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The SLAC E154 Collaboration

Abstract

We have measured the neutron structure function g_2^n and the virtual photon-nucleon asymmetry A_2^n 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 polarized ^{3}He. Results for A_2^n are significantly smaller than the $\sqrt{R}$ positivity limit over most of the measured range and data for g_2^n are generally consistent with the twist-2 Wandzura-Wilczek prediction. Using our measured g_2^n we obtain results for the twist-3 reduced matrix element d_2^n, and the integral $\int g_2^n(x)dx$ in the range $0.014 \leq x \leq 1.0$. Data from this experiment are combined with existing data for g_2^n to obtain an average for d_2^n and the integral $\int g_2^n(x)dx$.

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We have measured the neutron structure function g_2^n and the virtual photon-nucleon asymmetry A_2^n 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 polarized ^{3}He. Results for A_2^n are significantly smaller than the $\sqrt{R}$ positivity limit over most of the measured range and data for g_2^n are generally consistent with the twist-2 Wandzura-Wilczek prediction. Using our measured g_2^n we obtain results for the twist-3 reduced matrix element d_2^n, and the integral $\int g_2^n(x)dx$ in the range $0.014 \leq x \leq 1.0$. Data from this experiment are combined with existing data for g_2^n to obtain an average for d_2^n and the integral $\int g_2^n(x)dx$.

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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 virtual photon four-momentum squared $-Q^2$, provide insight into the internal spin structure of the nucleon. A large set of data for g_1 now exists for the proton, deuteron [1,2] and neutron [3,4]. These data have been used to test the fundamental Bjorken sum rule, and within the framework of the quark-parton model (QPM), to measure the quark contribution to the nucleon's spin. 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 QPM where such effects are not included. However, by interpreting g_2 using the operator product expansion (OPE) within QCD [5,6], 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 (DIS) in terms of a series of renormalized operators of increasing twist [5,6]. The leading contribution is twist-2, with higher twist terms suppressed by powers of $1/Q$. Keeping only terms up to twist-3, 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_j and d_j [6],

$$\int_0^1 x^j g_1(x, Q^2) dx = \frac{a_j}{2}, \quad j = 0, 2, 4, ...$$

$$\int_0^1 x^j g_2(x, Q^2) dx = \frac{1}{2}\frac{j}{j+1}(d_j - a_j), \quad j = 2, 4, ... \qquad (1)$$

In the expressions above, d_j directly appears in the equation for g_2 allowing us to study the higher twist structure of the nucleon at leading order. An expression for the twist-2 part of g_2 was derived by Wandzura and Wilczek [7] from these sum rules assuming that the twist-3 contributions d_j, are negligible,

$$g_2^{WW}(x, Q^2) = -g_1(x, Q^2) + \int_x^1 \frac{g_1(x', Q^2)}{x'} dx'. \qquad (2)$$

Comparing measured values of g_2 with this prediction enables us to extract information about higher twist contributions to g_2. There is an additional twist-2 contribution to g_2 [8,9] beyond the g_2^{WW} term which arises from the transverse polarization density in the nucleon, $h_T(x, Q^2)$. However, this term is suppressed by the ratio of the quark to nucleon mass m/M in DIS [8] and will be neglected in this analysis.

The structure function $g_2(x, Q^2)$ may be expressed in terms of two measurable asymmetries, $A_\parallel(x, Q^2)$ and $A_\perp(x, Q^2)$, corresponding to longitudinal and transverse target polarization with respect to the incoming electron beam helicity,

$$g_2(x, Q^2) = \frac{F_2(x, Q^2)(1 + \gamma^2)}{2x\,[1 + R(x, Q^2)]} \frac{y}{2d \sin \theta} \left[A_\perp \frac{E + E'\cos \theta}{E'} - A_\parallel \sin \theta \right], \quad (3)$$

where E and E' are the incident and scattered electron energies, θ is the scattering angle, $\gamma = 2Mx/\sqrt{Q^2}$, $y = (E - E')/E$, $d = (1 - \epsilon)(2 - y)/y[1 + \epsilon R(x, Q^2)]$, and $\epsilon^{-1} = 1 + 2\,[1 + \gamma^{-2}]\tan^2(\theta/2)$. Fits to existing data were used for the unpolarized structure function $F_2(x, Q^2)$ [10] and for $R(x, Q^2)$ [11], the ratio of longitudinal to transverse virtual photon absorption cross sections. At small scattering angles, the term $A_\parallel \sin \theta$ is small, and consequently the dominant contribution to g_2 comes from $A_\perp$.

