A new extraction of neutron structure functions from existing inclusive DIS data

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Abstract.
A recent reanalysis of world proton and deuteron structure function measurements showed that a significant amount of the apparent model dependence in the extraction of the neutron structure function was related to inconsistencies between the kinematics of the data and those assumed for the calculation, suggesting that the true model dependence is smaller than commonly believed. We present a detailed comparison of the neutron structure function as extracted using different models, with care taken to ensure that all other aspects of the comparison are done consistently. The neutron structure function is extracted using a fit to these data evaluated at fixed $Q^2=16$ GeV$^2$. We compare the results obtained using a variety of N–N potentials and deuteron binding models to determine the model dependence of the extraction. As in the recent extraction, $F_{2n}/F_{2p}$ falls with $x$ with no sign of plateau and follows the low edge of the wide range of earlier $F_{2n}$ extractions. The model-dependent uncertainty in $F_{2n}/F_{2p}$ is shown to be considerably smaller than previously believed, particularly at large-$x$.

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INTRODUCTION

Because of the experimental impracticality of performing precision scattering experiments with a neutron target, the determination of the structure functions of the neutron requires 1) inclusive DIS scattering data from both proton and deuteron targets and 2) a theoretical model that convincingly describes the impact on the structure function of the proton and neutron when bound together. Previous extractions of the neutron structure function, and more relevantly the ratio of the structure function of the neutron to that of the proton, $F_{2n}/F_{2p}$, were performed using different subsets of the world data on $F_{2p}$ and $F_{2d}$ with varying treatments of binding and kinematics. These produced significant variation in the resulting ratio, particularly at large-$x$. Some of these are shown in Figure 1. Because these different approaches yielded very different results, it was concluded that the model dependence of such an analysis was so large that no reliable information on the neutron could be obtained at large-$x$. However, as discussed in [1], a significant amount of the variation between results is related to self-inconsistencies in the extractions, giving the impression that our knowledge of this quantity is significantly worse than it will actually be shown to be. By carefully and uniformly treating the source data and restricting deuteron models to a set that is modern and compelling, a reasonable and significantly smaller uncertainty estimate can be made.
FIGURE 1. Several prior extractions of the ratio of the neutron to proton structure functions showing a large range, particularly at high-\(x\). The models shown are: off-shell (black squares) and on-shell (solid red diamonds) extractions from Ref. [2], pure Fermi-motion (open red diamonds) [3], and nuclear density dependent EMC effect based models (solid and open blue circles) from Ref. [3] and [4] respectively. The arrows on the right-hand side of the figure indicate various theoretical predictions of this ratio in the \(x = 1\) limit [2]. Exact spin-flavor SU(6) symmetry implies a value of 2/3, symmetry breaking through vector (\(S = 1\)) diquark suppression at large-\(x\) gives a value of 1/4, and a value of 3/7 is obtained if only the \(z\)-component, \(S_z = 1\) of the vector diquark’s spin determines its suppression.

**EXTRACTING \(F_{2n}/F_{2p}\)**

We begin with a summary of the extraction performed in Ref [1], as this provides the starting point for this comparison. The proton input, \(F_{2p}(x, Q^2)\), used in this analysis comes from a parameterization provided by M. E. Christy, which is fit to a large body of experimental experimental results. The deuteron to proton structure function ratio, \(F_{2d}/F_{2p}\), is taken from SLAC, BCDMS, and NMC measurements covering a range in \(Q^2\) from 3 to 230 GeV\(^2\). Data points for which \(6 < Q^2 < 30\) GeV\(^2\) and \(W^2 > 3.5\) GeV\(^2\) are interpolated to a common \(Q_0^2\) of 12 GeV\(^2\) (typically a 0.5% correction). The data points and fit function are shown in the left panel of Figure 2.

The nuclear modification of the proton and neutron was computed in a light cone impulse approximation, without any assumption of scaling or neglecting \(k_\perp\), using the CD-Bonn [5] effective two-body potential. This model is applied to the proton data and a \(R_{np}(\equiv F_{2n}/F_{2p})\) ratio of the form

\[
R_{np}(\xi, Q^2) = (p_1 + p_2 \, \xi) + p_3 \, e^{-p_4 \, \xi} + p_5 \, e^{-p_6 \, (1-\xi)} + p_7 \, \max(0, \xi - p_8)^2,
\]

