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# Precision Measurement of the Deuteron Spin Structure Function $g_1^d$

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We report on a high-statistics measurement of the deuteron spin structure function $g_1^d$ at a beam energy of 29 GeV in the kinematic range $0.029 < x < 0.8$ and $1 < Q^2 < 10$ (GeV/$c$)$^2$. The integral $\Gamma_1^d = \int_0^1 g_1^d \, dx$ evaluated at fixed $Q^2 = 3$ (GeV/$c$)$^2$ gives 0.042 ± 0.003(stat) ± 0.004(syst). Combining this result with our earlier measurement of $g_1^p$, we find $\Gamma_1^p - \Gamma_1^n = 0.163 \pm 0.010$(stat) ± 0.016(syst), which agrees with the prediction of the Bjorken sum rule with $O(\alpha_s^3)$ corrections, $\Gamma_1^p - \Gamma_1^n = 0.171 \pm 0.008$. We find the quark contribution to the proton helicity to be $\Delta q = 0.30 \pm 0.06$.

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The longitudinal and transverse spin-dependent structure functions $g_1(x, Q^2)$ and $g_2(x, Q^2)$ for polarized deep-inelastic lepton-nucleon scattering provide information on the spin structure of the proton and neutron. A fundamental QCD sum rule, originally derived from current algebra by Bjorken [1], predicts the difference $\Gamma_1^p - \Gamma_1^n = \frac{1}{6}(g_A/g_V)$ at infinite $Q^2$ where $\Gamma_1^{p(n)} = \int_0^1 g_1^{p(n)}(x, Q^2)\, dx$ for the proton (neutron), and $g_A$ and $g_V$ are the axial-vector and vector coupling constants in neutron $\beta$ decay. QCD corrections up to third order in $\alpha_s$ have been computed [2], thus making a test of the Bjorken sum rule possible at finite $Q^2$. Measurements of $\Gamma_1^p$ [3,4], $\Gamma_1^n$ from $^3$He [5], as well as results from deuterium [6] targets, are in agreement with this prediction within experimental uncertainties. Separate sum rules for $\Gamma_1^p$ and $\Gamma_1^n$ were derived by Ellis and Jaffe [7] under the assumptions of SU(3) flavor symmetry and an unpolarized strange sea. Higher order QCD corrections have been calculated [8,9].

The polarized spin structure function $g_1$ is related to the virtual photon asymmetries $A_1$ and $A_2$:

$$g_1 = \frac{F_1}{(1 + \gamma^2)} (A_1 + \gamma A_2), \tag{1}$$

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where $F_1$ is the unpolarized structure function, $\gamma^2 = Q^2/\nu^2$, $\nu = E - E'$, $E$ and $E'$ are incident and scattered electron energies, respectively, and $A_1$ and $A_2$ are virtual photon cross section asymmetries [10]. These asymmetries are related by kinematic factors to the experimentally measured electron asymmetries $A_\parallel$ and $A_\perp$. The longitudinal asymmetry $A_\parallel$ is the cross section asymmetry between negative- and positive-helicity electron beams when the target nucleon is polarized parallel to the beam direction. The transverse asymmetry $A_\perp$ is the asymmetry when the target nucleon is polarized transverse to the beam direction. We use the relationships $A_1 = (A_\parallel/D - \eta A_\perp/d)/(1 + \eta\zeta)$ and $A_2 = (\zeta A_\parallel/D + A_\perp d)/(1 + \eta\zeta)$, where $\eta = \epsilon\sqrt{Q^2/E^2}/(1 - \epsilon E'/E)$, $\zeta = \eta(1 + \epsilon)/2\epsilon$, $D = (1 - \epsilon E'/E)/(1 + \epsilon R)$ is the depolarization factor, $d = D\sqrt{2\epsilon/(1 + \epsilon)}$, $\epsilon^{-1} = 1 + 2[1 + (\nu^2/Q^2)]\tan^2(\theta/2)$, $R = \sigma_L/\sigma_T$, and $\theta$ is the electron scattering angle. Thus, the quantity $g_1$ can be written as $g_1 = (F_1/D')[A_\parallel + \tan(\theta/2)A_\perp]$, where $D' = (1 - \epsilon)(2 - y)/y(1 + \epsilon R)$, and $y = \nu/E$.

