Nucleon off-shell structure and the free neutron valence structure from A=3 inclusive electron scattering measurements

E.P. Segarra, 1 J.R. Pybus, 1 F. Haunstein, 1, 2 T. Kutz, 1, 3 D. Higinbotham, 4 G.A. Miller, 5 E. Piasetzky, 3 A. Schmidt, 6 M. Strikman, 7 L.B. Weinstein, 2 and O. Hen 1

1 Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
2 Old Dominion University, Norfolk, Virginia 23529, USA
3 School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel
4 Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA
5 Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
6 George Washington University, Washington, D.C., 20052, USA
7 Pennsylvania State University, University Park, PA, 16802, USA

Understanding the differences between the distribution of quarks bound in protons and neutrons is key for constraining the mechanisms of SU(6) spin-flavor symmetry breaking in Quantum Chromodynamics (QCD). While vast amounts of proton structure measurements were done, data on the structure of the neutron is much more sparse as experiments typically extract the structure of neutrons from measurements of light atomic nuclei using model-dependent corrections for nuclear effects. Recently the MARATHON collaboration performed such an extraction by measuring inclusive deep-inelastic electron-scattering on helium-3 and tritium mirror nuclei where nuclear effects are expected to be similar and thus be suppressed in the helium-3 to tritium ratio. Here we evaluate the model dependence of this extraction by examining a wide range of models including the effect of using instant-form and light-cone nuclear wave functions and several different parameterizations of nucleon modification effects, including those with and without isospin dependence. We find that, while the data cannot differentiate among the different models of nuclear structure and nucleon modification, they consistently prefer a neutron-to-proton structure function ratio of at \( x_B \rightarrow 1 \) of \( \sim 0.4 \) with a typical uncertainty (1σ) of \( \sim 0.05 \) and \( \sim 0.10 \) for isospin-independent and isospin-dependent modification models, respectively. While strongly favoring SU(6) symmetry breaking models based on perturbative QCD and the Schwinger–Dyson equation calculation, the MARATHON data do not completely rule out the scalar di-quark models if an isospin-dependent modification exist.

Detailed studies of the distribution of quarks bound in nucleons provides crucial insight into the theory of Quantum Chromodynamics (QCD), thereby improving our understanding of emergent QCD phenomena such as baryon structure, masses, and magnetic moments, the structure of matter, and the origin of visible mass in the universe [1, 2]. A typical measurement used for such studies is inclusive lepton deep-inelastic scattering (DIS) [3].

Comparing the distribution of high-momentum quarks in the proton and neutron is especially sensitive to models of SU(6) spin-flavor symmetry breaking mechanism in QCD, and thus have far reaching implications to our understanding of the fundamental structure of matter [2]. While vast amounts of proton DIS data exist, the lack of a free neutron target prevents equivalent measurements of the neutron DIS, challenging our ability to perform a direct test of QCD symmetry breaking mechanisms. Instead, the free neutron structure is extracted from measurements that are probing protons and neutrons bound in atomic nuclei, applying model-dependent theoretical corrections for nuclear effects such as binding, nucleon-motion, and nucleon structure modification [4–7]. The latter are minimized, but not cancelled, by focusing on the lightest atomic nuclei with 2 and three nucleons, where exact nuclear wave functions can be calculated and the effects of nucleon binding and Fermi motion and nucleon modification are generally small.

Here we use a wide model phase-space to analyze the recent Helium-3 and Tritium mirror-nuclei DIS measurements of the MARATHON collaboration [8] to examine the model systematic uncertainty associated with the constrain in places on the distribution of valence quarks in the free proton and neutron. Significant emphasis is placed on the correlation between the free neutron structure and bound nucleon modification which prevented such extractions using previous Deuterium and Helium-3 measurements but is mitigated by the use of Tritium and assumptions of isospin symmetry.

