Measuring the Neutron and ^{3}He Spin Structure at Low Q^2

Vincent A. Sulkosky *†

Jefferson Laboratory
12000 Jefferson Avenue, Newport News, VA 23606 - USA

Jefferson Lab experiment E97-110 was performed to provide precise data for the extended Gerasimov–Drell–Hearn integral and the moments of the neutron and ^{3}He spin structure functions at low Q^2 from 0.02 to 0.3 (GeV/c)^2. These data allow us to carry out a precise test of Chiral Perturbation Theory calculations in a region where they are expected to be valid. In these proceedings, the motivation for the experiment and the experimental details are discussed, and preliminary results are presented on the first moment of the $g_1\left(x, Q^2\right)$ structure function. Results on the $g_2\left(x, Q^2\right)$ integral were also presented at the conference [1].

1 Introduction

Since the 1980's, the study of nucleon spin structure has been an active field both experimentally and theoretically [2]. One of the primary goals of this work is to test our understanding of Quantum Chromodynamics (QCD), the fundamental theory that describes nucleons and their interactions. In the high energy region of asymptotically free quarks, QCD has been verified. However, verifiable calculations in the low energy region are difficult to obtain due to the complex interactions between the nucleon's constituents: quarks and gluons. In the non-perturbative regime, low-energy effective field theories such as Chiral Perturbation Theory provide calculations for the spin structure functions in the form of sum rules.

Spin-dependent sum rules such as the Gerasimov-Drell-Hearn (GDH) [3] sum rule are important tools available to study nucleon spin structure. Originally derived for real photon absorption, the GDH sum rule was first extended for virtual photon absorption in 1989 [4]. The extension involves replacing the photoproduction cross section with the electroproduction cross sections, though other extensions exist and are described in [5, 6].

In particular, the generalization by Ji and Osborne [6] takes advantage of the relationship between the forward Compton scattering amplitudes $S_1\left(Q^2\right)$ and $S_2\left(Q^2\right)$ and the spin-dependent structure functions $g_1\left(x, Q^2\right)$ and $g_2\left(x, Q^2\right)$. This serves as a natural extension of the sum rule to virtual-photon scattering and generates a Q^2-dependent sum rule, if the Compton amplitudes can be calculated for $Q^2 > 0$. The extension of the sum rule provides a unique relation, valid at any four-momentum transfer (Q^2), that can be used to study the nucleon spin structure and make comparisons between theoretical calculations and experimental data. This comparison allows a study of the transition between the non-perturbative region and the perturbative region of QCD.

Using a polarized ^{3}He target, we have measured both neutron spin structure functions at low Q^2 from 0.02 to 0.3 (GeV/c)^2 to test Chiral Perturbation Theory calculations. In addition, the GDH sum rule can be checked by extrapolating the data to the real photon point. The new data cover the quasi-elastic and resonance regions up to an invariant mass

*for the Jefferson Lab Hall A Collaboration
†E-mail: vasulk@jlab.org

$W = 2.5$ GeV depending on the values of Q^2. From the preliminary structure function data, the first moment of $g_1\left(x, Q^2\right)$ has been formed and compared to existing theoretical calculations. Results on the $g_2\left(x, Q^2\right)$ integral were also available and presented at the conference [1]. In the near future, the extended GDH integral and forward spin polarizabilities [7] will also be extracted.

2 The Experiment

Experiment E97-110 [8] took place at Jefferson Lab in Hall A [9]. The data were collected at seven incident electron beam energies and two angles to obtain the necessary kinematic coverage to form integrals at constant Q^2. The experiment covers an invariant mass range encompassing the elastic, quasi-elastic, resonance regions and deep into the continuum. The covered Q^2 range is from 0.005 to 0.4 $(\mathrm{GeV}/c)^2$. The scattered electrons were detected by one of the Hall A High Resolution Spectrometers [9]. The small scattering angles of $6°$ and $9°$ were achieved by placing an additional horizontally-bending dipole magnet [10] in front of the spectrometer; without this magnet the minimum spectrometer angle is $12.5°$.

The inclusive reaction $^3\vec{\mathrm{He}}(\vec{\mathrm{e}}, \mathrm{e}')$ was measured using a longitudinally polarized electron beam scattering from a longitudinally or transversely (in-plane) polarized ^{3}He target [9]. The electron beam was used with a current of up to 10 μA and an average polarization of 75%. The technique of spin-exchange optical pumping between rubidium atoms and ^{3}He nuclei was used to polarize the ^{3}He target. The polarization of the target was oriented in either the longitudinal or transverse direction with the aid of two sets of Helmholtz coils. Two independent polarimetries [9] were used to monitor the polarization: NMR and EPR. The average target polarization was $\sim 40\%$.

