QUARK HADRON DUALITY TESTS ON POLARIZED STRUCTURE FUNCTIONS USING CLAS

T.A. FOREST *

Center for Applied Physics Studies
Louisiana Tech University
P.O. Box 10348
Ruston, LA 71270, USA
E-mail: tforest@jlab.org

FOR THE CLAS COLLABORATION

Inclusive electron-nucleon scattering data from Jefferson Lab's Hall B have been analyzed to test quark-hadron duality for the polarized structure function $g_1(x, Q^2)$ over a Q^2 range from 0.2 to 3.5 GeV^2/c^2. Incident polarized electrons of energy 1.6 and 5.7 GeV were scattered by polarized $^{15}NH_3$ and $^{15}ND_3$ targets. The measured values of $g_1(x, Q^2)$ in the resonance region at Q^2 above 2.0 GeV^2/c^2 appear to be equivalent to a fit of $g_1(x, Q^2)$ in the deep inelastic scattering region at high Q^2. A quantitative test comparing the ratio of the first moment in the resonance region to the first moment in the deep inelastic region is consistent with unity when Q^2 goes beyond 2.0 GeV^2/c^2 but substantially departs from unity when $Q^2 < 1.0$ GeV^2/c^2.

1. Introduction

The theoretical description of baryon-baryon and baryon-lepton interactions has typically utilized quark-gluon degrees of freedom for high energy interactions and hadronic degrees of freedom at low energies. In 1970, Bloom and Gilman experimentally observed[1] that electroproduction measurements of the nucleon resonance region structure function, $\nu W_2(x, Q^2)$, at low values of the four momentum transfer squared ($0.4 < Q^2 < 2.4$ GeV^2/c^2) were equivalent to measurements of the structure function $F_2(x)$ made at $Q^2 \approx 7$ GeV^2/c^2, in the deep inelastic scattering (DIS) region, when the resonance data were averaged over the same range in scaling variable $\omega' = 1 + W^2/Q^2$ where W represents the invariant mass. To explain the experimental observations made by Bloom and Gilman, A. de Rújula, H.

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Georgi and H.D. Politzer employed a perturbative operator product expansion of QCD structure function moments[2]. Higher twist corrections (initial and final state interactions between the struck quark and target remnant) appeared to be sufficiently small or were canceling such that the values of the lower moments of F_2, averaged over a sufficient range in the fraction of the nucleon's momentum carried by the elastically scattered parton (x), were the same over a range of Q^2. This dual nature is commonly referred to as duality.

The data reported by Niculescu *et. al* [3] extended the Bloom and Gilman measurements and performed a quantitative comparison by testing the veracity of the expression

$$\int_{\xi_{min}}^{\xi_{max}} \nu W_2(\xi, Q^2) d\xi = \int_{\xi_{min}}^{\xi_{max}} F_2(\xi, Q^2 \to \infty) d\xi \tag{1}$$

where the Nachtmann[4] variables ξ_{min} and ξ_{max} are determined by the invariant mass cuts of 2 GeV, the conventional resonance-DIS border, and 1.08 GeV, the pion threshold ($\xi \equiv 2x/(1+\sqrt{1+4M^2x^2/Q^2})$). Equation 1 was tested as a function of Q^2 by using the data to evaluate the left hand side and three different models[5,6,7] to evaluate the right hand side. Equation 1 was shown to be valid at the 10% level for $Q^2 > 1$ GeV^2/c^2. If contributions from elastic scattering are included, then Equation 1 was found to hold at the same level down to $Q^2 = 0.2$ GeV^2/c^2.

Duality for the polarized structure function $g_1(x, Q^2)$ can also be investigated by comparing the integral of g_1 over the resonance region with that over an equivalent region in x in the deep inelastic region:

$$\int_{x_{min}}^{x_{max}} g_1^{res}(x, Q^2) dx = \int_{x_{min}}^{x_{max}} g_1^{DIS}(x, Q^2) dx. \tag{2}$$

The veracity of Equation 2 was checked by the HERMES collaboration[8] by comparing the average asymmetry $A_1(x, Q^2)$ in the resonance region with a Q^2 independent fit to the DIS data. The data between 1.2 GeV^2/c^2 and 12 GeV^2/c^2 were grouped into three Q^2 bins of about 1.5, 3, and 5 GeV^2/c^2. The equality Eq. 2 was found to hold to within 20% at the lowest Q^2 bin and no large effects due to target mass corrections were reported.

