Spin structure of the proton and deuteron with CLAS at Jefferson Lab

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Abstract. The EG1 experiment at Jefferson Lab used the CLAS detector to measure inclusive, semi-inclusive, and exclusive reactions with longitudinally polarized electrons scattering from longitudinally polarized protons and deuterons. Preliminary results for g_1^p and g_1^d are presented for a subset of the inclusive data. The data span a large kinematic range, $0.02 < Q^2 < 5 \text{ GeV}^2$ and $0.05 < x < 1$, covering the region where nucleon resonances dominate as well as the traditional DIS region.

The spin-dependent structure function $g_1(x, Q^2)$ for inelastic lepton-nucleon scattering is of fundamental importance in understanding the quark and gluon spin structure of the proton and neutron in the deep inelastic region of high Q^2 , as well as the resonant structure at low Q^2 and excitation energy. The goal of the CLAS EG1 experiment was to make precise measurements over the entire (x, Q^2) range currently accessible at Jefferson Lab in a single experiment, using both polarized proton and deuteron targets. Results from an initial data run in 1998 (EG1a) have recently been published [1, 2]. We report here on some of the data from the much higher statistics run in 2000.

Beam currents ranged from 0.3 nA to 6 nA. The helicity was frequently reversed to minimize instrumental asymmetries. The 1-cm-long polarized target cells contained pre-irradiated granules of $^{15}\text{NH}_3$ or $^{15}\text{ND}_3$ immersed in liquid He at 1 K in a uniform magnetic field of 5 T. Microwaves near 140 GHz were used to drive the hyperfine transition which aligns (or anti-aligns) the nucleon spins with the magnetic field, producing proton polarizations of typically 70% (30%) for NH_3 (ND_3). The sub-millimeter diameter electron beam spot was rastered over the 1.8 cm^2 front surface of the target to uniformly distribute beam heating and radiation damage. The target polarization direction was periodically reversed.

The product of target polarization P_t and beam polarization P_b was determined using the well-known double-spin asymmetry in ep elastic (quasielastic) scattering for NH_3 (ND_3). Results from single arm (e only) and double arm (both e and p detected) measurements were found to be consistent within statistical errors, and the average for the experiment was $P_b P_t \approx 0.5$ for protons and $P_b P_t \approx 0.2$ for deuterons.

Scattered electrons were tracked in the CLAS [3] toroidal field using drift chambers, and separated from hadrons by requiring a substantial signal in the gas Cherenkov counters and most of the particle energy to be deposited in the electromagnetic calorimeter. Data were taken with approximately equal running times with positive and negative torus polarity (corresponding to electrons bending inward or outward) with beam energies near 1.7, 2.4, 4.2, and 5.7 GeV. Approximately 2.3×10^{10} triggers were registered,

FIGURE 1. Preliminary results for g_1^p from the CLAS EG1 experiment using an incident electron energy of 1.6 GeV (left panel) and 5.7 GeV (right panel). The solid curves represent the EG1 fit to the data. The dashed curves indicate zero.

yielding about 10^{10} cleanly identified electrons. The present results are based on approximately half this total, as the 2.4 and 4.2 GeV data are still being processed.

The experimental asymmetries $A_{||}$ were determined from

$$A_{||} = \left(\frac{N_- - N_+}{N_- + N_+} \right) \frac{1}{f P_b P_t f_{RC}} + A_{RC}, \quad (1)$$

where the target polarization is parallel to the beam direction, N_- (N_+) is the number of scattered electrons per incident charge for negative (positive) beam helicity, f is the dilution factor representing the fraction of measured events originating from polarizable hydrogen within the target, and f_{RC} and A_{RC} take into account radiative corrections. Small corrections for the polarized nitrogen nuclei were also made.

The dilution factor f was determined by careful comparison of counting rates from the NH_3 and ND_3 targets with a target in which the polarized granules were replaced with a known amount of C, and another target with only liquid helium and the target windows. For NH_3 (ND_3), f varied with x and Q^2 between 0.12 (0.2) and 0.16 (0.24),

A correction to the asymmetries was made for pions misidentified as electrons (typically 2% of electron candidates, but up to 10% in the lowest x bins). The correction

FIGURE 2. Same as Fig. 1, except for g_1^d .

used the asymmetry measured for a large sample of inclusive pions, which was found to be close to zero at all kinematics. An additional correction was made for electrons from pair-symmetric processes (such as e^+/e^- pair production from photons) measured using identified positrons. The measured pair-symmetric $A_{||}$ was consistent with zero at all kinematics, so the correction is equivalent to a dilution factor correction of typically 10% at the lowest E' used, decreasing rapidly to a negligible correction at higher E' . No corrections have been applied for kinematic resolution.

