Spin Structure Moments of the Proton and Deuteron
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A. Aghalaryan,[1] A. Ahmidouch,[2] R. Asaturyan,[1] F. Bloch,[3] W. Boeglin,[4] P. Bosted,[5] C. Carasco,[3] R. Carlini,[5] J. Cha,[6] J.P. Chen,[5] M.E. Christy,[7] L. Cole,[7] L. Coman,[4] D. Crabb,[8] S. Danagoulian,[2] D. Day,[8] J. Dunne,[6] M. Elaasar,[9] R. Ent,[5] H. Fenker,[5] E. Frlez,[8] D. Gaskell,[5] L. Gan,[10] J. Gomez,[5] B. Hu,[7] J. Jourdan,[3] M. K. Jones,[5] C. Keith,[5] C.E. Keppel,[7] M. Khandaker,[11] A. Klein,[12] L. Kramer,[4] Y. Liang,[7] J. Lichtenstadt,[13] R. Lindgren,[8] D. Mack,[5] P. McKee,[8] D. McNulty,[8] D. Meekins,[5] H. Mkrtchyan,[1] R. Nasseripour,[4] I. Niculescu,[5] K. Normand,[3] B. Norum,[8] D. Pocanic,[8] Y. Prok,[8] B. Raue,[4] J. Reinhold,[4] J. Roche,[5] D. Rohe,[3] O.A. Rondón,[8] N. Savvinov,[14] B. Sawatzky,[8] M. Seely,[5] I. Sick,[3] K. Slifer,[8] C. Smith,[8] G. Smith,[5] S. Stepanyan,[1] L. Tang,[7] S. Tajima,[8] G. Testa,[3] W. Vulcan,[5] K. Wang,[8] G. Warren,[3,5] F.R. Wesselmann,[8,11] S. Wood,[5] C. Yan,[5] L. Yuan,[7] J. Yun,[15] M. Zeier,[8] and H. Zhu[8]

(The Resonance Spin Structure Collaboration)

[1] *Yerevan Physics Institute, Yerevan, Armenia*
[2] *North Carolina A&T State University, Greensboro, North Carolina 27411*
[3] *Universität Basel, CH-4056 Basel, Switzerland*
[4] *Florida International University, Miami, Florida 33199*
[5] *Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606*
[6] *Mississippi State University, Mississippi State, Mississippi 39762*
[7] *Hampton University, Hampton, Virginia 23668*
[8] *University of Virginia, Charlottesville, Virginia 22903*
[9] *Southern University at New Orleans, New Orleans, Louisiana 70126*
[10] *University of North Carolina, Wilmington, North Carolina 28403*
[11] *Norfolk State University, Norfolk, Virginia 23504*
[12] *Old Dominion University, Norfolk, Virginia 23529*
[13] *Tel Aviv University, Tel Aviv, 69978 Israel*
[14] *University of Maryland, College Park, Maryland 20742*
[15] *Virginia Polytechnic Institute & State University, Blacksburg, Virginia 24061*

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We present the first definitive evidence for dynamic higher twists via a measurement of the spin structure moments of the proton and neutron (deuteron) in the resonance region at a four momentum transfer of 1.279 GeV^2.

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I. INTRODUCTION

Experimental data on nucleon spin structure at intermediate momentum transfer provides valuable new information on the transition from asymptotic freedom to confinement. In the last twenty-five years, the experimental and theoretical study of the spin structure of the nucleon has provided many intriguing results [1]. During this time, much insight has been gained by exploring moments of the spin structure functions and their corresponding sum rules [2–4] This investigation began with tests of QCD in its perturbative regime via spin sum rules like the Bjorken sum rule [5], and has been crucial in understanding how the spin of the composite nucleon arises from the intrinsic degrees of freedom of the theory. Recently, a dedicated effort has attempted to understand QCD in the non-perturbative regime where higher twist effects complicate the simple PQCD interpretation. The lower momentum-transfer results offer insight into the coherent region where the collective behavior of the nucleon constituents give rise to the static properties of the nucleon, in contrast to the scaling regime, where quark-gluon correlations are suppressed.