The cross-section for lepton DIS off stationary nucleon targets at fixed momentum transfer squared \( Q^2 = [\bar{q}]^2 - \nu^2 \) and Bjorken scaling parameter \( x_B = Q^2/2m_N\nu \) is directly proportional to the inelastic structure function of the target nucleon, \( F_2(Q^2, x_B) \) in the limit \( F_2 = 2xF_1 \). Here \( q = (\bar{q}, \nu) \) is the four-momentum transfer from the electron to the target carried by the exchange of a virtual photon, and \( m_N \) is the nucleon mass. The parameter \( x_B \) coincides, in the infinite-momentum frame and \( Q^2 \rightarrow \infty \), with the momentum fraction, \( x \), of a parton struck in the scattering reaction.

In the simple quark-parton model, \( F_2(Q^2, x_B) \) is the linear combination of individual quark flavor distributions (up, down, strange...), each weighted by the square of its electromagnetic charge. Therefore, \( F_2(Q^2, x_B) \)
structure function extractions from lepton-nucleon DIS measurements contain valuable information on the internal structure of the nucleon.

To test the finer predictions of QCD, it is highly desirable to separate $F_2(Q^2, x_B)$ into the individual quark flavor distributions. Specifically, the ratio of the proton’s down to up quark distributions, $d/u$, in the $x \to 1$ limit has been shown to be extremely sensitive to the SU(6) spin-flavor symmetry breaking mechanism in QCD [2]. SU(6) is a broken symmetry in QCD, as is clear from the mass difference between the nucleon and $\Delta$-baryon, but if it were preserved, then the proton’s $d/u$ ratio at $x = 1$ would be 1/2 [11]; the proton has two valence up quarks, but only a single valence down quark. Specific models of the symmetry breaking mechanism predict a range of end points for $d/u$. A scalar di-quark picture predicts $d/u|_{x=1} = 0$ [12, 13], perturbative QCD predicts $d/u|_{x=1} = 1/5$ [14], and modern calculation using the Dyson-Schwinger equation predict a range of end points between 0.18 and 0.27 [2]. A precise experimental determination would therefore offer valuable insight into how this symmetry is broken in QCD.

Performing such flavor decomposition is a challenging task, which is often met by using isospin symmetry in comparing data from free proton and bound neutron measurements of light nuclei, with appropriate theoretical corrections to obtain the free neutron structure. While advances in nuclear structure theory have greatly improved the accuracy of nucleon motion and binding effects, there is still the problem of the largely unconstrained effects of the modification of the quark distributions in bound nucleons [15]. This bound structure modification is known as the EMC effect, and is the main limitation in extracting the free neutron structure function from inclusive DIS measurements of light nuclei.

This fundamental limitation is currently being addressed by several novel measurements, such as those of the BONuS [16–18] and MARATHON [8, 19] experiments. BONuS measures tagged-DIS (TDIS) reactions to identify scattering events from nearly free neutrons in the nuclear structure of the two nuclei. Recently, the MARATHON collaboration published its first results for $\Delta$-nuclei, where nuclear effects are expected to be small, while a single valence down quark. Specific models of the symmetry breaking mechanism predict a range of end points for $d/u$. A scalar di-quark picture predicts $d/u|_{x=1} = 0$ [12, 13], perturbative QCD predicts $d/u|_{x=1} = 1/5$ [14], and modern calculation using the Dyson-Schwinger equation predict a range of end points between 0.18 and 0.27 [2]. A precise experimental determination would therefore offer valuable insight into how this symmetry is broken in QCD.

Performing such flavor decomposition is a challenging task, which is often met by using isospin symmetry in comparing data from free proton and bound neutron measurements of light nuclei, with appropriate theoretical corrections to obtain the free neutron structure. While advances in nuclear structure theory have greatly improved the accuracy of nucleon motion and binding effects, there is still the problem of the largely unconstrained effects of the modification of the quark distributions in bound nucleons [15]. This bound structure modification is known as the EMC effect, and is the main limitation in extracting the free neutron structure function from inclusive DIS measurements of light nuclei.