Recently, there has been some effort to determine if the kinematic range over which the observables are averaged may be reduced, an effect referred to as local duality. This has created two categories of duality based on the kinematic interval used for averaging the observable. Observables which are averaged over the entire resonance region, traditionally $W < 2$ GeV, are typically used to evaluate "global duality" while "local duality" is evaluated by averaging over a subset of resonances[12]. One can perform a similar ratio test as in Eq. 1 where on the left-hand side ξ ranges over the region of one of the three prominent resonances $(\Delta P_{33}(1232), S_{11}(1535), F_{15}(1680))$. The authors of Ref. [3] found that the ratio to the integral of the average scaling curves in the same region of ξ was also unity to within 10% over the same Q^2 range[3].

The Cebaf Large Acceptance Spectrometer (CLAS) collaboration's EG1 run group at Jefferson Lab has completed taking data to measure polarized structure functions in Hall B. The tests of quark-hadron duality reported here are based on an analysis of the data taken at incident longitudinally polarized electron energies of 1.6 GeV and 5.7 GeV. The CLAS facilitates a kinematic coverage from 0.2 to 3.5 GeV^2/c^2 in Q^2 and x from 0.1 to 0.8 for this data set.

2. Apparatus

A detailed description of the CLAS may be found in Reference [13]. The spectrometer is equipped with a superconducting magnet and three drift chamber regions[14] which cover roughly 80% of the azimuthal angles and reconstruct the momentum of a charged particle which scatters within a polar angular range between 8^o and 142^o. An array of scintillator counters[15] covers the above angular range and is used to determine the time of flight for charged particles. A forward angle electron calorimeter[16], 16 radiation lengths thick, exists up to a polar angle of 45^o and is used along with the drift chambers to separate pions from electrons for this analysis. A Cherenkov detector[17] covers the same angular range as the calorimeter, is used in conjunction with the calorimeter to create a coincidence trigger, and allows the offline analysis to reject pions from the data sample.

The polarized structure function data were collected using ammonia ($^{15}NH_3$) and deuterated ammonia ($^{15}ND_3$) targets, polarized via Dynamic Nuclear Polarization (DNP)[18], in conjunction with longitudinally polarized electrons ranging in energy from 1.6 GeV up to 5.7 GeV. Although the incident electron polarization and target polarization were monitored by a Møller polarimeter and a Nuclear Magnetic Resonance (NMR) system respectively during the experiment, the measured elastic scattering asymmetry observed from events contained within the same data set as inelastic scattering events, a feature of the large acceptance detector, were used to determine the product of beam and target polarization $(P_b \times P_t)$. The measured product of $P_b \times P_t$ for the 1.6 GeV data set averaged to 54 ± 0.5% using the $^{15}NH_3$ target and 18.5 ± 0.3% using the $^{15}ND_3$ target. The data taken using a 5.7 GeV incident electron had an average value for $P_b \times P_t$ of 51 ± 1% using the $^{15}NH_3$ target and 23.2 ± 3.3% using the $^{15}ND_3$ target.

3. Preliminary Results

The polarized structure function $g_1(x, Q^2)$ as a function of the Nachtmann scaling variable (ξ) is shown for the proton in Figure 1 and for the deuteron in Figure 2. Unlike the method used in Reference[8], $g_1(x, Q^2)$ is extracted from the measured double spin asymmetry $A_\parallel$ such that

$$g_1(x, Q^2) = \frac{\tau}{1+\tau}\left[\frac{A_\parallel}{D} + \left(\frac{1}{\sqrt{\tau}} - \eta\right) A_2(x, Q^2)\right] F_1(x, Q^2) \qquad (3)$$