The spin structure moments have proven to be powerful tools to test QCD sum rules and its effective theories. However, most tests have focused on the longitudinal structure function g_1. The g_2^p structure function has been historically neglected due to the technical difficulties of producing a transversely polarized target, and due to the lack of a simple interpretation of g_2 in the classic parton model. Currently, the lowest momentum transfer that has been investigated [6] for the proton is $Q^2 = 5$ GeV^2. The absence of transverse proton data is particularly unsatisfying given the intriguing results found in the transverse neutron data: The SLAC E155 collaboration [6] found a three sigma violation of the proton Burkhardt-Cottingham sum rule at $Q^2 = 5$ GeV^2, while the E94010 collaboration [7–10] found that the neutron BC sum rule held within the experimental uncertainty below $Q^2 = 1$ GeV^2.

A. Nachtmann vs C-N

The Cornwall-Norton moments are defined as:

$$\Gamma_i^n(Q^2) = \int dx x^n g_i(x, Q^2) \quad (1)$$

where g_i can be g_1 or g_2. The Nachtmann moments are defined as:

$$M_n(Q^2) = \quad (2)$$

Nachtmann moments are used here to take into account the target mass corrections that become important at the kinematics of our experiment.

Wilson coefficients contain the logarithmic QCD corrections, $\xi = 2x/(1 + \sqrt{1 + (2Mx)^2/Q^2})$ is the Nachtmann scaling variable, and $g = 4\pi\alpha_s(Q^2)$.

B. Experiment

In this letter, we describe an investigation of the spin structure of the proton and deuteron in the resonance region at a momentum transfer of 1.279 GeV^2. Experiment E01-006 was conducted in Hall C of the Thomas Jefferson National Accelerator Facility by the Resonance Spin Structure (RSS) collaboration. We measured the parallel and perpedicular proton asymmetries in the scattering of 100 nA polarized 5.755 GeV electrons. Scattered electrons were detected at a scattering angle of 13.15° using the Hall C High Momentum Spectrometer. Full details of the experiment can be found in Refs. [11] and [12].

II. RESULTS FOR FIRST MOMENTS OF g_1

The first moment, $\bar{\Gamma}_1^p(Q^2)$ is defined as:

$$\bar{\Gamma}_1^p(Q^2) = \int_0^{1-\epsilon} g_1(x, Q^2)dx \quad (3)$$

where the overbar signifies exclusion the elastic contribution at $x = 1$. The RSS resonance region data covers the range $1090 < W < 1910$, $(0.3161 < x < 0.823)$. For the resonance region, we assume a 6.82% relative systematic following the conclusion of Ref. [13] to find $\Gamma_1^res = 0.0349 + -0.0008(stat) + -0.0024(syst)$.

The unmeasured contribution to the integral from the region $0 < x < 0.316$ is provided by a Regge inspired fit to SLAC E143 and E155 data: $g_1^p = ax^b(1-x)^3(1 + c/Q^2)$ where $a = 0.392 \pm 0.254b = 0.0676 \pm 0.084$,and, $c = 0.0636 \pm 0.681$ Integration and propagation of the fit errors results in: $\Gamma_1^{DIS} = 0.068 \pm 0.0069$

III. RESULTS FOR FIRST MOMENTS OF g_2

The unsubtracted dispersion relations for spin-dependent virtual-virtual Compton scattering (VVCS) amplitudes S_2 leads to a "super-convergence" relation that is valid for any value of Q^2,

$$\Gamma_2^p(Q^2) = \int_0^1 g_2(x, Q^2)dx = 0 \quad (4)$$

which is the Burkhardt-Cottingham (BC) sum rule [14]. To estimate the unmeasured contribution to Γ_2 as $x \to 0$ we assume that the Wandzura-Wilczek [15] relation holds:

$$g_2^{WW}(x, Q^2) = -g_1(x, Q^2) + \int_x^1 \frac{g_1(y, Q^2)}{y} dy \quad (5)$$

and that

$$\int_0^{x_0} g_2(x, Q^2)dx \simeq \int_0^{x_0} g_2^{WW}(x, Q^2)dx \quad (6)$$

$$= x_0 \int_{x_0}^1 \frac{g_1(x, Q^2)}{x} dx \quad (7)$$

where Eq. 7 follows from integration by parts.

