SPIN STRUCTURE FUNCTIONS OF THE PROTON AND DEUTERON FROM SLAC EXPERIMENTS E155 AND E155X

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Experiments E155 and E155X at SLAC were polarized deep inelastic scattering measurements of the parallel and perpendicular scattering asymmetries. We extracted the polarized structure functions g_1 and g_2 of the proton and deuteron. Both experiments made precision measurements through a wide range in x and Q^2. These data fall into the kinematic range between existing world data and have good consistency with them. In combination with the other world data, the results for g_1 allow increased constraint on NLO QCD fits to the polarized structure functions. For g_2 no significant world data existed before E155X. The E155X measurement provides information about the higher twist effects in the nucleon.

1. Introduction

The experiments E155[1] and E155X[2] were conducted at the Stanford Linear Accelerator Center in 1997 and 1999. Both experiments used polarized deep inelastic scattering (DIS) of electrons from polarized nuclei to measure the polarized structure functions for the proton and deuteron. E155 measured both g_1 and g_2, and E155X only measured g_2. The structure functions are extracted from the scattering asymmetries of polarized electrons from nucleons with spins aligned parallel ($A_\parallel$) and perpendicular ($A_\perp$) to the electron beam direction using[3]

$$g_1(x,Q^2) = \frac{F_1(x,Q^2)}{d'}\left[A_\parallel(x,Q^2) + \tan\tfrac{\theta}{2}\, A_\perp(x,Q^2)\right] \tag{1}$$

$$g_2(x,Q^2) = \frac{y\, F_1(x,Q^2)}{2d'} \left[\frac{E+E'\cos\theta}{E'\sin\theta} A_\perp(x,Q^2) - A_\parallel(x,Q^2)\right] \tag{2}$$

where E, E', and θ are the electron incident and scattered energies and scattering angle in the lab frame, y is the fraction of the incident energy

transfered in the interaction, F_1 is the unpolarized structure function, and d' contains kinematic factors.

Experiment E155 principally collected longitudinal asymmetry data, while E155X collected perpendicular asymmetry data. In both experiments the scattered electrons were detected in three magnetic spectrometers, with wide momentum acceptance, located at central scattering angles of 2.75°, 5.5°, and 10.5°. The three scattering angles and wide momentum acceptance resulted in data with a broad coverage in x and Q^2.

2. E155 Results for g_1

Since the extraction of g_1 is dominated by the $A_\parallel$ term, E155 used the measured $A_\parallel$ and a model of g_2 to extract g_1 using

$$\frac{g_1}{F_1} = \frac{A_\parallel}{d} + \frac{g_2}{F_1}\frac{2Mx}{2E-\nu} \tag{3}$$

where d is the same as d' from Eqn. (1), M is the nucleon mass, and ν is the energy transfer; an assumption of small θ has been made. The twist-2 prediction of g_2 by Wandzura and Wilczeck[4] was used for g_2

$$g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 g_1(\xi,Q^2)d\xi/\xi. \tag{4}$$

The E155 data for g_1 cover the x range from 0.015 to 0.750 and the Q^2 range from 1.22 GeV^2 to 34.72 GeV^2. Figure 1 shows the E155 data from the deuteron for g_1/F_1 versus Q^2 binned in x. The data fall in Q^2 between the SMC data[5] and the E143 data[3]. The data from the proton (not shown) cover the same range in x and Q^2, and similarly contribute to world data. The spin structure function for the neutron is extracted from those of the proton and deuteron using

$$g_1^n = \frac{2\,g_1^d}{1-1.5\omega_D} - g_1^p \tag{5}$$

where the deuteron D-state probability is $\omega_D = 0.05 \pm 0.01$.