where $\tau \equiv \nu^2/Q^2$, $D = \frac{1-(1-y)\epsilon}{1+\epsilon R(x,Q^2)}$, $F_1(x, Q^2)$ represents the unpolarized structure function, and $R(x, Q^2)$ is the ratio of the longitudinal photo absorption cross section (σ_L) to the transverse (σ_T)[19]. $y \equiv \nu/E$ is the fractional energy loss of the incident electrons, ν is the energy transferred to the target ($E - E'$), and ϵ is the magnitude of the virtual photon's longitudinal polarization given by

$$\epsilon = \left[1 + 2(1 + \nu^2/Q^2)\tan^2(\theta/2)\right]^{-1}$$

where θ is the electron scattering angle. The double spin asymmetry $A_\parallel$ is defined as

$$A_\parallel = \frac{\sigma_{\uparrow\downarrow} - \sigma_{\uparrow\Uparrow}}{\sigma_{\uparrow\downarrow} + \sigma_{\uparrow\Uparrow}} \qquad (4)$$

$$(5)$$

In this analysis, the functions $R(x, Q^2)$, $F_1(x, Q^2)$ and $A_2(x, Q^2)$ were extracted from fits to the present world data set[20]. The parametrization of $R(x, Q^2)$ is an update to the model used in Reference[8] and included data from recent measurements in the proton resonance region[21].

The structure function $g_1(x, Q^2)$ is predominantly negative for both the proton and deuteron at values of $Q^2 < 1$ GeV^2/c^2 and values of ξ which kinematically correspond to the $\Delta(1232)$ resonance (indicated by the triangles in Fig. 1). This observation is consistent with our description of the $\Delta(1232)$ resonance as a spin 3/2 state. In the limit of infinite Q^2, the structure function $g_1(x, Q^2)$ is proportional to the asymmetry A_1 and F_1 such that $A_1 \propto \sigma^{1/2} - \sigma^{3/2}$ (if g_2 and A_2 are sufficiently small) and F_1 is the unpolarized structure function. The coupling of a spin 1 virtual

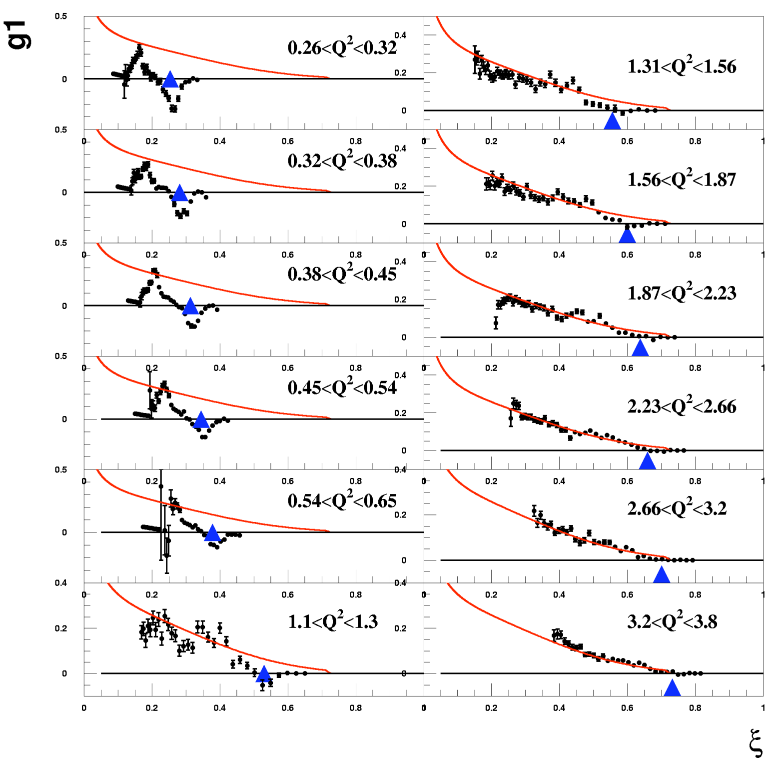

Figure 1. Measurements of the polarized structure function $g_1(x, Q^2)$ for the proton as extracted from the EG1 $^{15}NH_3$ data set. The line represents a fit[20] to the world's DIS data at $Q^2 = 10$ GeV^2/c^2. The triangles indicate the kinematic position of the $\Delta(1232)$ resonance.