The internal radiative corrections for $A_{||}$ were evaluated using the formulae of Kuchto and Shumeiko [4]. The cross sections entering the asymmetry were ‘externally radiated’ according to Tsai [5]. Comparison of Born and fully radiated asymmetries allowed us to extract the asymmetry corrections f_{RC} and A_{RC} . By splitting the radiative correction into these two parts, we can propagate consistently the experimental error to the extracted Born asymmetries for the corresponding kinematic bins, in the presence of ‘dilution’ from elastic and inelastic radiative tails.

The ratio of polarized to unpolarized structure functions was determined from $A_{||}$ using

$$g_1/F_1 = A_{||}/d + (g_2/F_1)[(2Mx)/(2E - \nu)], \quad (2)$$

where the virtual photon de-polarization factor $d = [(1 - \epsilon)(2 - y)]/\{y[1 + \epsilon R(x, Q^2)]\}$, $y = \nu/E$, and $\nu = E - E'$, where E is the incident and E' is the scattered electron energy

FIGURE 3. Preliminary EG1 results for A_1^p (left) and A_1^d (right) at high x for $Q^2 > 1.4 \text{ GeV}^2$ and $W > 2 \text{ GeV}$, compared to several quark models (with all have the limit $A_1 \rightarrow 1$ as $x \rightarrow 1$, [7] and the SU(6) spin-flavor symmetry limit [8]). Data from SLAC [9, 10] and SMC [11] are also shown.

in the lab frame, $\varepsilon^{-1} = 1 + 2[1 + \gamma^{-2}] \tan^2(\theta/2)$, $\gamma^2 = Q^2/v^2$, θ is the electron scattering angle, M is the nucleon mass, and $R(x, Q^2) = [F_2(x, Q^2)(1 + \gamma^2)]/[2xF_1(x, Q^2)] - 1$ is typically 0.2 for the kinematics of this experiment. For the contribution of the transverse spin structure function g_2 we used the twist-two result of Wandzura and Wilczek (g_2^{WW}) [6]

$$g_2^{WW}(x, Q^2) = -g_1(x, Q^2) + \int_x^1 g_1(\xi, Q^2) d\xi/\xi, \quad (3)$$

(evaluated using an empirical fit to g_1/F_1) at high W , and a unitary isobar model (MAID) in the resonance region. Values of g_1 where obtained from g_1/F_1 using a fit to F_1 .

Preliminary results for g_1^p and g_1^d are shown in Figs. 1 and 2 as a function of x at several values of Q^2 . For the present experiment, most systematic errors (beam polarization, target polarization, fraction of polarizable nucleons in the target) for a given target are common to all data and correspond to an overall relative normalization error of about 5%. The remaining systematic errors (model dependence of radiative corrections, model uncertainties for $R(x, Q^2)$, model dependence of f) vary smoothly with x in a locally correlated fashion, ranging from a few percent for mid-range x bins, up to 15% of the $E = 5.7 \text{ GeV}$ proton data for the highest and lowest bins.

At high x , g_1 is seen to decrease with increasing Q^2 for both proton and deuteron targets. Although space limitations do not allow for a figure in this proceedings, a plot of the ratios g_1/F_1 shows almost no dependence on Q^2 at fixed x for $Q^2 > 1.5 \text{ GeV}^2$, indicating that the QCD evolution of the two structure functions is very similar. At lower Q^2 , the data fall below the high Q^2 limit, corresponding to the excitation of the $\Delta(1232)$

FIGURE 4. Very preliminary CLAS results for the ratio the integral of g_1^p over the entire resonance region (top) and three individual resonance regions (below), to the corresponding DIS integral in the appropriate region of Nachmann ξ , as a function Q^2 in GeV^2 .

resonance. The small and sometimes negative values of g_1 in the $\Delta(1232)$ region are expected since this is predominantly a spin-flip transition. On the low x side of the $\Delta(1232)$ dip, positive enhancements can be seen corresponding to the predominately non-spin-flip transition to the $S_{11}(1520)$ resonance.

The CLAS data provide a considerable improvement in precision in the high x region, which is of particular interest in distinguishing between various models of the valence spin structure of the nucleon (see Fig. 3). The preliminary results for $A_1 = g_1/F_1 - \gamma^2 g_2/F_1$ clearly show a preference for the pQCD limit at $x = 1$ [7], compared to the SU(6) spin-flavor symmetry limit [8].