where \(\xi = 2x/(1 + \sqrt{1 + 4M^2x^2/Q^2})\) is chosen as the scaling variable to reduce the \(Q^2\) dependence. The free parameters are tuned using MINUIT to best reproduce the \(F_{2d}\) data in conjunction with the parameterized proton structure function. The result of this procedure is the curve in the right panel of Figure 2. Once \(R_{np}\) is determined, smearing ratios \(S_p = \tilde{F}_{2p}/F_{2p}\) and \(S_n = \tilde{F}_{2n}/F_{2n}\), where the tilde indicates the structure function of the
bound nucleon, are trivial to determine. Using these ratios, the individual $R_{dp} = F_{2d}/F_{2p}$ points can be converted to $R_{np}$ values, along with their individual uncertainties. In addition, detailed estimates of the systematic uncertainties associated with the extraction procedure and data normalization have been parameterized. The individual $R_{np}$ points as well as the systematic uncertainties are shown as the points and dotted bands in the right panel of Figure 2.

Figure 3 compares the results of this extraction to previous results, with the new data points rebinned to approximately match the previous binning. These results fall on the
FIGURE 4. Left panel: The calculated ratio $F_2^d/F_2^p$ evaluated at the average $Q^2$ for the given $x$ value (red), and at a common $Q^2_0 = 12$ GeV$^2$ (black). Right panel: The proton smearing ratio, $S_p$, for values of $Q^2$ ranging from 4.7 to 23.6 GeV$^2$ (corresponding to the average $Q^2$ value of each of the $R_{dp}$ points). The dark central line corresponds to the $Q^2_0=12$ GeV$^2$ used in this analysis. The red points indicate the value of $S_p$ at the average $Q^2$ of the input data.

lower edge of the wide range of previous results. Note that this extraction was performed using a single model of the deuteron structure and the CD-Bonn N–N potential. No estimate of the model dependence due to choice of nuclear models was included.

Most previous extractions of the neutron structure function treated the data as though it were at a fixed $Q^2$ when in fact there is a strong correlation between $x$ and $Q^2$ as one can see in the left panel of Figure 4. Furthermore, even the simple convolution models including only Fermi motion yield a significant $Q^2$ dependence at large $x$. This can be seen for the calculation of the smearing ratio in right panel of Figure 4 where $S_p(x)$ is given for different values of $Q^2$ and, for comparison, $S_p(x)$ points at the $Q^2$ of the data are overlaid. Neglecting this $x-Q^2$ correlation by applying nuclear corrections at fixed $Q^2$ can yield a significant error in the extraction. There are two ways to address this correlation. The first is to evolve the model of the deuteron to the $Q^2$ value of each data point, which is essentially the procedure used in the CTEQ6X global extraction of parton distributions [7]. The second, which is used in this work is to interpolate all of the data to a fixed value of $Q^2$. A benefit of this method is that the analysis can be performed purely in terms of structure functions, without invoking the parton picture, which leads to a particularly direct and accessible analysis scheme. Both of these recent approaches yield a similar result, with $R_{np}$ approaching 1/4 (and thus the $d(x)/u(x)$ ratio approaching zero) as $x$ becomes very large.

EXPLORING DEUTERON MODEL-DEPENDENCE

Given the observation that accounting for $Q^2$-dependent contributions is important in these analyses [1, 7], we perform a detailed study of the model dependence of the extracted neutron structure function when fully and consistently accounting for these effects in the comparison. We factor this problem into two parts: 1) the choice of a N-N potential and 2) the choice of a nuclear model. We begin by updating the interpolation of the global $R_{dp}$ measurements to fixed $Q^2$, this time choosing $Q^2=16$ GeV$^2$, as this more
closely matches the kinematics of the large-\(x\) measurements, where the \(Q^2\) dependence is largest. While this should have no impact on the comparison of the different extractions, it should minimize the corrections in the interpolation for all of the results.

We extract \(R_{np}\), repeating the analysis of Ref. [1] at \(Q_0^2=16\text{ GeV}^2\). We then take our input fit to \(F_{2p}\) along with the extracted \(F_{2n}\) as the starting point to calculate the smearing ratios (ratio of the proton or neutron structure function in the deuteron to the free structure function) for all of the different models, and use this to determine the change in the extracted neutron structure function. Variations in \(R_{np}\) can be studied for potential and model separately by varying the potential with a single baseline model and varying the model with a single baseline potential. These two procedures are depicted in the left and right panels of Figure 5 respectively. The model of Ref. [1] is used when comparing the different N–N potentials, while the CD-Bonn potential is used for comparison of the different calculations of the nuclear effects. We take the full range of the results shown in each panel as the one-sigma systematic band for the potential and model dependences of the extraction.

