European Muon Collaboration effect from short-range correlated nucleons in a nucleon swelling model

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The relation between the nuclear European Muon Collaboration (EMC) effect and the nucleon-nucleon short-range correlation is a hot topic in high-energy nuclear physics, ever since a peculiar linear correlation between these two phenomena was discovered. In this paper, the contribution to the nuclear EMC effect arising from the short-range correlated nucleons is examined in a nucleon-swelling model. We find that the structure modifications of the nucleon-nucleon short-range correlation (SRC) nucleons reproduce more or less the measured EMC ratios of light nuclei, while they are not enough to explain the measured EMC ratios of heavy nuclei. We speculate that the hypothesis of a causal connection between SRC and the EMC effect is not exact, or the universality of the inner structure of the SRC nucleon is violated noticeably from light to heavy nuclei, or there are other origins for the EMC effect.

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I. INTRODUCTION

The nuclear European Muon Collaboration (EMC) effect observed in lepton-nucleus deep inelastic scattering (DIS) [1–3] proves that the quark degrees of freedom inside the nucleon are influenced by the surrounding nucleons (cold nuclear medium). This phenomenon implies that the nuclear force between nucleons is emergent fundamentally from the strong interaction between the quarks inside different nucleons. Before the experiment of the EMC, the quark degrees of freedom were thought to be frozen and confined in the nucleon, and the nuclear force at the scale around nuclear binding energy cannot influence the nucleon inner structure to a sizable extent. It attracted a lot of interests soon after the discovery and has still been an interesting puzzle in high-energy nuclear physics through the decades [4–8]. Understanding of the mechanism of the EMC effect from quantum chromodynamics (QCD) remains quite challenging [9,10].

The nucleon-nucleon short-range correlation (*NN* SRC) is one microscopic and quite unusual structure inside an atomic nucleus [11–15]. Different from the mean-field description of the nuclear interaction and the single-nucleon motion given by the nuclear shell model, the *NN* SRC shows one kind of special close-proximity structure of the nucleon-nucleon distance about or even smaller than 1 fm [11,14]. In the *NN* SRC pair, the nucleon-nucleon interaction can reach the repulsive core of the nuclear force. Therefore the nucleon struck out from *NN* SRC could have the momentum way higher than the nuclear Fermi momentum. Thanks to the clean probe of the high-energy electron, the *NN* SRC is observed in the inclusive and exclusive processes, identified with the high nucleon momentum and the angle correlation between the high-momentum nucleon partners [16–25]. Though the short-range correlated nucleons interact extensively and strongly, they are the minorities in the nucleus compared to the mean-field nucleons. In heavy nuclei, only about 20% of the nucleons are in the *NN* SRC configuration [17].

There is no doubt that the nucleons in close-proximity interact with each other strongly. Their inner structures therefore can be greatly modified. Naively, the *NN* SRC is thus thought to be an important source of the EMC effect. Actually, with the finding of a linear correlation between the magnitude of the EMC effect and the relative number of *NN* SRC pairs [26,27], more and more physicists guess that the strong modification of SRC nucleons is the primary origin of the EMC effect. Theoretically, the linear correlation between the EMC effect and the *NN* SRC is explained with the scale separation phenomenon [28]. Experimentally, the CLAS collaboration tested the SRC-driven model for the nuclear EMC effect, with the simultaneous measurements of the DIS and quasielastic inclusive process on the deuteron and some heavier nuclei. They extracted the modification function of the structure function of the SRC nucleon and found that this modification function is more or less universal for different nuclei [25]. A latter study examined the SRC-driven EMC effect and the

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universal modification function in both the local-density and the high-virtuality pictures, and a truly universal modification function of SRC was found [29]. It is proposed that the EMC effect is not the traditional static modification on all the independent nucleons but a strong dynamical effect from two strongly interacting nucleons fluctuating into a temporary high-local-density SRC pair.

However, different people have different opinions in explaining the correlation between the EMC effect and the *NN* SRC. The relationship of these two phenomena is examined recently in details with a convolution model which incorporates the nuclear binding and the nucleon off-shell effects [30]. They argue that their analysis does not support the hypothesis that there is a causal connection between SRC nucleons and the EMC effect. The EMC effect of the low-momentum nucleon and the high-momentum nucleon are studied separately. They find that the Fermi motion effect overwhelms the off-shell effect for the SRC nucleons with various models for the off-shell correction. Thus they conclude that the SRC nucleons do not give a dominant part of the observed EMC effect [30], compared with the mean-field nucleons. In our previous paper [31], we also get the similar conclusion that only the modifications on the *NN* SRC nucleons are not enough to reproduce the measured EMC effect, with our current knowledge about the number of SRC pairs in the nuclei [17,20,32]. In our previous analysis, the x-rescaling model was applied for the off-shell-ness correction of the SRC nucleon, and the effective mass of SRC nucleon was taken from a recent analysis [32].

In this paper, the hypothesis that the nuclear EMC effect comes entirely form the *NN* SRC pairs is examined further at a more fundamental level. The conventional nuclear models usually take into account the reduced nucleon mass in medium or the nucleon virtuality for the EMC effect, leading to the x-rescaling models [33–38] and the off-shell-ness corrections [39–43]. Since the EMC effect is measured in the DIS process, it should be explained at the quark level instead of the nucleon level. The QCD-inspired models in explaining the EMC effect usually require an increase of the quark confinement or a simple picture of nucleon swelling. As the nucleons in the SRC pair are so close to each other and form into a high-local density cluster, the quarks inside could thus be deconfined. In the hadron bag picture, we can imagine the two nucleon bags merge into a big dinucleon bag. If the quarks can move freely from one nucleon to the other in the SRC pair, then the confinement space of the quark could be enlarged by as much as twice. Within the nucleon swelling model, the quark distributions inside the SRC nucleon can be calculated quantitatively [44,45]. Hence the contribution of the SRC nucleons to the EMC effect can be evaluated.

