in a bound nucleon are given by

$$q_{Vf}^A(x,Q^2)\ =\ R_V^A(x,Q^2)q_{Vf}^N(x,Q^2), \tag{10}$$

$$q_{Sf}^A(x,Q^2)\ =\ R_S^A(x,Q^2)q_{Sf}^N(x,Q^2), \tag{11}$$

where $q_{Vf}^N(x,Q^2)$ and $q_{Sf}^N(x,Q^2)$ are the corresponding momentum distribution functions inside a free nucleon, f denotes the flavor of quarks. From this we can see that the distributions for quarks in a bound nucleon can be obtained, as described before in Eqs. (7,8), by using parameters $\beta_V^*(x)$, $\beta_S^*(x)$ different from those used for the quarks in a free nucleon.

Table 1. Phenomenological parameters as a function of x in the range of $0.0010 \leqslant x \leqslant 0.9500$ ($Q^2 = 40$ GeV^2).

x	$\beta_V^*(x)$	$\beta_S^*(x)$	x	$\beta_V^*(x)$	$\beta_S^*(x)$
0.0010	−0.0098	−2.3198	0.6000	−1.6487	32.4496
0.0100	0.0237	−1.8703	0.6500	−1.8416	49.6185
0.0293	0.0880	−1.0848	0.6800	−1.9000	62.2980
0.0512	0.1485	−0.4628	0.7000	−1.8769	71.8577
0.0805	0.2089	−0.0186	0.7500	−1.6120	100.1080
0.1244	0.2565	−0.0106	0.7800	−1.2012	120.4380
0.1765	0.2481	−0.6628	0.8000	−0.7620	135.6020
0.2451	0.1348	−1.8147	0.8500	1.3384	180.1620
0.3439	−0.2119	−1.8523	0.8800	3.8905	212.5050
0.4390	−0.7081	3.0076	0.9000	6.6845	237.1180
0.5000	−1.0754	10.3060	0.9500	25.2534	315.5230

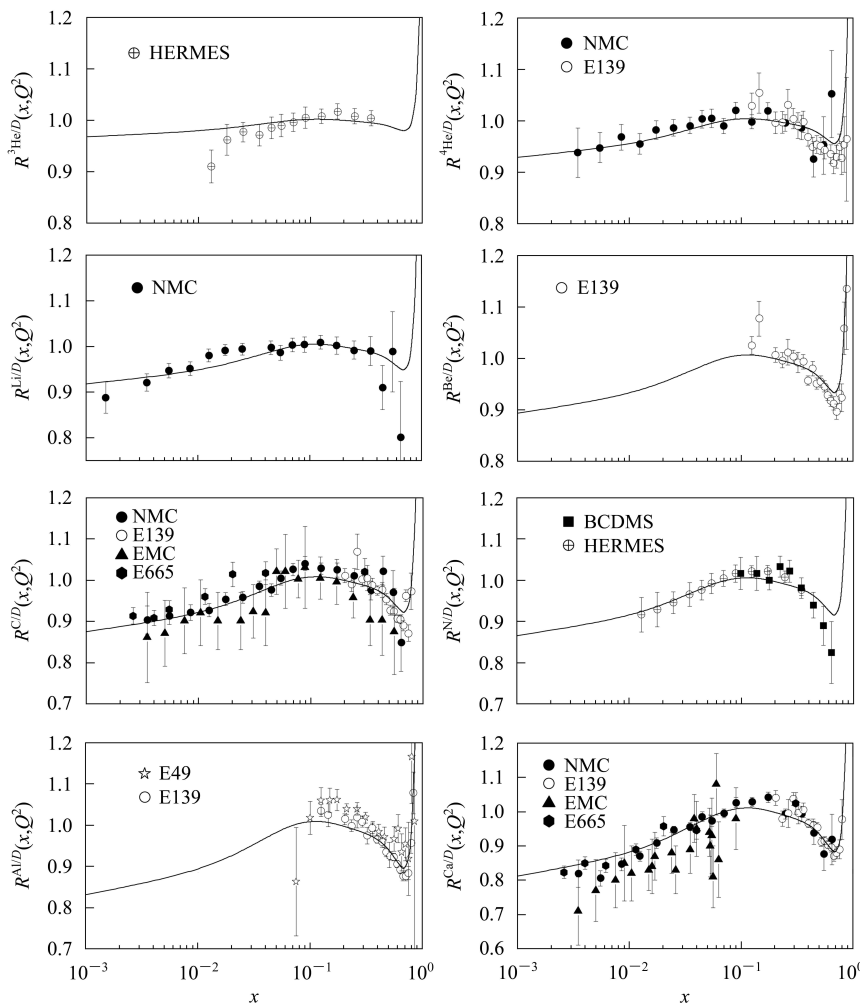

Fig. 1. The ratio $R^{A/D}(x,Q^2)$ versus the momentum fraction x in the region $0.0010 \leqslant x \leqslant 0.9500$, and the corresponding experimental data for $3 \leqslant A \leqslant 40$. The solid lines show the present theoretical results.

