Short-Range Correlations and the Nuclear EMC Effect in Deuterium and Helium-3

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The EMC effect in deuterium and helium-3 is studied using a convolution formalism that allows isolating the impact of high-momentum nucleons in short-ranged correlated (SRC) pairs. We assume that the modification of the structure function of bound nucleons is given by a universal (i.e. nucleus independent) function of their virtuality, and find that the effect of such modifications is dominated by nucleons in SRC pairs. This SRC-dominance of nucleon modifications is observed despite the fact that the bulk of the nuclear inelastic scattering cross-section comes from interacting with low-momentum nucleons. These findings are found to be robust to model details including nucleon modification function parametrization, free nucleon structure function and treatment of nucleon motion effects. While existing data cannot discriminate between such model details, we present predictions for measured, but not yet published, tritium EMC effect and tagged nucleon structure functions in deuterium that are sensitive to the neutron structure functions and bound nucleon modification functions.

INTRODUCTION

Determining the underlying cause of the modification of the partonic structure of nucleons bound in atomic nuclei, known as the EMC effect [1–7], is an outstanding question in nuclear physics. Decades after its discovery, there is still no universally accepted explanation for the origin of the EMC effect [8–10], despite a large number of high-precision measurements in a wide variety of atomic nuclei.

Modern models of the EMC effect account for both ‘conventional’ nuclear physics effects such as Fermi-motion and binding, as well as for the more ‘exotic’ effects of nucleon modification [9, 10]. The conventional nuclear physics effects are well understood and cannot reproduce experimental data alone, especially when including Drell-Yan data [10, 11]. While required to reproduce experimental data, nucleon modification models are far less constrained and their microscopic origin is debated [10].

An observed correlation between the magnitude of the EMC effect and the relative amount of short-range correlated (SRC) nucleon pairs in different nuclei [7, 12–14] suggests that the EMC effect is driven by the modification of nucleons in SRC pairs. SRCs are pairs of strongly interacting nucleons at short distances. Nucleons in SRC pairs have large spatial overlap between their quark distributions and are highly offshell ($E^2 \neq |p|^2 + m^2$), which makes them prime candidates for structure modification.

Most recently, it has been demonstrated [7, 15] that the EMC effect in nuclei from helium-3 ($^3$He) to lead can be explained by a single effective universal modification function (UMF) of nucleons in SRC pairs. The UMF was constructed to be as model-independent as possible. It is insensitive to the largely-unknown free-neutron structure function, $F_2^n$, and accounts for both conventional nuclear effects, such as the scheme dependence of the deuteron wave-function, and nucleon motion effects, as well as more exotic nucleon modification effects.

Here we study the EMC effect using a convolution formalism that allows us to separate the mean field and short range correlation contributions of nucleon modification effects to the total UMF. We consider only light nuclei (the deuteron and $^3$He), for which exact nuclear wave functions are available, and nucleon modification effects can be isolated. The sensitivity of the convolution formalism to parametrization of the nucleon modification function, $F_2^n$, and the treatment of nucleon motion effects are studied.

We find that, as expected, the bulk of the structure-function comes from interactions with low-momentum nucleons. However, nucleon modification effects, which are required for a complete reproduction of the measured data, are dominated by nucleons in SRC pairs. We also find that existing data cannot discriminate between different $F_2^n$ models or different parameterizations of bound nucleon modification functions. We predict new observables that can constrain these model inputs, including the tritium EMC effect, sensitive to $F_2^n$, and deuterium tagged nucleon structure functions, sensitive to bound nucleon modification functions. These predictions will soon be tested by data from the MARATHON [16], BAND [17], and LAD [18] Collaborations.
FORMALISM

\( F_2^A(x_B) \)

