Quark-Hadron Duality and Nucleon Valence Structure

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A newly-obtained data sample of inclusive electron-nucleon scattering from deuterium and hydrogen targets at Jefferson Lab has been analyzed for precision tests of quark-hadron duality. In all cases, duality appears to be a non-trivial dynamic property of the nucleon structure function. Assuming duality, the proton magnetic form factor is extracted from the inelastic data alone, and found to be in good agreement with the world's data. Higher twist contributions are found to be small on average, even down to $Q^2 \approx 0.5$ GeV^2. The investigation yields a scaling curve from duality arguments which resembles deep-inelastic neutrino-nucleus scattering data, indicating a potential sensitivity to valence and valence-like structure.

1. Introduction

The interpretation of the resonance region in inclusive electron-proton scattering and its possible connection with deep inelastic scattering has been a subject of interest for nearly three decades since quark-hadron duality ideas, which successfully described hadron-hadron scattering, were first extended to electroproduction. Bloom and Gilman [1] showed that it was possible to equate the nucleon resonance region structure function $\nu W_2(\nu, Q^2)$ (at some typically low Q^2 value) to the structure function F_2 in the deep inelastic regime of electron-quark scattering (at some higher value of Q^2). The resonance structure function was demonstrated to be equivalent in average to the deep inelastic one, with these averages obtained over the same range in a scaling variable $\omega' = 1 + W^2/Q^2$.

This relationship between resonance electroproduction and the scaling behavior observed in deep inelastic scattering suggests a common origin for both phenomena. Inclusive deep inelastic scattering on nucleons is a firmly-established tool for the investigation of the quark-parton model. At large enough values of W and Q^2, QCD provides a rigorous description of the physics that generates the Q^2 behavior of the nucleon structure function $F_2 = \nu W_2$. An analysis of the resonance region in terms of QCD was first presented in [2,3], where Bloom and Gilman's approach was re-interpreted, and the integrals of the average scaling curves were equated to the non-singlet n =2 QCD moments of the F_2 structure function. The moments can be expanded, according to the operator product expansion, in powers of $1/Q^2$, and the fall of the resonances along a smooth scaling curve with increasing Q^2 was explained in terms of this QCD twist expansion of the structure function. The conclusion of [2] was that changes in the lower moments of the F_2 structure function due to higher twist effects are small, so that averages of this function over a sufficient range in x at moderate and high Q^2 are approximately the same. Duality is expected to hold so long as $O(1/Q^2)$ or higher inverse power scaling violations are small.

Substantial progress has been made both theoretically in understanding QCD in the past twenty years and experimentally in determining the scaling behavior of the F_2 structure function. Combining the latter with the new precision resonance data here presented [4], it is now possible to revisit quark-hadron duality with a more quantitative approach, addressing the recent theoretical interest in the topic.

2. Verification of Quark-Hadron Duality

Sample νW_2 spectra extracted from the measured differential cross sections from hydrogen are plotted in Fig. 1 as a function of the Nachtmann scaling variable $\xi = 2x/(1+4M^2x^2/Q^2)$. It has been shown that ξ is the correct variable to use in studying QCD scaling violations in the nucleon [5,2]. The arrows indicate values of $x = 1$ (elastic scattering) for the three values of Q^2 shown. The solid and dashed curves are from a parameterization [6] of deep inelastic proton structure function data at $Q^2 = 10$ and 5 GeV^2, respectively. Notice that the resonance spectra at different Q^2 appear at different ξ on the deep inelastic scaling curve, but that the curve generally represents an average of the data at the disparate kinematics. This is a manifestation of the original Bloom and Gilman observation.

Figure 1. Sample hydrogen νW_2 structure function spectra obtained at $Q^2 = 0.45, 1.70$, and 3.30 GeV^2. Arrows indicate elastic kinematics. The solid (dashed) line represents the NMC fit (Ref. 9) of deep inelastic structure function data at $Q^2 = 10$ (GeV^2) ($Q^2 = 5$ GeV^2).

To quantify the observed duality, the ratio of the νW_2 structure function obtained from the resonance data, integrated in the region of ξ from pion threshold to the onset of the deep inelastic regime ($W^2 = 4$ GeV^2), compared to the F_2 deep inelastic structure function integrated in the same region of ξ, was evaluated. The total strength in the region below $W^2 = 4$ GeV^2, including the elastic and nucleon resonance regions, was found to be equivalent within 10% to the scaling curves evaluated, even at Q^2 values as low as 0.2 GeV^2. This indicates that higher twist effects are negligible if the data are integrated over the *full* region.

If the higher twist contributions are small in the region of the data, then duality allows for the determination of the nucleon form factor from data obtained in the purely inelastic region. Fig. 2 depicts the proton magnetic form factor, G_M^p, extracted using the NMC and JLab scaling curves integrated over the *entire* range in ξ, i.e. from 1 to the deep inelastic. The integral obtained from the resonance data (which starts at pion threshold rather than $\xi = 1$) is then subtracted from the scaling integrals. The magnetic form factor is then extracted from the remaining integrated strength using the prescription of [2]. In both cases, the extracted integrals are in remarkably good agreement with the Gari-Krümpelmann model [11] of the world's magnetic form factor data. For the JLab fit worst case, the proton magnetic form factor is reproduced to within 30% of the accepted value.

