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Quark-hadron duality in the free neutron F_2 structure function

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The Thomas Jefferson National Accelerator Facility (JLab) experiment BONuS used a novel spectator-tagging technique to measure the inclusive electron-free neutron scattering cross section and extract the F2 structure function. This data was used to reconstruct moments of F2 in the three prominent resonance region and the moments integrated over the entire resonance region.
Comparisons of the experimental results with moments obtained from global parton distribution function parametrization seem to suggest that the quark-hadron duality hypothesis holds locally for the neutron in the second and third resonance regions down to Q^2 of 1 GeV^2, with up to 20% violations observed in the first resonance region.

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1. Introduction

Since the late 60's inclusive electron scattering was used as a clean, reliable way of probing the nuclear and nucleon structure. Scattering of electrons of off the proton provided a very substantial body of data, allowing the study of the structure functions over several orders of magnitude in the Bjorken variable x and the squared four momentum transfer Q^2. These nucleon structure functions reflect many of the hallmarks of Quantum Chromodynamics (QCD): asymptotic freedom at the high energy scale and quark confinement at the large distance (low energy) scale.

In the naive quark parton model the structure function F_2 can be written as linear combinations of the (anti)quark distribution functions

$$F_2 = x \sum_q e_q^2 [q(x) + \bar{q}(x)], \tag{1.1}$$

where $q(x)$ and $\bar{q}(x)$ are the parton distribution functions (PDFs) (i.e. the probability of finding a quark of flavor q in the nucleon carrying a light cone momentum fraction x), and e_q is the charge of the quark q. Predictably the quantities of interest from equation 1.1 are the PDFs $q(x)$ and $\bar{q}(x)$.

The large body of proton structure function data provides strong constraints on the quark and gluon PDFs. However, in order to unambiguously gain access to the individual PDFs one needs access to more than one type of target. In short one needs to measure the structure functions on the neutron as well. This is not a very straight forward task as the short lifetime of neutron makes the building of high density free neutron targets impossible. Most inclusive electron scattering experiments obtain their neutron data by separately extracting the structure function for hydrogen and light nuclei (deuterium, helium) and then subtracting the Fermi smeared proton data from the nuclear result [1, 2, 3, 4, 5].

2. Quark–Hadron Duality

At low energy the inclusive electron–nucleon scattering is dominated by the nucleon resonances. Due to strong quark–gluon interactions non–perturbative effects are very important in this region. In the deep inelastic scaling region (i.e. at asymptotically high energies) the cross section can be calculated in terms of quark and gluon degrees of freedom. A phenomenon called *quark–hadron duality*, first observed by Bloom and Gilman in 1970 [6] has shown that low energy cross section, when integrated over an appropriate energy interval, resembles the integral of the high energy cross section calculated using the perturbative QCD formalism (over the same energy range). Quark–hadron duality can be seen as reflecting the relationship between confinement and asymptotic freedom and providing a quantitative correspondence between observations in the perturbative and in the non–perturbative regimes in QCD.

The availability of high statistics, high precision structure function data from Jefferson Lab [7, 8], over a large range of x and Q^2, made in–depth studies of the quark–hadron duality possible. It should be noted that while quark–hadron duality was first documented in the F_2 structure function, recent work [9, 10, 11, 12, 13, 14] showed evidence for this phenomenon for other observables.

A relatively new approach in the study of quark–hadron duality is the use of "truncated" structure function moments [15]. Like "full" moments of the F_2 structure function "truncated" moments are defined as:

$$M_n(x_{min}, x_{max}, Q^2) = \int_{x_{min}}^{x_{max}} dx x^{n-2} F_2(x, Q^2), \tag{2.1}$$

where the integration is carried over the interval (x_{min}, x_{max}). This method avoids extrapolation of the integrand into sparsely mapped kinematic regions, and is particularly well suited for the study of local duality where an x region can be defined by a resonance mass width via the relationship between x, Q^2, and the invariant mass squared W^2. This report presents a study of local quark–hadron duality for the neutron using the free neutron structure function obtained at JLab using the novel BONuS detector and the CLAS spectrometer.

3. The BONuS experiment

In order to eliminate or at least reduce some of the theoretical uncertainties associated with extracting neutron structure function results as documented above, the BONuS (Barely Off–shell Nucleon Structure) experiment [16, 17, 18] used a Radial Time Projection Chamber (RTPC) to tag backward–moving, low momentum spectator protons. The electrons were detected by the CLAS spectrometer [19] in experimental Hall B at Jefferson Lab. A pressurized deuteron gas target was used. Tagging low momentum, backward moving spectator protons minimizes final state interactions [20, 21, 22] and ensures that the neutron is just barely off its mass shell [17]. Fermi smearing effects are essentially eliminated by this experimental technique.

