Nuclear Shadowing in the Structure Function $F_3(x)$

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ABSTRACT

Nuclear modification of the structure function $F_3$ is investigated. Although it could be estimated in the medium and large $x$ regions from the nuclear structure function $F_2^A$, it is essentially unknown at small $x$. The nuclear structure function $F_3^A$ at small $x$ is investigated in two different theoretical models: a parton-recombination model with $Q^2$ rescaling and an aligned-jet model. We find that these models predict completely different behavior at small $x$: antishadowing in the first parton model and shadowing in the aligned-jet model. Therefore, studies of the ratio $F_3^A/F_3^D$ at small $x$ could be useful in discriminating among different models, which produce similar shadowing behavior in the structure function $F_2$. We also estimate currently acceptable nuclear modification of $F_3$ at small $x$ by using $F_2^A/F_2^D$ experimental data and baryon-number conservation.

* Email: kobar, kumanos, or 94sm10@cc.saga-u.ac.jp. Information on our research is available at [http://www.cc.saga-u.ac.jp/saga-u/riko/physics/quantum1/structure.html](http://www.cc.saga-u.ac.jp/saga-u/riko/physics/quantum1/structure.html) or at [ftp://ftp.cc.saga-u.ac.jp/pub/paper/riko/quantum1](ftp://ftp.cc.saga-u.ac.jp/pub/paper/riko/quantum1). Submitted for publication
1. Introduction

It is known that nuclear structure functions are not identical to the corresponding ones in the nucleon. The nuclear modification was first found by the European Muon Collaboration (EMC), so that it is called EMC effect. The phenomena have been well investigated theoretically and experimentally in the structure function $F_2$ \cite{1,2}. In recent years, the small $x$ region has been studied extensively. The ratio $R_2 \equiv F_2^A/F_2^N$ \cite{3} becomes smaller than unity at small $x$, which is referred to as shadowing in the structure function $F_2$. Models for explaining the $F_2$ shadowing include vector-meson-dominance-type models and parton-recombination-type models \cite{4}.

The former models describe the shadowing in the following way. A virtual photon transforms into vector-meson states (or $q\bar{q}$ states), which then interact with a target nucleus. The central constituents are “shadowed” due to the existence of nuclear surface constituents. The latter models explain the shadowing by interactions of partons from different nucleons in a nucleus, and the interactions are called parton recombinations. They become important especially at small $x$, where the longitudinal localization size of a parton exceeds the average nucleon separation in the nucleus.

Because these two different ideas produce similar shadowing results in $F_2$, it is difficult to distinguish among the models in comparison with experimental data. If accurate experimental $F_2$ data are obtained \cite{5}, it is perhaps possible to find the “correct” explanation. However, a better idea could be to look for other shadowing observables. We discuss in this paper that a promising way of testing the models could be to use the structure function $F_3$.

Except for the nuclear effects on $F_2$, modification of sea-quark and gluon distributions \cite{6} has been discussed recently. However, there is another interesting point to be investigated. It is the structure function $F_3$ in nuclei. In a naive parton model without next-to-leading-order corrections, $F_3$ is given by valence-quark distributions. Therefore, the ratio $R_3 \equiv F_3^A/F_3^N$ in the medium $x$ region should be well estimated from existing experimental data for $R_2$. So the essential point of our investigation is to study the small $x$ region. Although there is a certain restriction on $R_3$ due to baryon-number conservation, the $F_3$ shadowing is an undeveloped research area.

The purpose of our research is to investigate whether or not studies of the $F_3$ shadowing help us discriminate among different models, which produce similar results on the $F_2$ shadowing. In section 2, nuclear shadowing in $F_3$ is investigated in two models: 1) a parton recombination model with $Q^2$ rescaling effects and 2) an aligned-jet model. Then, using the existing data of $R_2$ and the conservation rule, we estimate an acceptable $F_3$ shadowing region. Our conclusions are given in section 3.
2. Shadowing in the structure function $F_3(x)$

We discuss model predictions of the nuclear-structure-function ratio $R_3$. In particular, two different models are employed. The first model is the parton-recombination model with $Q^2$ rescaling in Ref. [2]. The second model is the aligned-jet model by Frankfurt, Liuti, and Strikman [7, 8]. This model is based on the vector-meson-dominance model but it is modified due to $q\bar{q}$ continuum.