We estimate a 15% uncertainty to the DIS contribution by evaluating equation 7 with various models for g_1. $\Gamma_2^{DIS} = 0.0265 \pm 0.0038$ The SLAC E155x collaboration [6] previously reported a neutron BC result at high Q^2, which is consistent with zero but with a rather large error bar. On the other hand, the SLAC proton result deviates from the BC sum rule prediction by 3 standard deviations [6]. Fig. **??** displays $\Gamma_2 = \int g_2(x, Q^2)dx$. The total integral exhibits a striking cancellation of the inelastic (resonance+DIS) and elastic contributions, leading to satisfaction of the Burkhardt-Cottingham sum rule within uncertainties.

The sum rule of Gerasimov, Drell and Hearn (GDH) provides a link from the helicity-dependent cross sections measured in real photon scattering to the anomolous magnetic moment of a hadronic target. This sum rule for real photon scattering has provided a foundation for a powerful approach to interpreting the experimental results of electron scattering experiments. There are several possible generalizations of the GDH sum to finite Q^2, but we focus on the following formulation:

$$I(Q^2) = \frac{8\pi^2\alpha}{M} \int_{\nu_0}^{\infty} \frac{g_1 - \gamma^2 g_2}{K} \frac{d\nu}{\nu} \quad (8)$$

where $\gamma^2 = Q^2/\nu^2$, and ν_0 represents the inelastic threshold. There are three standard conventions used for the virtual photon flux K :

$$K_A = \nu \quad (9)$$

$$K_B = \sqrt{\nu^2 + Q^2} \quad (10)$$

$$K_C = \nu - \frac{Q^2}{2M} \quad (11)$$

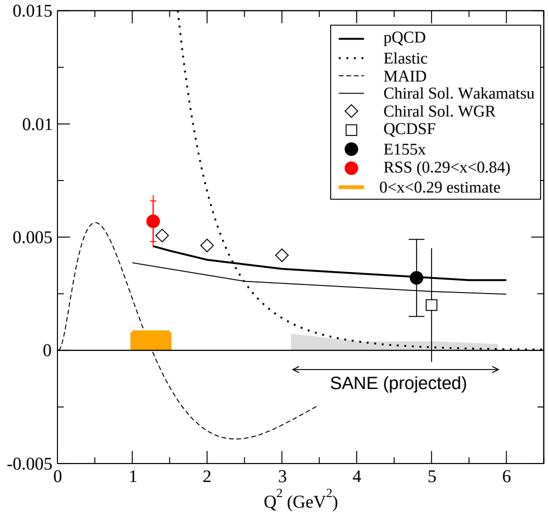

FIG. 1: $d_2^p(Q^2 = 1.279)$.

For completeness, we provide the RSS result in all three conventions.

IV. THIRD MOMENTS: d_2

Third moments d_2

A. Twist-3 matrix elements

The twist-3 matrix elements, representing qgq correlations, are related by the OPE to the Nachtmann moments of the spin structure functions [16]

$$M_2^n(Q^2) \equiv \frac{1}{2} d_n E_2^n(Q^2, g) \;=\; \int_0^1 \frac{dx}{x^2}\xi^{n+1}\Big[\frac{x}{\xi}g_1 + \Big\{\frac{n}{n-1}\frac{x^2}{\xi^2} \;-\; \frac{n}{n+1}\frac{M^2x^2}{Q^2}\Big\}g_2\Big] \tag{12}$$

where $n = 3, 5, 7, ..$ and where d_n are twist-3 matrix elements, E_2^n are the corresponding Wilson coefficients.