By measuring both target polarization orientations, we are able to extract both spin structure functions $g_1\left(x, Q^2\right)$ and $g_2\left(x, Q^2\right)$ from the polarized cross-section differences without the use of models via:

$$\Delta\sigma_{\parallel}\left(x, Q^2\right) = \frac{4\alpha^2}{M\nu Q^2}\frac{E'}{E}\left[\left(E + E'\cos\theta\right) g_1\left(x, Q^2\right) - \left(\frac{Q^2}{\nu}\right) g_2\left(x, Q^2\right)\right] \quad \text{and}$$

$$\Delta\sigma_{\perp}\left(x, Q^2\right) = \frac{4\alpha^2}{M\nu Q^2}\frac{E'}{E} E'\sin\theta\left[g_1\left(x, Q^2\right) + \frac{2E}{\nu} g_2\left(x, Q^2\right)\right],$$

where E is the beam energy, E' the scattered electron energy, θ the electron scattering angle, and $x = \frac{Q^2}{2M\nu}$ the Bjorken scaling variable. The mass of the nucleon and energy transfer are M and ν, respectively.

Once the structure functions are extracted, various integrals can be formed such as the extended GDH integral and the moments of the spin structure functions. The first moment of the g_1 structure function is given by

$$\overline{\Gamma}_1(Q^2) = \int_0^{x_0} g_1\left(x, Q^2\right) dx,$$

where x_0 is the inelastic threshold. This integral is related to the GDH sum rule as $Q^2 \to 0$. The Burkhardt-Cottingham sum rule [11], which is valid for all values of Q^2, is related to the first moment of g_2:

$$\Gamma_2(Q^2) = \int_0^1 g_2\left(x, Q^2\right) dx = 0.$$

For this experiment, the polarized ^{3}He target was used as an effective polarized neutron target. The neutron quantities are extracted using the prescription by Ciofi degli Atti and Scopetta [13]. At $Q^2 \leq 0.1$ (GeV/c)^2, the systematic uncertainty due to this extraction is at the 10% level. In addition, we have used the parameterization of Bianchi and Thomas [12] to account for the unmeasured low x region.

3 Preliminary results

Figure 1 shows the preliminary results for the integral of $g_1\left(x, Q^2\right)$ compared to previous data [14, 15, 16, 17] and theoretical calculations. The solid triangles represent the new data, whereas the inverted-triangles show the results from a previous neutron experiment [17] in Hall A at Q^2 between 0.1 and 0.9 (GeV/c)^2. The total uncertainties are shown by the error bars on the points. For the final results, the systematic uncertainties will be significantly improved. The preliminary results agree extremely well with data at $Q^2 \geq 0.1$ (GeV/c)^2, and show a smooth transition as $Q^2 \to 0$. The two model calculations [18, 19] also agree well with the new data. Near $Q^2 = 0$, two calculations from Chiral Perturbation Theory

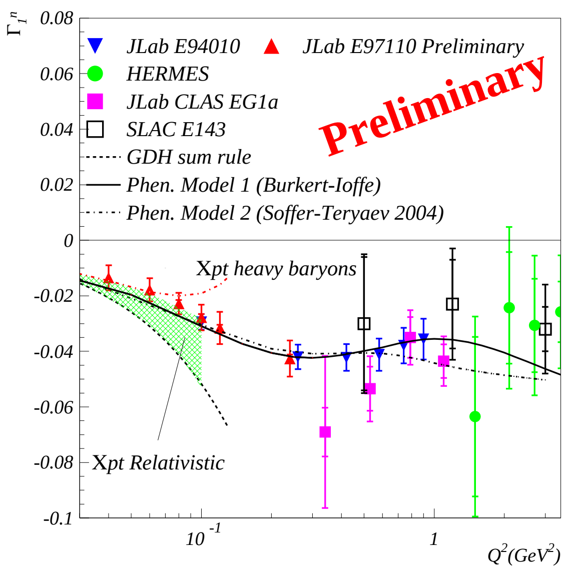

Figure 1: Preliminary neutron Γ_1 results (see text for details).

are available [20, 21]. One of the calculations includes an estimate of the Δ-resonance contribution and is represented by the band at low Q^2. The band is the result of the uncertainties on the parameters of the Δ resonance. Our data agree with the relativistic baryon calculation [20] within the experimental uncertainties, and the three lowest-Q^2 points agree well with the heavy baryon calculation [21].