A subject that has seen re-awakened interest lately is quark-hadron duality, in which structure functions averaged over suitable ranges in excitation energy become independent of Q^2 when an appropriate scaling variable is chosen. Although quark-hadron duality appears to be fairly well validated in the case of spin-averaged response function F_1 and F_2 in the region of the $\Delta(1232)$ resonance [12], it is manifestly broken in the case of g_1 , which is negative at the peak of the Δ at low Q^2 , but positive at high Q^2 , as shown in Fig. 4 for the proton. In this figure, the integral of g_1 over several regions in W is compared with high Q^2 parametrizations in the DIS region, taking target mass effects into account using the Nachmann scaling variable ξ instead of x . Even at $Q^2 = 5 \text{ GeV}^2$, the $\Delta(1232)$ integral lies below the DIS curve. This can be partially restored by pairing the $\Delta(1232)$ (lowest lying spin-3/2 state) with the ep elastic peak (lowest lying spin-1/2 state), but in this case spin-duality is approached from above unity, rather than from below. On the other hand, spin-duality appears to work remarkably well for higher mass resonance regions for $Q^2 > 1 \text{ GeV}^2$, as well as for the entire resonance region for $Q^2 > 1.5 \text{ GeV}^2$.

Combined with other data, the new CLAS data have been used to study the extended GDH Sum Rule [13] and the transition to Ellis-Jaffe [14] and Bjorken Sum [15] Rules at higher Q^2 . Using reasonable Regge models to extrapolate to $x = 0$, both $\Gamma_1^p(Q^2) = \int_0^{1-} g_1^p(x, Q^2) dx$ and $\Gamma_1^d(Q^2) = \int_0^{1-} g_1^d(x, Q^2) dx$ show a clear change of sign from being negative at low Q^2 as predicted by the GDH Sum Rule, to being positive at high Q^2 , with the cross-over point occurring at about $Q^2 = 0.3 \text{ GeV}^2$ for the proton and 0.5 GeV^2 for the deuteron.

In summary, the new high statistics measurements of g_1^p and g_1^d show great promise to shed light on several of the central issues in nucleon spin structure: the Q^2 evolution of the structure functions, the high- x behavior, the Q^2 dependence of the first moments of g_1 , and studies of duality. Semi-inclusive scattering results hold promise for flavor decomposition of the PDF's, and studies of fragmentation and single-spin asymmetries. More information on specific nucleon resonances will be obtained, particularly with the study of specific exclusive final states. For more information on all of these topics, the interested reader is invited to consult the many talks given at the recent GDH 2004 conference [16]

REFERENCES

1. The CLAS Collaboration, R. Fatemi *et al.*, nucl-ex/0306019 (2003).
2. The CLAS Collaboration, J. Yun *et al.*, Phys. Rev. **C 67**, 055204 (2003).
3. B. Mecking *et al.*, Nucl. Instrum. Meth. **A503**, 513 (2003).
4. T. V. Kuchto and N. M. Shumeiko, Nucl. Phys. **B219**, 412 (1983); I. V. Akusevich and N. M. Shumeiko, J. Phys. **G20**, 513 (1994).
5. Y. S. Tsai, Report No. SLAC-PUB-848, 1971; Y. S. Tsai, Rev. Mod. Phys. **46**, 815 (1974).
6. S. Wandzura and F. Wilczek, Phys. Lett. **B72**, 195 (1977).
7. G. Farrar and D. Jackson, Phys. Rev. Lett. **35**, 1416 (1975); N. Isgur, Phys. Rev. D **59** 034013 (1999); F.E. Close and W. Melnitchouk, Phys. Rev. C **68**, 035210 (2003).
8. F.E. Close, Phys. Lett. **43**, 42 (1973).
9. SLAC E143, K. Abe *et al.*, Phys. Lett. **B364**, 61 (1995); Phys. Rev. D **58**, 112003 (1998).
10. SLAC E155, P.L. Anthony *et al.*, Phys. Lett. **B493**, 19 (2000).
11. SMC, D. Adeva *et al.*, Phys. Rev. D **58**, 112001 (1998).
12. I. Niculescu *et al.*, Phys. Rev. Lett. **85**, 1186 (2000).
13. S. D. Drell and A. C. Hearn, Phys. Rev. Lett. **16**, 908 (1966); S. B. Gerasimov, Yad. Fiz. **2**, 598 (1966).
14. J. Ellis and R. Jaffe, Phys. Rev. D **9**, 1444 (1974); D **10**, 1669 (1974) (E).
15. J. D. Bjorken, Phys. Rev. **148**, 1467 (1966); Phys. Rev. D **1**, 1376 (1970).
16. Proceedings of the The 3rd International Symposium on the Gerasimov-Drell-Hearn Sum Rule and its extensions, Old Dominion University, Norfolk, Virginia, June 2-5, 2004.