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A Simple Model Describing the EMC Effect, Nuclear Drell-Yan Process, and Inelastic J/ψ Production

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A recombination factor is introduced to describe the nuclear shadowing and anti-shadowing effects in the small x region. Based on the consideration of the nuclear momentum conservation, a unified description of the EMC effect, the nuclear Drell-Yan process, and an inelastic J/ψ production are given in terms of the x-rescaling model with the recombination factor.

Key words: EMC effect, nuclear Drell-Yan process, inelastic J/ψ production.

1. INTRODUCTION

Since the discovery of the EMC effect by the European Muon Collaboration in 1982 [1], many theoretical models have been proposed to explain it. Most of them fall into one of the following categories: multi-quark cluster models [2], Q^2- and x-rescaling mechanisms [3], a constituent quark model [4], and a parton evolution model [5]. Although all these models give some significant explanations for EMC effect, the physical mechanism of the effect is still not clear. In the mid-1980s, Bickerstaff *et al.* [6] calculated the D-Y cross-section ratio for Fe and D using different EMC models; the calculated results showed that the ratios which obtained different models are quite different from each other. The D-Y process is expected to be a valuable tool for the testing of these EMC models.

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Li *et al.* [7] pointed out that the nature of the EMC effect can be explained if the x-rescaling mechanism is introduced by considering the Fermi-motion correction and the binding energy effect of a nucleon in the nucleus; however, the nuclear momentum is no longer conserved in this mechanism. To conserve the nuclear momentum, we employ a recombination factor which can describe the nuclear shadowing and anti-shadowing effect in a small x region, to calculate the ratio $R^{A/D}(x,Q^2)$ of the structure function of nucleus Fe to the one of a free nucleon, the ratios of D-Y cross sections of nuclei Fe, C, Ca, and W to the one of D and the gluon distribution ratio $R^{Sn/C}(x)$ in terms of the x-rescaling model. The calculated results are in good agreement with the experimental data.

2. RECOMBINATION FACTOR AND x-RESCALING MODEL

In the small x region, the nuclear shadowing and anti-shadowing could be induced by the spatial overlap of sea quarks and gluons from neighboring nucleons in the nucleus and their interactions result in momentum redistribution. In order to describe the nuclear shadowing and anti-shadowing, we employ a recombination factor:

$$R(x,A) = \begin{cases} \lambda_A & x > x_n \\ \lambda_A\left[1 - K_A \dfrac{\Delta V_A(x)}{V_A(x)}\right] & 0 < x \leqslant x_n \end{cases}, \tag{1}$$

where $\Delta V_A(x)/V_A(x)$ is the spatial overlapping factor from Ref. [7]:

$$\frac{\Delta V_A(x)}{V_A(x)} = 1 - \frac{4}{3} m_N x r_N(A), \tag{2}$$

$$r_N(A) = r_N[1 + 0.562\ln(2 - A^{-1/3})], \tag{3}$$

x_n is determined by $\Delta V_A(x)/V_A(x) = 0$, m_N and r_N are the mass and the radius of a free nucleon, and r_N is taken to be 0.85 fm.

In the x-rescaling model with the recombination factor, the momentum distributions of valence quarks, sea quarks, and gluons in a nucleus can be written as:

$$q_V^A(x, Q^2) = q_V^N(\delta_A \cdot x, Q^2); \tag{4}$$

$$q_S^A(x, Q^2) = R(x, A) \cdot q_S^N(\delta_A \cdot x, Q^2); \tag{5}$$

$$G^A(x, Q^2) = R(x, A) \cdot G^N(\delta_A \cdot x, Q^2). \tag{6}$$

where q_V^N, q_S^N, and G^N are the momentum distributions of valance quarks, sea quarks, and gluons in a free nucleon from Ref. [8]. In fact, the parameters δ_A, λ_A, and K_A in the equations above are not independent considering nuclear momentum conservation, and the two adjustable parameters can be determined by fitting the experimental data of the EMC effect, nuclear D-Y process, and inelastic J/ψ production process.

3. EXPLANATION OF THE EMC EFFECT

In the process of deep-inelastic lepton scattering on nuclei, within the x-rescaling mechanism by considering the Fermi-motion correction and binding energy effect, the structure function of the nucleus can be presented as

$$F_{2A}(x, Q^2) = \int_x^A \mathrm{d}z \cdot f(z) F_2^{N(A)}\left(\frac{x}{z}, Q^2\right), \tag{7}$$

where $f(z)$ is the Fermi-motion distribution, $F_2^{N(A)}$ is the structure function of a bound nucleon

$$F_2^{N(A)} = \sum_f e_f^2 x[q_f^A(x, Q^2) + \bar{q}_f^A(x, Q^2)]. \tag{8}$$

the average nuclear structure function of a nucleus is written as:

$$F_2^A(x, Q^2) = \frac{1}{A}\left[F_{2A}(x, Q^2) - \frac{1}{2}(N-Z)\cdot(F_2^n(x, Q^2) - F_2^p(x, Q^2))\right], \tag{9}$$

where A, N, and Z are the mass number, neutron number, and proton number, and F_2^n (F_2^p) is the free neutron (proton) structure function.