Convolution Approximation

In order to study the EMC effect in a framework that allows us to understand its dependence on nucleon momentum and offshellness, we calculate the nuclear structure function, \( F_2^A(x_B) \), using the nuclear convolution model for lepton-nucleus DIS \([8, 19-22]\):

\[
F_2^A(x_B) = \frac{1}{A} \int_{x_B}^{1} \frac{d\alpha}{\alpha} \int_{-\infty}^{0} d\tilde{x} \left[ Z\tilde{\rho}_p^A(\alpha, v) F_2^p(\tilde{x}) + N\tilde{\rho}_n^A(\alpha, v) F_2^n(\tilde{x}) \right] \times \left( 1 + v f_{\text{off}}(\tilde{x}) \right)
\]

where \( x_B = Q^2/(2m_N\nu) \), \( Q^2 \) is the four momentum transfer squared, \( m_N \) is the nucleon mass and \( \nu \) is the energy transfer (Fig. 1). \( \tilde{x} = \frac{Q^2}{2\nu} \), where \( q \) is the four-momentum of the virtual photon and \( p \) is the initial four-momentum of the struck off-shell nucleon. \( \tilde{x} \) reduces to \( x_B m_A/m_A \) in the Bjorken limit with lightcone momentum fraction \( \alpha = A(E + p_z)/m_A \) (see online supplementary materials for finite energy corrections to Eq. 1 at low \( Q^2 \)). Here \( z \) is opposite to the direction of the virtual photon, and \( v = (E^2 - |p|^2 - m_N^2)/m_N^2 \) is the bound nucleon fractional virtuality. \( \tilde{\rho}_N^A(\alpha, v) \) are the nucleon \((N = p \text{ or } n)\) lightcone momentum and virtuality distributions in nucleus \( A \), defined below. \( F_2^p(\tilde{x}) \) and \( F_2^n(\tilde{x}) \) are the free proton and neutron structure functions. For brevity we omit their explicit \( Q^2 \) dependences but note that \( F_2^p, F_2^n \), and \( F_2^A \) are always evaluated at the same \( Q^2 \) value. \( f_{\text{off}}(\tilde{x}) \) is a universal offshell nucleon modification function, assumed here to be the same for neutrons and protons and for all nuclei. In Eq. 1, we take the offshell effect to be linear in \( v \) (i.e., \( 1 + v f_{\text{off}}(\tilde{x}) \)) as a first-order Taylor expansion in virtuality; see Ref. [23] for additional discussion.

Lightcone densities

In our convolution, traditional nuclear contributions to the EMC effect such as nucleon motion and binding are treated within the one-body lightcone momentum and virtuality distribution, \( \tilde{\rho}_N^A(\alpha, v) \). It describes the joint probability to find a nucleon \((n \text{ or } p)\) in a nucleus \( A \) with lightcone momentum fraction \( \alpha \) and fractional virtuality \( v \). Integrating over fractional virtuality defines the lightcone momentum distribution of a nucleon

\[
\rho_N^A(\alpha) = \int_{-\infty}^{0} dv \tilde{\rho}_N^A(\alpha, v),
\]

that is normalized herein according to the baryon sum rule:

\[
\int_{0}^{1} \frac{d\alpha}{\alpha} \rho_N^A(\alpha) \equiv 1.
\]

To avoid producing an artificial EMC like effect in nucleon-only models when used in Eq. 1 [20], \( \rho_N^A(\alpha) \) must also satisfy the momentum sum rule:

\[
\frac{1}{A} \int_{0}^{1} \frac{d\alpha}{\alpha} \left( Z\rho_p^A(\alpha) + N\rho_n^A(\alpha) \right) = 1.
\]

It is necessary to know the functional form of \( \tilde{\rho}_N^A(\alpha, v) \) to proceed further. Although the nuclear wave functions for nuclei with \( A = 2 \) and \( A = 3 \) have been well-computed, they do not suffice to unambiguously yield the light-cone momentum distributions and their dependence on virtuality. This is because current calculations are non-relativistic and made with an underlying assumption that the nucleons are on their mass shell. Handling this issue on a fundamental level would require a first-principles light-front calculation including the effects of off-mass-shell dependence. Such a calculation could be done by solving the relevant Bethe-Salpeter equation, but does not yet exist.

