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Different Treatments of Nuclear Binding Effect in Deep Inelastic Lepton Nucleus Scattering

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We give a kinematic modification of the impulse approximation by adopting on-shell kinematics and the constraint of overall energy conservation, and calculate the nuclear binding effect in deep inelastic lepton nucleus scattering. We also compare this model with the off-shell model of nuclear binding effect, and find the two models give different results and predictions about the structure function $F_1^A(x)$ and the Callan-Gross ratio $R_A = \sigma_L/\sigma_T$ for bound nucleons. The comparison with experiments shows that the on-shell model can explain more experimental phenomena and also describe the data better than the off-shell model.

1.INTRODUCTION

In recent years deep inelastic lepton nucleus scattering experiments [1,2] revealed that the observed ratios of the differential cross section of nucleons bound in nucleus to that of nucleons bound in deuteron are different from the earlier theoretical expectations based upon the impulse approximation [3]. This significant difference between the data and the theoretical expectations has been called the EMC effect and it has received extensive attention both from nuclear physicists and particle physicists all over the world. Among the large number of existing models, most of them interpret the EMC effect as a manifestation of non-nucleonic degrees of freedom [4]. However, there has been another trend to explain it as a result of nuclear binding in recent years [5,6]. Models of the latter kind, which assume the validity of the impulse approximation and use a smaller effective

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nucleon mass [5] or off-shell kinematics [6] to account for the binding effect, have succeeded in explaining the bulk of the EMC effect. However, they cannot explain the detailed features of the SLAC data and the behaviors of the EMC data and the SLAC data at small x. In this paper, we propose an alternative model to reanalyze the EMC effect. The main point of this model is to extract a small fraction of the lepton energy loss to account for the binding effect, or from another point of view, to use the on-shell kinematics and the constraint of overall energy conservation to give a kinematic modification of the impulse approximation. It is encouraging to see that this model can explain, besides the bulk of the EMC effect, the detailed features of the SLAC data and the behaviors of the SLAC data and the EMC data at small x. Thus, it is shown in this paper that there are Q^2 (the square of lepton four momenta loss) and ε (the lepton incident energy) dependencies in deep inelastic lepton nucleus scattering, which are supported by the data. We also find that our prediction of the Callan-Gross ratio $R_A = \sigma_L/\sigma_T$ is different from that of the off-shell model. By comparing with the experiments, we see that our prediction seems to be favored by the available data.

2.THE OFF-SHELL MODEL AND RELATIVE DISCUSSIONS

We first give a few words about the impulse approximation and why we modify it. We know that the impulse approximation has been the basic method used in treating deep inelastic scattering of lepton on either nucleons or nuclei for many years. According to this picture, deep inelastic lepton nucleus scattering can be viewed as the sum of incoherent scattering of the lepton with individual nucleons bound in the nucleus. Since the lepton incident energy and the lepton energy loss (of the order of GeV) are very large compared with the binding energy (a few tens of MeV), it is generally believed that the binding can be neglected, and therefore it can be assumed that all the lepton energy loss is given to one of the struck nucleons; i.e., energy is conserved between the lepton and the struck nucleon. Actually, this is a over-strong assumption because the exact constraint should be the overall energy conservation between the lepton and the target nucleus. The recent works presented in Ref. [6] and Ref. [7] also revealed that the binding may have a significant effect in the deep inelastic region, which indicates the unavailability of the ordinary statement of the impulse approximation. The question we will discuss is: how should we take into account the binding effect?

In the off-shell treatment, the authors of Ref. [6] first assumed the validity of the impulse approximation, i.e., assumed that all the lepton energy loss is given to the struck nucleon, or in other words, energy is conserved between the lepton and the struck nucleon. In order to ensure overall energy conservation and to take into account the binding effect, they adopted the off-shell kinematics for the struck nucleon. This is equivalent to the use of a smaller effective nucleon mass $M^* = M - \varepsilon$, where $\varepsilon \approx$ 40MeV for $A = 56$. The Bjorken variable for bound nucleons then becomes

$$x' = \frac{Q^2}{2M^*\nu}, \tag{1}$$

and hence the structure function F_2^A for bound nucleons can be rescaled as

$$F_2^A(x) = F_2^N(x'). \tag{2}$$

if one neglects the Fermi smearing effect. They found this rescaling of the Bjorken variable is sufficient for explaining the bulk of the EMC effect.