2.1. *E155 parametric fit to g_1*

E155 performed a parametric fit to world data (E155, E143, E154[7], SMC, HERMES[8]), with the restrictions that $Q^2 > 1$ GeV^2 and missing mass $W > 2$ GeV; the fit is the dashed line in Figures 1 and 2. The fit is given

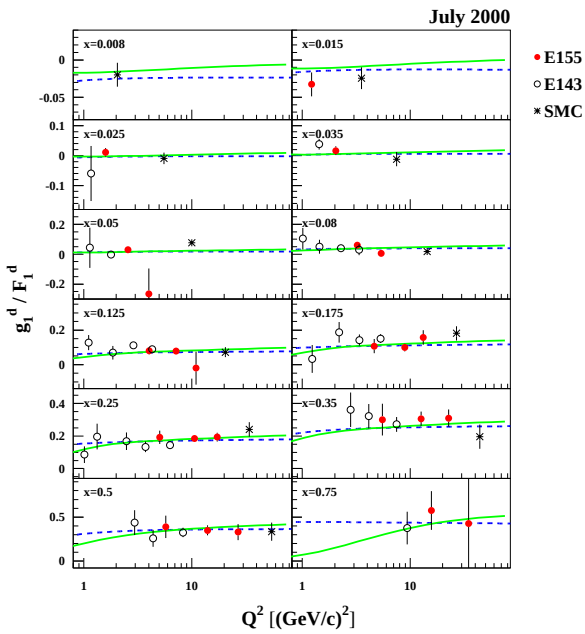

Figure 1. The ratio g_1/F_1 for the deuteron showing the Q^2 dependence per x bin. Data from E155, E143, and SMC are shown with the E155 parametric fit (dashed) and the E155 NLO QCD fit (solid).

by

$$\frac{g_1^p}{F_1^p} = x^{0.700}\left(0.817 + 1.014x - 1.489x^2\right)\left(1 - 0.04/Q^2\right) \tag{6}$$

$$\frac{g_1^n}{F_1^n} = x^{-0.335}\left(-0.013 - 0.330x + 0.761x^2\right)\left(1 + 0.13/Q^2\right). \tag{7}$$

This fit was used to evolve the E155 proton, deuteron, and extracted neutron data to a common value of $Q^2 = 5$ GeV^2 as is presented in Figure 2. The figure includes the data from E143, E154, SMC, and HERMES also evolved to $Q^2 = 5$ GeV^2; the data are in good agreement with each other. The neutron data are coming from two different target materials, deuterium (E155) and ^{3}He (E154 & HERMES) indicating that the nuclear corrections are under control.

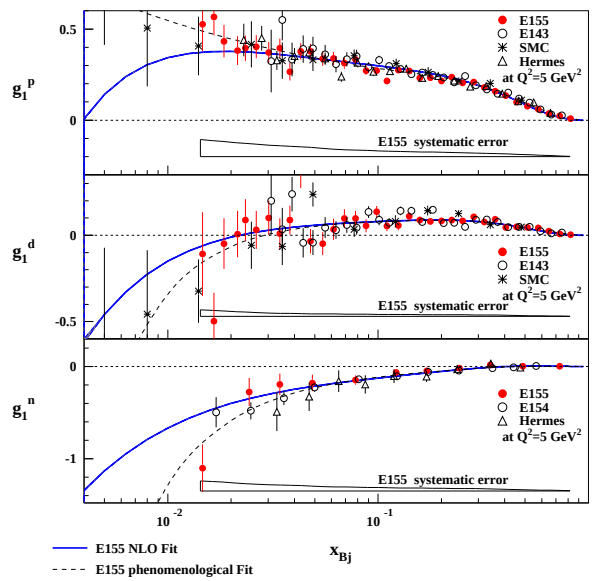

Figure 2. The structure function g_1 for the proton, deuteron, and neutron averaged at a Q^2 of 5 GeV^2. Data were evolved in Q^2 using the parametric fit. Data from E155, E143, E154, HERMES, and SMC are shown with the E155 parametric fit (dashed) and the E155 NLO QCD fit (solid).