Therefore, we consider here two approximations to estimate \( \tilde{\rho}(\alpha, v) \): a spectral-function (SF) approximation, where the momentum sum rule is violated if only nucleonic degrees of freedom are taken into account, and a generalized-contact formalism lightcone (GCF-LC) approximation.

Spectral function approximation

The nuclear spectral function \( S(E, p) \) defines the probability for finding a nucleon in the nucleus with momentum \( p \) and nucleon energy \( E \). Exactly calculable spectral
functions are available for light nuclei and allow calculating the nuclear lightcone distributions as [24, 25]

\[ \tilde{\rho}_{N,SF}^A(\alpha,v) = \int dE d^3p \ \rho_{N,SF}^A(E,p) \cdot \frac{E + p_s}{E} \delta \left( \alpha - \frac{Ap^\perp}{P^+} \right) \delta \left( v - \frac{E^2 - |p|^2 - m_N^2}{m_N^2} \right), \]  

(5)

where \( p = |p| \), \( p^+ = E + p_z = m_A \alpha / A \) is the plus-component of the momentum of the struck nucleon, \( P^+ = m_A \) is the plus-component of the momentum of the nucleus \( A \), and \( m_A \) is the nucleus mass.

The flux factor \((E + p_z)\) is introduced to help satisfy the momentum sum rule [20]. The \( \frac{1}{E} \) factor ensures SF-based lightcone distribution functions are appropriately normalized according to the Baryon sum-rule (Eq. 3). However, this also changes the interpretation of \( \rho(\alpha) \) from a simple probability density for finding a nucleon in a nucleus with lightcone momentum fraction \( \alpha \) (see discussion in refs. [20, 24, 25]).

For deuterium, considering a wave function calculated using the AV18 interaction, the momentum sum rule has a negligible violation \((< 0.1\%)\). For \(^3\text{He}\), using the AV18-based spectral function of Ref. [26], it is violated by \( \leq 1\% \). This small violation is expected to produce an artificial EMC effect [20] that should result in a smaller nucleon modification effect required to explain the experimental data.

Generalized-contact formalism lightcone approximation

To fully satisfy the \(^3\text{He}\) momentum sum rule, we examine an alternative approach for calculating \( \tilde{\rho}_{N,GCF}^A(\alpha,v) \) using a scale-separation approximation where the lightcone density function is separated into a mean-field (single-nucleon) part and an SRC part [14, 27–30]:

\[ \tilde{\rho}_{N,GCF-LC}^A(\alpha,v) = \tilde{\rho}_{N,GCF,SR}^A(\alpha,v) + \tilde{\rho}_{N,MF}^A(\alpha,v). \]  

(6)

The SRC part of the lightcone density can be formulated by integrating over the lightcone SRC decay function [30, 31], which describes the distribution of the momentum of the struck nucleon as well as its partner, here denoted the ‘spectator’ nucleon:

\[ \tilde{\rho}_{N,GCF,SR}^A(\alpha,v) = \int d^2p_\perp \frac{d\alpha_s}{\alpha_s} d^2p_\perp^N \rho_{SR}^N(\alpha, p_\perp^N, \alpha_s, p_\perp^s) \times \delta \left( v - \frac{p^- (m_A/A) \alpha - p_\perp^2 - m_N^2}{m_N^2} \right), \]  

(7)

where

\[ p^- = P^- - p_s^- - p_{A-2}^- = m_A - \frac{m_N^2 + (p_\perp^N)^2}{(m_A/A)\alpha_s} - \frac{m_{A-2}^2 + (p_{CM}^N)^2}{(m_A/A)(A - \alpha - \alpha_s)} \]  

(8)

is the off-mass shell minus-component of the struck nucleon’s momentum, \( \alpha_s \) is the spectator nucleon lightcone fraction, \( p_\perp \) and \( p_\perp^N \) are the transverse momentum of the struck nucleon and the spectator, respectively, and \( P_{CM}^N = p_\perp + p_{s,\perp} \). \( \rho_{SR}^N \) is a two-body (i.e. pair) lightcone density given by a convolution of the pair center-of-mass and relative momentum densities, see Ref. [30] and online supplementary materials for details.