Spin dependent DIS can also be described in terms of the spin asymmetries $A_1(x, Q^2)$ and $A_2(x, Q^2)$ for virtual photon absorption. The asymmetry $A_2(x, Q^2)$ is bounded by the positivity limit $|A_2(x, Q^2)| \leq \sqrt{R(x, Q^2)}$, and like g_2, it is dominated by $A_\perp$,

$$A_2(x, Q^2) = \frac{\gamma(2 - y)}{2d \sin \theta} \left[A_\perp \frac{y(1 + xM/E)}{(1 - y)} + A_\parallel \sin \theta \right]. \quad (4)$$

Measurements of g_2 and A_2 exist for the proton [12,13] and deuteron [12], and in the case of the neutron, a measurement was made at the Stanford Linear Accelerator Center (SLAC) by scattering 26 GeV polarized electrons from polarized ^{3}He [3]. In this Letter, we report a new measurement of g_2 and A_2 for the neutron made during experiment E154 at SLAC. For this experiment, the beam energy was increased to 48.3 GeV and two new large-acceptance spectrometers were constructed to provide broader kinematic coverage than previously measured. Results from this experiment for g_1^n and A_1^n have been reported elsewhere [4], and we focus here on the measurement of $A_\perp$ and the subsequent determination of g_2^n and A_2^n.

The target was a 30 cm long, thin-walled glass cell containing approximately 10.5 atmospheres (as measured at 20°C) of ^{3}He gas. The helium nuclei were polarized by spin-exchange collisions with rubidium atoms that were polarized by optical pumping [14]. The system was designed to allow continuous pumping of the target polarization in the longitudinal direction only. Therefore, to obtain transverse polarization, the ^{3}He spins were first pumped to a longitudinal polarization of 48% and then rotated to the transverse direction using two orthogonal sets of Helmholtz coils. In the transverse orientation, the polarization decreased to 33% over a period of 24 hours, at which time the

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target was re-polarized. Approximately 7×10^6 electron events were recorded during two cycles of transverse running.

The electron beam was produced in 250 ns pulses at a rate of 120 Hz, each containing approximately 3×10^{10} electrons. The average beam polarization was measured to be 0.826 ± 0.023 using a Møller polarimeter [15], and the helicity of each pulse was chosen randomly to reduce helicity-dependent systematic errors. Scattered electrons were measured using two independent spectrometers at scattering angles centered around $2.75°$ and $5.5°$, and the asymmetry $A_\perp$ was calculated as

$$A_\perp = \left(\frac{N^- - N^+}{N^- + N^+} \right) \frac{1}{P_b P_t f},$$

(5)

where N^+ and N^- are the measured electron rates for positive and negative beam helicities corrected for detection efficiency and normalized to the incident charge, P_b and P_t are the beam and target polarizations, and f is the dilution factor which corrects for electrons that scattered from materials in the target system other than ^{3}He.

Our measured asymmetry included not only DIS events, but also pions misidentified as electrons, and electrons produced in charge symmetric hadron decays. The rates and asymmetries for these backgrounds were measured and used to correct $A_\perp$. The asymmetry was also corrected for internal [16] and external [17] radiative effects. Uncertainties in the radiative corrections were estimated by varying the input models over a range consistent with the measured data. Finally, a neutron result was extracted from $A_\perp$ by applying a correction for the ^{3}He nuclear wave function [18] and using g_2^{WW} obtained from a fit to existing proton data [1,2] for g_1^p.