Note that in this comparison, we use models which include Fermi motion, binding, and in some cases off-shell effects and the contributions of nuclear pions. All of these represent “ground-up” calculations of the deuteron structure based on input proton and neutron structure functions and some N–N potential used to calculate the deuteron momentum distribution. Some of the earlier models which yielded exceptionally large results for \(R_{np}\) at large-\(x\) were based on models which neglected Fermi motion and binding and yielded a large effect through significant modification of the nucleon structure in the nucleus, e.g. the “scaled EMC effect” result of [3]. While such large nuclear effects are possible, they are not implemented in a realistic fashion in this approach. They do not include any direct calculation of Fermi motion, are scaled down for the deuteron using an extremely large assumed nuclear density density, neglect \(Q^2\) dependence in the nuclear effects, and effectively assume \(S_n = S_p\) which is not true when there is a significant difference in the \(x\) dependence of \(F_{2p}\) and \(F_{2n}\). Thus, we do not include models that use an explicit “EMC effect” for the deuteron, unless they are included (e.g. via the pion contributions and off-shell effect) along with Fermi motion and binding fashion [2, 8, 10, 7].

We note that the issue of the \(Q^2\) variation of the \(R_{dp}\) measurements is important even for the models including a large EMC effect in the deuteron. The model used to obtain

FIGURE 5. Left panel: \(R_{np}\) calculated using various N-N potentials assuming the deuteron model described previously [1]. Right panel: \(R_{np}\) calculated using different models [2, 8, 9, 10, 1] with the CD-Bonn N-N potential [5].
the highest set of data points from Figure 1 yields a smaller neutron structure function at large $x$ when applied to the $R_{d/p}$ measurements interpolated to a fixed $Q^2$ value. Thus, even if one were to include such models, the impact on the neutron structure function is smaller than one would expect based on these earlier comparisons.

Finally then, the systematic uncertainty bands from the experimental extraction (as parameterized in Ref. [1]) and the model and potential dependence of the result are combined in quadrature. This is shown in Figure 6 compared to the much larger range of prior $F_{2n}/F_{2p}$ extractions. Based on these results, it appears that the neutron structure function is relatively well known even to large $x$ values, under the assumption that there are no “exotic” contributions to the deuteron structure beyond the effects included in these models. This conclusion may seem to be at odds with the CTEQ6X analysis [7] where, even with the inclusion of large-$x$ data, the uncertainties in the high-$x$ $d$-quark distributions are extremely large. Figure 7 shows our extracted result for the value and uncertainty in the $d/u$ ratio for the proton, where we extract this from $F_{2n}/F_{2p}$ by neglecting contributions from strange and heavier quarks. The left panel shows the absolute value of the $d/u$ ratio, and it is clear from this that the $d$-quark distribution is becoming very small. The right panel shows the ratio compared to the reference fit, and shows that the relatively small absolute uncertainties on $F_{2n}/F_{2p}$ or $d/u$ can yield $>100\%$ uncertainties on the absolute value of the $d$-quark distributions. Thus, the uncertainty on the $d$-quark distribution is small relative to the size of the dominant $u$-quark distribution, which means that the data can yield significant constraints when comparing to predictions of the $d/u$ ratio at large $x$. However, the fractional uncertainty on the $d$-quark distribution is large, meaning that observables that are sensitive to the $d$-quark pdf at large $x$ are not well constrained. So the impact of the nuclear models is small for some purposes but large in others, and the context is clearly important in
determining whether we have sufficiently precise knowledge of the neutron structure function.

There are multiple model-independent extractions planned for the neutron structure function at large-$x$ as part of the 12 GeV upgrade plan [11]. These will improve the precision of the neutron extraction at high $x$, but more importantly will be sensitive to any physics beyond what is contained in these models, and thus are very sensitive to some of the more exotic explanations of the EMC effect.

CONCLUSIONS

A recent reanalysis of inclusive DIS data from proton and deuteron scattering, interpolating to a common value of $Q^2$ provided a new extraction of $F_{2n}/F_{2p}$. The result was found to decrease as $x$ becomes large and shows no sign of plateau, sitting near the low end of the wide range of previously extracted large-$x$ behaviors. However, some previous extractions yielded a neutron structure function that was too large because of inconsistent treatment of $x$-$Q^2$ correlations. We have extended this analysis to include a detailed extraction of the model dependence, using a range of deuteron models and potentials. We find that the sensitivity of the extracted $F_{2n}/F_{2p}$, and hence the model uncertainty, is relatively small, and significantly less than previously believed. While these results could be an underestimate if there is a larger than expected “EMC effect” in the deuteron, the comparison of this extraction with future model-independent measurements will be able to measure or significantly limit such modification of the nucleon structure in the deuteron.

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