Fig. 2. Lightcone momentum distributions \( \rho(\alpha) \) for deuteron (left) and protons (center) and neutrons (right) in \(^3\text{He}\) calculated using the spectral function (SF) and generalized contact formalism lightcone (GCF-LC) approximations. The discretization visible in the SF distributions (blue lines) is due to the discretization of the spectral function \( S(E,p) \) and integration of Eq. 5.

Fig. 3. \( F_2^p / F_2^p \) parametrizations used in this work that span the current range of models [15]. See text for details.
The mean-field part of the lightcone density is taken from the spectral functions using a linearized approximation, similar to Eq. 5, but which manifestly preserves the baryon number and momentum sum rules:

\[
\tilde{\rho}^A_{N,MF}(\alpha,v) = \alpha \int_0^{\infty} dE \int_0^{p_{cutoff}} d^3p S^A_N(E,p) \times \delta \left( \alpha - 1 - \frac{\rho_0}{\rho_{\pi}} \right) \delta \left( v - \frac{E^2 - |p|^2 - m_N^2}{m_N^2} \right). \tag{9}
\]

The cutoff momentum \(p_{cutoff} = 240 \text{ MeV}/c\) for \(^3\text{He}\) and was chosen such that the fraction of SRC pairs was equal to that extracted from ab-initio many-body calculations (10.1\% for neutrons and 5.9\% for protons) [32, 33].

We emphasize that the momentum sum rule for \(\tilde{\rho}^A_{N,GCF-LC}(\alpha,v)\) is manifestly satisfied in this approximation and that the resulting GCF-LC density is symmetric around unity, in contrast to that obtained in the SF approximation (Fig. 2).

**STRUCTURE FUNCTION AND MODIFICATION MODELS**

We compute Eq. 1 using parameterizations of \(f^{off}(\tilde{x})\), \(F^p_2(\tilde{x})\), and \(F^{off}_2(\tilde{x})\), and both \(\tilde{\rho}^A_{N,SF}\) and \(\tilde{\rho}^A_{N,GCF-LC}\). For the modification function \(f^{off}(\tilde{x})\) we consider three models:

\[
f^{off}_{const}(\tilde{x}) = C, \tag{10}
\]

\[
f^{off}_{lin}(\tilde{x}) = a + b \cdot \tilde{x}, \tag{11}
\]

\[
f^{off}_{KP,CJ}(\tilde{x}) = C(x_0 - \tilde{x})(x_1 - \tilde{x})(1 + x_0 - \tilde{x}), \tag{12}
\]

where \(f^{off}_{const}\) assumes a virtuality-dependent modification model that is independent of \(\tilde{x}\), and \(f^{off}_{lin,}\) is also linearly dependent on \(\tilde{x}\). The free parameters of these parameterizations \((C,a,\) and \(b)\) are determined by fitting Eq. 1 to experimental data as detailed below.

We also use modification functions determined by KP \(f^{off}_{KP}\) [34] and CJ \(f^{off}_{CJ}\) [35], who both chose to use a 3rd order polynomial in \(\tilde{x}\), albeit with different parameterizations. These are used here with their original parameters, extracted in Refs. [34, 35].

