Measurement of the Proton and Deuteron Spin Structure Function g_2 and Asymmetry A_2

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We have measured the structure function $g_2^{p,d}$ and the virtual photon-nucleon asymmetry $A_2^{p,d}$ over the kinematic range $0.014 \leq x \leq 0.7$ and $1.0 \leq Q^2 \leq 17.0$ by scattering 48.3 GeV longitudinally polarized electrons from transversely polarized NH_3 and ^6Li. $|A_2|$ is significantly smaller than the $\sqrt{R}$ positivity limit over the measured range. g_2 is generally consistent with the twist-2 Wandzura-Wilczek calculation. Using our measured g_2 we obtain results from this experiment and world averages for the twist-3 reduced matrix element d_2^p, d_2^d and d_2^n. The Burkhardt-Cottingham sum rule integral $\int g_2^n(x)dx$ is measured in the range $0.02 \leq x \leq 0.8$.

The deep inelastic spin structure functions $g_1(x, Q^2)$ and $g_2(x, Q^2)$, which depend on the Bjorken scaling variable x and the four-momentum squared $-Q^2$, provide insight into the internal spin structure of the nucleon. The g_2 structure function contains contributions from both the longitudinal and transverse polarization distributions within the nucleon. It is sensitive to higher twist effects such as quark-gluon correlations and quark mass contributions, and is not easily interpreted in the quark parton model (QPM) where such effects are not included. However, by interpreting g_2 using the operator product expansion (OPE) within QCD [1,2], it is possible to study contributions to the nucleon spin structure beyond the simple QPM.

The OPE allows us to write the hadronic matrix element in deep inelastic scattering in terms of a series of renormalized operators of increasing twist [1,2]. The leading contribution is twist-2, with higher twist terms suppressed by powers of $1/Q$. The moments of g_1 and g_2 at fixed Q^2 can be related to the twist-2 and twist-3 reduced matrix elements, a_n and d_n [2],

$$\int_0^1 x^n g_1(x, Q^2)dx = \frac{a_n}{2} + \sum_k r_{n,k}(\frac{M}{Q})^k, \quad n = 0, 2, 4, ...$$
$$\int_0^1 x^n g_2(x, Q^2)dx = \frac{1}{2}\frac{n}{n+1}(d_n - a_n) + \sum_k s_{n,k}(\frac{M}{Q})^k, \quad n = 2, 4, ... \quad (1)$$

In the expressions above, d_n directly appears in the equation for g_2 allowing us to study the twist-3 structure of the nucleon at leading order while the higher twist terms are suppressed at high Q^2. The twist-2 part of g_2 was derived by

Wandzura and Wilczek [3] from eqs. 1 by setting d_n and the other higher twist terms to zero.

$$\mathrm{g}_2^{WW}(x, Q^2) = -\mathrm{g}_1(x, Q^2) + \int_x^1 \frac{\mathrm{g}_1(y, Q^2)}{y} dy. \tag{2}$$

More generally g_2 is given by:

$$\begin{aligned} g_2(x, Q^2) &= g_2^{WW}(x, Q^2) - \int_x^1 \frac{\partial}{\partial y}\left(\frac{m}{M} h_T(y, Q^2) + \xi(y, Q^2)\right)\frac{dy}{y} \\ &= g_2^{WW}(x, Q^2) + \overline{g_2}(x, Q^2) \end{aligned} \tag{3}$$

where $h_T(x, Q^2)$ is an additional twist-2 contribution [4,5] which arises from the transverse polarization density in the nucleon which is suppressed by the ratio of the quark to nucleon mass [4] and will be neglected in this analysis. The d_n matrix element can be written as:

$$d_n = \frac{2(n+1)}{n} \int_0^1 x^n \overline{g_2}(x, Q^2) dx \tag{4}$$

Experimentally, the structure function $\mathrm{g}_2(x, Q^2)$ and the virtual photon absorption asymmetry $\mathrm{A}_2(x, Q^2)$ may be expressed in terms of two measurable asymmetries, $A_{\|}(x, Q^2)$ (dominant contribution) and $A_{\perp}(x, Q^2, \epsilon)$ (small contribution), corresponding to longitudinal and transverse target polarization with respect to the incoming electron beam helicity. Because measurements of these asymmetries were taken at two different beam energies, we determined g_2 and $\mathrm{A}_2(x, Q^2)$ from

