Neutron/Proton Structure Function Ratio at Large $x$

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Abstract

We re-examine the large-$x$ neutron/proton structure function ratio extracted from the latest deuteron data, taking into account the most recent developments in the treatment of Fermi motion, binding and nucleon off-shell effects in the deuteron. Our findings suggest that as $x \to 1$ the ratio of the neutron to proton structure functions ($F^p_n/F^p_p$) is consistent with the perturbative QCD expectation of 3/7, but larger than the value of 1/4 obtained in earlier analyses.

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I. SU(6) SYMMETRY BREAKING

The precise mechanism for the breaking of the spin-flavor SU(6) symmetry is a basic question in hadronic physics. In a world of exact SU(6) symmetry, the wave function of a proton, polarized say in the +z direction, would be simply [1]:

\[ p^\uparrow = \frac{1}{\sqrt{2}}u^\uparrow (ud)_{S=0} + \frac{1}{\sqrt{18}}u^\uparrow (ud)_{S=1} - \frac{1}{3}u^\downarrow (ud)_{S=1} - \frac{1}{3}d^\uparrow (uu)_{S=1} - \frac{\sqrt{3}}{3}d^\downarrow (uu)_{S=1}, \]  

(1)

where the subscript \( S \) denotes the total spin of the two-quark component. In this limit, apart from charge and flavor quantum numbers, the \( u \) and \( d \) quarks in the proton would be identical. The nucleon and \( \Delta \) isobar would, for example, be degenerate in mass. In deep-inelastic scattering (DIS), exact SU(6) symmetry would be manifested in equivalent shapes for the valence quark distributions of the proton, which would be related simply by \( u_V(x) = 2d_V(x) \) for all \( x \). For the neutron to proton structure function ratio this would imply:

\[ \frac{F_n^2}{F_p^2} = \frac{2}{3} \quad \text{[SU(6) symmetry].} \]  

(2)

In nature spin-flavor SU(6) symmetry is, of course, broken. The nucleon and \( \Delta \) masses are split by some 300 MeV. Furthermore, with respect to DIS, it is known that the \( d \) quark distribution is softer than the \( u \) quark distribution, with the neutron/proton ratio deviating at large \( x \) from the SU(6) expectation. The correlation between the mass splitting in the 56 baryons and the large-\( x \) behavior of \( F_n^2/F_p^2 \) was observed some time ago by Close [2] and Carlitz [3]. Based on phenomenological [2] and Regge [3] arguments, the breaking of the symmetry in Eq.(1) was argued to arise from a suppression of the “diquark” configurations having \( S = 1 \) relative to the \( S = 0 \) configuration, namely

\[ (qq)_{S=0} \gg (qq)_{S=1}, \quad x \to 1. \]  

(3)

Such a suppression is in fact quite natural if one observes that whatever mechanism leads to the observed \( N - \Delta \) splitting (e.g. color-magnetic force, instanton-induced interaction,
pion exchange), it necessarily acts to produce a mass splitting between the two possible spin states of the two quarks which act as spectators to the hard collision, \((qq)_S\), with the \(S = 1\) state heavier than the \(S = 0\) state by some 200 MeV \[4\]. From Eq.(11), a dominant scalar valence diquark component of the proton suggests that in the \(x \to 1\) limit \(F^n_2\) is essentially given by a single quark distribution (i.e. the \(u\)), in which case:

\[
\frac{F^n_u}{F^n_2} \to \frac{1}{4}, \quad \frac{d}{u} \to 0 \quad [S = 0 \text{ dominance}].
\] (4)

This expectation has, in fact, been built into most phenomenological fits to the parton distribution data \[3\].

An alternative suggestion, based on perturbative QCD, was originally formulated by Farrar and Jackson \[6\]. There it was argued that the exchange of longitudinal gluons, which are the only type permitted when the spins of the two quarks in \((qq)_S\) are aligned, would introduce a factor \((1-x)^{1/2}\) into the Compton amplitude — in comparison with the exchange of a transverse gluon between quarks with spins anti-aligned. In this approach the relevant component of the proton valence wave function at large \(x\) is that associated with states in which the total “diquark” spin projection, \(S_z\), is zero:

\[
(qq)_{S_z=0} \gg (qq)_{S_z=1}, \quad x \to 1.
\] (5)

Consequently, scattering from a quark polarized in the opposite direction to the proton polarization is suppressed by a factor \((1-x)\) relative to the helicity-aligned configuration.