Results for A_2^n and g_2^n from both spectrometers are given in Table 1 with statistical and systematic errors. 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 3.6 (GeV/c)^2. Systematic errors are dominated by the uncertainty in the radiative corrections, but are significantly smaller than the statistical error over the entire data range. No evidence of Q^2 dependence was seen for A_2^n or g_2^n within the experimental errors and the data from both spectrometers were averaged. The results for A_2^n are shown in Fig. 1 along with the $\sqrt{R}$ positivity limit and previous data from SLAC experiment E142 [3]. The data are in good agreement with the E142 measurement and are significantly smaller than the positivity limit over most of the measured range. Results for xg_2^n are shown in Fig. 2 along with the twist-2 prediction, xg_2^{WW}. To calculate g_2^{WW}, we assume that g_1/F_1 is independent of Q^2, and use a fit to our measured g_1^n data [4]. A comparison of our data with g_2^{WW} over the measured range gives a $\chi^2/$(dof) of 1.02 indicating good overall agreement. However, the data clearly do not rule

Table 1
Results for A_2^n and g_2^n for the 2.75° and 5.5° spectrometers.

x range	$<x>$	$<Q^2>$	A_2^n	g_2^n
		$(\mathrm{GeV/c})^2$	$\pm$stat$\pm$syst	$\pm$stat$\pm$syst
2.75° Spectrometer				
0.014 - 0.02	0.017	1.2	$0.03 \pm 0.07 \pm 0.01$	$7.36 \pm 15.74 \pm 2.24$
0.02 - 0.03	0.025	1.6	$0.00 \pm 0.06 \pm 0.01$	$0.15 \pm 7.19 \pm 0.98$
0.03 - 0.04	0.035	2.1	$-0.11 \pm 0.06 \pm 0.01$	$-7.90 \pm 4.91 \pm 0.96$
0.04 - 0.06	0.049	2.6	$0.10 \pm 0.06 \pm 0.01$	$4.60 \pm 2.50 \pm 0.54$
0.06 - 0.10	0.077	3.4	$0.06 \pm 0.06 \pm 0.01$	$1.32 \pm 1.34 \pm 0.25$
0.10 - 0.15	0.122	4.1	$0.13 \pm 0.11 \pm 0.03$	$1.22 \pm 0.95 \pm 0.24$
0.15 - 0.20	0.173	4.7	$-0.03 \pm 0.18 \pm 0.03$	$-0.08 \pm 0.81 \pm 0.14$
0.20 - 0.30	0.242	5.1	$-0.25 \pm 0.24 \pm 0.05$	$-0.48 \pm 0.51 \pm 0.11$
0.30 - 0.40	0.341	5.6	$0.63 \pm 0.55 \pm 0.13$	$0.54 \pm 0.46 \pm 0.15$
0.40 - 0.50	0.425	5.9	$0.16 \pm 1.40 \pm 0.04$	$0.04 \pm 0.57 \pm 0.02$
5.5° Spectrometer				
0.06 - 0.10	0.084	5.5	$0.16 \pm 0.10 \pm 0.02$	$4.08 \pm 2.40 \pm 0.43$
0.10 - 0.15	0.123	7.2	$0.01 \pm 0.08 \pm 0.02$	$0.23 \pm 1.00 \pm 0.20$
0.15 - 0.20	0.173	8.9	$0.05 \pm 0.11 \pm 0.02$	$0.40 \pm 0.72 \pm 0.15$
0.20 - 0.30	0.242	10.7	$0.15 \pm 0.14 \pm 0.03$	$0.48 \pm 0.41 \pm 0.10$
0.30 - 0.40	0.342	12.5	$-0.21 \pm 0.27 \pm 0.03$	$-0.22 \pm 0.31 \pm 0.04$
0.40 - 0.50	0.442	13.8	$-0.36 \pm 0.53 \pm 0.05$	$-0.16 \pm 0.24 \pm 0.03$
0.50 - 0.70	0.564	15.0	$-0.04 \pm 0.96 \pm 0.06$	$-0.01 \pm 0.13 \pm 0.01$

out the possibility of large twist-3 contributions and show marginal agreement with the twist-2 prediction in the region $0.03 < x < 0.1$.