This fundamental limitation is currently being addressed by several novel measurements, such as those of the BONuS [16–18] and MARATHON [8, 19] experiments. BONuS measures tagged-DIS (TDIS) reactions to identify scattering events from nearly free neutrons in the nuclear structure of the two nuclei. Recently, the MARATHON collaboration published its first results for $\Delta$-nuclei, where nuclear effects are expected to be small, while a single valence down quark. Specific models of the symmetry breaking mechanism predict a range of end points for $d/u$. A scalar di-quark picture predicts $d/u|_{x=1} = 0$ [12, 13], perturbative QCD predicts $d/u|_{x=1} = 1/5$ [14], and modern calculation using the Dyson-Schwinger equation predict a range of end points between 0.18 and 0.27 [2]. A precise experimental determination would therefore offer valuable insight into how this symmetry is broken in QCD.

Performing such flavor decomposition is a challenging task, which is often met by using isospin symmetry in comparing data from free proton and bound neutron measurements of light nuclei, with appropriate theoretical corrections to obtain the free neutron structure. While advances in nuclear structure theory have greatly improved the accuracy of nucleon motion and binding effects, there is still the problem of the largely unconstrained effects of the modification of the quark distributions in bound nucleons [15]. This bound structure modification is known as the EMC effect, and is the main limitation in extracting the free neutron structure function from inclusive DIS measurements of light nuclei.

This fundamental limitation is currently being addressed by several novel measurements, such as those of the BONuS [16–18] and MARATHON [8, 19] experiments. BONuS measures tagged-DIS (TDIS) reactions to identify scattering events from nearly free neutrons in the nuclear structure of the two nuclei. Recently, the MARATHON collaboration published its first results for $\Delta$-nuclei, where nuclear effects are expected to be small, while a single valence down quark. Specific models of the symmetry breaking mechanism predict a range of end points for $d/u$. A scalar di-quark picture predicts $d/u|_{x=1} = 0$ [12, 13], perturbative QCD predicts $d/u|_{x=1} = 1/5$ [14], and modern calculation using the Dyson-Schwinger equation predict a range of end points between 0.18 and 0.27 [2]. A precise experimental determination would therefore offer valuable insight into how this symmetry is broken in QCD.

Performing such flavor decomposition is a challenging task, which is often met by using isospin symmetry in comparing data from free proton and bound neutron measurements of light nuclei, with appropriate theoretical corrections to obtain the free neutron structure. While advances in nuclear structure theory have greatly improved the accuracy of nucleon motion and binding effects, there is still the problem of the largely unconstrained effects of the modification of the quark distributions in bound nucleons [15]. This bound structure modification is known as the EMC effect, and is the main limitation in extracting the free neutron structure function from inclusive DIS measurements of light nuclei.

This fundamental limitation is currently being addressed by several novel measurements, such as those of the BONuS [16–18] and MARATHON [8, 19] experiments. BONuS measures tagged-DIS (TDIS) reactions to identify scattering events from nearly free neutrons in the nuclear structure of the two nuclei. Recently, the MARATHON collaboration published its first results for $\Delta$-nuclei, where nuclear effects are expected to be small, while a single valence down quark. Specific models of the symmetry breaking mechanism predict a range of end points for $d/u$. A scalar di-quark picture predicts $d/u|_{x=1} = 0$ [12, 13], perturbative QCD predicts $d/u|_{x=1} = 1/5$ [14], and modern calculation using the Dyson-Schwinger equation predict a range of end points between 0.18 and 0.27 [2]. A precise experimental determination would therefore offer valuable insight into how this symmetry is broken in QCD.
produce existing DIS data from light nuclei [22].

