Confirmation of quark-hadron duality in the neutron $F_2$ structure function

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We apply a recently developed technique to extract for the first time the neutron $F_2^n$ structure function from inclusive proton and deuteron data in the nucleon resonance region, and test the validity of quark-hadron duality in the neutron. We establish the accuracy of duality in the low-lying neutron resonance regions over a range of $Q^2$, and compare with the corresponding results on the proton and with theoretical expectations. The confirmation of duality in both the neutron and proton opens the possibility of using resonance region data to constrain parton distributions at large $x$.

The quest to understand the strong interactions at intermediate energies, and particularly the transition from quark-gluon to hadron degrees of freedom, is one of the main outstanding challenges in modern nuclear physics. Considerable attention has been focused recently on the “duality” between quark and hadron descriptions of observables in electron–hadron scattering. A classic example is the finding \(^1\) that inclusive structure functions in the region dominated by the nucleon resonances on average resemble the structure functions measured in the deep inelastic scattering (DIS) region at higher energies.

With the availability of high-precision data from Jefferson Lab and elsewhere, duality has now been firmly established for the proton $F_2$ and $F_1$ structure functions \(^2,3\), and exploratory studies in spin-dependent and semi-inclusive scattering have provided tantalizing glimpses of the flavor and spin dependence of duality (for a review see Ref. \(^6\)). A complete picture of the workings of duality in the nucleon can only be constructed, however, with information on duality in the neutron, on which little empirical data exists.

Calculations based on quark models point to intriguing differences between duality in the proton and neutron \(^6\), and some arguments even suggest that duality in the proton may be due to accidental cancellations between quark charges, which do not occur for the neutron \(^7\). Confirmation of duality in the neutron would therefore firmly establish that the phenomenon is not accidental, but rather a robust feature of nucleon structure functions. More generally, understanding the transition between the resonance and DIS regions can lead to better constraints on parton distribution functions (PDFs) at large momentum fractions $x$, by allowing data at lower final state hadron masses $W$ to be used in global PDF fits \(^8,9\). Precise knowledge of large-$x$ PDFs, which are currently poorly constrained, is vital in searches for new physics beyond the Standard Model \(^10\), for instance, as well as in neutrino oscillation experiments \(^11\).

In this Letter we use a recently introduced technique \(^12\) to extract for the first time the neutron $F_2^n$ structure function from proton ($p$) and deuteron ($d$) $F_2$ data in the resonance region over a range of photon virtualities from $Q^2 = 0.6$ to 6.4 GeV$^2$. The new method is based on an iterative approach in which the nuclear corrections are applied additively, and has been found to accurately reproduce neutron structure functions of almost arbitrary shape in both the DIS and resonance regions \(^12\).

The extraction of reliable neutron information from deuterium data requires a careful treatment of nuclear effects \(^13\), and we use the latest theoretical developments which allow the deuteron structure function to be analyzed in both the resonance and DIS regions, at both low and high $Q^2$. In the weak binding approximation the deuteron $F_2^d$ structure function can be written as a sum of smeared proton and neutron structure functions $F_2^p(N=p,n)$, and an additive term which accounts for possible modification of the structure functions off-shell \(^12,14,15\).

$$F_2^d = \tilde{F}_2^p + \tilde{F}_2^n + \delta^{(off)} F_2^d.$$  \hfill (1)

The smeared nucleon structure functions are given by convolutions of the nucleon light-cone momentum distribution in the deuteron, $f_{N/d}$, and the bound nucleon structure functions \(^12,14\),

$$\tilde{F}_2^N = f_{N/d} \otimes F_2^N,$$  \hfill (2)

where the symbol $\otimes$ denotes a convolution. The nucleon momentum distribution (or smearing) function $f_{N/d}$ accounts for the effects of the nucleon’s Fermi motion and binding, including finite-$Q^2$ corrections \(^12,14\), and is taken to be identical for the proton and neutron. The off-shell correction $\delta^{(off)} F_2^d$ has been found in several models \(^14,16\) to be typically of the order 1–2% for $x \lesssim 0.9$.