Experiment E143 used the SLAC polarized electron beam with energies of 9.7, 16.2, and 29.1 GeV incident on polarized proton and deuteron targets in End Station A to measure $g_1^p$, $g_2^p$, $g_1^d$, and $g_2^d$ in the range $1 < Q^2 < 10$ (GeV/$c$)$^2$ and $0.029 < x < 0.8$. This Letter reports on our analysis of the 29.1 GeV data, which yielded $g_1^d$ results with considerably smaller statistical uncertainties than previous measurements [6]. We adopt the convention that $g_1^d$ refers to the average structure function of the nucleon in the deuteron: $g_1^d \approx \frac{1}{2}(g_1^p + g_1^n)$.

The helicity of the longitudinally polarized electron beam [11] was selected randomly on a pulse-to-pulse basis to minimize instrumental asymmetries, which were found to be negligible. The beam polarization $P_b$ was measured daily with a Møller polarimeter, and was found to vary with the cathode quantum efficiency from 0.83 to 0.86. An overall uncertainty on $P_b$ of ±0.02 was achieved [4].

The target [12] was a 3-cm-long 2.5-cm-diameter cylinder filled with granules of deuterated ammonia, $^{15}$ND$_3$, of greater than 98% isotopic purity. It was polarized by the technique of dynamic nuclear polarization in a 4.8-T magnetic field. An average in-beam polarization $P_t$ of 25% was measured with an NMR technique, and a maximum of greater than 40% was achieved. The NMR signal was calibrated by measuring the thermal-equilibrium polarization near 1.6 K. An overall relative uncertainty of 4% on $P_t$ was achieved.

Scattered electrons were detected in two independent spectrometers [13] at angles of 4.5° and 7° with respect to the incident beam. Electrons were identified in each spectrometer by use of two threshold gas Čerenkov counters and a 200-element shower-counter array of lead glass blocks 24 radiation lengths thick. Particle momenta and scattered angles were measured with seven planes of scintillator hodoscopes.

The experimental longitudinal and transverse asymmetries $A_\parallel$ and $A_\perp$ were determined from

$$A_\parallel \text{ (or } A_\perp) = C_1\left(\frac{N_L - N_R}{N_L + N_R}\frac{1}{fP_bP_t} - C_2\right) + A_{\mathrm{rc}}\,, \quad (2)$$

where $N_L$ and $N_R$ are the corrected numbers of scattered electrons per incident charge for negative and positive beam helicity, respectively. Charge-symmetric backgrounds measured by reversing the spectrometer polarity have no measurable asymmetry. They led to rate corrections of 10% at the lowest $x$ bin, decreasing rapidly with $x$. The rates were also corrected for dead time effects.

The correction factors $C_1$ and $C_2$ account for the polarizations of $^{15}$N, unsubstituted $^{14}$N, and residual protons in the target. The factor $C_2$ ranges from 3% to 5% of the measured proton asymmetry, and $C_1$ is typically 1.016. These factors were determined from measured nitrogen polarizations and a shell-model calculation to determine the contribution of the unpaired $p$-shell proton.

The dilution factor $f$ represents the fraction of measured events expected to originate from polarizable deuterons in the target. It was calculated from the composition of the target, which contained about 23% deuterons, 56% $^{15}$N, 10% $^4$He, 6% Al, 4% Cu, and 1% Ti by weight. The dilution factor varied from 0.22 at low $x$ to 0.25 at high $x$. The relative systematic error in $f$ was determined from uncertainties in the target composition and cross section ratios, and ranged from 2.2% to 2.6%.

The radiative correction $A_{\mathrm{rc}}$ includes both internal [14] and external [15] contributions, and typically changed $A_\parallel$ by 10% of its value. Systematic errors on $A_{\mathrm{rc}}$ were estimated based on uncertainties in the input models and correspond to relative errors on $A_\parallel$ of typically 7% for $x > 0.1$, increasing to 100% at $x = 0.03$.

Data from the two spectrometers, which differ by about a factor of 2 in average $Q^2$, are consistent with $A_1^d$, $A_2^d$, and $g_1^d/F_1^d$ being independent of $Q^2$ in the overlap region $0.07 < x < 0.55$, and therefore have been averaged together. The values of $A_1^d$ from this experiment at $E = 29.1$ GeV shown in Fig. 1 [16] are consistent with the higher $Q^2$ results from the SMC Collaboration [6].

