

The g_2 Spin Structure Function

Melissa Cummings*

The College of William and Mary

E-mail: melissac@jlab.org

Jefferson Lab has been at the forefront of a program to study the polarized structure of nucleons. Measurements of the spin-dependent structure functions, g_1 and g_2 , have proven to be powerful tools in testing and understanding Quantum Chromodynamics. To measure g_2 a transversely polarized target is needed, which proves to be challenging experimentally. Prior to JLab, the only dedicated experiment to measure g_2 was SLAC E155x, which shows consistency with the leading twist g_2^{WW} prediction, but has large uncertainties. The function g_2^n has been measured extensively in Hall A at JLab over a wide range of Q^2 . The Resonances Spin Structure (RSS) experiment in Hall C gave a precision measurement of g_2 for the proton and deuteron at intermediate Q^2 , providing the first world data for $g_2^{p,d}$ in the nucleon resonance region. The Spin Asymmetries of the Nucleon experiment (SANE), also performed in Hall C, provided a measurement of g_2 in the high Q^2 (DIS) region. More recently, the g_2^p experiment took data covering the low Q^2 region. The 0^h moment of g_2 provides a test of the Burkhardt-Cottingham sum rule, which states that the integral of g_2 over the Bjorken scaling variable x goes to zero. This sum rule, valid for all values of Q^2 , has been satisfied for the neutron, but a violation is suggested for the proton at high Q^2 . The 2^{nd} moment allows for a benchmark test of lattice QCD predictions at high Q^2 with d_2 , and a test of Chiral Perturbation Theory at low Q^2 . Specifically, the behavior of the longitudinally-transverse spin polarizability (δ_{LT}), as χ PT calculations of this quantity deviate significantly from the measured neutron data. This document will provide an overview of the JLab effort to measure g_2 , with a focus on the more recent g_2^p experiment; the current status of the analysis will be discussed along with preliminary results.

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*Speaker.

1. Introduction and Motivation

The proton's composition of quarks and gluons, which exhibit many-body interactions, make scattering from a proton significantly more complicated than a point-like particle. The four structure functions, F_1 , F_2 , g_1 and g_2 describe the deviation of a nucleon from point-like behavior in an inclusive scattering experiment, $N(e, e^-)$. For the case with an unpolarized nucleon and unpolarized electron, the scattering cross section can be described with the functions F_1 and F_2 (equation 1.1). For the more complicated case, with a polarized nucleon and polarized electron, two additional structure functions (g_1 and g_2) are necessary to completely parameterize the scattering cross section (equations 1.2 and 1.3). We can investigate the spin structure of the nucleon by using different combinations of the beam/target polarization, i.e. longitudinally polarized electrons with a longitudinally or transversely polarized nucleon.

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott} \left[\frac{1}{v} F_2(x, Q^2) + \frac{2}{M} F_1(x, Q^2) \tan^2(\theta/2) \right] \quad (1.1)$$

$$\Delta\sigma_{\parallel} = \frac{d^2\sigma}{d\Omega dE'} (\downarrow\uparrow - \uparrow\uparrow) = \frac{4\alpha^2}{MQ^2} \frac{E'}{vE} \left[(E + E' \cos \theta) g_1(x, Q^2) - \frac{Q^2}{v} g_2(x, Q^2) \right] \quad (1.2)$$

$$\Delta\sigma_{\perp} = \frac{d^2\sigma}{d\Omega dE'} (\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2 \sin \theta}{MQ^2} \frac{E'^2}{v^2 E} [v g_1(x, Q^2) - 2E g_2(x, Q^2)] \quad (1.3)$$

where v is the difference between the incoming and scattered electron energy, Q^2 is the 4-momentum transfer squared, and x is the Bjorken scaling variable.

To interpret these structure functions, we can start with the Quark-Parton model, which was put forth by Feynman in 1969. In the Bjorken scaling limit, the structure functions F_1 , F_2 and g_1 can be written in terms of parton distribution functions. However, as this model describes the partons as point-like non-interacting particles, g_2 has a value of zero. This is where we begin to see the cracks in the so-called "naive" quark model, as g_2 contains contributions from quark-gluon interactions. The function g_2 is usually expressed in terms of its twist expansion.

$$g_2(x, Q^2) = g_2^{WW}(x, Q^2) + \bar{g}_2(x, Q^2) \quad (1.4)$$

The first term of equation 1.4, g_2^{WW} , is known as the Wandzura-Wickczek relation; the leading twist-2 term which expresses g_2 entirely in terms of g_1 . The second term, \bar{g}_2 , contains terms that are twist-3, which arise from quark-gluon interactions. Higher twist processes can be thought of as involving more than one parton of the hadron in the scattering process. Instead of viewing only a bare quark, we begin to probe how the quarks and gluons interact in the context of the nucleon. The function g_2 offers the most direct view of these correlations, so it becomes an attractive quantity to measure.

