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CLAS Collaboration

Y. Prok
Old Dominion University, yprok@odu.edu

K. V. Dharmawardane
Old Dominion University

G. E. Dodge
Old Dominion University, gdodge@odu.edu

S. E. Kuhn
Old Dominion University, skuhn@odu.edu

See next page for additional authors

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Moments of the spin structure functions $g_1^p$ and $g_1^d$ for $0.05 < Q^2 < 3.0$ GeV$^2$

CLAS Collaboration

Y. Prok$^a$, P. Bosted$^{a1}$, V.D. Burkert$^{a1}$, A. Deur$^{a1}$, K.V. Dharmawardane$^{a3}$, G.E. Dodge$^{a,c}$, K.A. Griffioen$^{a3}$, S.E. Kuhn$^{a,c}$, R. Minehart$^{a1}$, G. Adams$^{a3}$, M.J. Amaryan$^{a3}$, M. Anghinolfi$^{a}$, G. Asryan$^{a1}$, G. Audit$^{a1}$, H. Avakian$^{a1}$, H. Bagdasaryan$^{a1}$, N. Bailie$^{a1}$, J.P. Ball$^{a1}$, N.A. Baltzell$^{a1}$, S. Barrow$^{a1}$, M. Battaglieri$^{a1}$, K. Beard$^{a1}$, I. Beddinsky$^{a1}$, M. Beketasoglu$^{a1}$, M. Bellis$^{a1}$, N. Benmouna$^{a}$, B.L. Berman$^{a}$, A.S. Biselli$^{a,b}$, L. Blaszczyk$^{a1}$, S. Boiarinov$^{a1}$, B.E. Bonner$^{a1}$, S. Bouchigny$^{a1}$, R. Bradford$^{a1}$, D. Branford$^{a1}$, W.J. Briscoe$^{a1}$, W.K. Brooks$^{a1}$, S. Bültmann$^{a3}$, C. Butuceanu$^{a1}$, J.R. Calarco$^{a1}$, S.L. Careccia$^{a1}$, D. S. Carmean$^{a1}$, L. Casey$^{a1}$, A. Cazes$^{a1}$, S. Chen$^{a1}$, L. Cheng$^{a1}$, M.H. Wood$^{a1}$, A. Yegneswaran$^{a1}$, J. Yun$^{a1}$, L. Zan$^{a1}$, J. Zhang$^{a1}$, B. Zhao$^{a1}$, Z.W. Zhao$^{a1}$, O. Pogorely$^{a}$, I. Popan$^{a}$, S. Pozdniakov$^{a}$, B.M. Preedo$^{a}$, J.W. Price$^{a1}$, S. Procureur$^{a1}$, D. Protopopescu$^{a1}$, V.S. Serov$^{a1}$, Y. G. Sharabian$^{a1}$, D. Sharovy$^{a}$, J. Shaw$^{a}$, N. V. Shvedunov$^{a1}$, A. V. Skaben$^{a1}$, E.S. Smith$^{a1}$, L.C. Smith$^{a1}$, D.I. Sober$^{a1}$, D. Sokhan$^{a1}$, A. Stavinsky$^{a1}$, S.S. Stepanyan$^{a1}$, S. Stepanyan$^{a1}$, B.E. Stokes$^{a1}$, P. Stoler$^{a1}$, I.I. Strakovsky$^{a1}$, S. Straub$^{a1}$, R. Suleiman$^{a1}$, M. Taitui$^{a1}$, D.J. Tedeschi$^{a}$, A. Tkabladze$^{a1}$, S. Tkachenko$^{a1}$, L. Todor$^{a1}$, M. Ungaro$^{a1}$, M.F. Vineyard$^{a1}$, A.V. Vlassov$^{a1}$, D.P. Watts$^{a1}$, L.B. Weinstein$^{a1}$, D.P. Weygand$^{a1}$, M. Williams$^{a1}$, E. Wolin$^{a1}$, M.H. Wood$^{a1}$, A. Yegneswaran$^{a1}$, J. Yun$^{a1}$, L. Zan$^{a1}$, J. Zhang$^{a1}$, B. Zhao$^{a1}$, Z.W. Zhao$^{a1}$