The above equation can be rewritten in terms of the conventional label for the twist-3 matrix elements, which for n=3 is $d_2 = d_3 E_2^3$, and the corresponding moment is then

$$d_2(Q^2) = \int_0^1 dx \xi^2 \Big(2\frac{\xi}{x}g_1 + 3(1 - \frac{\xi^2}{2}\frac{M^2}{Q^2})g_2\Big), \tag{13}$$

which for $M = 0$ or $Q^2 \gg M$ reduces to the more familiar C–N form.

We have calculated d_2 for the proton, deuteron, singlet, non-singlet and neutron structure functions, by adding to the contribution of our measured resonances region, which extends from $x_{min} \sim 0.3$ up to the inelastic production threshold, that of the low $x < x_{min}$ region. Our inelastic data has no contamination from elastic events due to our very good final state mass resolution, so the elastic contribution, which depends only on Q^2 dependent elastic form factors, can be trivially computed and added at any time, and it is not reported here.

For the contribution of the resonances we used the Nachtmann moments of Eq.(13) at constant $\langle Q^2 \rangle = 1.28$ GeV^2 using our fits [11] to our data. For the range $x_{min} = 0.316 < x < 0.84$ we obtain $d_2^{p\ Res} = 0.00365 \pm 0.0006 \pm 0.0004$ and $d_2^{d\ Res} = 0.0060 \pm 0.0020 \pm 0.0004$ where the first error is statistical and the second systematic.

The extrapolations into the DIS region, $d_2^{p,d\ DIS}$ are based on the behavior of our g_2 data near our low x limit, which for the proton show the twist-3 $\overline{g}_2 = g_2 - g_2^{WW}$ to be nearly constant and consistent with zero within errors [11], while for the deuteron they show a similar behavior, different from zero only at the one σ (statistical) level. We have combined the observed behavior of the proton data together with the expected decreasing contribution of higher twists at small x and the further suppresion of the low x region contribution due to the ξ^2 factors in the integral, to assume a zero twist-3 $d_2^{p\ DIS}$. The error in this assumption is taken to be equal to our fit's twist-3 error $\delta\overline{g}_2{}^p(x_{min}, \langle Q^2 \rangle) = 0.0106$ extrapolated as constant down to $x = 0$. Since the ratio $\xi/x \geq 0.94$ for $x < x_{min}$, we can use the simpler C–N moments to integrate the constant fit error and get $\delta d_2^{pDIS} = 3\int_0^{x_{min}} x^2 \delta\overline{g}_2{}^{p\ DIS} dx = 0.0008$ [This equation implies that $3\overline{g}_2 = 2g_1 + 3g_2$ is defined somewhere in the paper]. For the deuteron, we integrated $\overline{g}_2{}^{d\ DIS}$ using a constant and a linear extrapolation assumptions. The deuteron DIS contribution error was treated in the same way as the proton. We get $\delta d_2^{dDIS} = 0.0013$ (linear) and $\delta d_2^{dDIS} = 0.0011$ (constant). We averaged both assumptions and added quadratically one-half their difference to the error from the fit to obtain $\langle \delta d_2^{dDIS} \rangle = 0.0012 \pm 0.0012$.

The values indicated in Table I represent the inealstic part of d_2 including resonances and DIS contributions. The errors are statistical, systematic and low x extrapolation errors added in quadrature. The singlet and non-singlet results are based on negligible s quark contributions. The singlet $d_2^\Sigma = d_2^p + d_2^n$ is obtained from the deuteron result, corrected for the polarization of the deuteron D state $\gamma_D \simeq 0.925$ [17] .

We observe clear twist-3 at more than 3 sigma (total) for the proton and more than 2 sigma (total) for the neutron. As expected from isospin cancellation, the non-singlet matrix twist-3 matrix element is entirely consistent with zero.