\[
\frac{F^p_2(\tilde{x})}{F^{off}_2(\tilde{x})} \equiv R_{np}(\tilde{x}) = a_{np}(1 - \tilde{x}) + c_{np}, \tag{13}
\]

where \(R_{np}(\tilde{x} \to 1) = c_{np}\). We fit the \(a_{np},b_{np,}\) and \(c_{np}\) parameters by fitting Eq. 13 to one of two recent predictions by Segarra [15] and by Arrington [36], that represent two extreme models that capture the spread of current models [15] (see Fig. 3). We further assume that \(R_{np}(\tilde{x})\) has negligible \(Q^2\) dependence. We note that the original \(f^{off}_{KP}\) and \(f^{off}_{CJ}\) extractions were done using \(F^p_2/F^p_2\) that are respectively similar to the Segarra and Arrington models used herein.

\[
F^p_2(x_B,Q^2) \text{ was taken from GD11-P [37]. As DIS data are typically given in the form of } F^A_2/F^p_2 \text{ ratios to minimize higher twist effects, the only explicit } Q^2 \text{ dependence we assume is that of } F^p_2(x_B,Q^2), \text{ that is assumed to be negligible in the ratio } F^p_2/F^p_2.
\]

We estimated the parameters of \(f^{off}_{const}\) and \(f^{off}_{lin,}\) using a \(\chi^2\)-minimization inference from a simultaneous fit to both \(F^2_{He}/F^2_p\) [6] and \(F^2_{He}/(F^2_p + F^2_n)\) [38] data for \(0.17 \leq x_B \leq 0.825\). While data for \(F^2_{He}/F^2_p\) of [6] extends up to \(x_B \sim 0.9\), these high-\(x_B\) data are at low invariant mass, \(W\). Requiring \(W > 1.4 \text{ GeV} (W^2 > 2 \text{ GeV}^2)\) in the fitting procedure limited the data to \(x_B \leq 0.825\). However, we extrapolate our predictions up to \(x_B \sim 0.95\) for use by future measurements, such as MARATHON [16]. Isoscalar corrections previously applied to \(F^2_{He}/F^2_p\) data were removed and the quoted experimental normalization uncertainties of each data set were accounted for in the fit. In the calculation of each data point, \(F^p_2\) is evaluated at the \(Q^2\) value of the data. We performed 16 inference trials for different model assumptions for \(\tilde{\rho}(\alpha,v), F^p_2/F^p_2\) and \(f^{off}\) (see Tab. 1).
RESULTS

Inclusive data description

Figure 4 shows the resulting fit compared to the experimental data. We performed eight individual fits, switching between the two $F_2^P/F_2^P$ models, constant-in-$\bar{x}$ or linear-in-$\bar{x}$ off-shell parameterizations, and using either SF or GCF-LC lightcone densities. We also show calculations using $f_{KPCJ}^\text{off}$ and both $F_2^\alpha/F_2^\alpha$ and lightcone densities. For completeness, Fig. 5 shows the inferred off-shell functions for $f_\text{const}$ and $f_\text{lin}$ for the different convolution frameworks, along with $f_{KPCJ}^\text{off}$ [34, 35].

As can be seen from the strong overlap of many curves, these existing $^3\text{He}$ and $^2\text{H}$ data cannot definitely discriminate between the different off-shell function or nucleon motion effect models. The data can be adequately reproduced even with very different off-shell models.

Tab. I and Fig. 4 do show a systematic improvement when using the Segarra et al. $F_2^P/F_2^P$ parametrization (blue curves). Using $f_{KPCJ}^\text{off}$, the calculation does not describe the high-$x_B$ $^2\text{H}$ data. This is not unexpected as their off-shell function was not fit to BONUS data nor to high-$x_B$ deuterium data ($\geq 0.8$) [34]. $f_{KPCJ}^\text{off}$ does describe the $^3\text{He}$ EMC data markedly well due to the global nature of their analysis which captures the general EMC trend in a wide range of nuclei. Similarly, when using $f_{KPCJ}^\text{off}$, the calculation struggles as much as other models to accurately predict the $^3\text{He}$ EMC ratio. However, we note that their global fit does not consider $A > 2$ nuclear DIS data. Again, the agreement improves with the use of the Segarra et al. $F_2^P/F_2^P$.