To account for the quasi-elastic (QE) tail in the deuteron data the elastic nucleon contribution is smeared using the same $f_{N/d}$. Subtracting from the deuteron $F_2^d$ the QE contribution, together with the off-shell correction and the smeared proton $\tilde{F}_2^p$, one obtains an effective smeared neutron structure function $\tilde{F}_2^n$ and then solves Eq. \(^2\) for the neutron.

The nuclear effects are parametrized by an additive correction \(^12\),

$$\tilde{F}_2^n = N F_2^n + \delta f \otimes F_2^n,$$  \hfill (3)
The extraction and neutron data are compared with the global QCD fit from Refs. [12, 18], which investigates the neutron function and its ability to reliably estimate errors on the extracted neutron results. It is particularly important that the QE contribution to the deuteron $F_2^d$ be accounted for in the analysis, and we model this using the same smearing function, $f_{N/d}$, and nucleon form factors from Refs. [21, 22]. This is found to provide a good description of the QE peak as a function of $Q^2$.

An example of the extracted neutron $F_2^n$ structure function is displayed in Fig. 1 for $Q^2 = 1.7$ and $5$ GeV$^2$, together with proton and deuteron data, the complete data set will be shown in Ref. [23]. The starting value of the neutron for the iteration was $F_2^{n(0)} = F_2^p$, and the deuteron $F_2^d$ reconstructed from the proton and extracted neutron was found to be in good agreement with the data after two iterations. The spectrum of the $F_2^n$ structure function in the resonance region displays similar characteristics as observed from the proton spectrum: one finds three resonant enhancements which fall with $Q^2$ at a similar rate as for the proton.

To check that the extracted neutron structure function does not depend on the starting value of the iteration, the extraction procedure was repeated assuming a different boundary condition, $F_2^{n(0)} = F_2^p/2$. The difference between the two results $\Delta = (F_2^n(F_2^{n(0)}) - F_2^n(F_2^{p(0)})) / \sigma(F_2^n)$, normalized by the total $F_2^n$ uncertainty $\sigma(F_2^n)$, is shown in the insert of Fig. 1 after two iterations. One finds an almost Gaussian distribution centered around 0 (the mean of the distribution is around $-0.07$) with a width well within the typical total uncertainty of $F_2^n$. In fact only 6% of the total number of data points lie outside of a 2$\sigma$ range. More extreme boundary conditions, such as $F_2^{n(0)} = 0$, do not alter the characteristics of the extracted $F_2^n$ structure function spectrum, with the resonant structures already visible after just 1 iteration. On the other hand, as discussed in Ref. [12], more iterations are needed for poor choices of initial values, which increases the scatter of data points if the deuteron data in particular display any nonuniformities.

The effect of the off-shell correction $\delta^{(off)} F_2^d$ was taken into account using the model of Ref. [16], which gives $\approx -1.5\%$ correction over most of the $x$ range considered, and was argued to provide an upper limit on the correction. The $F_2^d$ data are corrected by subtracting half of the off-shell correction from $F_2^d$ and assigning a 100% uncertainty. When propagated into the $F_2^n$ uncertainty this was found to contribute less than 2% to the total error.

In Fig. 1 we also show $F_2^p$ and $F_2^n$ from global QCD fits to DIS data (with $W^2 > 4$ GeV$^2$) from Alekhn et al. [8], which illustrates the striking similarity between the QCD fit and the resonance data, reminiscent of Bloom-
Gilman duality \([1]\). To quantify this duality we consider ratios of “truncated” moments \(M_2\) \([24]\),

\[
M_2(Q^2, \Delta x) = \int_{\Delta x} dx F_2(x, Q^2),
\]

in the resonance region for specific intervals \(\Delta x\). Following previous proton data analyses \([2, 4]\), we consider the regions

- 1st resonance region \(\rightarrow W^2 \in [1.3, 1.9] \text{ GeV}^2\)
- 2nd resonance region \(\rightarrow W^2 \in [1.9, 2.5] \text{ GeV}^2\)
- 3rd resonance region \(\rightarrow W^2 \in [2.5, 3.1] \text{ GeV}^2\)

as well as the entire resonance region \(1.3 \leq W^2 \leq 4 \text{ GeV}^2\). At a given \(Q^2\), the lowest-\(W\) (\(\Delta\) resonance) region corresponds to the highest-\(x\) range, and for a fixed \(W\) interval the larger the \(Q^2\), the higher the \(x\).