2. Measurements of the g_2 Structure Function at Jefferson Lab

Measurements of the g_2 structure function require a target which is polarized transversely with respect to the polarization of the electron beam, which is more difficult experimentally. Prior to

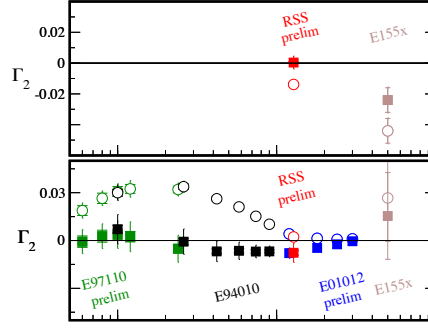


Figure 1: Current results for the BC sum rule. The top plot is for the proton and the bottom plot is for the neutron. Open circles represent the measured data, while black diamonds show the total integral with low- x and elastic contributions included. Reproduced from [8].

measurements at JLab, the only dedicated experiment to measure g_2 was SLAC E155x [6], which shows consistency with the g_2^{WW} prediction. The function g_2^n has been measured extensively in Hall A at JLab [8], but data on g_2^p remain scarce. The Resonances Spin Structure (RSS) experiment in Hall C gave a precision measurement of g_2 for the proton and deuteron at intermediate Q^2 , providing data for $g_2^{p,d}$ in the nucleon resonance region [1]. The Spin Asymmetries of the Nucleon experiment (SANE), also performed in Hall C, provided a measurement of g_2 in the high Q^2 (DIS) region [7]. More recently, the g_2^p experiment took data covering the low Q^2 region.

The 0^{th} moment of g_2 (no x -weighting) provides a test of the Burkhardt-Cottingham sum rule, shown in equation 2.1. The BC sum rule is not a parton model prediction, and is valid for all values of Q^2 . Current results for tests of the BC sum rule are show in figure 1. For the neutron, the BC sum rule has been tested over a large range of Q^2 and show consistency with the expected result of zero, within small uncertainties. The lack of data for the proton leaves the BC sum rule largely untested. The results from SLAC suggest an inconsistency on the level of 2.75σ , which arises from both a large experimental uncertainty as well as uncertainty associated with the low- x extrapolation that is difficult to quantify. The results from the RSS experiment show better agreement; the integral over the measured region is negative, but is consistent with zero once the low- x extrapolation is added in. Precision data from JLab is consistent with the BC sum rule in all cases, which suggests that g_2 is a well behaved function with good convergence. The data from the g_2^p experiment will provide an additional test for the proton at low Q^2 .

$$\Gamma_2 = \int_0^1 g_2(x, Q^2) dx = 0 \quad (2.1)$$

The 2^{nd} moment of g_2 provides insight o the generalized spin polarizabilities γ_0 and δ_{LT} (equations 2.2 and 2.3), which offer a benchmark test of Chiral Perturbation Theory (χ PT). For the quantity γ_0 , the difficulty in these calculations is in how to included the resonances, specifically the Δ resonance, which usually dominates.

$$\gamma_0(Q^2) = \frac{16\alpha M^2}{Q^6} \int_0^{x_0} x^2 \left[g_1(x, Q^2) - \frac{4M^2}{Q^2} x^2 g_2(x, Q^2) \right] \quad (2.2)$$