In order to compare this with the experimental data of the EMC effect, the ratio $R^{A/D}(x,Q^2)$ is defined as:

$$R^{A/D}(x, Q^2) = F_2^A(x, Q^2) / F_2^D(x, Q^2), \tag{10}$$

In Eq.(10), $F_2^D(x,Q^2)$ is the structure function of deuteron, which is substituted by a free nucleon structure function [8] since the binding energy of deuteron is very small. By introducing Eqs.(4) and (5) into Eq.(8), and using Eqs.(7), (9), and (10), the radio $R^{Fe/D}(x,Q^2)$ can be obtained with the values of parameters δ_A, K_A shown in Table 1. The calculated results are shown in Fig. 1. Apparently, our results are in good agreement with the experimental data of the EMC effect from Ref. [9].

4. EXPLANATION OF NUCLEAR DRELL-YAN PROCESS

The high mass $\mu^+\mu^-$ pair production has already shown the nuclear dependence in hadron-nuclear targets collisions; this is the nuclear Drell-Yan process [10]

$$\mathrm{h} + \mathrm{A} \to \mu^+\mu^- + \mathrm{X}.$$

The binding energy of the nucleons in a nucleus is much smaller than the energy of beam hadron; therefore, the $\mu^+\mu^-$ pair can be produced incoherently. An expression [13] is given for the Drell-Yan cross section:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x_1\mathrm{d}x_2} = K(x_F, Q^2)\frac{4\pi\alpha^2}{9M^2}\cdot\sum_f e_f^2[q_f^h(x_1, Q^2)\bar{q}_f^A(x_2, Q^2) + \bar{q}_f^h(x_1, Q^2)q_f^A(x_2, Q^2)], \tag{11}$$

where α is the fine structure constant and M is the mass of the dilepton, $q_f^{h(A)}(x)$ and $\bar{q}_f^{h(A)}(x)$ are the quark and antiquark momentum distributions with flavor f in beam hadron (nuclear target), K is the QCD correction factor ~ 2. With

$$H^{hA}(x_1, x_2, Q^2) = \sum_f e_f^2[x_1 q_f^h(x_1, Q^2)x_2\bar{q}_f^A(x_2, Q^2) + x_1\bar{q}_f^{h}(x_1, Q^2)x_2 q_f^A(x_2, Q^2)], \tag{12}$$

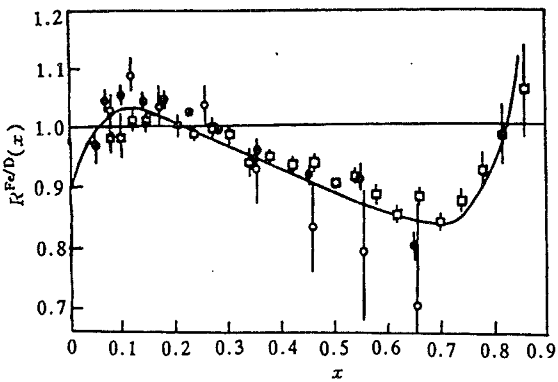

Fig. 1

The ratio $R^{A/D}(x,Q^2)$ plotted versus x for Fe/D.

□: SLAC 1983 Fe/D; •: BCDMS 1986 Fe/D; ○: EMC 1986 Cu/D.

Equation (11) can be presented as

$$\frac{d^2\sigma}{dx_1 dx_2} = K(x_F, Q^2)\frac{4\pi\alpha^2}{9M^2x_1x_2} H^{hA}(x_1, x_2, Q^2). \tag{13}$$

Because of

$$M^2 = sx_1x_2, \tag{14}$$

so Eq. (13) can be written as

$$\frac{d^2\sigma}{dx_1 dx_2} = K(x_F, Q^2)\frac{4\pi\alpha^2}{9sx_1^2x_2^2} H^{hA}(x_1, x_2, Q^2), \tag{15}$$

where $\sqrt{s}$ is the energy in the center-of-mass system.

For proton-nucleus reaction

$$\begin{aligned} H^{pA}(x_1, x_2, Q^2) = & \frac{1}{54}x_1[4u_V^p(x_1, Q^2) + d_V^p(x_1, Q^2)] \cdot x_2S^A(x_2, Q^2) \\ & + \frac{1}{54A} x_1 \circ S^p(x_1, Q^2) \cdot [(A+3Z)x_2u_V^A(x_2, Q^2) \\ & + (4A-3Z) \cdot x_2d_V^A(x_2, Q^2) + 2x_2AS^A(x_2, Q^2)]. \end{aligned} \tag{16}$$

For neutron-nucleus reaction

$$\begin{aligned} H^{nA}(x_1, x_2, Q^2) = & \frac{1}{54}x_1[u_V^p(x_1, Q^2) + 4d_V^p(x_1, Q^2)] \cdot x_2S^A(x_2, Q^2) \\ & + \frac{1}{54A}x_1 \cdot S^p(x_1, Q^2) \cdot [(A+3Z)x_2u_V^A(x_2, Q^2) \\ & + (4A-3Z) \cdot x_2d_V^A(x_2, Q^2) + 2x_2AS^A(x_2, Q^2)]. \end{aligned} \tag{17}$$

where only three kinds of flavor (u, d, and s) are considered.