2.1 A parton-recombination model with $Q^2$ rescaling

After the EMC finding of nuclear modification in 1983, there are many publications on the topic. There is no unique explanation for the EMC effect unfortunately. However, it is the fact that similar results are obtained in completely different models, for example, in a macroscopic model of nuclear binding and in a microscopic model of $Q^2$ rescaling. This duality is interpreted in the following way [9, 10]. As there is freedom to choose the renormalization point in an operator product expansion, the factorization scale in convolution formalism is not defined. A different factorization scale corresponds to a different interpretation of the EMC effect. In this sense, we could connect seemingly different models by a single scale change, which is called rescaling. According to Ref. [10], nuclear structure functions $F_2^A(x, Q^2)$ are given by rescaling $Q^2$ in the nucleon structure function $F_2^N(x, Q^2)$.

We use this $Q^2$ rescaling model with parton recombinations [2]. The rescaling model was originally proposed as a model for explaining the medium $x$ region, and the recombination [11] as a model in the small $x$ region. Using these two mechanisms, we explained the structure function $F_3^A$ from very small $x$ to large $x$ [2]. This unified model can be applied to the structure function $F_3$. In the naive parton model, the $F_3$ structure function of the nucleon is given by $F_3(x) = xu(x) + xd(x)$. The formalism in Ref. [2] is used in calculating the valence-quark distributions. The initial $Q^2$ was chosen at 0.8 GeV$^2$ in calculating the rescaling and the recombinations; however, the resulting evolution shows little $Q^2$ dependence in the ratio $R_2$. Calculated results at $Q^2$=0.8 GeV$^2$ are shown in Fig. 1 for the calcium nucleus. The dashed curve shows the $Q^2$ rescaling results. The ratio $R_3$ in the medium $x$ region is almost equal to the EMC effect in $F_2$. As $x$ increases, the ratio becomes smaller and typical nuclear effects are 10% in the medium size nucleus. Because the $Q^2$ rescaling satisfies the baryon-number conservation, the ratio $R_3$ becomes larger as $x$ decreases. There are other important effects at small $x$ due to parton recombinations. Their contributions on $F_3(x)$ are rather contrary to those in the $Q^2$ rescaling model as shown in Fig. 1. The recombinations decrease the ratio at small $x$ and increase it at medium and large $x$. In the model of Ref. [3], the valence-quark number is conserved, so that the ratio is above unity at small $x$ due to the medium $x$ suppression. The overall nuclear modification is very interesting in the sense that the ratio $R_3$ is much different from the one for the
structure function $F_2(x)$ at small $x$. In this parton model, the $F_3$ shadowing differs distinctively from the $F_2$ one:

$$\frac{F_A^3(x)}{F_N^3(x)} \neq \frac{F_A^2(x)}{F_N^2(x)} \quad \text{at small } x .$$

(2.1)

In other words, valence-quark modification is different from the sea-quark one. It is especially interesting to find in Fig. 1 that the model predicts antishadowing in the structure function $F_3$ instead of shadowing.

2.2 An aligned-jet model

Within the parton model in subsection 2.1, the $F_3$ modification at small $x$ is very different from the $F_2$ one. However, the situation is not so simple. There exists a model in which $F_2$ and $F_3$ shadowing predictions are similar. It is an aligned-jet model, for example, the one investigated in Ref. [7, 8]. It is based on a traditional idea, the vector-meson-dominance model. The virtual photon transforms into vector-meson states, which interact with a target. The propagation length of the hadronic fluctuation is estimated by $\lambda \approx \frac{1}{|E_H - E_\gamma|} \approx 0.2/x$ fm. The length exceeds the average nucleon separation in a nucleus at small $x$, so that shadowing phenomena occur due to multiple scatterings.

The aligned-jet model is an extension of this model. The virtual photon (or W) transforms into a $q \bar{q}$ pair, which then interacts with the target. However, the only $q \bar{q}$ pair aligned in the direction of $\gamma$ (W) interacts in a similar way to the vector-meson interactions with the target. In this model, vector-meson-like $q \bar{q}$ pairs interact with sea quarks and valence quarks in the same manner. Therefore, the $F_3$ shadowing is very similar to the $F_2$ one. In fact, the shadowing results in figure 3 of Ref. [8] are similar to those of the $F_2$ shadowing:

$$\frac{F_A^3(x)}{F_N^3(x)} \approx \frac{F_A^2(x)}{F_N^2(x)} \quad \text{at small } x .$$

(2.2)

It is interesting to find that the aligned-jet model predicts the shadowing, which is contrary to the antishadowing in the first parton model. In the following, we discuss whether or not both possibilities are allowed within existing data and the baryon-number conservation.
2.3 Experimental restriction and comparison