A similar result is also obtained in the treatment of Brodsky et al. \[7\] (based on counting-rules), where the large-\(x\) behavior of the parton distribution for a quark polarized parallel \((\Delta S_z = 1\) or antiparallel \((\Delta S_z = 0\) to the proton helicity is given by:

\[
q^{\uparrow\downarrow}(x) = (1-x)^{2n-1+\Delta S_z}, \quad \text{where } n \text{ is the minimum number of non-interacting quarks}
\]

(equal to 2 for the valence quark distributions). In the \(x \to 1\) limit one therefore predicts:

\[
\frac{F^n_2}{F^n_p} \to \frac{3}{4}, \quad \frac{d}{u} \to \frac{1}{5} \quad [S_z = 0 \text{ dominance}].
\] (6)

Note that the \(d/u\) ratio does not vanish in this model.
Clearly, if one is to understand the dynamics of the nucleon’s quark distributions at large \( x \), it is imperative that the consequences of these models be tested against experiment.

II. NUCLEAR EFFECTS IN THE DEUTERON

Because of the absence of free neutron targets it is difficult to obtain direct data on \( F_n^2 \). As a result, one usually uses a deuteron target and extracts neutron structure information from a knowledge of the proton structure function and the nucleon wave function in the deuteron [8]. The accuracy of the extracted neutron data naturally depends on the quality of the deuteron wave function, as well as on the extraction procedure.

Away from the small-\( x \) region (\( x \gtrsim 0.3 \)), the dominant contribution to the deuteron structure function arises from the impulse approximation, in which the total \( \gamma^*D \) amplitude is factorized into \( \gamma^*N \) and \( ND \) amplitudes (which one may call factorization at the amplitude level). To order \( (v/c)^2 \), with \( v \) the nucleon velocity, this leads to a convolution formula at the structure function level, in which the structure function of the nucleon is smeared with some momentum distribution, \( f(y) \), of nucleons in the deuteron [1][1][10]:

\[
F_2^D(\text{conv})(x, Q^2) = \int dy \ f(y) \ F_2^N \left( \frac{x}{y}, Q^2 \right),
\]

(7)

where \( F_2^N = F_2^p + F_2^n \). However, as explained in Refs. [1][1][12], in addition to the changes in \( f(y) \) which arise when nucleon binding is taken into account, explicit corrections to Eq.(7), which cannot be written in the form of a convolution, also arise when the off-mass-shell structure of nucleons is incorporated:

\[
F_2^D(x) = F_2^D(\text{conv})(x) + \delta^{(\text{off})} F_2^D(x).
\]

(8)

Here the correction \( \delta^{(\text{off})} F_2^D \) receives contributions from the off-shell components in the deuteron wave function, and from the off-mass-shell dependence of the bound nucleon structure function [12]. To ensure baryon number conservation, the first moment of \( \delta^{(\text{off})} F_2^D \) is identically zero. (For the explicit form of \( f(y) \) and \( \delta^{(\text{off})} F_2^D \) see Ref. [12].)
The size of the non-convolution correction $\delta^{(\text{off})} F_2^D$ (which is relativistic in origin) was the primary aim of our previous study in Ref. [12]. Although model dependent, $\delta^{(\text{off})} F_2^D$ was found to be less than 1–2% for most $x$ in realistic potential models of the $NN$ interaction [13–15]. Nevertheless, in any consistent covariant treatment, it must be included. Assuming in addition the conventional wisdom that $F_n^p/F_n^p \to 1/4$ as $x \to 1$, in Ref. [12] we also modeled the total deuteron structure function $F_2^D$. For the purposes of that study, the overall fit was quite impressive, even though on re-examination one sees that it was actually somewhat below the data at large $x$.

