Quark-Hadron Duality in Neutron ($^3$He) Spin Structure

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We present experimental results of the first high-precision test of quark-hadron duality in the spin structure function $g_1$ and the asymmetry $A_1$ of the neutron and $^3$He using a polarized $^3$He target in the four-momentum-transfer-squared range from 1.0 to 3.6 (GeV/c)$^2$. We observe global duality for the structure function $g_1$ for $Q^2 \gtrsim 1.8$ (GeV/c)$^2$ in both $^3$He and the neutron. We have also formed the photon-nucleon asymmetry $A_1$ in the resonance region for $^3$He and, as seen in deep inelastic scattering measurements, we found no strong $Q^2$-dependence above 2.2 (GeV/c)$^2$.

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Lepton-nucleon scattering experiments have provided a window into the fundamental sub-structure of the nucleon and helped establish quantum chromodynamics (QCD) as the fundamental theory governing the strong interaction. An important subset of these experiments has probed the nucleon spin structure using polarized lepton beams and polarized targets.

In high-energy lepton-nucleon scattering, the lepton interacts with the nucleon by exchanging a virtual photon with one of the quarks in the nucleon. This process depends on two variables, $Q^2$ and $x$. The quantity $Q^2$ is the four-momentum squared of the exchanged virtual photon, $x = Q^2/(2M\nu)$ is the Bjorken scaling variable where $M$ is the mass of the nucleon and $\nu$ is the energy transfer between the lepton and the nucleon. The invariant mass $W$ of the virtual photon-nucleon system is related to $Q^2$ and $x$ through $W^2 = M^2 + Q^2/x - Q^2$. The scattering cross section is parametrized in terms of two unpolarized structure functions ($F_1$ and $F_2$) and two polarized structure functions ($g_1$ and $g_2$). These structure functions are related to the polarized and unpolarized quark distribution functions in the nucleon. Another observable that provides a direct insight into the polarized quark distributions in the nucleon is the photon-nucleon asymmetry,
$A_1$, which is approximately equal to the ratio of the polarized and unpolarized structure functions, $g_1/F_1$.

In the deep inelastic scattering (DIS) region, at asymptotically large values of $Q^2$ and $W$, the electron scatters off a point-like free quark. As a result, the structure functions are independent of $Q^2$ (x-scaling), modulo logarithmic corrections due to gluon radiation. On the other hand, at low values of $Q^2$ and $W$, the quarks strongly interact with each other and resonance production dominates. In this nucleon resonance region, the electron can be considered to be scattering off a correlated cluster of quarks and gluons, the nucleon. Thus, the structure functions are expected to depend strongly on $Q^2$. However, more than 30 years ago, Bloom and Gilman [1] observed a remarkable similarity between the unpolarized structure function data taken in DIS and in resonance kinematics at the Stanford Linear Accelerator Center (SLAC). They reported that the scaling curve seen for DIS data at high $Q^2$ is an average over the resonances at lower $Q^2$ but at the same value of $x$.

Several years after the observation of duality, De Rujula, Georgi and Politzer [2] suggested an explanation of duality in a framework based on the QCD operator product expansion (OPE) of the moments of the structure functions. They pointed out that the experimental observation of duality, i.e. the $Q^2$-independence of the moments of the structure functions even at low $Q^2$, indicated that the higher-twist contributions are small or cancel on average. The authors, however, could not explain why the higher-twist contributions are suppressed in this manner. Since then there have been numerous theoretical attempts to explain quark-hadron duality. For a review of the full body of theoretical work see Ref. [3].

Duality for $F_2$ can be expressed as

$$\int_{x_1}^{x_2} dx \frac{F_2^{\text{res}}(x, Q^2)}{x} = \int_{x_1}^{x_2} dx \frac{F_2^{\text{DIS}}(x, Q^2)}{x},$$

(1)

where $F_2^{\text{res}}(W^2, Q^2)$ is the structure function measured in the resonance region at low $Q^2$ while $F_2^{\text{DIS}}(W^2, Q^2)$ is the scaling function evolved down to the same $Q^2$. Global duality is said to hold when the integration is performed over the entire resonance region. Local duality would be observed if the above equality holds when integrated over a resonance bump [4]. Data from Jefferson Lab (JLab) Hall C [5] have demonstrated that for unpolarized structure functions Bloom-Gilman duality holds to 10% down to $Q^2 = 0.5$ (GeV/c)^2. These data also show that local duality holds for each of the three prominent resonance regions.