The best fits with the Segarra et al. $F_2^P/F_2^P$ (blue curves) and Arrington (red curves) find a comparable off-shell function $f_{\text{off}}^\alpha$ with the LC approximation as compared to the SF approximation, see Fig. 5.

The GCF-LC framework does just as well at describing the $^3\text{He}$ data and deuterium data, again, with improve-

![Fig. 5. Offshell functions $f_{\text{off}}(\bar{x})$ resulting from $\chi^2$-minimization procedure with SF (left) and LC (right) approximations. The blue and red curves were minimization trials using a $F_2^P/F_2^P$ fit to two recent predictions by Segarra [15] (Seg.) and Arrington [36] (Arr.), respectively. The two black lines are the offshell functions as described in [34, 35] and were taken as fixed for the minimization procedure which is why they are identical for both convolution frameworks.](image1)

![Fig. 6. Ratio of SRC contribution to MF contribution of the structure function. See text for details. (Top-left) SF ratio on $F_2^P$. (Top-right) LC ratio on $F_2^P$. (Bottom-left) SF ratio on $F_2^{^3\text{He}}$. (Bottom-right) LC ratio on $F_2^{^3\text{He}}$. Curves are shown with $Q^2 = 5$ GeV$^2$](image2)

| $\tilde{\rho}(\alpha,\nu)$ | $F_2^\alpha/F_2^\alpha$ | $f_{\text{off}}(\bar{x})$ | $\chi^2_2$ | $\chi^2_2/\text{d.o.f.}$ |
|--------------------------|-----------------------|--------------------------|------------|--------------------------|
| SF                       |                       |                          |            |                          |
| Const.-x                 | 1.4                   | 12.4                     | 19.8 / 31  | 0.63                     |
| Lin.-x                   | 7.7                   | 15.4                     | 30 / 51    |                          |
| KP                       | 12.9                  | 25 / 32                  | 0.78       |
| CJ                       | 6.0                   | 34 / 32                  | 0.94       |
| Arr.                     |                       |                          |            |                          |
| Const.-x                 | 17.4                  | 69 / 31                  | 86.5 / 31  | 2.79                     |
| Lin.-x                   | 25.9                  | 41.9 / 30                | 140        |
| KP                       | 12.1                  | 33 / 32                  | 1.05       |
| CJ                       | 6.7                   | 119.8 / 32               | 3.71       |
| GCF-LC                   |                       |                          |            |                          |
| Const.-x                 | 8.4                   | 19.2                     | 27.6 / 31  | 0.89                     |
| Lin.-x                   | 7.2                   | 23.6 / 30                | 0.79       |
| KP                       | 9.8                   | 20.3 / 32               | 0.65       |
| CJ                       | 11.8                  | 26.8                     | 38 / 32    | 1.02                     |
| Arr.                     |                       |                          |            |                          |
| Const.-x                 | 22.9                  | 69.3                     | 92.2 / 31  | 2.97                     |
| Lin.-x                   | 25.4                  | 78.5 / 30                | 2.02       |
| KP                       | 8.7                   | 73.2 / 32                | 2.29       |
| CJ                       | 12.9                  | 110.8 / 32               | 3.87       |
Fig. 7. Decomposition of $F_A^4$ (offshell) for various model assumptions within the SF approximation. Top: offshell effect in $^2\text{H}$ for model assumptions of (from left-to right) 1) constant-in-x with Seg. $F_2^H/F_2^H$, 2) constant-in-x with Arr. $F_2^H/F_2^H$, 3) linear-in-x with Arr. $F_2^H/F_2^H$, 4) KP-offshell function with Seg. $F_2^H/F_2^H$, and 5) CJ-offshell function with Seg. $F_2^H/F_2^H$. Bottom: offshell effect in $^3\text{He}$ for the same models. Solid black lines represent the full offshell contribution. Dashed blue lines are the contribution due to SRC nucleons ($> 240$ MeV/c in the SF assumption). Similarly, dotted red lines are the contribution due to MF nucleons ($< 240$ MeV/c). Curves not shown for other model assumptions considered can be viewed in the online supplementary materials. Curves are shown at $Q^2 = 5$ GeV$^2$.

