Nuclear Gluon Distributions in a Parton Model

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ABSTRACT

Gluon distributions in the carbon and tin nuclei are investigated by using a $Q^2$ rescaling model with parton recombination effects. We obtain strong shadowings in the small $x$ region due to the recombinations. The ratio $G_A(x)/G_N(x)$ in the medium $x$ region is typically 0.9 for medium size nuclei. At large $x$, the ratio becomes large due to gluon fusions from different nucleons. Comparisons with recent New Muon Collaboration data for $G_{Sn}(x)/G_C(x)$ indicate that more accurate experimental data are needed for testing the model.

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Recent measurements of gluon distribution ratios $G_{Sn}(x)/G_{C}(x)$ by New Muon Collaboration (NMC) [1] are the first data which could shed light on gluon distributions in nuclei [2].

Modifications of the structure function $F_{2}(x)$ in nuclei were discovered by European Muon Collaboration (EMC effect) [3]. This effect has been an interesting topic in the sense that it may provide an explicit quark signature in nuclear phenomena. On the contrary, “gluonic EMC effect” is little known. Gluon distribution functions in the nucleon [4] have been investigated by using muon (electron, or neutrino) deep inelastic scattering data [5,6], direct photon data [7,8], and muon induced $J/\psi$ production data [9,10]. Although there are some theoretical predictions [11,12,13,14] for gluon distributions in nuclei, we have little experimental data. There are direct photon data for proton reactions with nuclear targets [15,16]; however, there is no available large $p_T$ data in the WA80 case [15]. Accuracy is not good enough for extracting a gluon distribution function of the beryllium (Be) nucleus from the E706 data [16]. In any case, we do not expect much modification of the gluon distribution in light nuclei such as Be.

The NMC analyzed inelastic $J/\psi$ production data by a color singlet model [17] and obtained gluon distribution ratios $G_{Sn}(x)/G_{C}(x)$ [1]. These are interesting data which indicate modifications of the gluon distribution in nuclei. We should note that it is very important to know the gluon distributions in nuclei. For example, $J/\psi$ suppressions in heavy-ion collisions were proposed as a signature of quark-gluon plasma [18]. Although other initial and final state interactions may explain the $J/\psi$ suppression phenomena, it is important that initial conditions as local (gluonic) EMC effects [19] should be subtracted out for investigating the physics origin of the suppressions [20]. Such issues have not been well studied yet because there is little data for gluon distributions in nuclei.

As a model for explaining the EMC effect, we take a $Q^2$ rescaling model [21] and apply it for the gluon distribution. The model was proposed originally for the structure function $F_{2}(x)$ by considering the possibility that an effective confinement radius for quarks is changed in a nuclear environment. In fact, strong nucleon overlaps are expected in nuclei by noting the fact that the nucleon diameter is approximately equal to the average nucleon separation in nuclei. From this confinement-radius change and the $Q^2$ evolution equation,
the $Q^2$ rescaling model was proposed [21]. In this research, we use the above simple picture also for gluons. Namely, the nuclear gluon distribution function in the rescaling model is given by $G_A(x, Q^2) = G_N(x, \xi_A Q^2)$, where $\xi_A$ is called as the rescaling parameter.

Other new features which exist if a nucleon resides in a nucleus are parton recombinations (fusions). The mechanism has been investigated for explaining the shadowing region $F_2(x < 0.1)$ in parton models [11,12,22]. The recombinations also have important effects on the gluon structure function due to processes shown in Fig. 1. We find that there are strong shadowings in the small $x$ region ($x < 0.05$) and strong anti-shadowings in the medium $x$ region [12]. In Ref. 22, it was shown that a model of the $Q^2$ rescaling with the recombination can explain experimental data of $F_2(x)$ fairly well in the wide $x$ region ($0.005 < x < 0.8$).