The observation of duality in unpolarized structure functions raises the exciting question whether quark-hadron duality holds for spin structure functions as well. Indeed duality in spin structure functions would be even more intriguing than in the unpolarized case; since the spin structure functions come from the differences of cross sections, they are not necessarily positive definite. As a result a spin structure function measured at the same value of $x$ in resonance and DIS regions can, in principle, have opposite signs. For example, the contribution to $g_1^p$ at the Delta resonance is negative at low $Q^2$, while the scaling curve for $g_1^p$ is positive.

Recent data from Jefferson Lab [6, 7] and DESY [8] have shown that quark-hadron duality holds globally, in the case of polarized structure functions of the proton and the deuteron, down to $Q^2 = 1.7$ (GeV/c)^2. However the high-precision results from Jefferson Lab Hall B indicated that local duality is violated for the proton and deuteron polarized structure functions at the Delta resonance even for $Q^2$ values as high as 5.0 (GeV/c)^2 [6].

Polarized structure functions measured previously over the low $Q^2$ range of 0.1-0.9 (GeV/c)^2 using a polarized $^3$He target as an effective neutron target [9], have shown hints of quark-hadron duality for the polarized structure functions of the neutron. However, until now there has been no resonance-region neutron spin-structure data in the intermediate $Q^2$-range where quark-hadron duality is expected to manifest. This has prevented a precision test of quark-hadron duality for neutron spin-structure functions. In this letter we report results from Jefferson lab experiment E01-012 where we measured polarized structure functions in the resonance region over the $Q^2$-range up 1.0-4.0 (GeV/c)^2 using a polarized $^3$He target as an effective polarized neutron target. These new results provide a precision test of quark-hadron duality for neutron spin-structure functions.

E01-012 took place in early 2003 in Hall A at Jefferson Lab where inclusive scattering of longitudinally polarized electrons from a longitudinally or transversely polarized $^3$He target was studied. We formed asymmetries and polarized cross-section differences for data taken at a scattering angle of 25° for three incident beam energies, 3.028, 4.018 and 5.009 GeV, and at 32° for an incident beam energy of 5.009 GeV.

The polarized electron beam was produced from a strained GaAs photocathode which was illuminated by circularly polarized light. The helicity of the beam was pseudo-randomly reversed at a rate of 30 Hz. The beam polarization was monitored by a Möller polarimeter and was found to be between 70 and 85% for the production data with a total uncertainty of 3.4%. The beam current delivered on the target was kept below 15 μA in order to limit target depolarization.

The polarized target consists of two connected chambers with an admixture of rubidium (Rb) and $^3$He in the upper chamber where spin-exchange optical pumping [10] takes place. About 90 W of 795 nm light produced by fiber-coupled laser diode arrays and an oven heated to 170°C allowed to achieve the optimal polarization. Under running conditions, the $^3$He density was 3.20 x 10^20 cm^-3 in the lower chamber where the electron beam passed through and from which the Rb was absent due to the lower temperature. The polarization of the target was monitored by two independent polarimeters: one based on nuclear magnetic resonance (NMR) [11] and the other on the electron paramagnetic resonance frequency shift.
(EPR) [12]. Both polarimeters rely on the adiabatic fast passage (AFP) technique [11]. The average target polarization was 0.38 ± 0.02. The cells also contain a small amount of nitrogen gas (at about 1% of the 3He density) that quenches radiative transitions which limit the optical pumping efficiency. However, this introduces a dilution factor in the extracted physics quantities. Nitrogen dilution factors were determined from measurements on a reference cell filled with nitrogen gas and were found to dilute the asymmetries by 5 to 9%. The asymmetry of elastic scattering \( e - 3\text{He} \) was extracted from data taken at an incident beam energy of 1.046 GeV and a scattering angle of 16° in order to obtain an independent measurement of the product of beam and target polarizations and nitrogen dilution. Theoretical and experimental elastic asymmetries were found to agree within a total uncertainty of 6% [13].