The organization of the paper is as follows. The hypothesis that the nuclear EMC effect arises dominantly from the *NN* SRC pairs and the related formula are given in Sec. II. The nucleon swelling model for calculating the structure function of the SRC nucleon is discussed in Sec. III. The results of the SRC driven model for the EMC effect are shown in Sec. IV. A brief summary of the analysis is given in Sec. V.

II. NUCLEAR EMC EFFECT FROM *N-N* SRC

A haunting question we try to answer in this work is whether the *NN* SRC is wholly responsible for the nuclear EMC effect. Therefore we employ the so-called "SRC-driven model" for the EMC effect. That means that the inner structures of short-range correlated nucleons are substantially modified while the inner structures of the nucleons in the mean field are nearly unmodified. The *NN* SRC is the only (or dominant) source of the EMC effect. The long-range nuclear interaction has no influence on the short-distance structure in the nucleon.

Many experiments have revealed that the majority of *NN* SRC pairs are the proton-neutron correlated pairs [19–22]. This isophobic property is actually consistent with the theoretical calculations based on the assumption that the medium-range tensor force is primarily responsible for the formation of *NN* SRC pairs [24,46–48]. In this paper, we study the model which assumes that the *NN* SRC is the primary source of the EMC effect. For the simplicity of model calculations, we ignore the *p-p* and *n-n* SRC pairs, since they together are surely the minorities ($\lesssim$10%) compared to the *p-n* SRC pairs. Thus the per-nucleon nuclear structure function is given by

$$F_2^{\rm A} = \big[n_{\rm SRC}^{\rm A} F_2^{\rm p\,in\,SRC} + n_{\rm SRC}^{\rm A} F_2^{\rm n\,in\,SRC} + \big(Z - n_{\rm SRC}^{\rm A}\big)F_2^{\rm p} + \big(A - Z - n_{\rm SRC}^{\rm A}\big)F_2^{\rm n}\big]/A, \quad (1)$$

in which $n_{\rm SRC}^{\rm A}$ is the number of *p-n* SRC pairs in nucleus A, $F_2^{\rm p\,in\,SRC}$ and $F_2^{\rm n\,in\,SRC}$ are the modified nucleon structure functions in the SRC pair, and $F_2^{\rm p}$ and $F_2^{\rm n}$ are the free nucleon structure functions. Z, N, and A are, respectively, the proton number, neutron number, and the mass number to define a particular nucleus. Note that the universality of the *p-n* SRC pair in different nuclei is assumed for Eq. (1).

The *NN* SRC is a compact and short-time lived state from the fluctuations of the many-body dynamics of nuclear force. The formations and dissociations of *NN* SRC pairs keep on going inside the nucleus. Thus in Eq. (1), the number of SRC pairs $n_{\rm SRC}$ should be viewed as a mean value in the measurements. Take the deuteron for an example, the mean number of $p - n$ SRC pairs in the deuteron is less than one ($n_{\rm SRC}^{\rm d} \ll 1$), for the *NN* SRC configuration happens very occasionally.

For the SRC-driven model, the number of SRC pairs in a nucleus (A) is an indispensable parameter. In experiment, the relative number of *NN* SRC pairs is characterized by the SRC scaling ratio a_2 in the region $1.4 \lesssim x_B \lesssim 1.9$. Then the number of SRC pairs in nucleus A $n_{\rm SRC}^{\rm A}$ is computed with the measured a_2 and the number of SRC pairs $n_{\rm SRC}^{\rm d}$ in deuteron, which is written as

$$n_{\rm SRC}^{\rm A} = \big[A \times a_2(A) \times n_{\rm SRC}^{\rm d}\big]/2. \quad (2)$$

The SRC scaling ratio a_2 is measured using the high-energy electron inclusive scattering process off the nuclear targets [17,18,25]. The number of SRC pairs in the deuteron has already been determined in our previous analysis [32]. Table I lists the values of a_2 of some nuclei, measured by the CLAS collaboration [17,25] and JLab Hall C collaboration [18], and also the averaged values that were used in this analysis. Note

TABLE I. The experimental data of SRC scaling factor a_2 from CLAS and JLab Hall C collaborations, and the resulting average values, for various nuclei.

Nucleus	CLAS06 [17]	CLAS19 [25]	Hall C [18]	Average
^{3}He	1.97 ± 0.10		2.13 ± 0.04	2.11 ± 0.04
^{4}He	3.80 ± 0.34		3.60 ± 0.10	3.62 ± 0.10
^{9}Be			3.91 ± 0.12	3.91 ± 0.12
^{12}C	4.75 ± 0.41	4.49 ± 0.17	4.75 ± 0.16	4.64 ± 0.11
^{27}Al		4.83 ± 0.18		4.83 ± 0.18
^{56}Fe	5.58 ± 0.45	4.80 ± 0.22		4.95 ± 0.20
^{208}Pb		4.84 ± 0.20		4.84 ± 0.20

that in Eq. (2), the small effect of the pair motions [17,18] is not considered. Contrary to the SRC universality, the pair center-of-mass (c.m.) motion effect is nuclear-dependent.