The combined effects of binding, Fermi motion and nucleon off-shellness on the calculated ratio $F_2^D/F_2^N$ in [12] were found to be about 4–5% at $x \sim 0.7$. This was qualitatively similar to the EMC effect found by Kaptari and Umnikov [16], and Braun and Tokarev [17], who used a formalism similar to ours, but did not include the non-convolution correction term $\delta^{(\text{off})} F_2^D$. On the other hand, these results differed substantially from earlier, on-mass-shell calculations [18], in which the EMC effect in the deuteron was only around 1%. The source of these differences in the behavior of $F_2^D/F_2^N$ may be either a difference in the neutron structure function input, or differences in the treatment of the nuclear effects in the deuteron, parametrized through the distribution function $f(y)$. In fact, we will demonstrate that the kinematic effect of binding plays a critical role in the analysis, aside from any assumptions about the neutron structure function.

In Fig.1 we illustrate the model dependence of the ratio, $R_p$, of the same free proton structure function, smeared with the function $f(y)$ calculated in the on-shell model of Ref. [18], $f_{\text{on}}(y)$, to that smeared with the function $f(y)$ calculated in Ref. [12] with the inclusion of binding, $f_{\text{off}}(y)$:

$$R_p(x) = \frac{\int dy \ f_{\text{on}}(y) \ F_2^p(x/y)}{\int dy \ f_{\text{off}}(y) \ F_2^p(x/y)}.$$  \hspace{1cm} (9)

In both cases the Paris wave function [15] has been used. Clearly the smearing in the on-shell model [18] produces a dramatically faster rise above unity for $x \gtrsim 0.7$ than for the off-shell model [12]. Since the same proton structure function data [13,20] are used in both
the on-shell and off-shell calculations, one concludes that the deviations at large $x$ arise from the different treatments of the kinematics. These differences are vital if one is interested in the large-$x$ behavior of the neutron structure function.

The on-shell calculation [18] was performed in the infinite momentum frame, where the nucleons are on their mass shells, and the physical structure functions can be used in Eq. (7). One problem with this approach is that the deuteron wave function in the infinite momentum frame is not explicitly known. In practice one usually makes use of the ordinary non-relativistic $S$- and $D$-state deuteron wave functions calculated in the deuteron rest frame [15]. This procedure is analogous to including only Fermi motion effects in the deuteron because one knows that the effect of binding in the infinite momentum frame shows up in the presence of additional Fock components (e.g. $NN$-meson(s) ) in the nuclear wavefunction, which which have not yet been computed but which must take momentum away from the nucleons.

On the other hand, the calculation of $f(y)$ in Ref. [12] draws on the extensive experience obtained, since the discovery of the nuclear EMC effect, on the importance of taking into account binding in the treatment of the impulse approximation — e.g., see Ref. [21] for a recent review. Noting the theoretical significance of the issue, and the fact that binding has either been ignored or treated in a very approximate way (see below) in all published analyses of deuteron data, it is of some importance therefore to reanalyze the deuteron data using the distribution function $f(y)$ which includes the effect of binding [12], but without making any assumptions for the neutron structure function.

III. EXTRACTION OF $F_2^N$

Here we examine the consequences of analyzing the $F_2^D$ data with the most recent treatment of deep-inelastic scattering from the deuteron, in which binding and other off-shell effects are taken into account. To extract the neutron structure function in a manner which is as unambiguous as possible we shall follow the same extraction procedure used in previous
SLAC [19] and EMC [20] data analyses, namely the smearing (or deconvolution) method discussed by Bodek et al. [22]. (For an alternative method of unfolding the neutron structure function see for example Ref. [23].) For completeness we briefly outline the main ingredients in this method.

Firstly, one subtracts from the deuteron data, $F_D^2$, the small, additive, off-shell corrections, $\delta^{(\text{off})} F_D^2$, to give the convolution part, $F_D^2 (\text{conv})$. Then one smears the proton data, $F_p^2$, with the nucleon momentum distribution function $f(y)$ in Eq.(7) to give $\tilde{F}_2^p \equiv F_2^p / S_p$. The smeared neutron structure function, $\tilde{F}_2^n$, is then obtained from

$$\tilde{F}_2^n = F_D^2 (\text{conv}) - \tilde{F}_2^p.$$ 

(10)

Since the smeared neutron structure function is defined as $\tilde{F}_2^n \equiv F_2^n / S_n$, we can invert this to obtain the structure function of a free neutron,

$$F_2^n = S_n \left( F_D^2 (\text{conv}) - F_2^p / S_p \right).$$ 

(11)

The proton smearing factor $S_p$ can be computed at each $x$ from the function $f(y)$, and a parametrization of the $F_p^2$ data (for example, the recent fit in Ref. [24] to the combined SLAC, BCDMS and NMC data). The neutron $F_2^n$ structure function is then derived from Eq.(11) taking as a first guess $S_n = S_p$. These values of $F_2^n$ are then smeared by the function $f(y)$, and the results used to obtain a better estimate for $S_n$. The new value for $S_n$ is then used in Eq.(11) to obtain an improved estimate for $F_2^n$, and the procedure repeated until convergence is achieved.