$^a$ Argonne National Laboratory, USA
$^{a1}$ Arizona State University, Tempe, AZ 85287-1504, USA
$^b$ University of California at Los Angeles, Los Angeles, CA 90095-1547, USA
$^c$ California State University, Dominguez Hills, Carson, CA 90747, USA
$^d$ Carnegie Mellon University, Pittsburgh, PA 15213, USA
$^e$ Catholic University of America, Washington, DC 20064, USA
$^f$ CEA-Saclay, Service de Physique Nucléaire, 91191 Gif-sur-Yvette, France
$^g$ Christopher Newport University, Newport News, VI 23606, USA
$^h$ CLAS Collaboration
$^i$ Edinburgh University, Edinburgh EH9 3JZ, United Kingdom
$^j$ Fairfax University, Fairfax, VA 22030, USA


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The spin structure functions $g_1$ for the proton and the deuteron have been measured over a wide kinematic range in $x$ and $Q^2$ using 1.6 and 5.7 GeV longitudinally polarized electrons incident upon polarized NH$_3$ and ND$_3$ targets at Jefferson Lab. Scattered electrons were detected in the CEBAF Large Acceptance Spectrometer, for $0.05 < Q^2 < 5$ GeV$^2$ and $W < 3$ GeV. The first moments of $g_1$ for the proton and deuteron are presented – both have a negative slope at low $Q^2$, as predicted by the extended Gerasimov–Drell–Hearn sum rule. The first extraction of the generalized forward spin polarizability of the proton $\gamma_0^p$ is also reported. This quantity shows strong $Q^2$ dependence at low $Q^2$. Our analysis of the $Q^2$ evolution of the first moment of $g_1$ shows agreement in leading order with Heavy Baryon Chiral Perturbation Theory. However, a significant discrepancy is observed between the $\gamma_0^p$ data and Chiral Perturbation calculations for $\gamma_0^p$, even at the lowest $Q^2$.

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be available in the moderate $Q^2$ region below the range of applicability of the OPE. At low $Q^2$, $S_1$ can be calculated in $\chi$PT, a model-independent effective field theory [16], but it is not clear how high in $Q^2$ these calculations can be applied [17, 18]. Thus $I_1$ presents a calculable observable that spans the entire energy range from fundamental degrees of freedom (quarks and gluons) to effective ones (hadrons).

Higher moments of $g_1$ are interesting as well. In our kinematic domain, these moments emphasize the resonance region over DIS kinematics because of extra factors of $x$ in the integrand. The fundamental generalized forward spin polarizability of the nucleon is given by [19]

$$\gamma_0(Q^2) = C(Q^2) \int_0^{x_0} g_1(x, Q^2) \frac{4M^2}{Q^2} x^2 dx,$$

where the kinematic factor $C(Q^2) = 16\pi M^2/Q^6$ and $\alpha$ is the fine structure constant. At high $Q^2$ one would expect $g_2$ to diminish significantly and $g_1$ to vary logarithmically with $Q^2$, thus $\gamma_0$ weighted by $Q^6$ should be largely independent of $Q^2$ [1, 19, 20].

A measurement of $\gamma_0$ on the neutron indicates no evidence for such “scaling” below $Q^2 = 1$ GeV$^2$, and furthermore the data barely agree with $\chi$PT calculations at low $Q^2$ [21]. No measurement of $\gamma_0$ on the proton has been reported so far.

In order to advance our theoretical understanding of the nucleon spin, it is essential to have data on the spin structure functions at low $Q^2$ and in the resonance region, as well as at DIS kinematics. Data in the resonance region are necessary to calculate moments, especially at low and moderate $Q^2$. Until recently, data in the resonance region were quite scarce [22], but new measurements of spin structure functions in the resonance region have now been reported on proton [23, 24], deuteron [25] and $^3$He targets [31]. These data cover a wide kinematic range that includes invariant mass and beam production and pion contamination. Polarization and dilution factors were divided out and radiative corrections applied. The resulting asymmetry, $A_1$, is proportional to a linear combination of the two virtual photon asymmetries $A_1$ and $A_2$ [25]. Using a parametrization of the world data to model $A_2$ [25], the unpolarized structure function $F_1$ [36, 37], and the ratio of transverse to longitudinal structure functions $F_2$ [36], $A_1$ and $g_1$ were extracted using:

$$A_1(x, Q^2) = \frac{1}{\gamma} A_{1\parallel} - \eta A_{2\parallel},$$

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

where the depolarization factor $D$ depends on $R$, $\eta$ is a kinematic factor and $\gamma^2 = Q^2/M^2$. The generalized forward spin polarizability for the proton was calculated from the data for $A_1$ and the $F_1$ parameterization using $\gamma_0(Q^2) = C \int_0^{x_0} F_1 x^2 dx$, which is equivalent to Eq. (2).