In order to quantify the possible contribution of higher twist effects to g_2^n, Eq. 1 can be solved for the twist-3 reduced matrix elements d_j^n at fixed Q^2,

$$d_j^n(Q^2) = 2 \int_0^1 x^j \left[g_1^n(x, Q^2) + \left(\frac{j+1}{j} \right) g_2^n(x, Q^2) \right] dx, \quad j = 2, 4, \dots \quad (6)$$

The combination of g_1 and g_2 in the above expression effectively cancels any twist-2 components allowing us to look for a net twist-3 contribution to g_2. The matrix element was calculated using our $g_2(x, Q^2)$ data and a fit to our
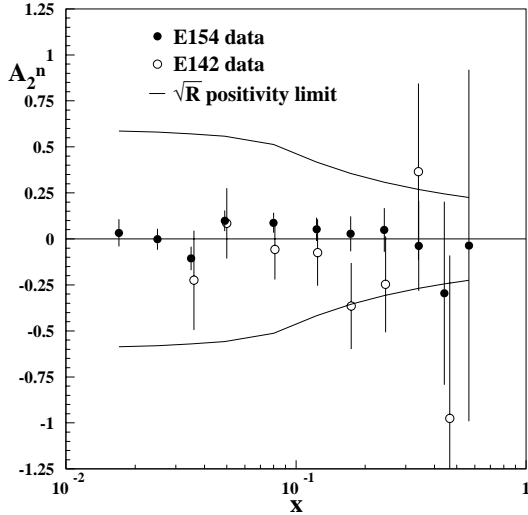
Fig. 1. The asymmetry A_2^n for both spectrometers combined, and the corresponding $\sqrt{R}$ positivity limits. Also shown are the neutron data from SLAC experiment E142. Errors are statistical only.
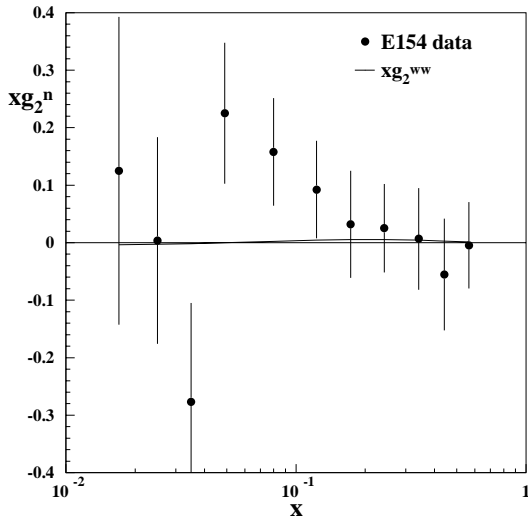

Fig. 2. The structure function $x g_2^n$ for both spectrometers combined. Also shown is the the twist-2 g_2^{WW} prediction. Errors are statistical only.

measured $g_1(x, Q^2)$. Because the integrand in Eq. 6 is purely twist-3, we assumed the unmeasured region $0.7 \le x \le 1$ behaves like $(1 - x)^2$ as suggested by Brodsky *et al.* [19], and fit our last data point to this form to extrapolate to $x = 1$. We neglected any contribution from the region $0 \le x < 0.014$ because it is suppressed by the x^j term. For the $j = 2$ moment, we obtain a value of $d_2^n = -0.004 \pm 0.038 \pm 0.005$ with an average Q^2 of 3.6 (GeV/c)^2. The contribution from the high-x extrapolation is much smaller than the experimental errors and does not significantly change the result for the matrix element.