If the off-shell treatment is really a proper way to account for the binding effect, then it must manifest this effect in other region where nuclear binding effect also plays a role, such as in the quasielastic scattering region. So before further discussions, let us take a look at the nuclear binding effect in quasielastic scattering and see whether the features arising from the nuclear binding can be really reproduced by the off-shell treatment.

It is clear that the quasielastic peak is the result of elastic scattering of electrons by individual nucleons in the target nucleus [8]. In this case if all of the electron energy loss ν and momentum $\boldsymbol{q}$ are given to one of the nucleons, then that nucleon will recoil with momentum $\boldsymbol{q}$ and kinetic energy $q^2/2M$, and the quasielastic peak will be at the position $\nu = q^2/2M$. However, it was found in experiments that the position of the quasielastic peak for bound nucleons becomes

$$\nu = \frac{q^2}{2M} + \varepsilon, \tag{3}$$

where ε is a shift from the elastic peak for free nucleons, of about 40MeV for $A = 56$ [9]. It is believed that this shift of peak is caused by the binding of nucleons in nuclei. Usually two methods are used to reproduce this shift [8]. The first one simply extracts an average energy $\bar{\varepsilon}$ from the lepton energy loss ν, and assumes that this energy is used to overcome the binding between the struck nucleon and the residual nucleus. This implies that the energy transferred to the struck nucleon should be $\nu' = \nu - \bar{\varepsilon}$, so the peak would be at the position $\nu - \bar{\varepsilon} = q^2/2M$. If one adopts $\bar{\varepsilon} = \varepsilon$, the above expression is just the same as (3); this indicates that this method can reproduce the shift of the peak. The second method uses a smaller effective nucleon mass $M' = 0.7M$ to account for the strong interaction of the struck nucleon with the surrounding nucleons. Then the peak would be at the position $\nu = q^2/2M'$. In the quasielastic region, $(q^2/2M' - q^2/2M)$ is about a few tens of MeV, this indicates that one can reproduce the shift of the peak by adopting an appropriate M'.

It is true that the off-shell treatment also uses a smaller effective nucleon mass $M^* = M - \varepsilon$. But the shift caused by using M^* rather than M' is very small, it is about 4MeV for $A = 56$. This indicates that the off-shell treatment cannot reproduce the shift of the quasielastic peak. So we think that the off-shell treatment is not a good method to account for the binding effect.

3. THE PROPOSAL OF THE ON-SHELL MODEL

We now use an alternative way to account for the binding effect. The main point of our model is to assume that in deep inelastic lepton nucleus scattering, the energy transferred to the struck nucleon is

$$\nu' = \nu - \varepsilon \tag{4}$$

rather than ν. This assumption can be regarded as an inspiration from the shift of quasielastic peak in deep inelastic electron nucleus scattering. It can also be obtained from another point of view. Abandoning the assumption in the impulse approximation that all the lepton energy loss is given to the struck nucleon, we adopt the on-shell kinematics for the struck nucleon and use the overall energy conservation between the lepton and the target nucleus to calculate the energy transferred to the struck nucleon. Thus we find that the energy transferred to the struck nucleon should be

$$\nu' = \nu - \varepsilon', \tag{4'}$$

for bound nucleons, where ε' is a somewhat complicated expression and it is about 40 MeV on average for $A = 56$. It should be noticed that we have assumed the on-shell kinematics for the struck nucleon in the above argument, but this does not mean that we really consider the struck nucleon as being free in nucleus. In fact, de Forest showed in Ref. [10] that there are ambiguities in the ways of treating nuclear binding effect, and therefore it is the same case with the results one predicts. On-shell treatment is also one way used by some people in treating deep inelastic lepton nucleus scattering, such as Refs. [10,11]. At least this method can reproduce the shift of the quasielastic peak for bound nucleons. We shall show that this method also gives different results from that of the off-shell model in deep inelastic region, and moreover, it is more successful in explaining the EMC effect than the off-shell model.

4. COMPARISON OF THE ON-SHELL MODEL WITH THE OFF-SHELL MODEL

In fact, ε in (4) is very small in comparison with ν, but it has, as will be seen, a surprising effect in deep inelastic scattering. Qualitatively speaking, the change of the energy transferred to the struck nucleon from ν for free nucleon to $\nu'$for bound nucleon can be equally described as a change of the Bjorken variable from $x = Q^2/2M\nu$ for free nucleon to

$$x'' = \frac{Q''^2}{2M\nu'}, \tag{5}$$

for bound nucleon, where $Q'^2 = q^2 - \nu'^2$. So the structure function F_2^A for bound nucleons can be rescaled as

$$F_2'^A(x) = F_2^N(x''), \tag{6}$$

a result corresponding to Eq.(2). However, as $x'/x = 1 + \varepsilon/M$ and $x''/x = 1 + \varepsilon/Mx$, the change of the Bjorken variable from x to x'' will have a more strong effect in the small x region than the change of the Bjorken variable from x to x'. So it can be seen that our treatment and the off-shell treatment will give different results at small x.