photon and a spin 1/2 nucleon to a spin 3/2 $\Delta(1232)$ results in a smaller amplitude for a total spin 1/2 z-projection ($S_z = 1/2$) final state than

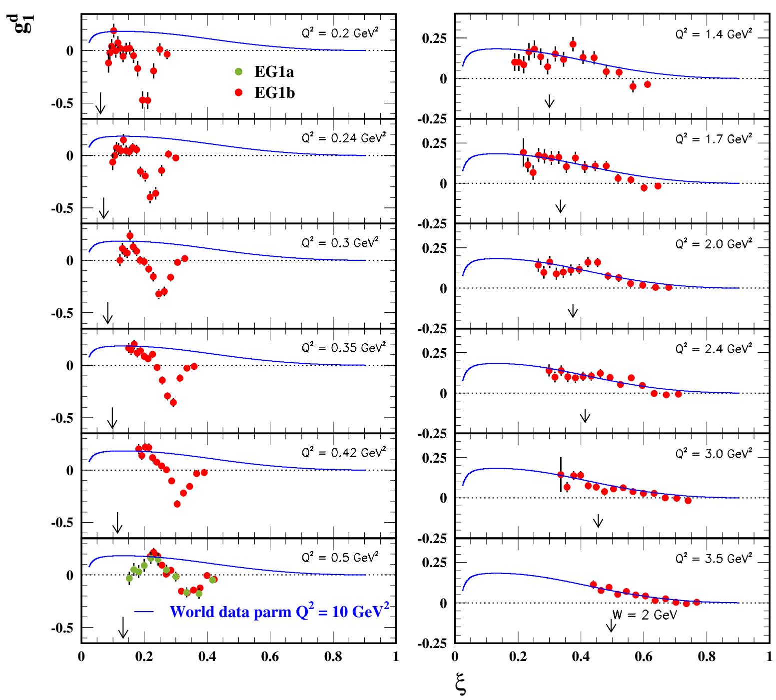

Figure 2. Measurements of the polarized structure function ($g_1(x, Q^2)$) for the deuteron as extracted from the EG1 $^{15}ND_3$ data set. The arrow indicates the kinematic location of the conventional DIS domain ($W > 2$ GeV). The line represents a fit[20] to the world's DIS data at $Q^2 = 10$ GeV^2/c^2.

$S_z = 3/2$ and as a result the difference $\sigma^{1/2} - \sigma^{3/2}$ is expected to be negative. As Q^2 becomes substantially larger than 1 GeV^2/c^2 though, the data indicate that $g_1(x, Q^2)$ moves closer to zero and may even be positive in a kinematic region which corresponds to the $\Delta(1232)$ resonance. As a result of this behavior, the generalized GDH integral[22] for the proton becomes negative as Q^2 falls below 0.5 GeV^2/c^2 [23]. Alternatively, the contribution of the $\Delta(1232)$ resonance to the generalized GDH integral decreases as Q^2 increases. One may expect the $\Delta(1232)$ to play a similar role in Equation 2 to the point that the equality is not maintained unless an equally large but opposite contribution, such as the elastic contribution, is included.