Within the standard nuclear convolution approximation, the measured inelastic structure function of a nuclear target, \( F_2^A(x_B) \), is related to the free proton and neutron structure functions by [23–27]:

\[
F_2^A(x_B) = \frac{1}{A} \int_{x_B}^{1} \frac{d\alpha}{\alpha} \int_{-\infty}^{0} dv \frac{F_2^p(\tilde{x})}{F_2^N(\tilde{x})} \left[ \rho_n^A(\alpha,v) + N \rho_n^A(\alpha,v) \right] F_2^F(\tilde{x}) \left( 1 + v f^{\text{off}}(\tilde{x}) \right),
\]

where \( Z \) and \( N \) are respectively the proton and neutron numbers of the target nucleus, \( A = Z + N \), \( \alpha \) is the nucleon light-cone momentum fraction, \( v \) is the fractional virtuality of the bound nucleon defined by \( v = (E^2 - |\vec{p}|^2 - m_N^2)/m_N^2 \), \( \rho_n^A(\alpha,v) \) are the nucleon \((N = p \text{ or } n) \) light-cone momentum and virtuality distributions in nucleus \( A \), \( F_2^N(\tilde{x}) \) are the free nucleon structure functions, \( \tilde{x} = \frac{Q^2}{2p_\perp^2} \), and \( p_\perp \) is the four-momentum of the struck off-shell nucleon, and the function \( f^{\text{off}}(\tilde{x}) \) is the bound nucleon off-shell modification function. When working in coordinates where \( \tilde{z} \) is opposite the direction of \( \vec{q} \), \( \alpha = (E+p_z)/m_A \). For brevity we omit the explicit \( Q^2 \) dependences of \( F_2^p \), \( F_2^n \), and \( F_2^A \), but note that they are evaluated at the same \( Q^2 \) value.

This convolution combines nuclear wave function input in the form of the nucleon momentum and virtuality distributions from relatively well-known nuclear structure calculations with partonic input in the form of nuclear/nucleon structure and off-shell modification functions. While the nuclear and free proton structure functions \( F_2^A \) and \( F_2^p \) are directly measured, both the neutron-to-proton structure function ratio \( F_2^n/F_2^p \) and bound nucleon off-shell modification function \( f^{\text{off}} \) are not.

As can be seen by Eq. 1, for a given nucleus \( A \), one can shift strength between \( F_2^n/F_2^p \) and \( f^{\text{off}} \) while still reproducing \( F_2^A \) data. Therefore, \( F_2^n/F_2^p \) and off-shell nucleon modification are correlated when studying a single asymmetric nucleus and/or several symmetric nuclei.

This situation is different for case of \( A = 3 \) mirror nuclei where, by exploiting isospin symmetry, i.e. \( \rho_3^{\text{He}}(\alpha,v) = \rho_3^{\text{H}}(\alpha,v) \) and \( \rho_3^{\text{He}}(\alpha,v) = \rho_3^p(\alpha,v) \), and by assuming \( f^{\text{off}} \) is the same for both nuclei, the convolution equations become

\[
\begin{align*}
F_2^{\text{He}}(x_B) &= \frac{1}{3} \int_{x_B}^{1} \frac{d\alpha}{\alpha} \int_{-\infty}^{0} dv \frac{F_2^p(\tilde{x})}{F_2^N(\tilde{x})} \left[ 2\tilde{\rho}_p\tilde{\rho}_n(\alpha,v) + \tilde{\rho}_n(\alpha,v) F_2^N(\tilde{x}) \right] \\
&\times \left( 1 + v f^{\text{off}}(\tilde{x}) \right),
\end{align*}
\]

and the degeneracy between \( F_2^n/F_2^p \) and \( f^{\text{off}} \) is broken. Therefore, data from mirror nuclei should improve constraints on \( F_2^n/F_2^p \), although the exact results obtained can still depend on the assumed model \( f^{\text{off}} \). Indeed, while previous studies show that inclusive DIS data of deuterium and helium-3 can be explained using a wide range of functional forms of \( f^{\text{off}} \), the MARATHON collaboration’s extraction of \( F_2^n/F_2^p \) used only one model for \( f^{\text{off}} \) by KP.