4 Summary

The extended GDH integral, or equivalently $\overline{\Gamma}_1$, is an important tool used to study the nucleon spin structure over the full Q^2 range. Experiment E97-110 was conducted to provide precise spin structure data for the neutron and ^{3}He at low Q^2, 0.02 to 0.3 (GeV/c)^2. From the measured structure functions, the generalized GDH integral, moments of the spin structure functions and forward spin polarizabilities are extracted. At low Q^2, these quantities provide an important benchmark check of Chiral Perturbation Theory calculations. Here, we have presented the preliminary results on the integral of $g_1\left(x, Q^2\right)$. The data show good agreement with published data at higher Q^2 and both calculations from Chiral Perturbation Theory. Systematic checks are ongoing, and final neutron results are expected soon.

5 Acknowledgments

This work was supported by the U.S. Department of Energy contract DE-AC05-84ER40150 Modification No. M175 under which the Southeastern Universities Research Association operates the Thomas Jefferson National Accelerator Facility.

References

[1] Slides:
http://indico.cern.ch/contributionDisplay.py?contribId=260&sessionId=22&confId=24657

[2] B. W. Filippone and X. Ji, Adv. Nucl. Phys. **26** 1 (2001).

[3] S. B. Gerasimov, Sov. J. of Nucl. Phys. **2** 430 (1966);
S. D. Drell and A. C. Hearn, Phys. Rev. Lett. **16** 908 (1966).

[4] M. Anselmino, B. L. Ioffe and E. Leader, Sov. J. of Nucl. Phys. **49** 136 (1989).

[5] D. Drechsel, S. S. Kamalov and L. Tiator, Phys. Rev. **D63** 114010 (2001);
D. Drechsel, B. Pasquini and M. Vanderhaeghen, Phys. Rep. **378** 99 (2003);
D. Drechsel and L. Tiator, Annu. Rev. Nucl. Part. Sci. **54** 69 (2004).

[6] X. Ji and J. Osborne, J. Phys. **G27** 127 (2001).

[7] J.-P. Chen, A. Deur and Z.-E. Meziani, Mod. Phys. Lett. **A20** 2745 (2005).

[8] For details see V. Sulkosky's thesis at http://hallaweb.jlab.org/experiment/E97-110/thesis.html.

[9] J. Alcorn *et al.*, Nucl. Instrum. Meth. **A522** 294 (2004).

[10] P. Brindza *et al.*, IEEE Transactions on Applied Superconductivity **11** 1594 (2001).

[11] H. Burkhardt and W. N. Cottingham, Annals. Phys. **56** 453 (1970).

[12] N. Bianchi and E. Thomas, Nucl. Phys. B, Proc. Suppl. **82** 256 (2000).

[13] C. Ciofi degli Atti and S. Scopetta, Nucl. Phys. **B404** 223 (1997).

[14] P. L. Anthony *et al.*, Phys. Rev. **D54** 6620(1996);
K. Abe *et al.*, Phys. Rev. **D58** 112003 (1998);
K. Abe *et al.*, Phys. Rev. Lett. **79** 26 (1997).

[15] A. Airapetian *et al.*, Eur. Phys. J. **C26** 527 (2003).

[16] J. Yun *et al.*, Phys. Rev. **C67** 055204 (2003).

[17] M. Amarian *et al.*, Phys. Rev. Lett. **89** 242301 (2002);
M. Amarian *et al.*, Phys. Rev. Lett. **92** 022301 (2004);
M. Amarian *et al.*, Phys. Rev. Lett. **93** 152301 (2004).

[18] V.D. Burkert and B. L. Ioffe, Phys. Lett. **B296** 223 (1992).

[19] J. Soffer and O. V. Teryaev, Phys. Rev. **D70** 116004 (2004).

[20] V. Bernard, T. R. Hemmert and U.-G. Meissner, Phys. Lett. **B545** 105 (2002);
V. Bernard, T. R. Hemmert and U.-G. Meissner, Phys. Rev. **D67** 076008 (2003).

[21] X. Ji, C. Kao and J. Osborne, Phys. Lett. **B472** 1 (2000).