We can use the pQCD evolution [18, 19] of d_2^Σ and d_2^{NS} to compare our result $d_2^p(5\text{GeV}^2) = 0.0021 \pm 0.0006$ with the result of SLAC's measurements at $\langle Q^2 \rangle = 5$ GeV^2 [6], corrected for target mass effects following [20],

Proton d_2^p	Deuteron d_2^d	Singlet $d_2^\Sigma = d_2^d/\gamma_D$	Non-Singlet $2d_2^p - d_2^\Sigma$	Neutron $d_2^n = d_2^\Sigma - d_2^p$
0.0036 ± 0.0011	0.0060 ± 0.0024	0.0065 ± 0.0026	0.0008 ± 0.0034	0.0029 ± 0028

TABLE I: $d_2(0 < x < 0.84, Q^2 = 1.28\text{GeV}^2)$

$d_2^p = 0.0025 \pm 0.0015$. SLAC's result does not include the elastic contribution (0.0003 at 5 GeV^2). Similarly $d_2^n(5\text{GeV}^2) = 0.0053 \pm 0.0052$ and SLAC's inelastic, TM corrected $d_2^n = 0.0074 \pm 0.0045$ agree within errors.

We have also calculated the NLO corrections to our singlet and non-singlet results [21**?**]. Applying the resulting Wilson coefficients at our kinematics $F_3^{2\Sigma} = 1.436$ and $F_3^{2NS} = 1.26$ (notation of [21]) we get $d_2^p = 0.0026 \pm 0.0005 \pm 0.0006$ where the first error represents combined measured errors and the second one comes from the low x extrapolation.

V. SUMMARY

In summary, we have measured the spin structure function moments of the proton, deuteron and neutron in the resonance region at $Q^2 = 1.279$ GeV^2. We find good agreement with world data for Γ_1, satisfaction of the BC sum rule, and a dramatic improvement in precision for the proton GDH sum rule compared to previous measurements.

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[1] B. W. Filippone and X.-D. Ji, Adv. Nucl. Phys. **26**, 1 (2001).
[2] J. P. Chen, A. Deur, and Z.-E. Meziani, Mod. Phys. Lett. **A20**, 2745 (2005).
[3] J. Edelmann, G. Piller, N. Kaiser, and W. Weise, Nucl. Phys. **A665**, 125 (2000), hep-ph/9909524.
[4] M. Osipenko et al., Phys. Rev. **D71**, 054007 (2005), hep-ph/0503018.
[5] J. D. Bjorken, Phys. Rev. **148**, 1467 (1966).
[6] P. L. Anthony et al. (E155), Phys. Lett. **B553**, 18 (2003).
[7] M. Amarian et al., Phys. Rev. Lett. **89**, 242301 (2002).
[8] M. Amarian et al., Phys. Rev. Lett. **92**, 022301 (2004).
[9] M. Amarian et al., Phys. Rev. Lett. **93**, 152301 (2004).
[10] S. K. et al.
[11] F. R. Wesselmann et al. (RSS), Phys. Rev. Lett. **98**, 132003 (2007), nucl-ex/0608003.
[12] M. K. Jones et al. (Resonance Spin Structure), Phys. Rev. **C74**, 035201 (2006), nucl-ex/0606015.
[13] O. Rondon, *Rss note dual_d2_sys.pdf*.
[14] H. Burkhardt and W. N. Cottingham, Annals Phys. **56**, 453 (1970).
[15] S. Wandzura and F. Wilczek, Phys. Lett. **B72**, 195 (1977).
[16] S. Matsuda and T. Uematsu, Nucl. Phys. **B168**, 181 (1980).
[17] O. A. Rondon, Phys. Rev. **C60**, 035201 (1999).
[18] E. V. Shuryak and A. I. Vainshtein, Nucl. Phys. **B201**, 141 (1982).
[19] X.-D. Ji and C.-h. Chou, Phys. Rev. **D42**, 3637 (1990).
[20] Y. B. Dong, Phys. Rev. **C77**, 015201 (2008).
[21] X.-D. Ji, W. Lu, J. Osborne, and X.-T. Song, Phys. Rev. **D62**, 094016 (2000), hep-ph/0006121.