The total systematic error on $g_1$ varies greatly depending on the kinematic bin; for the proton it is roughly 10% and for the deuteron it is typically 15% for the 1.6 GeV data and 20% for the high energy data. The systematic error is dominated by model uncertainties on $A_2$, $F_1$ and $R$, which are estimated by using different parameterizations of the world data. For the deuteron data the uncertainty in $P_S P_T$ also contributes substantially to the systematic error.

The values of $g_1^p$ and $g_1^n$ were extracted for $Q^2$ from 0.05 to 5 GeV$^2$ and for $x$ greater than 0.1; all results are available from the CLAS database [38]. At low $Q^2$, the $\Delta(1232)$ resonance is quite prominent, with a negative asymmetry as expected for this transition. It decreases steadily in strength as $Q^2$ increases. In the mass region above the $\Delta(1232)$ resonance, $g_1$ increases from nearly zero to large positive values as $Q^2$ increases. In the $\Delta(1232)$ region and at low $Q^2$, $g_1^p/2$ is consistent with $g_1^n$, as expected for a transition to an isospin $1/2$ state. However, at high $Q^2$, $g_1^n$ is significantly larger than $g_1^p/2$, indicating a negative contribution from the neutron.

The first moments of $g_1^p$ and $g_1^n$ are shown in Figs. 1 and 2, respectively. The parameterization of world data [38] is used to include the unmeasured contribution to the integral down to $x = 0.001$. The systematic uncertainty (shown by the grey bands) includes the model uncertainty from the extrapolation to the unmeasured region. Only the $Q^2$ bins in which the measured part (summed absolute value of the integrand) constitutes at least 50% of the total integral are shown. For the proton, the parameterization is also used at high $x$ (in the range $1.09 < W < 1.14$ (1.15) GeV for the 1.6 (5.7) GeV data). For the deuteron, the integration is carried out up to the nucleon pion production threshold at high $x$, excluding the quasi-elastic and electro-disintegration contributions. Our low $Q^2$ coverage allows us to observe, for the first time, the slope changing sign at low $Q^2$, consistent with the expectation of a negative slope given by the GDH sum rule at very low $Q^2$. In general the data are well described by the phenomenological models of Burkert and Ioffe [39, 40] and Soffer and Teryaev [41].

The low $Q^2$ $I_1^n$ data are shown in more detail in the right-hand panels of Figs. 1 and 2. It is possible to make a quantitative comparison between our results for $I_1^n$ at low $Q^2$ and the next-to-leading order $\chi$PT calculation by Ji et al. [18], who find $I_1^n(Q^2) = -x^2/Q^2 + 3.89 Q^4 + \ldots$ and $I_3^n(Q^2) = -x^2/Q^2 + 3.15 Q^4 + \ldots$. Treating the deuteron as the incoherent sum of a
The rule on the deuteron here excludes the two-body breakup part, \( \omega \), where \( \omega \) is fixed at \(-0.451 \) (proton) and \(-0.451 \) (deuteron) by the GDH sum rule. Note that the GDH sum rule on the deuteron here excludes the two-body breakup part, which otherwise nearly cancels the inelastic contribution [43]. The fit results for the proton, \( b = 4.31 \pm 0.31 \) (stat) \( \pm 1.36 \) (syst), and for the deuteron, \( b = 3.19 \pm 0.44 \) (stat) \( \pm 0.68 \) (syst), are both consistent with the \( Q^4 \) term predicted by Ji et al. [18]. The fit (labelled “Poly Fit”) is shown in the right-hand panels of Figs. 1 and 2 along with Ji’s prediction. Clearly the \( Q^6 \) term becomes important even below \( Q^2 = 0.1 \) \( \text{GeV}^2 \) and this term needs to be included in the \( \chi \text{PT} \) calculations in order to extend the range of their validity beyond roughly \( Q^2 = 0.06 \) \( \text{GeV}^2 \). The \( \chi \text{PT} \) calculation by Bernard et al. [17] is also shown in Figs. 1 and 2. Not shown is the result from Bernard et al. that includes an estimate of the \( \Delta(1232) \) and vector meson degrees of freedom, which are important at low \( Q^2 \). That result has large uncertainties and is consistent with our data.