The ratio of the truncated moments of the resonance data to the global QCD fit \([8]\), computed over the same \(x\) range, is shown in Fig. 2 as a function of \(Q^2\). Globally, the agreement between the QCD fit and the resonance data is quite remarkable, with deviations of \(\lesssim 10\%\) observed over the entire \(Q^2\) range. Locally, in the individual resonance regions the deviations are generally \(\lesssim 15 - 20\%\), somewhat larger only in the 1st resonance region at the largest \(Q^2\). This is not surprising given the fact that the \(\Delta\) region at \(Q^2 = 6.4 \text{ GeV}^2\) covers the highest-\(x\) regime studied, \(x \sim 0.9\), where the QCD fit is mostly beyond its limit of applicability.

The isospin dependence of duality can be studied by comparing the truncated neutron moments with the analogous proton moments. The ratio of these is displayed in Fig. 3 as a function of \(Q^2\) for the various resonance regions, and compared with global QCD fits from Alekhin et al. \([8]\) and MSTW \([25]\), corrected for target mass effects \([26]\). The MSTW fits are shown for \(Q^2 \gtrsim 2 \text{ GeV}^2\), which corresponds to their approximate limit of validity.

The ratios show good agreement with the data, with the exception of the \(\Delta\) region which is somewhat underestimated. Since the proton and neutron transitions to the \(\Delta\) are isovector, the resonant contributions should be identical; on the other hand, the DIS structure functions in the \(\Delta\) region are expected to be rather different, with \(F_2^p \ll F_2^n\), so that violation of duality here is expected to be strongest. In addition, the QCD fits are least constrained in this region due to the scarcity of large-\(x\) DIS data. This is especially the case for the MSTW fit \([25]\), which limits the data sets to \(W^2 > 15 \text{ GeV}^2\).

The \(M_2^n/M_2^p\) ratios at fixed \(Q^2\) are shown in Fig. 4 as a function of \(x\) for the three resonance regions, compared with the QCD fits as in Fig. 3. The global fits offer a good description of the 2nd and 3rd resonance region data, revealing clear evidence of duality down to \(Q^2\) as low as \(0.6 \text{ GeV}^2\). The fits underestimate the \(\Delta\)-region ratios and this trend becomes more pronounced as one moves to larger \(Q^2\) (\(\gtrsim 4 \text{ GeV}^2\)) and larger \(x\). The Alekhin et al. fit \([8]\) offers a better description at large \(x\), which is likely due to its inclusion of lower-\(W\), lower-\(Q^2\) data.

Our results can be compared with quark model ex-
In conclusion, we have extracted the neutron structure function $F_2^n$ for the first time in the resonance region from inclusive proton and deuteron data. Our comparisons of empirical truncated moments to those extracted from global QCD fits to high-$W^2$ data show clear signatures of Bloom-Gilman duality, with better than $15-20\%$ agreement in the 2$^{nd}$ and 3$^{rd}$ resonance regions, and less than 10$\%$ deviations when integrated over the entire $W^2 < 4$ GeV$^2$ region. The confirmation of duality in the neutron establishes that the phenomenon is not accidental, but is a general property of nucleon structure functions. Our findings suggest that averaged resonance data could in future be used to constrain the large-$x$ behavior of global QCD fits by relaxing the $W^2$ cuts down to the 2$^{nd}$ resonance region, $W^2 \sim 1.9$ GeV$^2$. This could also have significant impact for searches for new physics beyond the Standard Model at colliders and neutrino oscillations experiments.

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