ment with the use of the Segarra et al. $F_2^H/F_2^H$. In the GCF-LC framework, the high-$x_B$ $^3\text{He}$ data not used in the fitting procedure (due to having low-$W$) is not as well described as in the SF framework. We also note that the $f_{CJ}^{off}$ did not use $^3\text{He}$ data as a constraint, and, therefore, struggles at describing the data, especially at high-$x_B$.

**SRC contribution to nucleon modification**

Using the inferred parameters from the global fit as described above, we can now separate the contributions of the mean-field and SRC nucleons to the EMC effect. To this end we constructed $F_2^A = F_2^A(MF) + F_2^A(SRC)$ by splitting the integral in Eq. 1 to contributions of Mean-Field and SRC nucleons. This separation is natural for the GCF-LC approach. For the SF based approach this is done by assigning all nucleons with moment above 240 MeV/c as members of SRC pairs. Our findings are largely insensitive to the exact momenta we choose.

Figure 6 shows the ratio of the structure functions: 

$$\frac{[F_2^{HE}(SRC)]}{[F_2^{HE}(MF)]} \text{ and } \frac{[F_2^A(MF)]}{[F_2^A(SRC)]}.$$ 

As expected, mean-field nucleons account for most of the structure function in Eq. 1, except at very high-$x_B$ where nucleon motion effects are important and therefore the contribution of SRCs becomes significant. This is to be expected as SRC nucleons account for a small fraction of the nuclear wave function, especially in deuterium.

Next we explicitly examine the contribution of mean-field and SRC nucleons to the offshell modification effect in the EMC. This is done by defining the offshell decomposition as $F_2^A(\text{off-shell}) = F_2^A(\text{full}) - F_2^A(\text{no off-shell})$, where $F_2^A(\text{full})$ is calculated using Eq. 1 and $F_2^A(\text{no off-shell})$ is calculated using the same equation but by setting $f_{CJ}^{off}(\vec{x}) = 0$.

Figure 7 shows the decomposition of $F_2^A$ (offshell) due to SRC and mean-field nucleons within the SF approach (LC calculations are qualitatively similar and can be found in the online supplementary materials). While high momentum nucleons did not significantly contribute to the full convolution ratio in Fig. 6, these nucleons dominate the offshell modification function (i.e., the dashed blue lines track the solid black lines closely, especially at high $x_B$) in all models even though the offshell behavior is different for each model.

This holds true even in deuterium at high $x_B$, although at $x_B \sim 0.6$, the mean-field and SRC contributions are closer to 1:1. This is still surprising given the high-momenta fraction of the nuclear momentum-distribution is only $O(\sim 4\%)$ [39]. Adding to this surprise is the feature that a significant contribution to the wave function comes from $np$ separations larger than the range of the nuclear forces [40].

Furthermore, in the results shown here using the SF approach, the momentum sum rule is violated by $\sim 1\%$. While small, this violation still induces an artificial EMC
effect, thereby reducing the strength of the actual offshell contribution to the structure function (i.e. the absolute y-scale of Fig. 7). Alternatively, in the LC approach, the sum rules are manifestly satisfied, and the extracted offshell contribution is much larger for the models of $F_{2}^{3H}/F_{2}^{p}$, by a factor of about $1.5-3$ (see online supplementary materials).

Our findings are robust to the exact underlying offshell function used in Eq. 1, even though $f_{off}^{sf}(x)$ (Fig. 5) varies dramatically among the models. Therefore, the results shown in Fig. 7 contradict the recent claims of Ref. [41], where the SRC UMF was analyzed without proper separating its contributions from nucleon motion and modification effects. For completeness we note that the UMF extracted by Ref. [7, 15] is reproduced with the convolution framework used here for $^{3}$He, see online supplementary materials.