The BONuS experiment acquired electron–deuteron scattering data at three electron beam energies: 2.140, 4.223, and 5.262 GeV in 2005. This report used data obtained at the two higher energies. To isolate electron–neutron interactions this experiment used an RTPC based on three layers of gas electron multipliers surrounding a thin, pressurized gas deuterium target to tag spectator protons with momenta as low as 70 MeV/c. The experiment and data analysis are described in detail in [18]. Ratios of neutron to proton F_2 structure functions and the neutron F_2 structure function were extracted over a wide kinematic range and for proton spectator momenta between 70 and 100 MeV/c. The total systematic uncertainty in the neutron structure function extracted is 8.7% [18]. Additionally there is an overall 10% scale uncertainty due to cross normalization of the BONuS data to existing F_2^n/F_2^d parameterizations.

4. Results

The kinematic coverage is shown in Figure 1 (4.223 and 5.262 GeV results combined). It extends from the quasielastic peak to the deep inelastic region corresponding to final state invariant masses of ~ 3 GeV. The curves shown represent the W^2 thresholds for the three prominent resonance regions.

F_2^n results for $Q^2 = 1.2$ and $Q^2 = 2.4$ GeV^2 are shown in Figure 2. The open/closed symbols correspond to 4.2 and 5.2 GeV electron beam energies respectively. Predictions, with and without higher twist effects, of the QCD fit ABKM [23] are also shown.

The second ($n = 2$) truncated moments, M_2, obtained from the BONuS experiment are shown in Fig. 3 as a function of Q^2. The uncertainties quoted take into account the experimental statistical and systematic uncertainties and include a 10% scale/normalization uncertainty for all points. A detailed description of this analysis and its results was recently published [24].

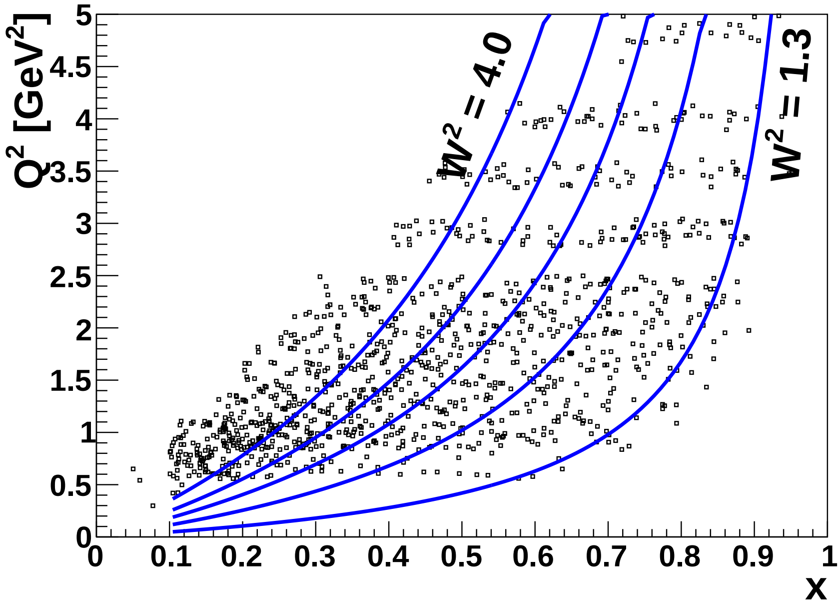

Figure 1: Kinematic coverage of the BONuS data. The lines represent the W^2 thresholds: 1.3, 1.9, 2.5, and 4.0 GeV^2.

5. Conclusion

As seen in Figure 3 the ABKM parameterization prediction agrees well with the data in the second and third resonance regions but it significantly underestimates the BONuS result in the first resonance region. A possible explanation might be that in conventional parameterizations of parton distribution functions the d/u ratio tends to either zero or infinity as $x \to 1$, depending on the parameterization of the d PDF [25]. However, at x above 0.8 (which maps largely in the first resonance region) the uncertainties on the PDFs, especially the d, are considerable, due to deuteron nuclear model corrections and to the lack of high x data. So the neutron PDF is largely unconstrained in this kinematic regime while the abundance and precision of the proton data put clear limits on the proton PDF. Therefore violations of local quark hadron duality are expected to be greatest in this region. This is consistent with the results reported here.