In this report, the gluonic EMC effect is investigated by the $Q^2$ rescaling model combined with the parton recombinations in Ref. 22. Using this model we calculate gluon distributions in the carbon (C) and tin (Sn) nuclei. Results in our model are compared with the recent NMC ratios $G_{Sn}(x)/G_C(x)$.

In order to investigate recombination effects, we calculate contributions to $G(x)$ from processes in Fig. 1 as investigated by Close, Qiu, and Roberts [12]. For example, a gluon with momentum fraction $x$ is produced by a fusion of gluons from the nucleon 1 and 2. A modification of a parton distribution $p_3(x_3)$, due to the process of producing the parton $p_3$ with the momentum fraction $x_3$ by a fusion of partons $p_1$ and $p_2$, is given by [12,22]

$$\Delta p_3(x_3) = K \int dx_1 dx_2 \ p_1(x_1) \ p_2(x_2) \ \Gamma_{p_1 p_2 \to p_3}(x_1, x_2, x_3 = x_1 + x_2) \ \delta(x, x_1, x_2) \ , \ (1)$$

where $K$ is given by $K = 9A^{1/3} \alpha_s/(2R_0^2 Q^2)$ with $R_0=1.1$ fm and the strong-interaction coupling constant is $\alpha_s(Q^2) = 4\pi/[9 \ln(Q^2/\Lambda^2)]$. The $\delta$ function is given by $\delta(x - x_1 - x_2)$ for the processes in Figs. 1a, 1d, and 1e and $\delta(x - x_1)$ for Figs. 1b, 1c, 1f, 1g, 1h, and 1i. The parton fusion function $\Gamma(x_1, x_2, x_3)$ is a probability for producing a parton $p_3$ with momentum fraction $x_3$ by a fusion of partons $p_1$ and $p_2$ with momenta $x_1$ and $x_2$ respectively.

Now, we discuss numerical analysis. In evaluating recombination contributions $\Delta G(x)$ by using Eq. (1) [23], we assume that a leak-out parton (we denote $p^*(x)$) is a sea quark
or a gluon and that the momentum cutoff function \([12,24]\) for this parton is taken as
\[
w(x) = \exp(-m^2 x^2 / 2)\] with \(z_0 = 0\) or 2 fm. Then, distributions for the leak-out partons are
\[
q^*(x) = w(x)q_{sea}(x), \quad \bar{q}^*(x) = w(x)\bar{q}(x), \quad \text{and} \quad G^*(x) = w(x)G(x).
\]
Input parton distributions are given by a recent parametrization in Ref. 4. \(Q^2 = 5 \text{ GeV}^2\) is used in the parametrization and for calculating \(K\) in Eq. (1). The QCD scale parameter \(\Lambda\) in \(\alpha_s(Q^2)\) is taken as \(\Lambda = 0.2 \text{ GeV}\). In our theoretical analysis, targets nuclei are assumed as \(^{12}\text{C}\) or \(^{118}\text{Sn}\). The rescaling parameters for these nuclei are taken from Ref. 21, and they are \(\xi_A(C) = 1.60\) and \(\xi_A(Sn) = 2.24\).