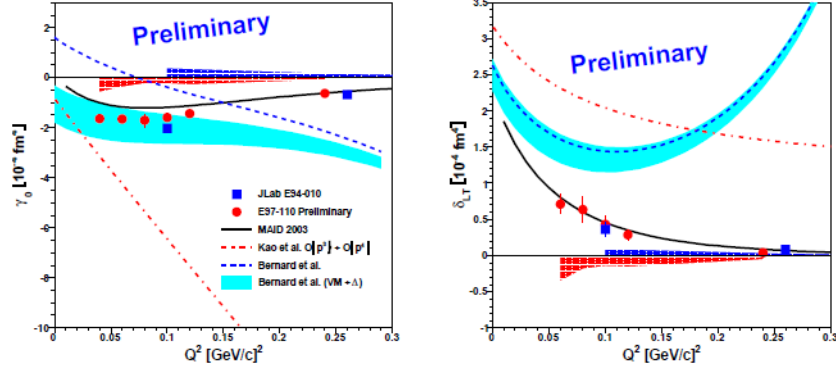


Figure 2: On the left are the current neutron results for the generalized spin polarizability γ_0 , and on the right are neutron results for δ_{LT} . The blue squares represent published data from E94010, while the red circles are preliminary data from E97110. Reproduced from [9].

$$\delta_{LT}(Q^2) = \frac{16\alpha M^2}{Q^6} \int_0^{x_0} x^2 [g_1(x, Q^2) + g_2(x, Q^2)] \quad (2.3)$$

The neutron results for the generalized polarizabilities are shown in figure 2. Shown alongside the data for γ_0 is the relativistic baryon χ PT prediction (represented by the blue dotted line) and the same calculation, but explicitly including the Δ resonance and vector meson contributions (light blue band). The prediction at low Q^2 matches well with the experimental results, but there is disagreement at high Q^2 . The quantity δ_{LT} is thought to be a better testing ground for χ PT due to its insensitivity to the Δ resonance. In this case, as seen in figure 2, explicitly including the vector meson and Δ contribution shifts the central value of the prediction, but does not change the overall shape, indicating that the Δ contribution is not large for these calculations. However, there is clearly a large difference between the data and predictions for δ_{LT} [2]. The g_2^p experiment will provide an additional test of these quantities at low Q^2 for the proton.

3. The Experiment

The g_2^p experiment ran from March to May of 2012. An inclusive measurement was performed in the low Q^2 region $0.02 < Q^2 < 0.2 \text{ GeV}^2$ at forward angles to obtain the proton spin-dependent cross sections. To extract g_2 , both $\Delta\sigma_{\parallel}$ and $\Delta\sigma_{\perp}$ are needed. This experiment measured $\Delta\sigma_{\perp}$, results from the Hall B EG4 experiment will be used as input for $\Delta\sigma_{\parallel}$. Some data were taken in the longitudinal setting during this experiment as a cross check of the Hall B results. The kinematic coverage achieved during the experiment is shown in figure 3.

This experiment required a large scale installation in Hall A (see figure 4). A solid ammonia target was polarized through the process of dynamic nuclear polarization. In order to compensate for the deflection of the beam by the large target magnetic field, a pair of chicane magnets were installed upstream of the target. To reach the small scattering angle of 5.69° necessary for this kinematic range, a septum magnet was installed downstream of the target. New beamline diagnostics, to monitor the beam position and beam current, were required due to the low beam current

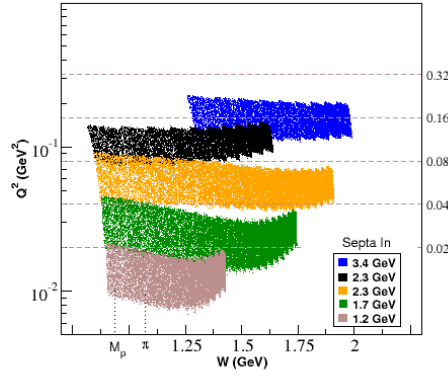


Figure 3: Kinematic coverage of the g_2^p experiment.

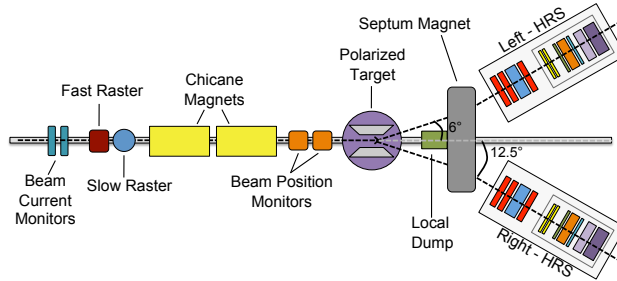


Figure 4: Hall A beamline for the g_2^p experiment.