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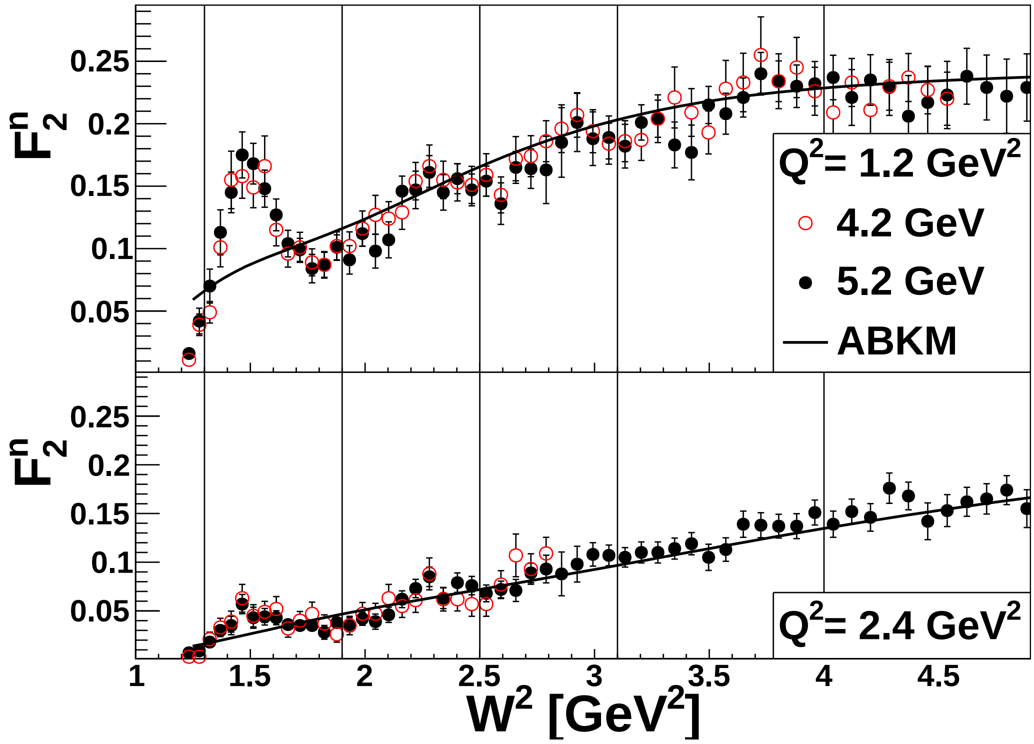

Figure 2: Representative neutron structure function data from the BONuS experiment at $Q^2 = 1.2$ GeV^2 (top panel) and $Q^2 = 2.4$ GeV^2 (bottom panel).

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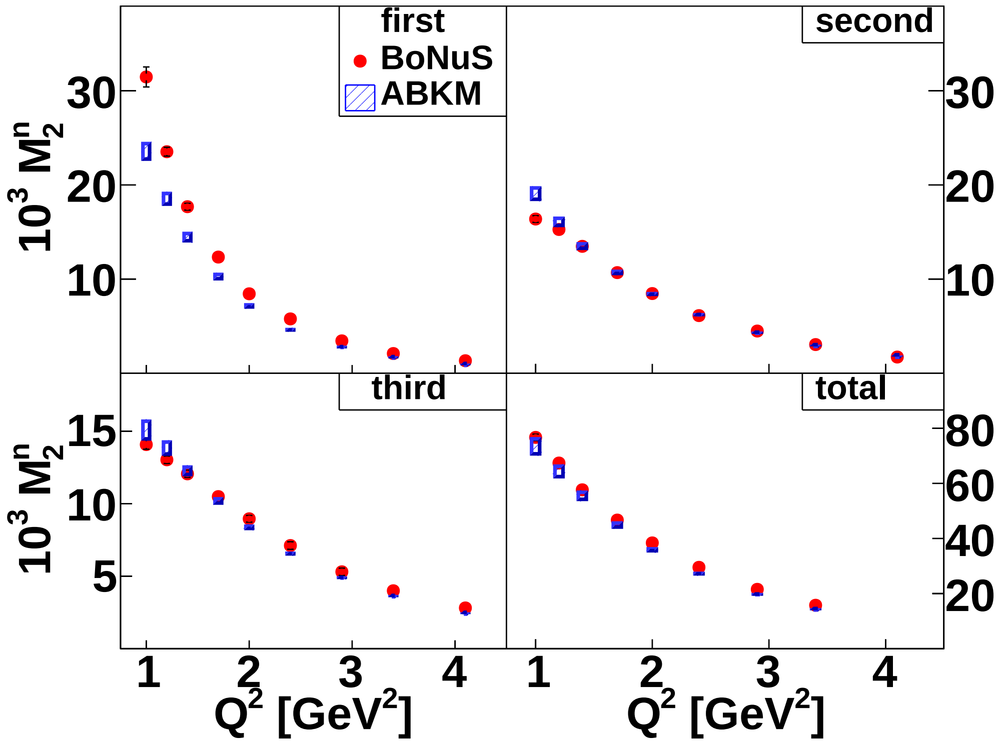

Figure 3: BONuS neutron truncated moments as a function of Q^2 (closed circles). For comparison the blue rectangles are the moments obtained from the ABKM parameterization [23] including target mass and higher twist corrections.

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