We assume the validity of the Callan-Gross relation

$$F_2^N(x) = 2\,xF_1^N(x) \tag{7}$$

for free nucleons, and take the simple parametrization

$$F_2^N(x) = x^{\frac{1}{2}}(1-x)^3 + 0.15(1-x)^4. \tag{8}$$

In the off-shell treatment, the structure function F_1^A for bound nucleons can be simply written as

$$F_1^A(x) = F_1^N(x'); \tag{9}$$

whereas in the on-shell treatment, it can be written as

$$F_1'^A(x) = F_1^N(x''). \tag{10}$$

Using Relation (7), we obtain

$$r_1 = F_1^A(x)/F_1^N(x) = \frac{xF_2^N(x')}{x'F_2^N(x)} = \frac{x}{x'}r_2; \tag{11}$$

in the off-shell treatment, and

$$r_1' = \frac{F_1'^A(x)}{F_1^N(x)} = \frac{x}{x''}r_2'. \tag{12}$$

in our on-shell treatment, where $r_2 = F_2^A(x)/F_2^N(x)$ and $r'_2 = F_2'^A(x)/F_2^N(x)$.

Fig. 1 shows the behaviors of r_1, r_2 and r'_1, r'_2. It can be seen that these two models give different results at small x. The r_1 and r_2 in the off-shell treatment have similar behaviors, whereas in the on-shell treatment, r_1 and r_2 behave differently. The ratio of the differential cross section for bound nucleons to that for free ones can be expressed as

$$r = \frac{\left(1 - y - \frac{Mxy}{2\varepsilon}\right)\frac{F_2^A(x)}{F_2^N(x)} + \frac{y^2}{2}\frac{F_1^A(x)}{F_1^N(x)}}{\left(1 - y - \frac{Mxy}{2\varepsilon}\right) + \frac{y^2}{2}}, \tag{13}$$

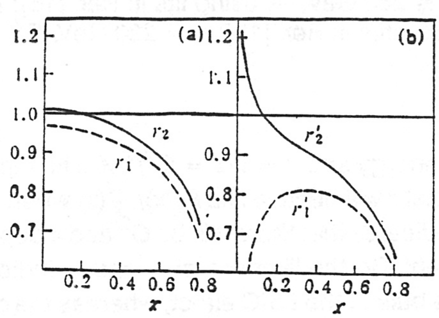

FIG. 1 The calculated ratios $r_1 = F_1^A(x)/F_1^N(x)$ and $r_2 = F_2^A(x)/F_2^N(x)$ in two models:
(a) r_1 and r_2 in the off-shell model.
(b) r_1' and r_2' in the on-shell model.