The other important input for the model of the SRC-induced EMC effect is the modified structure function of SRC nucleon. The structure function at intermediate x_B is closely related to the valence quark distributions. A model derived from the expansion of quark confinement is employed to estimate the quark distributions and the structure function of the SRC nucleon. We discuss such a model in detail in the following section.

III. SWELLING EFFECT FOR SRC NUCLEONS

How we compute the structure functions of the free nucleon and the SRC nucleon are presented in this section. The structure function F_2 is directly connected to the parton distribution functions (PDFs). In the calculations, we take the dynamical PDFs, which are generated from Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equations [49–51] with the input of three valence quark distributions at an extremely low Q_0^2. The initial three valence quark distributions at Q_0^2 of the free nucleon are taken from an estimation of the maximum entropy method [52], which produce the structure function consistent with the experimental data at high Q^2. In the nucleon swelling model, all the nuclear modifications are reflected in the increase of the quark confinement space. Therefore, to evaluate the structure function of the SRC nucleon, we need just to modify the initial three valence quark distributions due to the swelling of the SRC nucleon.

The enlargement of the confinement size of SRC can be understood in three different pictures. (1) In the hadron bag model, the high local density reduces the pressure of the vacuum in which the nucleon embedded, thus resulting in a bigger size of the nucleon bag. (2) If the quarks can exchange between the nucleons in the SRC pair, then it means that the confined space of the quark is increased. (3) The enlargement of the confinement size is also vividly illustrated with the multiquark cluster model [53–57]. When two nucleons form into a six-quark cluster, the confinement space of this six-quark cluster is naturally larger than the three-quark cluster (the nucleon) if the quark density is the same. Moreover, the calculations of quark-meson coupling (QMC) model [58–60] and nuclear potential model [61–63] also give a small deconfinement of the quark in the nuclei. Miller analyzed the elastic electron-nucleus scattering under the Ward-Takahashi identity, and find that with the input of lattice QCD the off-shell nucleon expands the size [64].

There are two ways to apply the nucleon swelling effect to the quark distributions. (1) A bigger nucleon is equivalent to a higher resolution power of the photon probe in DIS. In the language of QCD evolution, the Q^2 rescaling [65–69] (an higher resolution power) is carried out to interpret the effect. (2) Due to the change of quark confinement space, the quark momentum distribution also varies according to the Heisenberg uncertainty principle. If the uncertainty of the spatial distribution becomes larger, the uncertainty of the valence quark distribution reduces accordingly [44,45]. The uncertainty of a random variable is quantified with the width of the distribution. The width can be taken as the standard deviation of the distribution. Thus the widths of the valence distributions are given by

$$\begin{aligned}
\sigma(x_u) &= \sqrt{\langle x_u^2\rangle - \langle x_u\rangle^2},\\
\sigma(x_d) &= \sqrt{\langle x_d^2\rangle - \langle x_d\rangle^2},\\
\langle x_u\rangle &= \int_0^1 x\frac{u_v(x, Q_0^2)}{2}dx,\\
\langle x_d\rangle &= \int_0^1 x d_v(x, Q_0^2)dx,\\
\langle x_u^2\rangle &= \int_0^1 x^2\frac{u_v(x, Q_0^2)}{2}dx,\\
\langle x_d^2\rangle &= \int_0^1 x^2 d_v(x, Q_0^2)dx. \qquad (3)
\end{aligned}$$

In this work, we apply the second method to evaluate the PDFs and the structure function of the SRC nucleon. We also tried the Q^2-rescaling model [65,66]. The Q^2-rescaling model does not generate the antishadowing effect, and the EMC effect produced from the Q^2-rescaling model is smaller than that from our distribution-changing model.

The quark confinement space of the six-quark bag from NN SRC is twice that of the nucleon bag, assuming that the quark density is the same. If we assume the quarks exchange completely freely between the two nucleons in SRC, the swelling factor of the quark confinement space also can be as large as two. We do not have a certain answer for the quark confinement of the SRC pair. In this work, we try to see the largest nuclear modification that the SRC nucleons can provide. If the largest nuclear modification from SRC nucleons cannot explain the EMC effect, then we should look for more origins of the EMC effect. Therefore, in this work we assume that the quark confinement space in the SRC pair is twice that of the free nucleon. Therefore the quark confinement radius in the SRC pair is then $(2)^{1/3}$ times that of the free nucleon. According to the Heisenberg uncertainty principle, the width of the valence quark distribution in the SRC nucleon