Here we study the model dependence of the \( F_2^n/F_2^p \) extraction from the MARATHON \( ^3\text{He}/^3\text{H} \) data. First, we use both light-cone and spectral function approaches for the calculation of \( \tilde{\rho}_N(\alpha,v) \). Both

![Fig. 2](image-url)

FIG. 2. Fit results for an isospin-dependent off-shell nucleon modification function. The panels are arranged as in Fig. 1.
approaches are detailed in Ref. [22], but we emphasize that the modification of ν(α, v) satisfy baryon and momentum sum rules in the light-cone approach while the momentum sum rule is slightly violated in the spectral function approach. Second, we examine the impact of different off-shell modification models. Note from Eq. 2 that dependence on virtuality is built into the convolution. We explored various dependencies by applying the following set of f_{\text{off}} functions:

\begin{align}
& f_{\text{off}}^{\text{con}}(\bar{x}) = C, \quad (3) \\
& f_{\text{off}, N}^{\text{const}}(\bar{x}) = C_N, \quad (4) \\
& f_{\text{off}, p}^{\text{lin}}(\bar{x}) = a + b \cdot \bar{x}, \quad (5) \\
& f_{\text{KP, CJ}}^{\text{off}}(\bar{x}) = C(x_0 - \bar{x})(x_1 - \bar{x})(1 + x_0 - \bar{x}) \quad (6)
\end{align}

The first two models assume modification that is independent of \bar{x}, and is either the same (f_{\text{off}}^{\text{const}}) or different (f_{\text{off}, N}^{\text{const}, \text{iso}}) for neutrons and protons. The third model assumes a linear dependence on \bar{x}. The fourth uses a more complex function form whose free parameters (C, x_0, and x_1) were previously determined by the global analyses of Ref. [28] (KP) and [6] (CJ) and are held fixed in his work.

Using these f_{\text{off}} parameterizations, we performed a simultaneous fit of Eq. 1 to the F_{2}^{n}/F_{2}^{p} and F_{2}^{3He}/F_{2}^{p} data by BONuS [9] and Seely [10] respectively, and examined the correlation between the off-shell modification parameters and F_{2}^{n}/F_{2}^{p}|_{x_{B} → 1}. We then repeated the fits including the MARATHON F_{2}^{3He}/F_{2}^{3H} data and examined the impact on the correlations.

In our fits, we used the \frac{F_{2}^{n}(\bar{x})}{F_{2}^{p}(\bar{x})} parametrization of Ref [22]:

\begin{equation}
\frac{F_{2}^{n}(\bar{x})}{F_{2}^{p}(\bar{x})} \equiv R_{np}(\bar{x}) = a_{np}(1 - \bar{x})^{b_{np}} + c_{np}, \quad (7)
\end{equation}

which is both functionally flexible and has a single fit parameter \rho_{np} that describes F_{2}^{n}/F_{2}^{p}|_{x_{B} → 1}. This parameterization neglects the weak Q_{2}-dependence of F_{2}^{n}/F_{2}^{p}. We do include the full Q_{2}-dependence of F_{2}^{p}, for which we use the results of the GD11-P global analysis [29].

Figure 1 shows the results for fitting the data using the f_{\text{off}}^{\text{const}} and f_{\text{off}}^{\text{lin}} functions. In all figures, results obtained using light-cone and spectral function formulations of the nuclear wave function are shown in dashed and solid lines, respectively. Fits with and without the MARATHON data are shown in red and blue, respectively. All confidence region contours are shown at the 90\% confidence level.