From Eqs. (10,11) we see that once we know the momentum distribution functions $q_{Vf}^N(x,Q^2)$ and $q_{Sf}^N(x,Q^2)$ of the valence and sea quarks in a free nucleon, we can obtain those in bound nucleons ($q_{Vf}^A(x,Q^2)$ and $q_{Sf}^A(x,Q^2)$) by using $R_V^A(x,Q^2)$, $R_S^A(x,Q^2)$. Then we can calculate the function $R^{A_1/A_2}(x,Q^2)$ describing the effect of the nuclear medium to the process under consideration.

3 Results and discussion

In the quark-parton model one describes the nucleons as being composed of point-like and quasi-free quarks. In the improved nuclear density model, used for the description of charged lepton-nucleus deep inelastic scattering, the bound nucleon structure function is defined as

$$F_2^A(x,Q^2) = \sum_f e_f^2 x[R_V^A(x,Q^2)q_{Vf}^N(x,Q^2)+ R_S^A(x,Q^2)q_{Sf}^N(x,Q^2)]. \quad (12)$$

$F_2^A(x,Q^2)$ denotes the average nucleon structure function of an ideal nucleus with on equal number of protons and neutrons ($N=Z=\frac{1}{2}A$). The nuclear medium effect on the nucleon structure function is usually characterized by the following ratio

$$R^{A_1/A_2}(x,Q^2)=F_2^{A_1}(x,Q^2)/F_2^{A_2}(x,Q^2). \quad (13)$$

Using Eqs. (7—13) and the phenomenological parameters of Table 1, various functions $R^{A_1/A_2}(x,Q^2)$ for $A\geqslant 3$ in l-A DIS processes have been calculated and compared with the experimental data. For the parton momentum distribution functions of the free nucleon, the results given by Glück M, Reya E and Vogt A (GRV)[19] have been adopted.

Our theoretical results for $R^{A_1/A_2}(x,Q^2)$ in l-A DIS processes in the region $0.0010\leqslant x\leqslant 0.9500$ are shown in Figs. 1—3 together with the experimental data of Refs. [9, 20—35]. It can be seen that our extended quark distribution model describes the experimental data for most of the $A\geqslant 3$ nuclei quite well in the whole x region. This also shows that our assumptions have been reasonable. However, some of the functions, namely $R^{^3\mathrm{He}/D}(x,Q^2)$, $R^{\mathrm{Sn}/D}(x,Q^2)$ and $R^{\mathrm{Ca/Li}}(x,Q^2)$ deviate from the experiment data in the small x region. We think that the reason for this is the GRV momentum distribution functions[19] which we used have only been extracted up to the leading order (LO) and are not sensitive to the nuclear effects in the small x region[36]. In addition, the charm-quark distributions[37] and the non-perturbation QCD effects[38] may also contribute to the nuclear medium effects in the small x region. In this work, the charm-