The results of this procedure for $F_2^n / F_2^p$ are presented in Fig.2, for both the off-shell calculation (solid) and the on-shell model (dotted). The increase in the off-shell $n/p$ ratio at large $x$ can be seen as a direct consequence of the larger EMC effect associated with the ratio $R_p$ for the off-shell model shown in Fig.1. To illustrate the role of the non-convolution correction, $\delta^{(\text{off})} F_D^2$, we have also performed the analysis setting this term to zero, and approximating $F_D^2$ by $F_D^2 (\text{conv})(x)$. The effect of this correction (dashed curve in Fig.2) appears minimal. One can therefore attribute most of the difference between the off- and
on-shell results to the kinematic effect of binding in the calculation of $f(y)$, since both calculations involve the same deuteron wave functions.

The reanalyzed SLAC [19,25] data points themselves are plotted in Fig.3, at an average value of $Q^2 \approx 12$ GeV$^2$. The very small error bars are testimony to the quality of the SLAC $p$ and $D$ data. The data represented by the open circles have been extracted with the on-shell deuteron model of Ref. [18], while the filled circles were obtained using the off-shell model of Refs. [11,12]. Most importantly, the $F_n^d/F_p^p$ points obtained with the off-shell method appear to approach a value broadly consistent with the Farrar-Jackson [3] and Brodsky et al. [7] prediction of 3/7, whereas the data previously analyzed in terms of the on-shell formalism produced a ratio that tended to the lower value of 1/4.

The $d/u$ ratio, shown in Fig.4, is obtained by simply inverting $F_n^d/F_p^p$ in the valence quark dominated region. The points extracted using the off-shell formalism (solid circles) are again significantly above those obtained previously with the aid of the on-shell prescription. In particular, they indicate that the $d/u$ ratio may actually approach a finite value in the $x \to 1$ limit, contrary to the expectation of the model of Refs. [2,3], in which $d/u$ tends to zero. Although it is a priori not clear at which scale the model predictions [2,3,6,7] should be valid, for the values of $Q^2$ corresponding to the analyzed data the effects of $Q^2$ evolution are minimal.

Naturally it would be preferable to extract $F_n^m$ without having to deal with uncertainties in the nuclear effects. In principle this could be achieved by using neutrino and antineutrino beams to measure the $u$ and $d$ distributions in the proton separately, and reconstructing $F_n^m$ from these. Unfortunately, as seen in Fig.4, the neutrino data from the CDHS collaboration [26] do not extend out to very large $x$ ($x \lesssim 0.6$), and at present cannot discriminate between the different methods of analyzing the electron–deuteron data.

We should also note that the results of our off-shell model are qualitatively similar [25] to those obtained using the nuclear density method suggested by Frankfurt and Strikman [27]. There the EMC effect in deuterium was assumed to scale with that in heavier nuclei according to the ratio of the respective nuclear densities, so that the ratio $F_D^d/F_N^p$ in the
trough region was depleted by about 4%. While this is qualitatively a reasonable way to
deal with the binding correction, the extrapolation from heavier nuclei to the deuteron was
based on an average density approximation. Because of the special nature of the deuteron,
where the neutron and proton are on average more than 4 fm apart and there is a significant
$D$-state component, such an extrapolation cannot be considered quantitatively reliable.