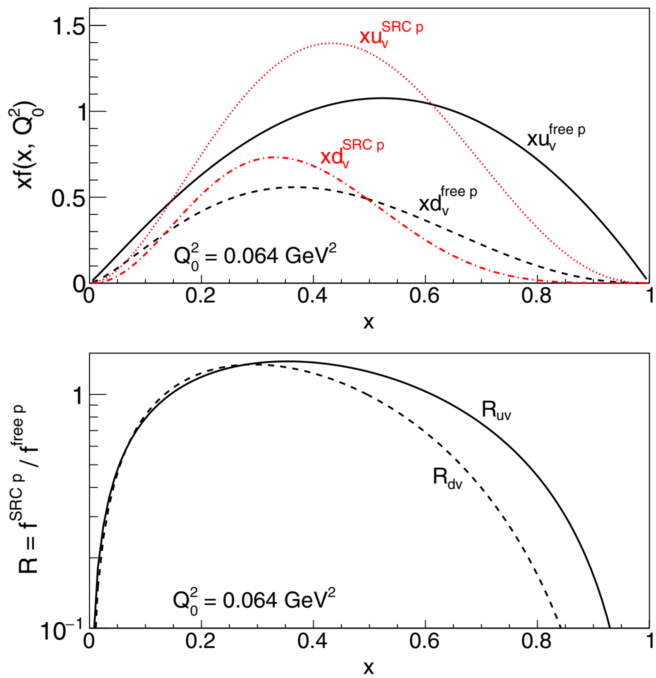

FIG. 1. The upper panel shows the valence quark distributions of the free proton and the SRC proton at the initial scale Q_0^2. The lower panel shows the nuclear modification ratios of the valence quark distributions at the initial scale Q_0^2. The change of the width of the valence quark distribution in the SRC proton is made according to the Heisenberg uncertainty principle and the swelling of the quark confinement.

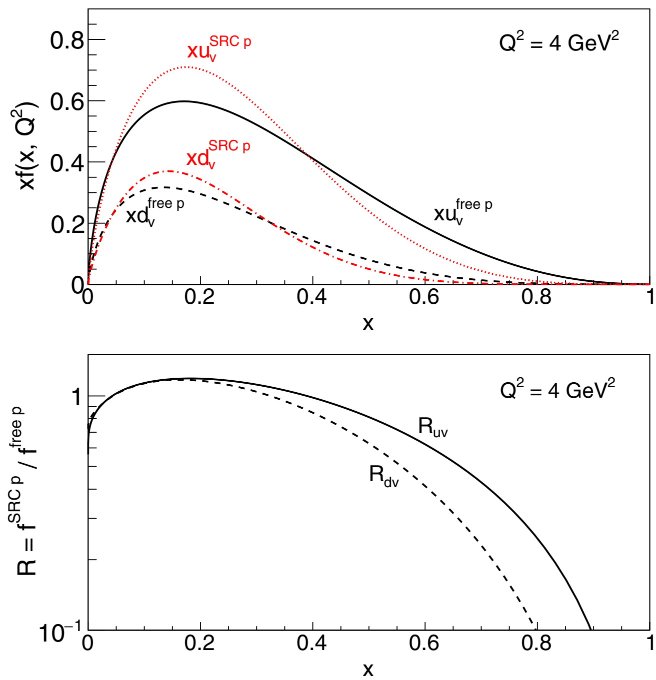

FIG. 2. The upper panel shows the valence quark distributions of the free proton and the SRC proton at the Q^2 relevant to the experimental measurements. The lower panel shows the nuclear modification ratios of the valence quark distributions at the experimental scale Q^2. The valence quark distributions are given with DGLAP evolution equations and the input valence quark distributions at the hadronic scale.

is reduced by a factor of $(2)^{-1/3}$, which is written as

$$\frac{\sigma\left(x_q^{\mathrm{SRC\,N}}\right)}{\sigma\left(x_q^{\mathrm{free\,N}}\right)} = \left(\frac{1}{2}\right)^{1/3}, \quad (q = u, d). \tag{4}$$

In the calculation, the valence quark distributions of the free nucleon and the SRC nucleon are all parametrized as the β function $Ax^B(1-x)^C$. The momentum sum rule and the valence sum rule are also required at Q_0^2, which are written as

$$\begin{aligned} \int_0^1 x\left[u_v\left(x, Q_0^2\right) + d_v\left(x, Q_0^2\right)\right]dx = 1, \\ \int_0^1 u_v\left(x, Q_0^2\right)dx = 2, \\ \int_0^1 d_v\left(x, Q_0^2\right)dx = 1. \end{aligned} \tag{5}$$

The benchmark valence quark distributions of the free nucleon are taken from Ref. [52]. The valence quark distributions of the SRC nucleon are solved with Eqs. (3) and (4). The input valence quark distributions at Q_0^2 ($\sim$0.1 GeV^2) of the free proton and the SRC proton are shown in Fig. 1. One sees that the nuclear modification at Q_0^2 on the valence quark distributions are strong for the SRC nucleon.

With the obtained valence quark distributions at Q_0^2, the PDFs and the structure function at high Q^2 are given by the DGLAP evolution equations [49–51]. The initial scale Q_0^2 and the strong coupling α_s are taken from Refs. [52,70]. Q_0^2 is set at 0.064 GeV^2, where there are only valence quarks at the scale. The running strong coupling is taken as $\alpha_s = 4\pi/[\beta_0 \ln(Q^2/\Lambda^2)]$ with $\beta_0 = 11 - 2n_f/3$ and $\Lambda_{\mathrm{LO}}^{3,4,5,6} = 204$, 175, 132, 66.5 MeV. The parton-parton recombination correction [71,72] is included in order to slow down the fast splitting process due to the large α_s at low Q^2. For the calculations of the neutron PDFs and structure function, the isospin symmetry of the nucleon is assumed as $u^n = d^p$ and $d^n = u^p$.

Applying the DGLAP evolution equations discussed above, the valence quark distributions at a high Q^2 (4 GeV^2) are obtained and shown in Fig. 2. The shapes of the valence quark distributions change dramatically during the evolution from Q_0^2 to Q^2. At the high Q^2 scale, the valence distributions of the SRC nucleon are lower than those of the free nucleon in the intermediate x range of $x \gtrsim 0.35$, which is consistent with the EMC effect observed in experiment. The valence-distribution ratios of the SRC nucleon to the free nucleon are also shown in Fig. 2 at high Q^2.