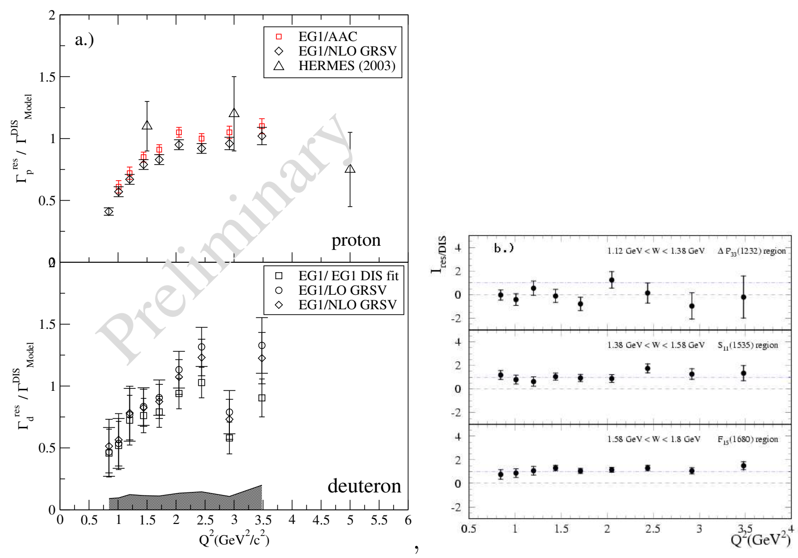

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Figure 3. a.)The ratio of the first moment of $g_1(x, Q^2)$ measured in the resonance region (Γ^{res}) to the first moment of a global fit to $g_1(x, Q^2)$ in the deep inelastic region (Γ^{DIS}_{Model}) for several different Q^2 values. The top plot uses the proton data and the bottom plot is for the deuteron. Both integrals are over the same kinematic region in x. Neither integral included elastic contributions. (Γ^{DIS}_{Model}) was evaluated using fits to the world data set given by EG1[20], AAC[24] and the GRSV[25]. b.) The same ratio as in a.) using only the ND_3 target and three intervals of W in the resonance region.

To test duality, Equation 2 is cast in the form

$$\Gamma^{res}/\Gamma^{DIS} \equiv \frac{\int_{x_{min}}^{x_{max}} g_1^{res}(x, Q^2)dx}{\int_{x_{min}}^{x_{max}} g_1^{DIS}(x, Q^2)dx}. \tag{6}$$

The integrations limits x_{min} and x_{max} are determined by the measured invariant mass (W) limits for a given Q^2 bin. The ratio ($\Gamma^{res}/\Gamma^{DIS}$) is shown in Figure 3a. The EG1 data are in general agreement with the HERMES data, but provide a much more precise and detailed picture of the onset of duality and may be used to investigate local duality as well, see Figure 3b. Figure 3a indicates that the ratio test begins to fail at the two sigma level when Q^2 becomes less than 1 GeV^2/c^2. Equation 2 is valid within 10% for the proton and 30% for the deuteron after Q^2 goes beyond 2 GeV^2/c^2.

Figure 3b evaluates Equation 2 for Deuterium using the three separate W intervals within the resonance region ($\Delta P_{33}(1232), S_{11}(1535), F_{15}(1680)$)

used for the unpolarized structure function measurements in Ref. [3]. The $S_{11}(1535)$ and $F_{15}(1680)$ resonance regions show local duality characteristics down to a Q^2 of 1 GeV^2/c^2, considerably lower than the 2 GeV^2/c^2 found for global duality. Local duality does not seem to be valid around the $\Delta P_{33}(1232)$ resonance. Close and Isgur[12] have argued, in the framework of a Quark Model, that local duality may be observed if the negative contributions from the $\Delta P_{33}(1232)$ were offset by incorporating the nucleon ground state.

4. Summary

Measurements of the polarized structure function $g_1(x, Q^2)$ have illustrated the principle of quark-hadron duality for values of Q^2 above 2.0 GeV^2/c^2 for the proton and deuteron but substantially depart from this principle when Q^2 is less than 1 GeV^2/c^2. The common conjecture is that higher order terms in the perturbative QCD twist expansion, which are expected to dominate as $x \to 1$, are instead canceling or very small in kinematic regions where duality holds[26]. Liuti, *et. al.*[26] further assert that, in the case of polarized structure functions, contributions from dynamical Higher Twists become large and negative at low x and Q^2 unlike the unpolarized structure functions. This may be one reason why the onset of duality for $g_1(x, Q^2)$ occurs at substantially larger values of Q^2 than the unpolarized structure function F_2. Local duality does appear to hold for the deuteron data set when resonances above the $\Delta P_{33}(1232)$ are grouped according to the averaging procedure outlined by Close and Isgur[12]. A future direction will be to determine if local duality holds when the ground state and $\Delta P_{33}(1232)$ are combined. Analysis of the data taken at electron energies of 2.4 GeV and 4.2 GeV is underway and should improve the precision of these measurements at moderate Q^2.

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