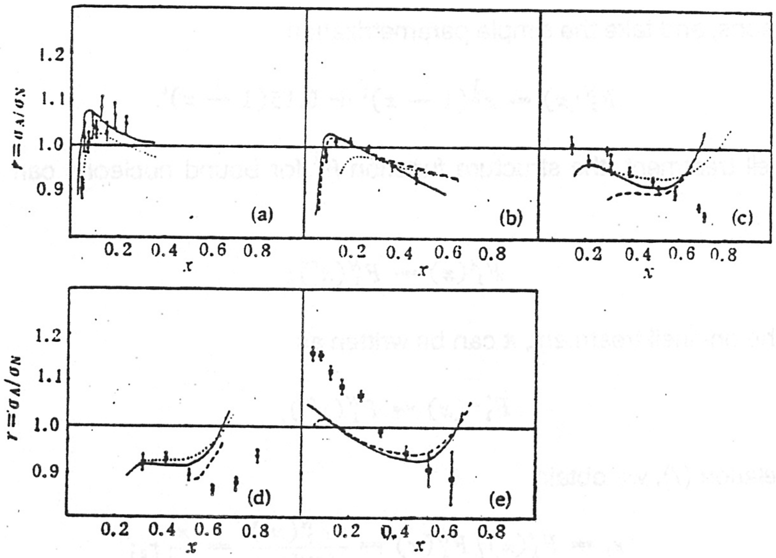

FIG. 2 Comparison of our calculated r (in which the Fermi motion effect are included) with the data. The input fits of F_2^N corresponding to these curves are those obtained by Bodek et al. [13], Buras and Gaemers [14], and Duke and Owens [15]. The parameters Q^2 and ε for every curve and the regions of Q^2 and ε for the data are indicated as follows: (a) ϕ, SLAC A = Cu data: ε = 20 GeV, $0.9 < Q^2 < 1.6$ GeV^2; —, using fits of F_2^N in Ref. [13]: ε = 20 GeV, Q^2 = 1.0 GeV^2; ......, using fits in Ref. [13]: ε = 20 GeV, Q^2 = 1.6 GeV^2. (b) ϕ, SLAC A = Fe data: Q^2 = 2 GeV^2, $8 < \varepsilon < 24.5$ GeV; —, using fits in Ref. [14]: ε = 25 GeV, Q^2 = 2 GeV^2; ---, using fits in Ref. [13]: ε = 25 GeV, Q^2 = 2 GeV^2; ....., using fits in Ref. [13]: ε = 10 GeV, Q^2 = 2 GeV^2. (c) ϕ, SLAC A = Fe data: Q^2 = 5 GeV^2, $8 < \varepsilon < 24.5$ GeV; —, using fits in Ref. [15]: ε = 25 GeV, Q^2 = 5 GeV^2; ---, using fits in Ref. [15]: ε = 10 GeV, Q^2 = 5 GeV^2; ......, using fits in Ref. [13]: ε = 25 GeV, Q^2 = 5 GeV^2. (d) ϕ, SLAC A = Fe data: Q^2 = 10 GeV^2, $8 < \varepsilon < 24.5$ GeV; —, using fit in Ref. [15]: ε = 25 GeV, Q^2 = 10 GeV^2; ---, using fits in Ref. [15]: ε = 10 GeV, Q^2 = 10 GeV^2; ......, using fits in Ref. [13]: ε = 25 GeV, Q^2 = 10 GeV^2. (e) ϕ, old EMC A = Fe data: $9 < Q^2 < 170$ GeV^2, $120 \le \varepsilon \le 280$ GeV; —, using fits in Ref. [15]: ε = 280 GeV, Q^2 = 10 GeV^2; ---, using fits in Ref. [13]: ε = 280 GeV, Q^2 = 10 GeV^2.

where ε is the lepton incident energy and $y = \nu/\varepsilon = Q^2/2Mx\varepsilon$ is another Bjorken variable. From Eq.(13), it can be seen that r will behave like $F_2^A(x)/F_2^N(x)$ when $y \to 0$ and behave like $F_1^A(x)/F_1^N(x)$ when $y \to 1$. This indicates that there will be Q^2 and ε dependencies in the ratio r if F_1^A/F_1^N and F_2^A/F_2^N are different. So the likeness of r_1 and r_2 indicates that the off-shell treatment can only explain the bulk of the EMC effect, whereas the difference between r'_1 and r'_2, as will be seen, is very useful in explaining, besides the bulk of the EMC effect, many detailed features of the SLAC data and the muon data at small x.

5. COMPARISON OF THE ON-SHELL MODEL WITH THE EXPERIMENTS

In fact, the SLAC data are exactly the ratio of the differential cross sections; the muon data should also be considered as the ratio of the differential cross sections since the EMC group [1,12] and the BCDMS group [12] have assumed R = σ_L/σ_T = 0 in extracting the structure function F_2^N and F_2^A. So we should compare the calculated r, rather than F_2^A/F_2^N, with both the SLAC data and the muon data. From Fig. 2, where our calculated r(in which the contributions from Fermi motion are also included) are presented, it can be seen that our model can reproduce many detailed features of the data:

(1) Our model can explain the earlier SLAC data [16] at small Q^2 = 1GeV^2 where the ratio r exhibits an enhancement around x = 0.1 and a turnover at very small x = 0.05. See Fig. 2a for details.

(2) Our model reveals that there are Q^2 dependence in the SLAC data [17]. From Fig. 2a–d,it can be seen that the ratio r will decrease with the increase of Q^2 at small x. This feature is consistent with our model whereas it is contrary to the "shadowing explanation" which expects that the ratio r will increase with the increase of Q^2.

(3) Our model can explain the turnover around x = 0.2 observed in the new muon data [12], as shown in Fig. 2e.