IV. RESULTS AND DISCUSSIONS

The predicted EMC ratios based on the assumptions of the SRC-driven EMC effect and the SRC nucleon swelling model are shown in Figs. 3–5, for light nuclei and heavy nuclei, respectively. The experimental data are taken from the analyses by the CLAS collaboration [25] and JLab Hall C collaboration

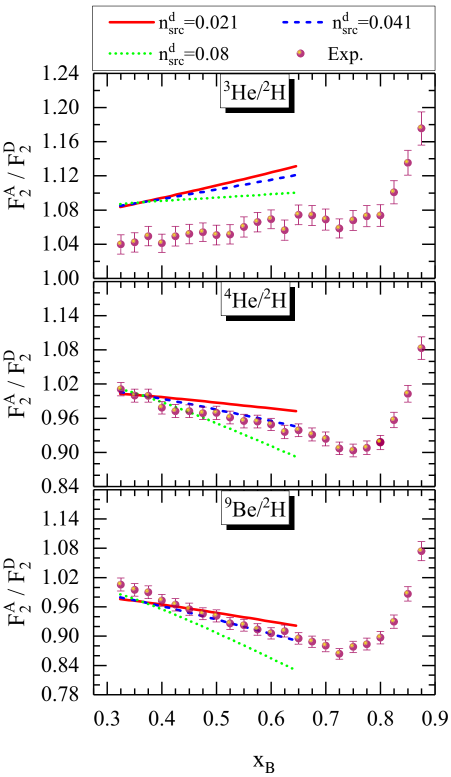

FIG. 3. Comparisons between our SRC-driven model calculations for the EMC effect and the experimental measurements of light nuclei [73,74]. The swelling effect of the SRC nucleon is assumed to be the origin of the EMC effect in our calculations. The curves of different styles show the results with different input values for the parameter $n^{\rm d}_{\rm SRC}$. See the main text for more explanations.

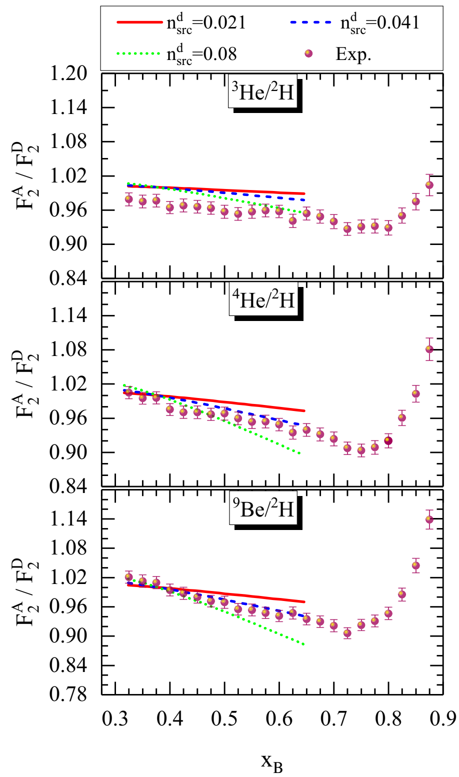

FIG. 4. Comparisons between our SRC-driven model calculations for the EMC effect and the experimental measurements of light nuclei [73,74] with the isoscalar corrections for both the theoretical calculations and the experimental data. The swelling effect of the SRC nucleon is assumed to be the origin of the EMC effect in our calculations. The curves of different styles show the results with different input values for the parameter $n^{\rm d}_{\rm SRC}$. See the main text for more explanations.

[73,74]. The number of SRC pairs in the deuteron are estimated to be from 0.021 to 0.041. $n^{\rm d}_{\rm SRC} = 0.021$ is obtained from the fit to the correlation between the nuclear mass and the SRC scaling ratio a_2 [32]. $n^{\rm d}_{\rm SRC} = 0.041$ is estimated by counting the nucleons of momentum above $k_F \approx 275$ MeV/c [17,20]. For light nuclei, one sees that the EMC effect from SRC nucleons can reproduce the experimental data within our nucleon swelling model and with $n^{\rm d}_{\rm SRC} = 0.041$. However, for the heavy nuclei, our model calculations from the swelling SRC nucleons are not enough to explain the experimental observations with either $n^{\rm d}_{\rm SRC} = 0.021$ or $n^{\rm d}_{\rm SRC} = 0.041$.

In Fig. 3, the discrepancy between our model and the experimental data is big for ^{3}He, which hints that the $d(x)/u(x)$ ratio may not be consistent with the real $F_2^{\rm n}/F_2^{\rm p}$ measurements. To minimize the influence of the untuned $d(x)/u(x)$ ratio in our model, we also made the comparisons for the isoscalar corrected EMC effect, which is shown in Fig. 4. The experimental data of the EMC effect with isoscalar corrections are taken from Ref. [74]. The proton number and the neutron number are required to be the same in the theoretical calculations accordingly. One finds that the big disagreement between our model and the data is reduced for ^{3}He. And the conclusion does not change for the isoscalar corrected EMC effect. For light nuclei, the EMC effect merely from