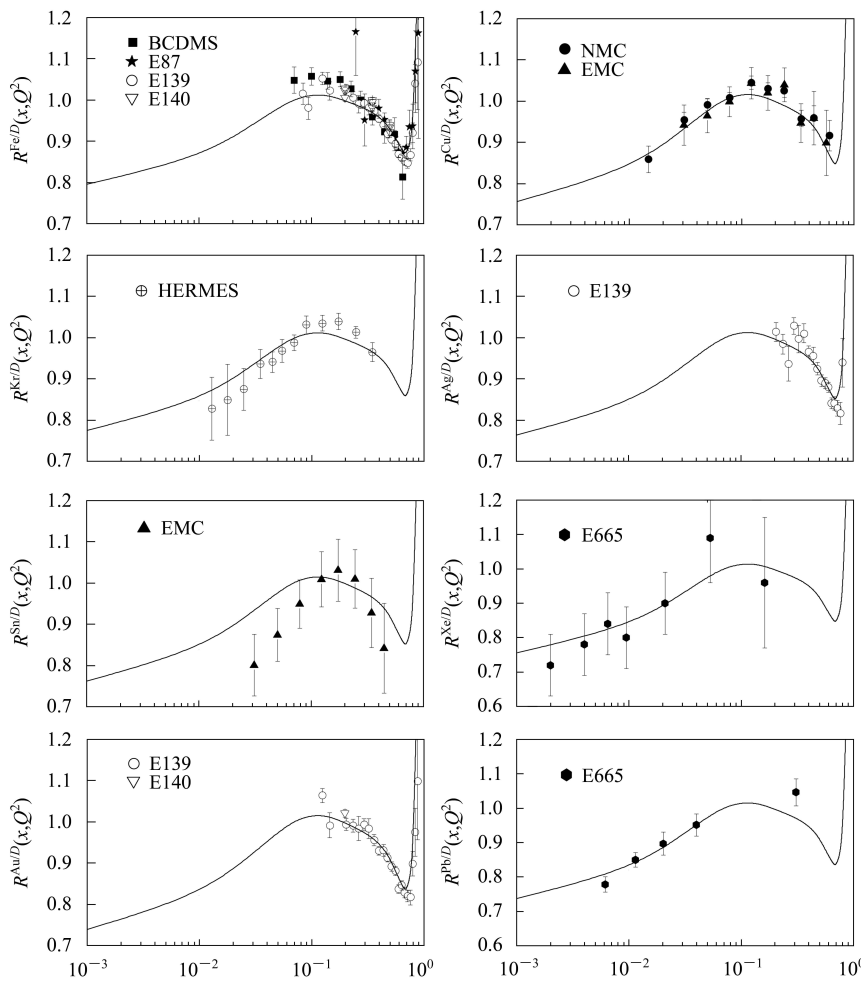

Fig. 2. The ratio $R^{A/D}(x,Q^2)$ versus the momentum fraction x in the region $0.0010\leqslant x\leqslant 0.9500$ with corresponding experimental data $56\leqslant A\leqslant 208$. The meaning of the lines is the same as that in Fig. 1.

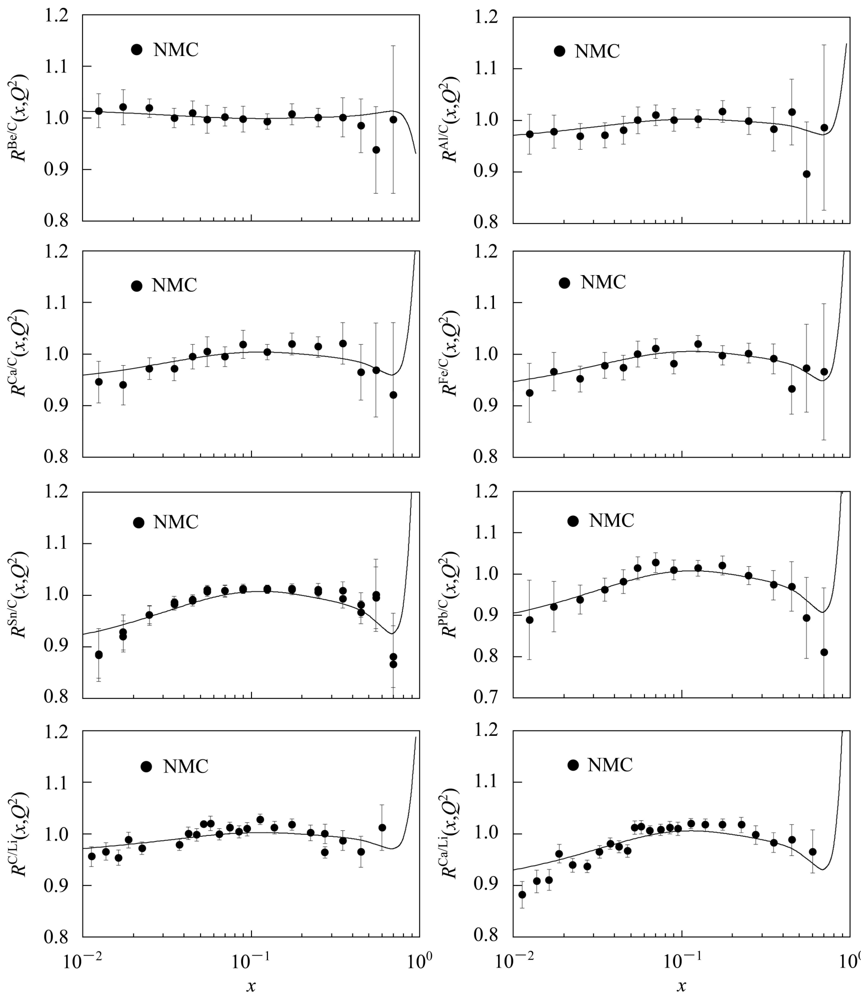

Fig. 3. The ratio $R^{A/C}(x,Q^2)$ and $R^{A/\mathrm{Li}}(x,Q^2)$ versus the momentum fraction x in the region $0.0100\leqslant x \leqslant 0.9500$ and the corresponding experimental data $9\leqslant A\leqslant 208$. The meaning of the lines is the same as that in Fig. 1.

quark distributions and the non-perturbation QCD effects have been neglected. Thus, if all the nuclear medium effects in the small x region should be accurately reproduced by fitting the experimental data with high precision, it is necessary to take the next leading order (NLO) and all the other mentioned possible corrections into account. It will need further improvement of our model and more precise experiment data to verify whether our ideas are reasonable.

4 Conclusions

In summary, we obtained the extended quark distribution functions and the phenomenological parameters of the valence quark and sea quark distributions in the region $0.0010\leqslant x\leqslant 0.9500$ through fitting a large amount of experimental data in l-A DIS processes. Using our extended model with the parameters of Table 1 we achieved a consistent and satisfactorily description of a large amount of data of l-A DIS experiments with $A\geqslant 3$ nuclei. Our knowledge on the influence of the nuclear medium on the quark distribution functions in bound nucleons could be improved. For a few nuclei, larger deviations from the experimental data occured in the nuclear shadowing region (low x values) leading to the conclusion that investigations are needed in particular in view on future high precision experiments.

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