Fig. 3 shows the result for the generalized forward spin polarizability of the proton \( \gamma_0^d(Q^2) \). Since \( \gamma_0 \) is weighted by an additional factor of \( x^2 \) compared to \( \gamma_1 \), the integral is mostly saturated by the \( \Delta(1232) \) resonance and uncertainties due to the low-\( x \) extrapolation are greatly reduced. The MAID 2003 [46] model follows the trend of the data but lies systematically below them. The MAID model is consistent with our data for \( A_1 \) in the \( \Delta \) resonance region, but MAID includes only single-pion production channels, which leads to an underestimation of the unpolarized structure function \( F_1 \), entering the definition of \( \gamma_0 \).

Unlike \( \gamma_1 \), \( \gamma_0 \) is not constrained at \( Q^2 = 0 \) and is therefore a more stringent test of Chiral Perturbation calculations. The leading order heavy baryon \( \chi \text{PT} \) calculation by Kao et al. [45], shown by the dotted line in Fig. 3, includes the \( \Delta \) resonance contribution. Their 4th order calculation (dashed line) is of opposite sign and shows no sign of convergence; neither calculation reproduces the trend or magnitude of the data. The relativistic \( \chi \text{PT} \) calculation of Bernard et al. converges better at 4th order [17]. That calculation, including the resonance contribution, is represented by the grey band in Fig. 3, and is also in serious disagreement with the data. The \( \Delta(1232) \) and vector meson contribution is negative (around \(-2 \times 10^{-4} \text{ fm}^4 \)) and is consistent with the calculation by Kao et al.
at \( Q^2 = 0 \), suggesting that the discrepancy at low \( Q^2 \) is mainly due to the non-resonance terms [47].

In the right-hand panel of Fig. 3, \( g_p^1 \) is weighted by a factor of \( Q^2/(16\pi^2M^2) \). In the limit of very large \( Q^2 \), this expression converges to the third moment of \( g_1 \), \( d_2 \), which is expected to scale approximately in the framework of OPE. Our data seem to be leveling off above \( Q^2 = 1.5 \text{ GeV}^2 \), but do not go high enough in \( Q^2 \) to confirm scaling behavior. We also show an evaluation of \( \int_0^1 x^2 dA_F(\gamma, Q^2) \) (shaded band) based on our model for \( F_1 \) and a fit to the world data for \( A_1 \) (mostly from SLAC, SMC, and HERMES in addition to our own data). The width of the shaded band indicates the combined one-sigma uncertainty of the models of \( F_1 \) and \( A_1 \). Our model confirms the leveling-off around \( Q^2 = 2 \text{ GeV}^2 \) and shows a logarithmic fall-off at higher \( Q^2 \).

In summary, \( g_1(x, Q^2) \) for the proton and the deuteron have been measured over a vastly expanded kinematic range at low and intermediate momentum transfer, which includes the entire resonance region and part of the DIS regime. These measurements enable us to evaluate moments of \( g_1 \) over a wider range in \( Q^2 \), decreasing extrapolation uncertainties. The first extraction of the resonance region and part of the DIS regime. These measurements have also been reported along with a new precise mapping of \( \chi_{P}^{0}Q \) down to lower \( Q^2 \) as low as 0.05 \text{ GeV}^2. It is important to note, however, that these \( \chi_{P}^{0}Q \) calculations fail to describe our results for \( \chi_{P}^{0}Q \), even for \( Q^2 \) as low as 0.05 \text{ GeV}^2. The \( \chi_{P}^{0}Q \) calculations are increasingly being used to extract results from lattice QCD and it is critical to understand their range of applicability [16]. Data for the isoscalar quantity \( g_d^1 \) have also been published by our collaboration and may give additional guidance to future theoretical work in this area [48]. We also look forward to results from new experiments at Jefferson Lab, in which spin structure functions down to \( Q^2 = 0.01 \text{ GeV}^2 \) will provide a more stringent test of \( \chi_{P}^{0}Q \) [28–30].

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