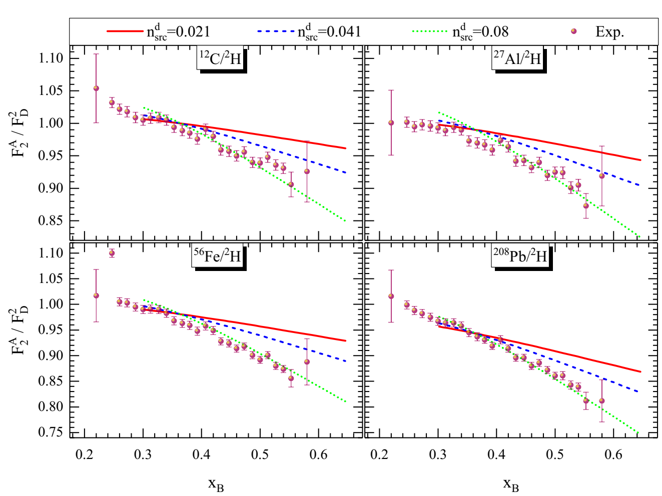

FIG. 5. Comparisons between our SRC-driven model calculations for the EMC effect and the experimental measurements of heavy nuclei [25]. The swelling effect of the SRC nucleon is assumed to be the origin of the EMC effect in our calculations. The curves of different styles show the results with different input values for the parameter $n^{\rm d}_{\rm SRC}$. See the main text for more explanations.

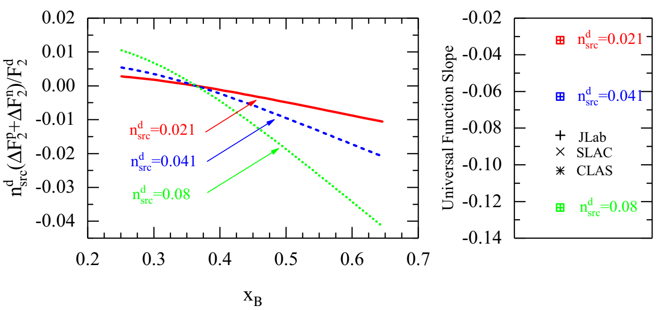

FIG. 6. The universal modification function for the structure function of the SRC nucleon inside the deuteron calculated in the nucleon swelling model. The curves of different styles show the results with different input values for the parameter $n^{\rm d}_{\rm SRC}$. In the right panel, the slopes of modification functions are shown. The extracted slopes of the universal function are taken from Ref. [25], and the original experimental data are from SLAC [76], JLab Hall C [73,74], and CLAS [25]. See the main text for more explanations.

SRC nucleons can reproduce the experimental data within our nucleon swelling model with $n^{\rm d}_{\rm SRC} = 0.041$.

In order to explain the EMC effect of heavy nuclei, the parameter $n^{\rm d}_{\rm SRC}$ in our model should be tuned up to 0.08. However, with $n^{\rm d}_{\rm SRC} = 0.08$ our model cannot reproduce the EMC effect of light nuclei. More importantly, $n^{\rm d}_{\rm SRC} = 0.08$ is not consistent with the previous estimations by counting the high-momentum nucleons above the Fermi motion region [17,20]. In order to explain the contradiction, we speculate that the universality of the SRC nucleon structure is violated, or there are more origins of the EMC effect for the heavy nuclei in order to agree with the experimental observations. And other origins for the EMC effect have nuclear dependence from light nuclei to heavy nuclei. A previous analysis also suggested that the underlying physics of the EMC effect for the heavy nuclei is different from that for the light nuclei [75].

The universal modification function of the SRC nucleon in the deuteron is calculated and shown in Fig. 6, based on the nucleon swelling model discussed in the previous section. The slope of the universal modification function is also evaluated by the CLAS collaboration from the experimental data at SLAC [76], JLab [73,74], and CLAS [25], which are shown in Fig. 6. The experimental extractions give the slope in a range from about 0.08 to 0.11, consistently. Our model predictions are weaker than the result from the experimental analysis in terms of the slope of the universal modification function with $n^{\rm d}_{\rm SRC} = 0.021$ and $n^{\rm d}_{\rm SRC} = 0.041$. Therefore, one may conclude that either the assumption that the EMC effect only comes SRC nucleons is wrong, or the universality of the SRC nucleon structure is violated, or the nucleon swelling model for the SRC nucleon needs improvement.

With the recent analysis of the experimental data from JLab Hall C [74], the EMC effects for the heavy nuclei are found to be weaker than those measured by the CLAS collaboration [25]. Therefore there are also small inconsistences among the experiments. This kind of small inconsistence is also shown in the slopes of the universal modification function in Fig. 6. Furthermore, these differences among different experiments can be evaluated and removed with more experiments, improved apparatuses, and analysis methods.

In our model calculations for the SRC-induced EMC effect, the pair c.m. motion effect is not considered. In a heavy nucleus, this effect reduces about 20% of the probability of a nucleon being in the SRC correlation [17,18]. Thus, considering the pair c.m. motion effect, the predicted EMC effect in our model also decreases about 20% for the heavy nucleus. The discrepancy between the model prediction and the experimental data however increases slightly for the heavy nuclei. Therefore the conclusions given in this work do not change with the consideration of the pair c.m. motion effect. In our model, the 20% reduction in the SRC scaling factor of the heavy nucleus corresponds to a 20% increase in the parameter $n^{\rm d}_{\rm SRC}$, to reproduce the same magnitude of the EMC effect.