Values of $g_1^d$ at the average $Q^2 = 3$ (GeV/$c$)$^2$ of this experiment are shown in Fig. 2(a). The evaluation of $g_1^d$ at constant $Q^2$ is model dependent. We made the assumption that $g_1^d/F_1^d$ is independent of $Q^2$. For $F_1^d/(1 + \gamma^2) = F_2^d/2x(1 + R)$ we used the NMC fit [17] to $F_2^d$ and the SLAC fit to $R$ [18]. Using the SLAC fit to $F_2^d$ [19] gives similar results. The systematic error on $F_1^d$ is typically 2.5%, increasing to 5% at the lowest $x$ bin and 15% at the highest $x$ bin. The integral of $g_1^d$ at $Q^2 = 3$ (GeV/$c$)$^2$ and over the measured $x$ range is $\int_{0.029}^{0.8} g_1^d(x)\,dx = 0.040 \pm 0.003(\text{stat}) \pm 0.004(\text{stat})$. The integral is decreased by 0.002 if we make an alternate assumption that $A_1^d$ and $A_2^d$ are independent of $Q^2$.

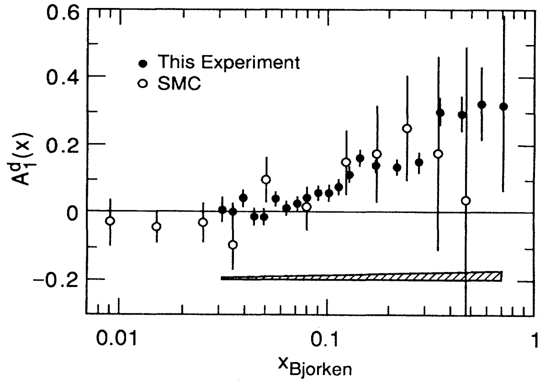

FIG. 1. The virtual photon asymmetry $A_1^d$ from this experiment. The systematic errors are indicated by the shaded band. The average $Q^2$ varies from 1.3 $(\text{GeV}/c)^2$ at low $x$ to 9 $(\text{GeV}/c)^2$ at high $x$. Data from the SMC Collaboration [6] are also shown.

Assuming $g_1^d$ varies as $(1-x)^3$ at high $x$ [20], the extrapolation for $x > 0.8$ yields $\int_{0.8}^{1} g_1^d(x)\,dx = 0.000 \pm 0.001$. To make the extrapolation to $x = 0$, we make a model-dependent assumption that the data are described by the Regge-motivated form [21] $g_1^d(x) = Cx^{-\alpha}$, where $\alpha$ is allowed to be in the range $-0.5$ to 0 [22]. A fit to the data of this experiment in the range $x < x_{\max} = 0.1$ gives $\int_0^{0.029} g_1^d(x)\,dx = 0.001 \pm 0.001$. The uncertainty includes a statistical component, the uncertainty in $\alpha$, and the effect of varying the fitting range from $x_{\max} = 0.05$ to $x_{\max} = 0.12$. Including the SMC data [6] in the fit does not change the results. An alternate form [23], $g_1^d(x) = C' \ln(x)$, which provides good fits to low $x$ data on $F_2$ from HERA, gives similar results. Thus, we obtain the total integral $\Gamma_1^d(\text{E143}) = 0.042 \pm 0.003(\text{stat}) \pm 0.004(\text{syst})$, to be compared with the results of SMC at $Q^2 = 4.7$ $(\text{GeV}/c)^2$: $\Gamma_1^d(\text{SMC}) = 0.023 \pm 0.020(\text{stat}) \pm 0.015(\text{syst})$. The contributions to systematic uncertainties are given in Table I.

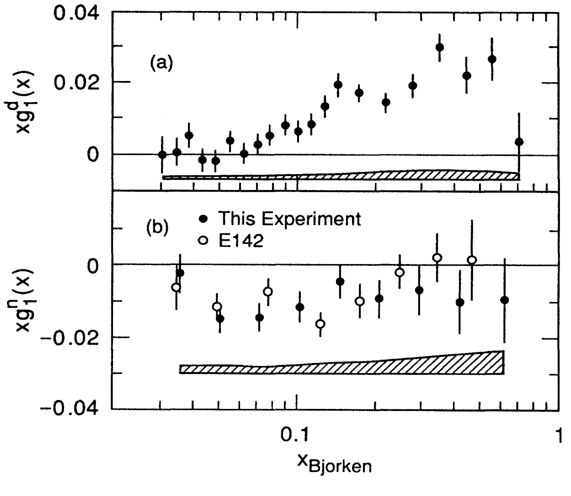

FIG. 2. Values of $xg_1$ from this experiment (E143) as a function of $x$ for (a) the deuteron and (b) the neutron. The errors are statistical only. Systematic errors are indicated by the shaded bands. Also shown are the neutron results from SLAC E142 [5].