As can be seen, without the MARATHON data a very broad correlation exists between the extracted F_{2}^{n}/F_{2}^{p}|_{x_{B} → 1} and the off-shell modification. This results in a wide distribution for F_{2}^{n}/F_{2}^{p}|_{x_{B} → 1} that is centered near the SU(6) symmetry prediction of 2/3. Adding the MARATHON F_{2}^{3He}/F_{2}^{3H} data significantly limits this correlation and results in F_{2}^{n}/F_{2}^{p}|_{x_{B} → 1} = 0.43 ± 0.04(1\sigma) for the constant and linear modification models. These values are consistent with the pQCD and DSE predictions and reject the scalar diquark prediction by 4.5 standard deviations. In both cases the light-cone and spectral

FIG. 3. Fit results for the CJ and KP off-shell nucleon modification function. The left and middle columns shows the best-fit results compared to the BONuS (top), Seely (middle), and MARATHON (bottom) data for the CJ and KP off-shell functions respectively. The right column shows the best-fit result translated into a probability distribution function (PDF) for F_{2}^{n}/F_{2}^{p}|_{x_{B} → 1}, exactly as in Figs. 1 and 2.
function wave function formulation have minimal impact on $F_{2}^{p}/F_{2}^{n}|_{x_B \to 1}$.

Next, we examine the case of isospin-dependent modification of protons and neutrons (Fig. 2). In this case, without the MARATHON data $F_{2}^{p}/F_{2}^{n}|_{x_B \to 1}$ is essentially unconstrained. With the MARATHON data, it is constrained to $0.40 \pm 0.07(1\sigma)$ with constant-in-x modification, and to $0.43 \pm 0.10(1\sigma)$ and $0.49 \pm 0.07(1\sigma)$ for the SF and LC approaches, respectively, with linear modification. These constraints are in good agreement with the isospin independent results of Fig 1, but with larger uncertainties that reject SU(6) or scalar diquark predictions. Since we do not currently consider available data constraining the specific virtuality-dependence of nucleon modification, and therefore sheds little light on the nature of the EMC Effect. A wide range of forms and parameters for the nucleon modification function can easily accommodate the MARATHON, BONuS, and Seely data. We see this as strong motivation to look to new observables beyond inclusive DIS to help constrain models of the EMC Effect, such as spectator-tagged DIS, on which the results of the BONuS12 [18] and BAND and LAD [31, 32] experiments are anticipated.

We thank a bunch of people for insightful discussions. This work was supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under Award Numbers DE-FG02-94ER40818, DE-SC0020240, DE-FG02-96ER40960, DE-FG02-93ER40771.
[1] A. Bashir, L. Chang, I. Cloet, B. El-Bennich, Y. Liu, C. Roberts, and P. Tandy, Commun. Theor. Phys. 58, 79 (2012), arXiv:1201.3366 [nucl-th].

[2] C. D. Roberts, R. J. Holt, and S. M. Schmidt, Phys. Lett. B727, 249 (2013), arXiv:1308.1236 [nucl-th].

[3] J. D. Bjorken and E. A. Paschos, Phys. Rev. 185, 1975 (1969).

[4] E. P. Segarra, A. Schmidt, T. Kutz, D. W. Higinbotham, E. Piasetzky, M. Strikman, L. B. Weinstein, and O. Hen, Phys. Rev. Lett. 124, 092002 (2020).

[5] S. Dulat, T.-J. Hou, J. Gao, M. Guzzi, J. Huston, P. Nadolsky, J. Pumplin, C. Schmidt, D. Stump, and C. P. Yuan, Phys. Rev. D93, 033006 (2016), arXiv:1506.07443 [hep-ph].

[6] A. Accardi, L. T. Brady, W. Melnitchouk, J. F. Owens, and N. Sato, Phys. Rev. D93, 114017 (2016), arXiv:1602.03154 [hep-ph].

[7] J. Arrington, J. G. Rubin, and W. Melnitchouk, Phys. Rev. Lett. 108, 252001 (2012), arXiv:1110.3362 [hep-ph].

[8] D. Abrams et al. (MARATHON), Phys. Rev. C92, 015211 (2015), arXiv:1506.00871 [hep-ph].

[9] K. A. Griffioen et al., Nucl. Instrum. Meth. A978, 164356 (2020), arXiv:2004.10339 [physics.ins-det].