V. SUMMARY

We have tested the hypothesis that the *NN* SRC is the dominant source for the nuclear EMC effect. Based on the nucleon swelling model for the SRC nucleon and that the number of SRC pairs in the deuteron is about 0.041, we find that the nuclear corrections on the SRC nucleons more or less explain the nuclear EMC effect of the light nuclei. However, with the same model and inputs, only the nuclear modifications on the SRC nucleons cannot reproduce the nuclear EMC effect of the heavy nuclei. We guess that the inner structure of the mean-field nucleon is also modified, or the SRC universality is violated, or there are more origins for the EMC effect beyond the *NN* SRC. Although the SRC universality is favored in experiments, our analysis hints that the modification on the structure function of the SRC nucleon may be stronger in the heavy nuclei compared to that of the light nuclei. Another explanation is that there are more origins for the EMC effect (such as 3*N* and 4*N* SRCs) and the number of these multinucleon SRC pairs does not linearly scale with the number of *NN* SRC pairs.

Based on the current knowledge of the number of $p-n$ SRC pairs in the deuteron and the nucleon swelling model for the modification of valence quark distributions, our obtained universal modification function of the SRC nucleon $n^{\rm d}_{\rm SRC}(\Delta F^{\rm p}_2 + \Delta F^{\rm n}_2)/F^{\rm d}_2$ is not consistent with the analysis of the experimental data. The experimental extraction of the universal modification function of the SRC nucleon is performed with the assumption that the EMC effect is completely driven by *NN* SRC. Based on the analysis in this work, we conclude that there is the correlation between the *NN* SRC strength and the EMC effect, but there is not a causal relation between these two phenomena. This conclusion is consistent with the recent results from the calculations of the off-shell-ness correction [30] and the *x*-rescaling model [31] for the SRC nucleon.

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[1] J. J. Aubert (European Muon Collaboration) *et al.*, Phys. Lett. B **123**, 275 (1983).
[2] J. Ashman (European Muon Collaboration) *et al.*, Phys. Lett. B **202**, 603 (1988).
[3] A. Bodek *et al.*, Phys. Rev. Lett. **50**, 1431 (1983).
[4] M. Arneodo, Phys. Rep. **240**, 301 (1994).
[5] D. F. Geesaman, K. Saito, and A. W. Thomas, Annu. Rev. Nucl. Part. Sci. **45**, 337 (1995).
[6] P. R. Norton, Rep. Prog. Phys. **66**, 1253 (2003).
[7] O. Hen, D. W. Higinbotham, G. A. Miller, E. Piasetzky, and L. B. Weinstein, Int. J. Mod. Phys. E **22**, 1330017 (2013).
[8] S. Malace, D. Gaskell, D. W. Higinbotham, and I. Cloet, Int. J. Mod. Phys. E **23**, 1430013 (2014).
[9] W. Detmold, M. Illa, D. J. Murphy, P. Oare, K. Orginos, P. E. Shanahan, M. L. Wagman, and F. Winter (NPLQCD Collaboration), Phys. Rev. Lett. **126**, 202001 (2021).
[10] F. Winter, W. Detmold, A. S. Gambhir, K. Orginos, M. J. Savage, P. E. Shanahan, and M. L. Wagman, Phys. Rev. D **96**, 094512 (2017).
[11] O. Hen, G. A. Miller, E. Piasetzky, and L. B. Weinstein, Rev. Mod. Phys. **89**, 045002 (2017).
[12] J. Arrington, D. W. Higinbotham, G. Rosner, and M. Sargsian, Prog. Part. Nucl. Phys. **67**, 898 (2012).
[13] L. L. Frankfurt and M. I. Strikman, Phys. Rep. **160**, 235 (1988).
[14] N. Fomin, D. Higinbotham, M. Sargsian, and P. Solvignon, Annu. Rev. Nucl. Part. Sci. **67**, 129 (2017).
[15] J. Arrington, N. Fomin, and A. Schmidt, Annu. Rev. Nucl. Part. Sci. **72**, 307 (2022).
[16] L. L. Frankfurt, M. I. Strikman, D. B. Day, and M. Sargsyan, Phys. Rev. C **48**, 2451 (1993).
[17] K. S. Egiyan (CLAS Collaboration) *et al.*, Phys. Rev. Lett. **96**, 082501 (2006).
[18] N. Fomin *et al.*, Phys. Rev. Lett. **108**, 092502 (2012).
[19] R. Subedi *et al.*, Science **320**, 1476 (2008).
[20] M. Duer (CLAS Collaboration) *et al.*, Nature (London) **560**, 617 (2018).
[21] O. Hen *et al.*, Science **346**, 614 (2014).
[22] M. Duer (CLAS Collaboration) *et al.*, Phys. Rev. Lett. **122**, 172502 (2019).
[23] E. O. Cohen (CLAS Collaboration) *et al.*, Phys. Rev. Lett. **121**, 092501 (2018).
[24] A. Schmidt (CLAS Collaboration) *et al.*, Nature (London) **578**, 540 (2020).
[25] B. Schmookler (CLAS Collaboration) *et al.*, Nature (London) **566**, 354 (2019).
[26] L. B. Weinstein, E. Piasetzky, D. W. Higinbotham, J. Gomez, O. Hen, and R. Shneor, Phys. Rev. Lett. **106**, 052301 (2011).
[27] O. Hen, E. Piasetzky, and L. B. Weinstein, Phys. Rev. C **85**, 047301 (2012).
[28] J.-W. Chen, W. Detmold, J. E. Lynn, and A. Schwenk, Phys. Rev. Lett. **119**, 262502 (2017).
[29] J. Arrington and N. Fomin, Phys. Rev. Lett. **123**, 042501 (2019).
[30] X. G. Wang, A. W. Thomas, and W. Melnitchouk, Phys. Rev. Lett. **125**, 262002 (2020).
[31] R. Wang, N.-N. Ma, and T.-F. Wang, Chin. Phys. C **47**, 044103 (2023).
[32] R. Wang, X.-R. Chen, and T.-F. Wang, Chin. Phys. C **45**, 021001 (2021).
[33] C. A. Garcia Canal, E. M. Santangelo, and H. Vucetich, Phys. Rev. Lett. **53**, 1430 (1984).
[34] M. Staszel, J. Roznynek, and G. Wilk, Phys. Rev. D **29**, 2638 (1984).
[35] S. V. Akulinichev, S. Shlomo, S. A. Kulagin, and G. M. Vagradov, Phys. Rev. Lett. **55**, 2239 (1985).
[36] L. L. Frankfurt and M. I. Strikman, Phys. Lett. B **183**, 254 (1987).
[37] H. Jung and G. A. Miller, Phys. Lett. B **200**, 351 (1988).
[38] C. Ciofi degli Atti, L. P. Kaptari, and S. Scopetta, Eur. Phys. J. A **5**, 191 (1999).
[39] G. V. Dunne and A. W. Thomas, Phys. Rev. D **33**, 2061 (1986).
[40] F. Gross and S. Liuti, Phys. Rev. C **45**, 1374 (1992).
[41] S. A. Kulagin, G. Piller, and W. Weise, Phys. Rev. C **50**, 1154 (1994).
[42] S. A. Kulagin and R. Petti, Nucl. Phys. A **765**, 126 (2006).
[43] S. A. Kulagin and R. Petti, Phys. Rev. C **90**, 045204 (2014).
[44] R. Wang, R. Dupre, Y. Huang, B. Zhang, and S. Niccolai, Phys. Rev. C **99**, 035205 (2019).
[45] R. Wang, X. Chen, and Q. Fu, Nucl. Phys. B **920**, 1 (2017).
[46] R. Schiavilla, R. B. Wiringa, S. C. Pieper, and J. Carlson, Phys. Rev. Lett. **98**, 132501 (2007).
[47] M. Alvioli, C. Ciofi degli Atti, and H. Morita, Phys. Rev. Lett. **100**, 162503 (2008).
[48] T. Neff, H. Feldmeier, and W. Horiuchi, Phys. Rev. C **92**, 024003 (2015).
[49] Y. L. Dokshitzer, Sov. Phys. JETP **46**, 641 (1977).
[50] V. N. Gribov and L. N. Lipatov, Sov. J. Nucl. Phys. **15**, 438 (1972).
[51] G. Altarelli and G. Parisi, Nucl. Phys. B **126**, 298 (1977).
[52] R. Wang and X. Chen, Phys. Rev. D **91**, 054026 (2015).
[53] R. L. Jaffe, Phys. Rev. Lett. **50**, 228 (1983).
[54] C. E. Carlson and T. J. Havens, Phys. Rev. Lett. **51**, 261 (1983).
[55] M. Chemtob and R. B. Peschanski, J. Phys. G **10**, 599 (1984).
[56] G. A. Miller, Phys. Rev. Lett. **53**, 2008 (1984).
[57] B. C. Clark, S. Hama, B. Mulligan, and K. Tanaka, Phys. Rev. D **31**, 617 (1985).
[58] P. A. M. Guichon, Phys. Lett. B **200**, 235 (1988).
[59] P. A. M. Guichon, K. Saito, E. N. Rodionov, and A. W. Thomas, Nucl. Phys. A **601**, 349 (1996).
[60] K. Saito, K. Tsushima, and A. W. Thomas, Prog. Part. Nucl. Phys. **58**, 1 (2007).
[61] M. Oka and R. D. Amado, Phys. Rev. C **35**, 1586 (1987).
[62] G. Kaelbermann, L. L. Frankfurt, and J. M. Eisenberg, Phys. Lett. B **329**, 164 (1994).