Data from SLAC experiments E142 [3] and E143 [12] were combined with this experiment to yield a average neutron result for g_2 with an average Q^2 of 3.0
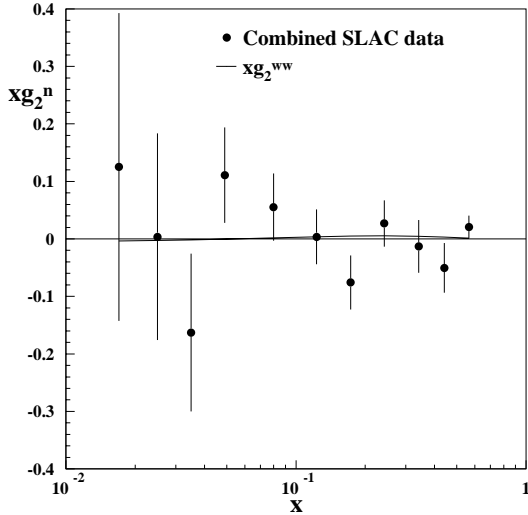
Fig. 3. The structure function xg_2^n for SLAC experiments E142, E143 and E154 combined. Also shown is the twist-2 g_2^{WW} prediction. The average Q^2 for the combined data is 3.0 $(\text{GeV/c})^2$. Errors are statistical only.

Table 2
Comparison of experimental and theoretical results for the reduced twist-3 matrix element d_2^n.

	$d_2^n \times 10^2$	Q^2 $(\text{GeV/c})^2$
E154 result	-0.4 ± 3.8	3.6
SLAC Average	-1.0 ± 1.5	3.0
Bag model [8]	-0.253	5.0
Bag model [12,20]	0.03	5.0
Bag model [21]	0	5.0
QCD sum rule [22]	-3 ± 1	1.0
QCD sum rule [23]	-2.7 ± 1.2	1.0
Lattice QCD [24]	-0.39 ± 0.27	4.0

$(\text{GeV/c})^2$. Neutron results were extracted from the E143 proton and deuteron data assuming a 5% D-state in the deuteron. The results are shown in Fig. 3 along with the g_2^{WW} prediction. Comparing the combined data with g_2^{WW} gives a $\chi^2/(\text{dof})$ of 1.01, again indicating good agreement with g_2^{WW}. Using the combined data, we obtain the result $d_2^n = -0.010 \pm 0.015$ at an average Q^2 of 3.0 $(\text{GeV/c})^2$. The measured d_2^n along with various model predictions are summarized in Table 2, and while the data are consistent with zero, the precision is insufficient to rule out models which contain significant twist-3 contributions.

From the OPE it is not possible to obtain an expression for the $j = 0$ moment

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of g_2. However, Burkhardt and Cottingham [25] have derived the sum rule $\int_0^1 g_2(x)dx = 0$, which is valid to first order in pQCD [26], using dispersion relations for virtual Compton scattering. To evaluate the integral, the g_2^{WW} expression in Eq. 2 was used to evolve the twist-2 part of our measured g_2 to a Q^2 of 3.6 $(\text{GeV}/c)^2$ assuming g_1/F_1 is independent of Q^2 and fitting our g_1^n data as before. At large x, we see from Eq. 2 that $g_2^{WW} \approx -g_1$ and we therefore assume that $g_2 \propto (1-x)^3$ for the extrapolation to $x = 1$. The result is $\int_{0.014}^1 g_2(x)dx = 0.19 \pm 0.17 \pm 0.02$ with an average Q^2 of 3.6 $(\text{GeV}/c)^2$. The Q^2 evolution and high-x extrapolation do not contribute significantly to the integral and the uncertainties in these quantites are included in the error. Combining this result with data from SLAC experiments E142 [3] and E143 [12] yields a result of $\int_{0.014}^1 g_2(x)dx = 0.06 \pm 0.15$ at an average Q^2 of 3.0 $(\text{GeV}/c)^2$, 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^n as $x \to 0$ is not known.

In summary, we have presented a new measurement of A_2^n and g_2^n in the kinematic range $0.014 \leq x \leq 0.7$ and $1.0 \leq Q^2 \leq 17.0$ $(\text{GeV}/c)^2$. Our results for A_2^n are significantly smaller than the $\sqrt{R}$ positivity limit over most of the measured range and data for g_2^n are generally consistent with the twist-2 g_2^{WW} prediction. The values obtained for the twist-3 matrix element d_2^n 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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