$$\begin{aligned} \mathrm{g}_2(x, Q^2) &= \frac{F_1(x, Q^2)}{\gamma(1+\gamma^2)}\left[A_{\perp}(x, Q^2, \epsilon)/d + A_1(x, Q^2)(\zeta - \gamma)\right] \\ \mathrm{A}_2(x, Q^2) &= A_{\perp}(x, Q^2, \epsilon)/d + \zeta A_1(x, Q^2) \end{aligned} \tag{5}$$

where $\zeta = \eta(1+\epsilon)/(2\epsilon)$, $\eta = \epsilon\sqrt{Q^2}/(E - E'\epsilon)$, E and E' are the incident and scattered electron energies, $\gamma = 2Mx/\sqrt{Q^2}$, $d = (1 - E'\epsilon/E)\sqrt{2\epsilon/(1+\epsilon)}/(1 + \epsilon R)$, and $\epsilon^{-1} = 1 + 2\left[1 + \gamma^{-2}\right]\tan^2(\theta/2)$. We used a new Q^2 dependent parameterization of A_1 using existing data [6,7] and data from this experiment. The NMC fit to $F_2(x, Q^2)$ [8] and the SLAC fit to $R(x, Q^2) = \sigma_L/\sigma_T$ [9] were used.

The Burkhardt-Cottingham sum rule [10] for g_2 at large Q^2, $\int_0^1 g_2(x) dx = 0$, was derived from virtual Compton scattering dispersion relations. It does not follow from the OPE since the $n = 0$ sum rule is not defined for g_2.

Measurements of g_2 and A_2 exist for the proton [7,11] deuteron [7,11], and neutron [12,13,14]. We report new measurements of g_2 and A_2 for proton and deuterium made at the end of experiment E155 at SLAC. A 38.8 GeV longitudinally polarized electron beam struck transversely polarized NH_3 or ^{6}LiD targets [7]. Scattered electrons were detected in three independent spectrometers located at 2.75°, 5.5°, and 10.5° [15]. Further information on the technique can be found in references [7,15,16]. Only the 2.75° and 5.5° data are reported here. The deuteron result was extracted from the ^{6}LiD results by applying a correction for both the Lithium and deuterium nuclear wave functions.

The data cover the kinematic range $0.014 \leq x \leq 0.7$ and $1.0 \leq Q^2 \leq 17.0$ (GeV/c)^2 with an average Q^2 of 5 (GeV/c)^2. The statistical errors are much larger than the systematic errors. No evidence of Q^2 dependence was seen for A_2 or g_2 within the experimental errors and the data at a given x from the two spectrometers were averaged. The results for A_2 are shown in Fig. 1a along with the $\sqrt{R}$ positivity limit and data from previous experiments. The data are in good agreement with the previous measurements and are significantly smaller than the positivity limit over most of the measured range. A_2^p is significantly larger than zero around $x \sim 0.2$. Results for xg_2 are shown in Fig. 1b along with the twist-2 component, xg_2^{WW} calculated using our parameterization of the A_1 data [15]. The combined SLAC data agrees with g_2^{WW} with a χ^2/(dof) of 1.1 and 1.1 for proton and deuterium respectively. The corresponding comparison with $g_2 = 0$ has poorer agreement with χ^2/(dof) of 1.6 and 1.3.

We used eq. 4 to calculate the matrix elements d_n assuming that $\overline{g_2}$ is independent of Q^2 in the measured region. This is not unreasonable since d_n is supposed to be independent of Q^2. The part of the integral for x below the measured region was assumed to be zero because of the x^n suppression. For $x \geq 0.8$ we used $\overline{g_2} \propto (1-x)^m$ where m=2 or 3 normalized to the data for $x \geq 0.5$. Because $\overline{g_2}$ is small at high x, the contribution was negligible for both cases. We obtain values of $d_2^p = -0.004 \pm 0.009$ and $d_2^d = 0.005 \pm 0.007$ with an average Q^2 of 5 (GeV/c)^2. We combined these results with those from SLAC experiments on the neutron (E142 [12] and E154 [15]) and proton and deuteron (E143 [7]) and obtained average values $d_2^p = 0.005 \pm 0.004$ and $d_2^n = 0.000 \pm 0.011$.

Figure 2 shows the experimental values of d_2 for proton and neutron with their error, plotted along with theoretical calculations using Bag Models (Song [4],Stratmann [17],Ji [18]); QCD sum rules (Stein [19], BBK [20], Ehrnsperger [21]); and Lattice QCD [22]. The results are compatible with all the models within the still large errors.