[63] J. Dukelsky, F. Fernandez, and E. Moya de Guerra, J. Phys. G **21**, 317 (1995).
[64] G. A. Miller, Phys. Rev. Lett. **123**, 232003 (2019).
[65] F. E. Close, R. G. Roberts, and G. G. Ross, Phys. Lett. B **129**, 346 (1983).
[66] R. L. Jaffe, F. E. Close, R. G. Roberts, and G. G. Ross, Phys. Lett. B **134**, 449 (1984).
[67] O. Nachtmann and H. J. Pirner, Z. Phys. C **21**, 277 (1984).
[68] F. E. Close, R. L. Jaffe, R. G. Roberts, and G. G. Ross, Phys. Rev. D **31**, 1004 (1985).
[69] F. E. Close, R. G. Roberts, and G. G. Ross, Nucl. Phys. B **296**, 582 (1988).
[70] R. Wang and X. Chen, Chin. Phys. C **41**, 053103 (2017).
[71] A. H. Mueller and J.-w. Qiu, Nucl. Phys. B **268**, 427 (1986).
[72] W. Zhu, Nucl. Phys. B **551**, 245 (1999).
[73] J. Seely *et al.*, Phys. Rev. Lett. **103**, 202301 (2009).
[74] J. Arrington *et al.*, Phys. Rev. C **104**, 065203 (2021).
[75] C. A. García Canal, T. Tarutina, V. Vento, and V. Vento, Eur. Phys. J. A **49**, 105 (2013).
[76] J. Gomez *et al.*, Phys. Rev. D **49**, 4348 (1994).