We find that the calculated $F_3$ results are much different in both models. In this subsection, an experimental restriction on the $F_3$ shadowing is discussed. If next-to-leading-order effects are neglected, the $F_3$ structure function is identical to the valence-quark distribution:

$$F_3(x) = u_v(x) + d_v(x) \equiv V(x).$$

We assume $R_V \equiv V_A(x)/V_N(x) = R_3$ in our investigation. The $F_2$ structure function at medium and large $x$ is dominated by the valence-quark distributions. Therefore, the ratio $R_3$ for the structure function $F_3$ at medium and large $x$ should be equal to $R_2$, which has been measured experimentally. The major point of our study is then to estimate the small $x$ region. There is a restriction on the valence-quark modification due to the baryon-number conservation

$$\int dx V(x) = 3.$$  

Because the ratio $R_3$ is less than unity at medium $x$, there are two major possibilities at small $x$. One is that the ratio increases as $x$ decreases (antishadowing), and the other is that the ratio is significantly enhanced at $x \approx 0.1$ and it becomes smaller than unity at very small $x$ (shadowing).

In order to study these possibilities, we assume that the ratio $R_V$ at $x > 0.3$ is equal to $R_2$ by neglecting sea-quark contributions. SLAC experimental data $R_2$ [12] of the calcium nucleus are shown in Fig. 2 in the $x$ region, $x > 0.3$. These data are fitted by a smooth analytical function shown by a solid curve. We extrapolate the curve into the small $x$ region by considering the baryon-number conservation. First, a straight line in the logarithmic $x$ is simply drawn from $x=0.3$ as shown by the dashed line in Fig. 2 so that it satisfies the conservation rule. The line is roughly the upper limit of nuclear modification. Second, the curve is smoothly extrapolated into the small $x$ region by allowing about 6% antishadowing at $x = 0.1 - 0.2$. Considering experimental antishadowing in $F_2$ at $x = 0.1 - 0.2$ [13] and a nuclear sea-quark distribution [14], we think that 6% is roughly an upper bound for the valence-quark antishadowing in this region. If accurate data are obtained in $R_2$ and in the sea-quark-distribution ratio $S_A(x)/S_N(x)$ at $x = 0.1 - 0.2$, we could have a better estimate of the antishadowing. Because of this antishadowing, the ratio could become smaller than unity at very small $x$ in order to satisfy the conservation. This dotted curve at small $x$ is considered to be a rough lower bound for the nuclear modification. The shaded area between these curves is the area of possible nuclear modification, which is allowed by present experimental data of $R_2$ and the baryon-number conservation. It should be emphasized that the region is a very naive estimate of the experimental restriction.

It is noteworthy that the first parton-model (model 1) prediction is roughly equal to the upper bound curve, and the aligned-jet model (model 2) prediction is to the lower bound curve. So the models are two extreme cases, which are both acceptable in our present knowledge. We have not investigated the details of other model predictions. However, it is very encouraging to investigate the (anti)shadowing phenomena of $F_3$ in the sense that the observable could be useful in discriminating among different models, which produce similar results in the $F_2$ shadowing.

There are reasonably accurate data for $F_3$ of a medium size nucleus, but we do not
have accurate deuteron data [13]. We hope that future neutrino experiments provide us accurate information on nuclear modification of $F_3$.

3. Conclusions

We investigated nuclear modification of the structure function $F_3$ in two different models: the parton-recombination with $Q^2$ rescaling and the aligned-jet model. These two models predict completely different behavior at small $x$: antishadowing in the first model and shadowing in the second model. Within our present experimental and theoretical knowledge, both results are allowed even though they are two extreme cases. Therefore, it is possible to rule out one possibility by measuring $F_3^A/F_3^D$. Furthermore, the $F_3$ shadowing could be useful in discriminating among various shadowing models. Our investigation is merely a starting point in studying details of the $F_3$ shadowing. In particular, other model predictions and experimental possibility should be explored.

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Figure Captions

**Fig. 1** Nuclear modification of $F_3$ in the calcium nucleus is predicted in the parton recombination model with $Q^2$ rescaling. The dashed curve shows the results in the $Q^2$ rescaling model. Effects of the parton recombinations are shown by the arrows. The overall results including the rescaling and the recombinations are shown by the solid curve.

**Fig. 2** The model-1 curve is the prediction of the nuclear modification of $F_3$ in the calcium by the parton model in subsection 2.1, and the model-2 curve is the one by the aligned-jet model. The dashed and dotted curves are estimated by using existing data of $F_2^{Ca}/F_2^D$ at $x > 0.3$ and the baryon-number conservation. The shaded area is roughly the currently acceptable region. Note that the experimental data are for $F_2^{Ca}/F_2^D$. 
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