Table 1

Parameter	C	Ca	Fe	Sn	W
δ_A	1.025	1.025	1.025	1.03	1.03
K_A	0.18	0.18	0.2	0.3	0.3

The D-Y ratio measured by the E772 Collab. [11] is the ratio of D-Y differential cross section in nucleon-nucleus scattering to that in nucleon-nucleon scattering:

$$T^{A/D}(x_2, Q^2) = \frac{\int \frac{d^2\sigma^{hA}}{dx_1 dx_2} \cdot dx_1}{\int \frac{d^2\sigma^{hD}}{dx_1 dx_2} \cdot dx_1} = \frac{\int \frac{H^{hA}(x_1, x_2, Q^2)}{x_1^2} \cdot dx_1}{\int \frac{H^{hD}(x_1, x_2, Q^2)}{x_1^2} \cdot dx_1}, \tag{18}$$

Equation (18) is determined according to the kinematic region of the experiment in Ref. [11], i.e., $\sqrt{s} = 40$, $4 < M < 9$ and $M > 11$, $x_1 - x_2 > 0$. The D-Y ratios from nuclei Fe, C, Ca and W to D are calculated with the values of parameters shown in Table 1. In Fig. 2, we present our calculations together with the experimental data from Ref. [11]. We can see from the figure that the calculated results are satisfactory.

5. EXPLANATION OF INELASTIC J/ψ PRODUCTION

Recently, the NMC measured the cross section ratio of inelastic J/ψ production from Sn and C, and obtained the average value of $R_{in}^{Sn/C} = 1.13 \pm 008$. R_{in} should be the ratio of the gluon distributions

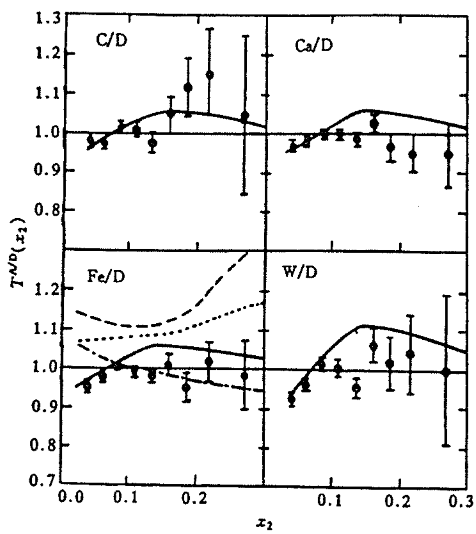

Fig. 2
The nuclear Drell-Yan ratios $T^{A/D}$.
---- : vector-meson dominance model;
···· : multi-quark cluster model;
-·- : Q^2-rescaling model;
— : our model

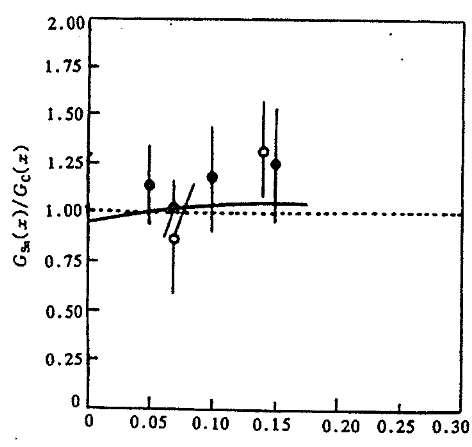

Fig. 3
The comparison of our result of $G_{Sn}(x)/G_C(x)$ with NMC data.
○: 200 GeV; •: 280 GeV.

of Sn to the one of C as a function of x

$$R_n^{Sn/C}(x) = G_{Sn}(x) / G_C(x). \tag{19}$$

According to Eqs.(6) and (19), the result of $G_{Sn}(x)/G_C(x)$ are calculated in our model with the values of parameters shown in Table 1 and presented in Fig. 3 together with experimental data from NMC [12]. The experiment on the process of inelastic J/ψ production showed that the gluon momentum distribution of a bound nucleon is different from that of a free nucleon. Our results confirm this fact.

6. CONCLUSION

By introducing the recombination factor to describe the nuclear shadowing and anti-shadowing, a unified description of the EMC effect, the nuclear Drell-Yan process, and inelastic J/ψ production is obtained in terms of the x-rescaling model. Our results are satisfactory and shown that the x-rescaling model with the recombination factor is a good model.

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