Both Hall A high resolution spectrometers [14] were set at the same momentum and angle configurations and tuned to optimize the detection of the scattered electrons. This symmetric configuration has the advantage of obtaining two independent measurements and therefore controlling part of our systematic uncertainties. A gas Čerenkov counter combined with a two-layered lead-glass calorimeter provided particle identification with a pion rejection better than 10^3:1 while keeping the electron efficiency better than 99%. The remaining contamination from pions to the asymmetries has a negligible maximum effect on the asymmetries of 15 ppm [13], which is much smaller than the statistical uncertainties.

We formed the longitudinal and transverse polarized cross-section differences using:

\[
\Delta \sigma_{\|{\perp}} = \frac{\partial^2 \sigma^{\|{\perp}}(\rightarrow)}{\partial \Omega \partial E'} - \frac{\partial^2 \sigma^{\|{\perp}}(\rightarrow)}{\partial \Omega \partial E'} \tag{2}
\]

where the superscript \( \| \) (\( \perp \)) represents the incident electron spin and \( \|^\perp \) (\( \rightarrow \)) the target spin. The quantities \( E' \) and \( \Omega \) correspond to the scattered electron energy and the spectrometer solid angle, respectively. The polarized structure function \( g_1 \) can be formed directly from the polarized cross section differences as follows:

\[
g_1 = \frac{M Q^2 \nu}{4 \alpha^2} \frac{1}{E'(E + E')} \left[ \Delta \sigma_{\|} + \tan \frac{\theta}{2} \Delta \sigma_{\perp} \right] \tag{3}
\]

Here \( \alpha_e \) is the fine structure constant, \( \theta \) is the scattering angle and \( E \) is the energy of the incident electron beam.

External and internal radiative corrections have been applied to the polarized cross-section differences following the formalism of Mo and Tsai [21] for the spin-independent part and the approach of Akhiezer and Shumeiko [22] for the spin-dependent part.

The structure function \( g_1 \) was generated at constant energies and scattering angles. Also extracted was the structure function \( g_2 \) which will be reported in a subsequent publication. Prior to forming the partial moment of \( g_1 \), interpolation of \( g_1 \) to a constant \( Q^2 \) was performed. The coverage of our data allows interpolation of \( g_1 \) to the four \( Q^2 \)-values of 1.2, 1.8, 2.4 and 3.0 (GeV/c)^2. The results for 3He are shown in Fig. 1. The DIS parameterizations of \( g_1 \) for the proton and the neutron, from Blumlein and Böttcher (BB) [17], GRSV group [18], AAC collaboration [19] and Leader, Sidorov and Stamenov (LSS) [20], were evolved to those \( Q^2 \)-values and then combined to obtain the 3He DIS parametrizations using the effective polarization equation [23]:

\[
g_1^3\text{He} = p_n g_1^n + 2 p_p g_1^p. \tag{4}
\]

The effective polarizations of the neutron and the proton are \( p_n = 0.86 \pm 0.02 \) and \( p_p = -0.028 \pm 0.004 \), respectively [24]. All parameterizations were taken at Next-to-Leading Order. Target-mass corrections [25] have been applied to the DIS parameterizations in order to take into account the finite mass of the nucleon. Also plotted are the highest precision world data on \( g_1^3\text{He} \) in the DIS region from SLAC E154 [15] and JLAB E99-117 [16]. It can be observed that our resonance data at \( Q^2 = 1.2 \) (GeV/c)^2 oscillate around the DIS curves and are significantly lower in the \( \Delta(1232) \) region (\( x \simeq 0.65 \)). As \( Q^2 \) increases, our data approach the DIS results indicating quark-hadron
FIG. 2: $\tilde{\Gamma}_{1}^{3He}$ and $\Gamma_{1}^{n}$: test of spin duality on $^{3}\text{He}$ (top) and neutron (bottom). Also plotted are the DIS parameterizations of Blümlein and Bottcher [17] (grey band), GRSV [18] (solid curve), AAC [19] (dashed curve) and LSS [20] (dotted curve) after applying target mass corrections. The open circles are data from JLab E94-010 [9]. The bands on the x-axis represent the systematic uncertainty of each data set.

duality.