Before discussing the gluon distributions in C and Sn, we first check that our model can explain structure functions \(F_A^2(x)\) of these nuclei. As shown in Ref. 22, our results are consistent with SLAC, EMC, and E665 experimental data for \(F_A^2(x)\) of C, Ag, Sn, and Xe nuclei in the wide \(x\) range \((0.005 < x < 0.8)\). In explaining these data, the most important factor is the gluon shadowing. Taking modified parton distributions due to the recombinations at small \(Q^2\), we should calculate distributions at large \(Q^2\), where the structure functions were measured. Instead of solving the evolution exactly, we simply used a solution [25] for the Altarelli-Parisi equation in the small \(x\) region
\[
(x \delta q^\text{sea}_i(x) = -\frac{x}{12} \frac{\partial}{\partial x} [x \Delta G(x)],
\]
where \(i = u, d,\) or \(s\). This approximate way of treating the evolution violates the momentum conservation even though it is satisfied in the recombinations. The effect due to this extra term is given by
\[
6 \int dx \ x \delta q^\text{sea}_i(x) = \frac{1}{2} \lim_{x \to 0} x^2 \Delta G(x) + \frac{1}{2} \int dx x \Delta G(x).
\]
The first term vanishes if the input gluon distribution satisfies, for example, \(\lim_{x \to 0} x G(x) = \text{constant}\). Dominant contributions to \(\Delta G(x)\) come from the gluon-gluon fusion processes; however, they satisfy the momentum conservation by themselves \((\int dx x \Delta G_{GG\to G}(x) = 0)\). Therefore, the violation is a small effect due to \(q\bar{q} \to G, Gq \to q,\) and \(G\bar{q} \to \bar{q}\) processes. A numerical evaluation for the Ca nucleus indicates that such violation effect is less than 1\% \((6 \int dx x \delta q^\text{sea}_i(x) = -0.005)\); hence it is not a serious effect on the momentum conservation.

Using our model, which can explain at least the structure function \(F_A^2(x)\), we predict \(G_C(x)\) and \(G_{Sn}(x)\). We take the same rescaling parameter for all partons by taking a naive consideration that the confinement radius change modifies all parton momenta at the same rate. Predicted gluon distributions for C and Sn are shown in Figs. 2a and 2b.
In these figures, the dashed curves are recombination effects shown by

\[ R_A(\text{recombination}) = 1 + \frac{\Delta G_A(x, Q^2)}{G_N(x, Q^2)}, \quad (2) \]

\( \Delta G_A(x, Q^2) \) is calculated by using Eq. (1) (note that no \( Q^2 \) rescaling is used) and explicit expressions are given in Ref. 22. Solid curves are combined contributions from the rescaling and recombinations and they are shown by the ratio

\[ \frac{G_A(x, Q^2)}{G_N(x, Q^2)} = \frac{\tilde{G}_A(x, Q^2) + \Delta \tilde{G}_A(x, Q^2)}{G_N(x, Q^2)}. \quad (3) \]

In these equations, \( \tilde{G}_A(x, Q^2) \) and \( \Delta \tilde{G}_A(x, Q^2) \) are given by the rescaling model, \( \tilde{G}_A(x, Q^2) = G_N(x, \xi_A Q^2) \) and \( \Delta \tilde{G}_A(x, Q^2) = \Delta G(x, \xi_A Q^2) \). The recombination mechanism produces strong shadowing effects in the small \( x \) region due to gluon-gluon and gluon-quark fusion processes in Fig. 1. In the medium-large \( x \) region, contributions are dominated by the gluon-gluon fusion process in Fig. 1a. It is interesting to note in our model that gluon distributions at \( x > 1 \) could be produced in the fusion process. This is the reason why the ratio goes to infinity at \( x \to 1 \) in Figs. 2a and 2b. The \( Q^2 \) rescaling contributions are opposite to the recombination. The rescaling effects are positive in the small \( x \) region and are negative in the medium-large \( x \) region. Combined contributions shown by the solid curves in Figs. 2a and 2b indicate strong shadowings in the very small \( x \) \( (x < 0.02) \) region, depletions \( (0.8-1.0) \) in the medium \( x \) \( (0.2 < x < 0.6) \), and large ratios in the large \( x \) \( (x > 0.7) \).