(4) From Eq.(13), it can be seen that the ratio r will increase with the increase of ε at small x when Q^2 is fixed. At large Q^2, the SLAC data seem to be below the new muon data at small x. This discrepancy between the SLAC data and the muon data (though not so large for the new muon data [12]) can be explained by ε dependence in our model since ε used in the SLAC experiments(8–24.5GeV) are significantly different from that used in the muon experiments(120–280GeV). See Figs. 2d,e for details. It seems that the ε dependence given by our model is consistent with the data in trend.

6. R_A = σ_L/σ_T IN TWO MODELS

We now turn to the Callan-Gross ratio R_A = σ_L/σ_T. In the limit $Q^2 \to \infty$, R_A can be written as

$$R_A = \frac{F_2^A(x)}{2\,xF_1^A(x)} - 1. \tag{14}$$

In the off-shell treatment, we obtain

$$R_A = \frac{F_2^N(x')}{2xF_1^N(x')} - 1 = \frac{x'}{x} - 1 = \frac{\varepsilon}{M}; \tag{15}$$

whereas in our on-shell model, we obtain

$$R'_A = \frac{F_2^N(x'')}{2\,xF_1^N(x'')} - 1 = \frac{x''}{x} - 1 = \frac{\varepsilon}{Mx}. \tag{16}$$

It can be seen from Fig. 3 that these two models also give different predictions about R_A.

It is clear that our model gives a non-zero value of R_A for heavy nuclei at small x. From

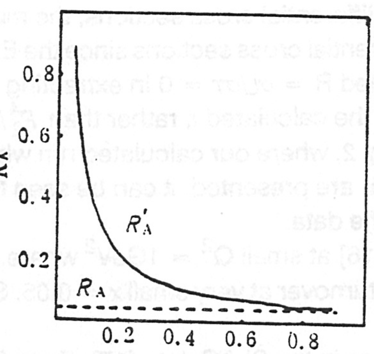

FIG. 3 Comparison of the Callan-Gross ratio $R_A = \sigma_L/\sigma_T$ in two models: the dashed curve is R_A in the off-shell model, whereas the solid curve is R' in the on-shell model.

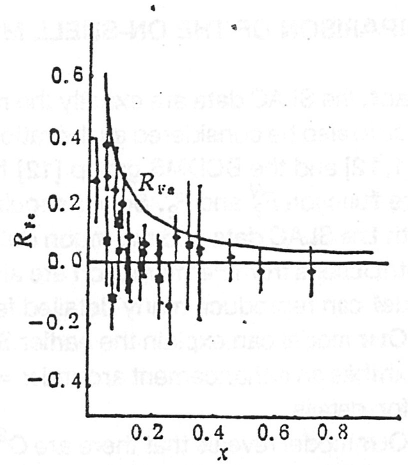

FIG. 4 Comparison of our calculated R_{Fe} (solid curve) with the data: ♦, the EMC μ-Fe data [18]; ♠, the CDHSW ν - Fe data [19]. The EMC μ-p data [20], ♦, are also presented for comparison.

the data presented in Fig. 4, we can see that R_{Fe} seems to have a non-zero value while R for free proton is rather small. The R_{Fe} obtained from the neutrino experiment are also presented in Fig. 4. We can see that our results are qualitatively in agreement with the available data, whereas the off-shell treatment even fails to explain the bulk of the data [21]. Of course, more data should be measured, especially at small x, for further comparison.

7. DISCUSSIONS AND SUMMARIES

First, we should point out that we have neglected the Fermi motion effect in the formula in this paper. But this does not alter our results since our attention is focused on the small x region, where it has been shown by Bodek and Ritchie [3] that Fermi motion will give trivial contribution. Second, we point out that our results are sensitive to the input structure functions for free nucleons. That is why we used the fits of F_2^N in Refs. [13-15] rather than Eq.(8). This also indicates that we can reduce the discrepancies between the calculated curves and the data by choosing other fits of $F_2^N(x,Q^2)$ in the calculation. Third, it seems from Figs.2c-e that our model overestimates r at small x. But this is also the case for off-shell treatment if Fermi motion effect is included. Perhaps this implies that present models still give a too large Fermi motion effect.

In summary, we compared two models in explaining the EMC effect and found that they give different results and predictions. Although both models use certain ways to take into account the binding effect, however, they are not equivalent: the on-shell model can reproduce the shift of the quasielastic peak whereas the off-shell model cannot; the on-shell model can explain many detailed features of the SLAC data and the muon data whereas the off-shell model can only explain the bulk of the data. The on-shell model seems to be more successful than the off-shell model.

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