Figure 2. The proton magnetic form factor extracted from the inelastic data using duality assumptions as described in the text. The extracted data are compared to the model curve of Ref. 11

3. Valence Sensitivity

The extracted F_2 data in the nucleon resonance region are shown in Fig. 3a for the hydrogen target, and in Fig. 3b for the deuterium target. It is clear from Fig. 3 that indeed the data oscillate around an average scaling curve. This suggests that the higher-twist terms in the *averaged* kinematic region are still small [2,3]. The curves shown represent an average scaling curve extracted from our data (solid), and a global fit to the world's deep inelastic data [9] for a fixed $Q^2 = 10$ GeV^2 (NMC10, dashed), and, in Fig. 3a, for a fixed $Q^2 = 2$ GeV^2 (NMC2, dot-dashed). Whereas the difference between the NMC fit for fixed $Q^2 = 10$ GeV^2 and $Q^2 = 2$ GeV^2 is small, and expected from logarithmic scaling violations, the difference between these NMC fits and our data (with $Q^2 \approx 0.3$ GeV^2) derived from the duality-averaged scaling curve is dramatic at low ξ. Clearly, the Q^2 dependence of F_2 in this low ξ region is a signature of non-perturbative effects.

Figure 3. Extracted F_2 data in the nucleon resonance region for hydrogen (a) and deuterium (b) targets, with curves as described in the text. For clarity, only a selection of the data are shown here.

In the deuterium case (Fig. 3b), the *input* distributions at $Q^2 = 0.34$ GeV^2 for the next-to-leading order calculations of Glück, Reya and Vogt (GRV, dot-dashed) [13] are displayed. In the GRV model, the shape of the gluon and quark-antiquark sea seen by experiment is dynamically generated through gluon bremsstrahlung. As an example, although no strange sea is assumed at the finite Q^2 value for the input distribution, the strange sea carries a finite fraction of the nucleon's momentum at $Q^2 \simeq 10$ GeV^2, not in disagreement with measured values [12,14,15]. The GRV input distribution has been fixed by assuming only valence and valence-like (the input sea quark distributions also approach zero as $x \to 0$) quark distributions at a finite Q^2 value, constrained with appropriate Q^2-evolutions to SLAC, NMC, and BCDMS [7,16,17] deep inelastic F_2 data at $Q^2 = 5$ GeV^2. The dotted curves in Figs. 3a and 3b denote the GRV input distributions reflecting *only* their valence quark distributions (i.e. there are no sea quark contributions at all). At large ξ, the discrepancy between the GRV input distributions (at $Q^2 = 0.34$ GeV^2) and the data can be attributed to the logarithmic scaling violations. Although in the very low Q^2 region below 1 GeV^2 non-perturbative higher-twist contributions are expected to become relevant [18], the similarity of the input distributions of Ref. [13] and the average scaling curve given by the nucleon resonance data suggests that the duality-averaged scaling curve is dominated by valence-quark or valence-like quark contributions.

To verify this, Fig. 4 shows a comparison of the averaged scaling curve from the deuterium resonance data (solid curve) with a selection of the world's data for the xF_3 structure function. The xF_3 structure function can be accessed by deep inelastic neutrino-iron scattering [19,20], and is associated with the parity-violating term in the hadronic current. Thus xF_3 measures in the quark-parton model the difference between quark and anti-quark distributions, and is to first order insensitive to sea quark distributions. To enable a direct comparison, the JLab average scaling curve is multiplied by a factor of 18/5 to account for the quark charges, and a straightforward nuclear correction to the xF_3 data is applied to obtain neutrino-deuterium data [21]. Although the agreement between the averaged F_2 scaling curve of the deuterium resonance region and the deep inelastic neutrino xF_3 data is not perfect, the similarity is striking. The observation of Bloom and Gilman that there may be a common origin between the electroproduction of resonances and deep inelastic scattering seems to be true for even the lowest values of Q^2 if one assumes sensitivity to a valence-like quark distribution only.

Figure 4. A comparison of the duality-averaged F_2 scaling curve, determined from the nucleon resonance region data with a deuterium target, with the CDHSW data on xF_3 from deep inelastic neutrino-nucleus scatttering data.

4. Conclusions

By utilizing new inclusive data in the resonance region at large x, it has been possible to revisit quark-hadron duality experimentally for the first time in nearly three decades. The original duality observations are verified, and the QCD moment explanation indicates that higher twist contributions to the F_2 structure function are small or cancelling, even in the low Q^2 regime. The magnetic form factor has been extracted from the inelastic data using duality techniques and is in good agreement with global measurements. Cross sections have been measured for both hydrogen and deuterium targets, and the F_2 structure function extracted from these oscillates around an average scaling curve, down to the lowest momentum transfers measured. This average curve resembles deep inelastic xF_3 structure function data, indicating a lack of sensitivity to sea quarks.

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