(50-100 nA) needed to maintain the target polarization. For certain kinematics, a local beam dump was necessary, located just downstream of the septum magnet. The standard Hall A high resolution spectrometers (HRS) were used with a detector stack containing two pairs of vertical drift chambers (VDC), two planes of scintillators, a gas Cherenkov counter, and a lead glass calorimeter. The VDCs provide tracking information for the scattered electrons. The two planes of scintillators, placed ~ 2 m apart, provide the trigger for the data acquisition system. Sandwiched between the scintillator planes is a gas Cherenkov counter, which contains CO_2 . At these kinematics, electrons that pass through the gas will produce Cherenkov light, whereas heavier particles will not. Finally, two layers of lead glass form an electromagnetic calorimeter; energetic particles that pass through the material will produce a cascade of secondary particles. As this “shower” of particles propagates through the lead glass, the particle’s energy is converted to light, which is collected and used to determine the initial energy of the particle. The gas Cherenkov and lead glass calorimeter are used for particle identification.

4. Status of Analysis

Analysis of the g_2^p data is pushing forward. Detector calibration and efficiency studies have been completed for the gas Cherenkov, lead glass calorimeters and scintillator detectors in addition

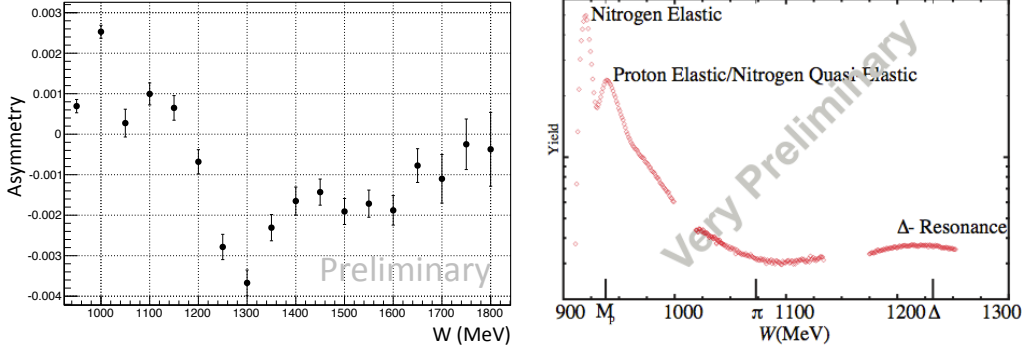


Figure 5: Preliminary results for the g_2^p experiment. On the left are asymmetry results (normalized by beam and target polarizations) and on the right are yield results.

to tracking analysis, including analysis of multi-track events. Scaler analysis, including beam current monitor calibrations, helicity decoding and deadtime calculations are finished. The target polarization analysis is also completed, with an average polarization of $\sim 70\%$ and $\sim 15\%$ for the 5T and 2.5T settings, respectively. Optics analysis was made more difficult for this experiment with the large target magnetic field, the septum field, and chicane magnets, but a first round of optics calibrations for the left HRS with target field on have been finished. Beam position calibrations were recently completed, and raster size calibrations are currently underway. Extraction of the packing fraction and dilution factor, necessary to understand the fraction of events that scattered from unpolarized target material, is in progress. In addition, analysis of elastic events and radiative corrections for cross section analysis are currently underway. Preliminary asymmetries and yields can be seen in figure 5. The asymmetry has been scaled by the beam and target polarization, but does not include the dilution factor. The uncertainty shown here is purely statistical, and radiative corrections have not been included. In the yields, we see good separation between the nitrogen and hydrogen elastic peaks. Additional data was taken on carbon, empty target cells, and helium to be used in dilution factor analysis. We expect to have preliminary results for g_2 in ~ 6 -12 months.

5. Summary

In these proceedings, we have discussed the measurements of the g_2 structure function for the proton. From Jefferson Lab, the RSS and SANE experiments have provided measurements of this spin observable at intermediate and high Q^2 , but the most recent g_2^p experiment will provide the first measurement of this quantity at low Q^2 . These data will provide a benchmark test for χ PT calculations of the generalized spin polarizabilities γ_0 and δ_{LT} . Previous tests for the neutron suggest a discrepancy between data and calculations; these data will provide further insight in the low Q^2 . In addition, they will allow for a test of the Burkhardt-Cottingham sum rule at low Q^2 for the proton. This sum rule is satisfied for the neutron, but lack of data for g_2^p leaves it largely untested for the proton.

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