**PREDICTING FORTHCOMING OBSERVABLES**

While existing data cannot constrain $F_{2}^{n}/F_{2}^{p}$, we predict $F_{2}^{3H}/F_{2}^{d}$, which was recently measured by the MARATHON collaboration [16], and should be sensitive to $F_{2}^{p}$. Fig. 8 shows the convolution prediction for $F_{2}^{3H}/F_{2}^{d}$ obtained using the constrained offshell modification function and assuming isospin symmetry in the lightcone distributions. The different $F_{2}^{n}/F_{2}^{p}$ parametrizations, which are both consistent with $F_{2}^{3He}/F_{2}^{d}$ data, predict very different $F_{2}^{3H}/F_{2}^{d}$ at high-$x_B$ that MARATHON can test. Still, as seen in Fig. 8, there are predictions of $F_{2}^{3H}/F_{2}^{d}$ which overlap for different $F_{2}^{n}/F_{2}^{p}$ and $f_{off}^{sf}$ behaviors. In particular, taking the $f_{KP}^{off}$ with $F_{2}^{n}/F_{2}^{p}$ is overlapping with the differences of the offshell modification function ($f_{off}^{sf}$). This indicates a combined analysis of nuclear DIS data with forthcoming data by MARATHON will be needed to disentangle $F_{2}^{n}/F_{2}^{p}$ and $f_{off}^{sf}$, similar to efforts Ref. [34] has performed in the past.

While the MARATHON results will be very sensitive to $F_{2}^{n}/F_{2}^{p}$, they will be less sensitive to the exact nature of the offshell modification function ($f_{off}^{sf}$). This can however be tested in a new set of tagged deep inelastic scattering measurements off deuterium which will study the dependence of the bound nucleon structure function on $\alpha$:

$$F_{2}^{p}(x, \alpha) = F_{2}^{p}(\tilde{x}) \left[ 1 + \langle v \rangle |_{\alpha} f_{off}^{sf}(\tilde{x}) \right],$$

(14)

where $\langle v \rangle |_{\alpha}$ is the average fractional virtuality for the given $\alpha$, see online supplementary materials Figs. 1 and 2.

By taking a ratio of the bound-to-free proton structure function, one can access the offshell modification function, and can examine the differences of the offshell contribution at high-$\tilde{x}$ and low-$\tilde{x}$, see Fig 9. The predictions here are similar to those made by Ref. [42] and will be directly tested by the LAD [18] and BAND [17] Collaborations. The latter already completed 50% data taking and results are anticipated soon. While predictions here are made for $p_T = 0$, experiments will have some finite acceptance in $p_T$. As seen in Fig 9, there are significant uncertainties due to uncertainties in $F_{2}^{p}/F_{2}^{n}$ and for $p_T = 0$. However, after precise measurements on $F_{2}^{n}/F_{2}^{p}$ by the MARATHON Collaboration [16], these uncertainties will be greatly reduced.
SUMMARY

We present an extensive study of nucleon modification effects in nuclei using a convolution formalism and measurements of the EMC effect in deuterium and $^3$He. We examine a range of off-shell modification functions, free-neutron structure function models and different treatments of nucleon motion effects. In all cases we find that nucleons in SRC pairs are the dominant contribution to nucleon modification effects in deuterium and $^3$He.

With upcoming precise measurements of $^3$H, our study can be extended to test the isospin dependence of the universal offshell modification function and the ability to use nuclear DIS data to constrain the free neutron structure function. We stress that an isospin-dependent EMC effect, in the sense of a different average modification for protons and neutrons, as e.g. suggested by Refs. [10, 43, 44], can be obtained in all models discussed in this paper if the proton and neutron lightcone densities have different average virtualities. In addition we make predictions for new measurements of the bound nucleon structure function. These measurements will allow us to further constrain the elements of our model.

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