In investigating shadowings in \( F_2(x) \) in Ref. 22, we used the rescaling for parton distributions at \( x < 0.1 \). Although the rescaling produces large positive contributions, they are counterbalanced by the large shadowings produced through gluon distributions \( (\delta F_2 \text{ in Ref. 22}) \). Therefore, combined contributions are not very dependent (about 5% differences) whether or not the rescaling is used in the region \( (0.005 < x < 0.1) \). On the contrary, gluon distributions at small \( x \) are very sensitive to whether or not the rescaling is used as shown in Figs. 2a and 2b. If there is no rescaling at \( x < 0.1 \), we should have strong gluon shadowings in the region \( x < 0.1 \) as shown by the dashed curves. However, if the rescaling is used, gluon distributions are shadowed only in the very small \( x \) region \( (x < 0.02) \) as shown by the solid curves.
The nuclear gluon distributions in the medium-large $x$ region are very sensitive to the momentum cutoff as shown in Figs. 2a and 2b. For example, $G_{Sn}(x)/G_N(x) = 1.02$ (for $z_0 = 0$) at $x = 0.4$, but it is 0.87 if $z_0 = 2$ fm. Because $G_N(x)$ itself is very small at $x = 0.4$, it may seem to be an insignificant problem. However, it is important for describing e.g. $p_T$ dependence of $J/\psi$ in heavy-ion collisions. The rapid increase of $G_A(x)/G_N(x)$ in the medium $x$ region could be responsible for the $p_T$ dependence of $J/\psi$ suppressions observed by NA38 [26], although the $p_T$ slope obtained in the local gluonic EMC effect is rather small [20] compared with the NA38 data at this stage. The gluon distributions at the medium $x$ are so sensitive to the momentum cutoff $w(x)$ that we need to study more about the cutoff [24]. We leave the problem of the cutoff as a future research topic.

Calculated gluon distributions are compared with the NMC data for $G_{Sn}(x)/G_C(x)$ [1] in Fig. 3. The dashed curve shows recombination results with $z_0=0$ and the solid (dash-dot) curve shows combined results of the $Q^2$ rescaling and the recombinations with $z_0=0$ ($z_0 = 2$ fm). Our theoretical results shown by the solid and dash-dot curves indicate ratios $G_{Sn}(x)/G_C(x) < 1$ at $x < 0.03$ due to the gluon shadowing. The ratios are about 1.03 in the region ($0.05 < x < 0.20$) and are dependent on the momentum cutoff $w(x)$ in the medium $x$ ($x > 0.2$). We notice that experimental errors are very large in comparison with typical theoretical modifications. Because our model predictions for the modifications are less than 5% in the range $0.05 < x < 0.2$, we need accurate data better than 5% accuracy in order to test the model. Because the NMC data for $G_{Sn}(x)/G_C(x)$ are not accurate enough, we should wait for better measurements of $G_A(x)$, for example a proposed experiment at RHIC [27], in the small $x$ region for investigating details of the gluon shadowing. It is also important to know gluon distributions in the medium $x$ region ($0.3 < x < 0.6$), although distributions themselves are very small, for studying $J/\psi$ productions in heavy-ion collisions [20].

In summary, we investigated gluon distributions in the nuclei C and Sn by the rescaling model with parton recombinations effects. We obtained shadowings in the nuclear gluon distributions in the small $x$ region due to the recombinations and depletions [typically $G_A(x)/G_N(x) \sim 0.9$] in the medium $x$ region. The ratio $G_A(x)/G_N(x)$ becomes large at $x > 0.6$ due to gluon fusions from different nucleons. The ratio in the medium-large $x$ region is very sensitive to the momentum cutoff for leak-out partons in our model.
Comparisons with the NMC data indicate that more accurate experimental data are needed for testing the model.

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Figure Captions

1. Modifications of $G(x)$ due to parton recombinations.

2. Predicted gluon distributions in the nuclei (a) C and (b) Sn. The dashed curves indicate parton recombination effects (Eq. (2)) and the solid curves are combined results (Eq. (3)) of the recombination and the $Q^2$ rescaling. $\xi_A=1.60$ for C and 2.24 for Sn.

3. Comparisons of our theoretical results with NMC data [1]. The dashed curve indicate parton recombination effects with $z_0=0$ and the solid (dash-dot) curve shows combined results of the recombination and the $Q^2$ rescaling with $z_0=0$ ($z_0=2$ fm).