The Ellis-Jaffe sum rule for the deuteron is related to the sum rules for the proton and the neutron by $\Gamma_1^d = \frac{1}{2}(\Gamma_1^p + \Gamma_1^n)(1 - 1.5\omega_D)$, where $\omega_D$ is the probability that the deuteron is in a $D$ state. We use $\omega_D = 0.05 \pm 0.01$ [24] given by $N$-$N$ potential calculations. No other nuclear contributions to $\omega_D$ are included. The sum rule predicts $\Gamma_1^d(\text{EJ}) = 0.069 \pm 0.004$, where we have used $F + D = g_A/g_V = 1.2573 \pm 0.0028$ and $F/D = 0.575 \pm 0.016$ [25], and $\alpha_s = 0.35 \pm 0.05$ [26] for QCD corrections [8] to $Q^2 = 3$ $(\text{GeV}/c)^2$. Our measurement of $\Gamma_1^d$ provides a precise test of the Ellis-Jaffe sum rule, and shows a disagreement of more than 3 standard deviations.

The spin structure function integral can be used in the quark parton model to extract the helicity contributions to the proton of each type of quark and antiquark. Measurements using the deuteron are expected to be more sensitive than those using either the proton or the neutron [27]. We find the total contribution from all quarks to be $\Delta q = 0.30 \pm 0.06$, and the contribution from strange quarks and antiquarks to be $\Delta s = -0.09 \pm 0.02$. They are the most precise determinations to date and are consistent with earlier results [28].

The neutron spin structure function can be extracted using the relation $g_1^n(x) = 2g_1^d(x)/(1 - 1.5\omega_D) - g_1^p(x)$. The results obtained using our earlier measurements [4] of $g_1^p(x)$ are compared in Fig. 2(b) with the results obtained by E142 [5] at $Q^2 = 2$ $(\text{GeV}/c)^2$ using a $^3$He target. Using the same extrapolation procedure, we find $\Gamma_1^n(\text{E143}) = -0.037 \pm 0.008(\text{stat}) \pm 0.011(\text{syst})$, compared with $\Gamma_1^n(\text{E142}) = -0.022 \pm 0.007(\text{stat}) \pm 0.009(\text{syst})$. The correlations between proton and deuteron measurements were accounted for when determining the systematic uncertainty contributions in Table I.

The Bjorken sum rule prediction of $\Gamma_1^p - \Gamma_1^n = 0.171 \pm 0.008$ at 3 $(\text{GeV}/c)^2$ can be tested by combining

TABLE I. Contributions to the systematic uncertainties of $\Gamma_1^d$, $\Gamma_1^n$, and $\Gamma_1^p - \Gamma_1^n$.

| Uncertainty | $\delta\Gamma_1^d$ | $\delta\Gamma_1^n$ | $\delta(\Gamma_1^p - \Gamma_1^n)$ |
|---|---|---|---|
| $P_b$ | 0.001 | 0.001 | 0.004 |
| $P_t$ | 0.002 | 0.005 | 0.007 |
| $f$ | 0.002 | 0.006 | 0.008 |
| $A_{\text{rc}}$ | 0.002 | 0.006 | 0.007 |
| $F_2$ and $R$ | 0.001 | 0.002 | 0.005 |
| Extrapolation | 0.001 | 0.004 | 0.006 |
| Total | 0.004 | 0.011 | 0.016 |

proton and deuteron results: $g_1^p(x) - g_1^n(x) = 2g_1^p(x) - 2g_1^d(x)/(1 - 1.5\omega_D)$. Following the same extrapolation procedure as in the case of the deuteron, we find $\Gamma_1^p(\mathrm{E143}) - \Gamma_1^n(\mathrm{E143}) = 0.163 \pm 0.010(\mathrm{stat}) \pm 0.016(\mathrm{syst})$, consistent with the prediction. Contributions to systematic uncertainties are given in Table I. This result is also consistent with that obtained by combining the $\Gamma_1^p$ result from this experiment [4] and the $\Gamma_1^n$ result from E142 [5]: $\Gamma_1^p(\mathrm{E143}) - \Gamma_1^n(\mathrm{E142}) = 0.149 \pm 0.014$.

In conclusion, we have performed a high-statistics measurement of the deuteron spin structure function $g_1^d$, and find that it disagrees with the Ellis-Jaffe sum rule by more than 3 standard deviations. When combined with our earlier results on $g_1^p$, we find the difference $\Gamma_1^p - \Gamma_1^n$ is in agreement with the fundamental Bjorken sum rule.

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