We evaluated the Burkhardt-Cottingham sum rule in the measured region of $0.02 \leq x \leq 0.8$ and $Q^2 = 5$ by again assuming that $\overline{g_2}$ is independent of

Q^2 and thus that all the dependence is in g_2^{WW}. The results for the proton and deuterium are -0.10 ± 0.05 and 0.08 ± 0.05 respectively. Averaging with the E143 results over a slightly more restrictive x range gives -0.03 ± 0.03 and 0.04 ± 0.04 which is consistent with the Burkhardt-Cottingham sum rule. However, this does not represent a conclusive test of the sum rule because the behavior of g_2 as $x \rightarrow 0$ is not known.

In summary, we have presented a new measurement of A_2 and g_2 for the proton and deuterium in the kinematic range $0.02 \leq x \leq 0.8$ and $1.0 \leq Q^2 \leq 17.0$ (GeV/c)^2. Our results for A_2 are significantly smaller than the $\sqrt{R}$ positivity limit over most of the measured range and data for g_2 are generally consistent with the twist-2 g_2^{WW} prediction. The values obtained for the twist-3 matrix element d_2 from this measurement and the SLAC average are also consistent with zero. However, further measurements are needed to make a conclusive statement about the higher twist content of the nucleon.

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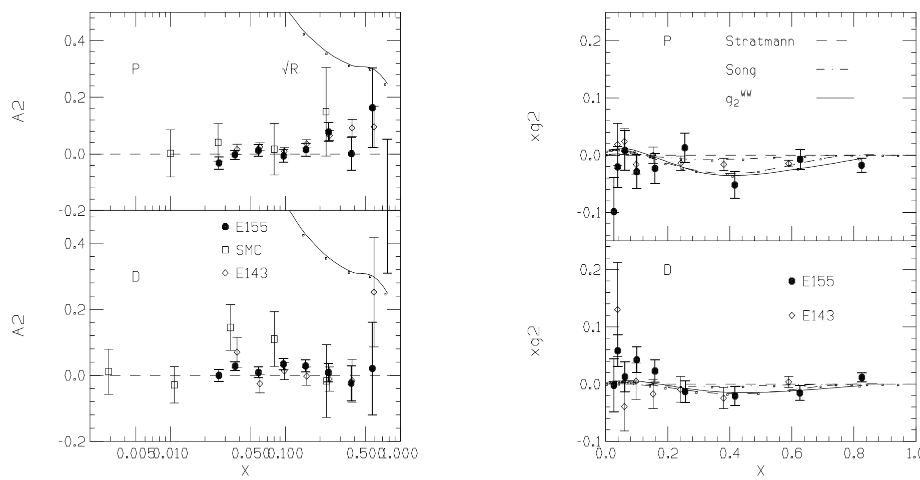

Figure 1: a) The asymmetries A_2^p and A_2^d for two spectrometers combined, and the corresponding $\sqrt{R}$ positivity limits. Also shown are the data from SLAC E143 [7] and SMC [6]. b) The structure function xg_2 for two spectrometers combined. Also shown is the the twist-2 g_2^{WW} and the calculations of Stratmann [17] and Song [4].

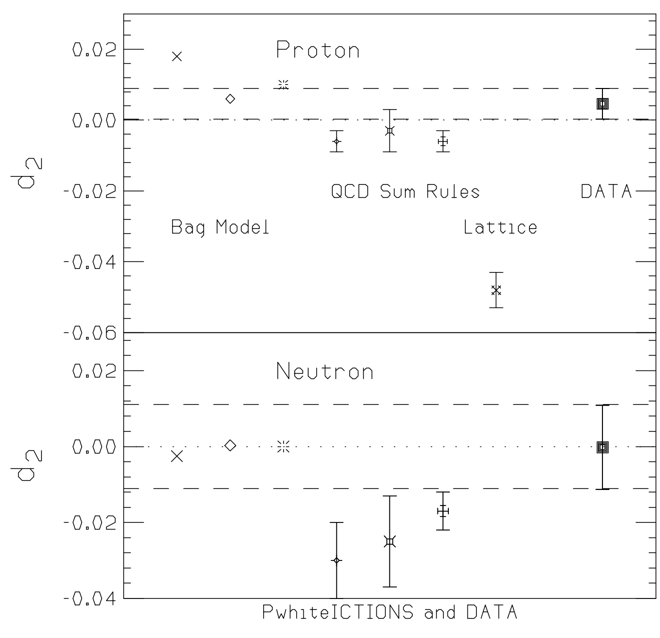

Figure 2: The twist-3 matrix element d_2^p and d_2^n for for SLAC experiments E142, E143, E154 and E155 combined (DATA). Also shown are theoretical models from left to right: Bag Models [4,17,18], QCD Sum Rules [19,20,21] and lattice QCD [22].