On the other hand, our results contradict those of Liuti and Gross [28], who have recently
tried to extract $F_n^2/F_p^2$ using an extension of the nuclear extrapolation method of Ref. [27]
and the formalism of Ref. [29], in combination with a non-relativistic expansion formula
approximation for $F_D^2$. It is known, however, that the expansion formula is reliable only
at moderate values of $x$ ($x \lesssim 0.7$), and indeed overestimates the convolution results above
$x \sim 0.7$ [10]. This is clear because in its derivation one has to neglect the lower limit on the
$y$-integration in Eq.(6), effectively replacing $y_{\text{min}} = x$ with $y_{\text{min}} = 0$. At very large $x$ this
approximation must start to break down, resulting in an underestimate of $F_n^2$. This may
explain the lower values for the $n/p$ ratio obtained in Ref. [28].

IV. SUMMARY

As explained above, earlier analyses of the large-$x$ behavior of the neutron structure
function based on deuteron data have either ignored the effect of binding or have used a
more qualitative treatment based on an extrapolation in terms of an average density. In
view of the demonstrated importance of binding we have reanalyzed the latest proton and
deuteron structure function data at large $x$, in order to obtain more reliable information on
the structure of the neutron in the limit $x \to 1$. Including all of the currently known nuclear
effects in the deuteron, namely Fermi motion, binding, and nucleon off-mass-shell effects, we
find that the total EMC effect is larger than in previous calculations based on on-mass-shell
kinematics, from which binding effects were essentially excluded. This translates into an
increase in the ratio $F_n^2/F_p^2$ at large $x$. Our results indicate that the limiting value as $x \to 1$
is above the previously accepted result of 1/4, and broadly consistent with the perturbative
QCD expectation of 3/7. This also implies that the $d/u$ ratio approaches a non-zero value around 1/5 as $x \to 1$.

We should also point out similar consequences for the spin-dependent neutron structure function $g_1^n$, where the Close/Carlitz [2,4] and Farrar/Jackson [6,7] models also give different predictions for $g_1^n / g_1^p$ as $x \to 1$, namely 1/4 and 3/7, respectively. Quite interestingly, while the ratio of polarized to unpolarized $u$ quark distribution is predicted to be the same in the two models,

$$\frac{\Delta u}{u} \to 1 \quad [S = 0 \text{ or } S_z = 0 \text{ dominance}],$$

the results for the $d$-quark distribution ratio differ even in sign:

$$\frac{\Delta d}{d} \to -\frac{1}{3} \quad [S = 0 \text{ dominance}], \quad (13a)$$

$$\to 1 \quad [S_z = 0 \text{ dominance}]. \quad (13b)$$

To extract information on the polarized parton densities at large $x$ that is capable of discriminating between these predictions, the same care will need to be taken when subtracting the nuclear effects from $g_1^D$ and $g_1^3He$. In particular, the results of Refs. [10,30] indicate that while the simple prescription [31] of subtracting the $g_1^p$ structure function from the $D$ data, modified only by the deuteron $D$-state probability, is surprisingly good for $x \lesssim 0.6$, it is completely inadequate for $x \gtrsim 0.7$.

Finally, for more definitive tests of the nuclear effects in the deuteron, it has been suggested that one might perform a series of semi-inclusive experiments on deuteron targets, measuring in coincidence both the scattered lepton and recoiling proton or neutron. Such experiments are already planned for CEBAF and HERMES [32], and should provide critical information on the size and importance of relativistic and other short-distance nuclear effects in the deuteron.
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FIG. 1. Model dependence of the ratio $R_p(x)$ of the free proton structure function [19,20], smeared with a nucleon momentum distribution, $f(y)$, calculated in the the on-mass-shell [18] and off-mass-shell [11,12] models.
FIG. 2. $F_2^n/F_2^p$ ratio as a function of $x$, for the off-shell model (solid), off-shell model without the convolution-breaking term (dashed), and the on-shell model (dotted). On the right-hand axis are marked the $x \to 1$ limits of the SU(6) symmetric model (2/3), and the predictions of the models of Refs. [2,3] (1/4) and [6,7] (3/7).
FIG. 3. Deconvoluted $F_2^n/F_2^p$ ratio extracted from the SLAC $p$ and $D$ data [19,25], at an average value of $Q^2 \approx 12$ GeV$^2$, assuming no off-shell effects (open circles), and including off-shell effects (full circles).
FIG. 4. Extracted $d/u$ ratio, using the off-shell deuteron calculation (full circles) and using on-shell kinematics (open circles). Also shown for comparison is the ratio extracted from neutrino measurements by the CDHS collaboration [26].