2.2. *E155 NLO QCD fit*

In next-to-leading order perturbative QCD, the polarized structure function has contributions from both the polarized quark and gluon distributions

$$g_1(x, Q^2) = \frac{1}{2}\sum_i^{N_f} e_i^2 \left[C_q \otimes \Delta q_i + \frac{1}{N_f} C_G \otimes \Delta G \right] \tag{8}$$

where N_f is the number of active quark flavors[7]. The Wilson coefficients, C_q and C_G, are perturbative series in α_S, calculated in the $\overline{\text{MS}}$ scheme. By parameterizing the polarized quark and gluon distributions and using the form of Eqn. (8) to fit to the world data on g_1, the polarized quark and gluon distributions can be modeled. In the E155 next-to-leading order perturbative QCD fit, the polarized parton distributions were parameterized as a product of the GRV98[9] unpolarized parton distributions and the function, $A_f x^{\alpha_f}$ (where A_f and α_f are parameters), at the input scale, $Q_0^2 = 0.40$ GeV^2. The polarized parton distributions are evolved from the input scale (Q_0^2) to the experimental Q^2 using the NLO DGLAP equations in the $\overline{\text{MS}}$ scheme, then used in Eqn. (8) to fit to the world data.

The difference between the integrals over all x at fixed Q^2 of g_1 for the proton (Γ_1^p) and the neutron (Γ_1^n) are related to the neutron beta decay coupling constant (g_A) by the Bjorken sum rule

$$\Gamma_1^p(Q^2) - \Gamma_1^n(Q^2) = \int_0^1 \left(g_1^p(x,Q^2) - g_1^n(x,Q^2)\right) dx = \frac{1}{6} g_A C_{ns} \tag{9}$$

where C_{ns} is the nonsinglet QCD correction. The low-x extrapolation can significantly impact the evaluation of the first moments of g_1, therefore it is better to use the NLO fit to evalutate them. The proton and neutron first moments and the Bjorken sum rule result shown in Table 1 were evaluated at $Q^2 = 5$ GeV^2. The Bjorken sum rule result is consistent with the prediction to order α_s^3 evaluated at $Q^2 = 5$ GeV^2 of 0.182 ± 0.005. The integrals of the polarized parton distribution give the polarization of the quarks, $\Delta\Sigma$, and the gluon polarization, ΔG, also shown in Table 1. The quark helicity contribution to the nucleon is $\frac{1}{2}\Delta\Sigma$, so the quarks contribute about one quarter of the total nucleon spin. The gluon spin contribution, ΔG, is poorly constrained by this measurement.

Table 1. Sum rule results calculated from the E155 NLO QCD fit.

$\Gamma_1^p = 0.118 \pm 0.004 \pm 0.007$	$\Delta\Sigma = 0.23 \pm 0.04 \pm 0.06$
$\Gamma_1^n = -0.058 \pm 0.005 \pm 0.008$	$\Delta G = 1.6 \pm 0.8 \pm 1.1$
$\Gamma_1^p - \Gamma_1^n = 0.176 \pm 0.003 \pm 0.007$	

3. E155X Results for g_2

E155X measured the perpendicular asymmetry; however there was a small correction because the target polarization was not exactly perpendicular to the beam, but at an angle of $\alpha = 92.4°$. The measured asymmetry, $\tilde{A_\perp}$, was used with the E155 fit to g_1 to extract g_2

$$g_2 = \frac{yF_1}{2E'(\cos\Theta - \cos\alpha)} \left[\tilde{A_\perp}\nu\frac{1+\epsilon R}{1-\epsilon} - \frac{g_1}{F_1}\left[E\cos\alpha + E'\cos\Theta\right]\right] \tag{10}$$

where Θ and ϵ are kinematic terms, and the SLAC fit[3] to $R(x,Q^2) = \sigma_L/\sigma_T$ was used.

The measured data from the three spectrometers cover a range in Q^2 from about 0.7 GeV^2 to about 20 GeV^2, as shown in Figure 3. The precision of the data is a substantial improvement compared to the previous results. The data generally follow g_2^{WW} (calculated from the E155 g_1 fit), but also a bag model calculation by Stratmann[10].