To perform a quantitative test of quark-hadron duality, $g_1$ was integrated over the $x$-interval corresponding to the resonance region [26] covered by our data, which is from pion threshold ($x_\pi$) to an $x$ corresponding to $W=1.905$ GeV ($x_{\text{min}}$):

$$\tilde{\Gamma}_{1}(Q^2) = \int_{x_{\text{min}}}^{x_\pi} dx \ g_1(x, Q^2)$$

The experimental $g_1$-integral for the neutron was extracted using the method described in Ref. [27]:

$$\tilde{\Gamma}_{1}^{n} = \frac{1}{p_n} \tilde{\Gamma}_{1}^{3\text{He}} - 2 \frac{P_p}{p_n} \tilde{\Gamma}_{1}^{p}$$

Data from JLab experiment EG1b on the proton spin-structure function [6] were used to perform the neutron extraction. Figure 2 shows the comparison of the integral of $g_1$ over the resonance region to the DIS parameterizations. Data from JLab E94-010 [9] are also plotted and a smooth transition can be observed with our data.

At the lowest $Q^2$, our data deviate slightly from the DIS parameterizations for both $^{3}\text{He}$ and neutron. As $Q^2$ increases, resonance data and DIS parametrization show good agreement indicating global quark-hadron duality holds for $Q^2=1.8$ (GeV/c)$^2$ and above. It is important to note that, for the proton and the deuteron, global duality was previously observed for $Q^2$ above 1.7 (GeV/c)$^2$ [6, 28].

Quark-hadron duality was also studied for the photon-nucleon asymmetry $A_1$. From the parallel and perpendicular asymmetries $A_1$ was extracted as follows:

$$A_1(x, Q^2) = \frac{A_{||}(x, Q^2)}{D(1 + \zeta \eta)} \frac{d}{d(1 + \zeta \eta)}$$

where

$$D = \frac{1 - \epsilon E'}{1 + \epsilon R(x, Q^2)}; \quad d = D \sqrt{\frac{2\epsilon}{1 + \epsilon}}; \quad \zeta = \frac{1 + \epsilon}{2\epsilon}$$

$$\eta = \frac{\epsilon \sqrt{Q^2}}{E - E'}; \quad \epsilon = \frac{1}{1 + 2(1 + \nu^2/Q^2) \tan^2 \frac{\theta}{2}}$$

$D$ is the photon depolarization factor and $\epsilon$ is the photon polarization. The longitudinal to transverse cross-section ratio $R(x, Q^2)$ has never been measured on $^{3}\text{He}$ in the resonance region. We assumed that $R$ is unmodified by the nuclear medium and that quark-hadron duality holds for $R$ [3]. We then studied the sensitivity of $A_1$ to different models of $R$. The systematic effects on $A_1$ were found to be smaller than the relative statistical uncertainties and was added to the systematic uncertainties.
The photon-nucleon asymmetry $A_1$ for $^3$He in the resonance region is presented in Fig. 3. Also plotted are the DIS data in order to provide a direct comparison between the deep inelastic scattering behavior and the resonance data trend. We performed a parametric fit of the $^3$He DIS data resulting in: $x_0^{0.580}(-0.135 + 0.336x - 0.174x^2)(1 + 0.578/Q^2)$. For $Q^2$ below 2.0 (GeV/c)$^2$, it can be seen that $A_1^{^3\text{He}}$ in the vicinity of the $\Delta(1232)$ peak is large and negative unlike the DIS behavior. At higher $Q^2$, our $A_1^{^3\text{He}}$ data cross zero and become positive even in the $\Delta(1232)$ region. This is due to the increasing importance of the non-resonant background with respect to the resonance strength. The most noticeable feature is that, for values of $Q^2$ above 2.2 (GeV/c)$^2$, $A_1^{^3\text{He}}$ from our two data sets agrees very well indicating little or no $Q^2$-dependence; a key feature of the DIS data. Furthermore, these data closely follow the DIS data from E99-117 becoming positive at high $x$, a prediction for DIS data from both pQCD inspired models [31] and Relativistic Constituent Quark models [32].

In summary, global duality has been demonstrated to hold for the neutron and $^3$He polarized structure function $g_1$ down to $Q^2 = 1.8$ (GeV/c)$^2$. We also observed no strong $Q^2$-dependence in the photon-nucleon asymmetry $A_1^{^3\text{He}}$ measured in the resonance region for $Q^2 \geq 2.2$ (GeV/c)$^2$. This lack of $Q^2$-dependence of the resonance data, a behavior expected in the DIS region, provides evidence for duality in $A_1^{^3\text{He}}$. The results presented in this paper are the first precision test of quark-hadron duality for the neutron spin-structure function.

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