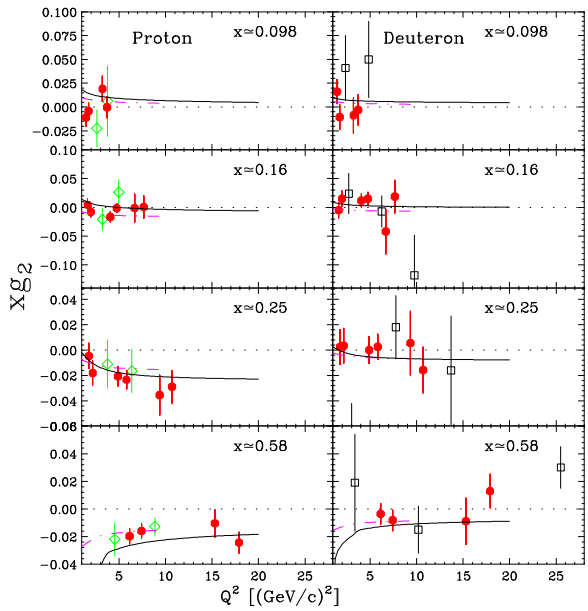

Figure 3. Circles: E155X spectrometer average; Open diamonds: E143; Open Squares: E155; Solid curve: xg_2^{WW} ; Dot-dash: Stratmann.

3.1. *Sum Rules for g_2*

The twist-3 matrix elements d_n from the operator product expansion (OPE) are related to the even moments of $\overline{g_2} = g_2 - g_2^{WW}$. For the E155X analysis, the $\overline{g_2}$ is interpreted as due to twist-3 quark-gluon correlations. The matrix elements are sensitive to deviations from the leading twist-2 (g_2^{WW}) behavior of g_2. The leading twist-3 matrix element is:

$$d_2 = 3\int_0^1 x^2\overline{g_2}(x, Q^2)dx \tag{11}$$

As the Q^2 dependence is approximately given by g_2^{WW}, that dependence is used to average the E155X data from the three spectrometers together for the integration. Combining the E155X g_2 data with that from E155, E143, E142[11], and E154 yields the matrix elements for the proton and neutron shown in Figure 4. The results are consistent with zero within 2 standard deviations. These combined SLAC determinations of d_2 are compared to theoretical calculations using Bag Models, QCD sum rules, Chiral Soliton Model, and Lattice QCD. Complete references for these calculations can be found in Reference (2). The models are in good agreement with the data

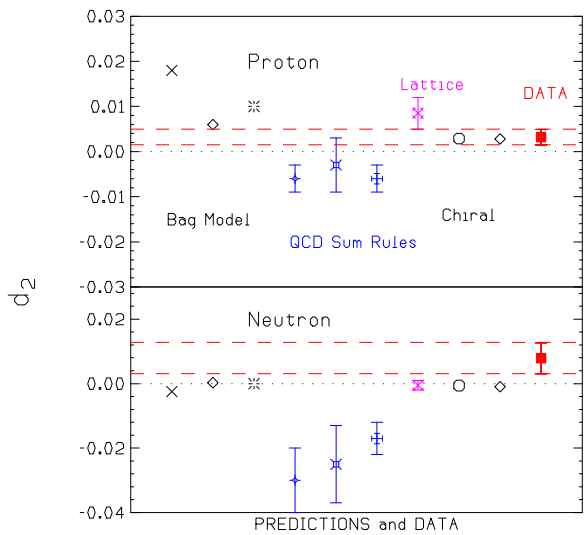

Figure 4. The d_2 matrix element from the combined SLAC data compared to theoretical calculations.

for the proton, but are low compared to the neutron data.

4. Role of E155/E155X in World Data

Experiment E155 expanded the range of x and Q^2 over which precision measurements of the structure function g_1 of the proton and deuteron were made. In combination with other world data, these measurements result in improved constraints within NLO QCD fits, yielding smaller errors on sum rule predictions.

E155X made substantially improved measurements of the structure function g_2 over a wide range in x and Q^2. These results are in good agreement with the twist-2 g_2^{WW} over much of the kinematic range, but show some deviation in certain x ranges. The twist-3 matrix element is consistent with zero at two standard deviations.

Acknowledgments

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