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Jefferson Lab has been at the forefront of a program to study the polarized structure of nucleons using electron scattering. Measurements of the spin dependent structure functions, g_1 and g_2, have proven to be powerful tools in testing and understanding QCD. The neutron structure function g_2^n has been measured extensively in Hall A at Jefferson Lab over a wide range of Q^2, but data for g_2^p remains scarce. This docment will discuss the g_2^p experiment, which ran in Hall A at Jefferson Lab in the spring of 2012, and will provide the first measurement of g_2^p in the resonance region; covering $0.02 < Q^2 < 0.2$ GeV^2. The 0th 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 2nd moment allows for a benchmark test of χPT at low Q^2. Specifically, the behavior of the longitudinally-transverse spin polarizability (δ_{LT}), as χPT calculations of this quantity deviate significantly from the measured neutron data. This document will discuss the current status of the analysis along with preliminary results.

1. Introduction and Motivation

Inclusive electron scattering is a powerful tool for probing the inner structure of the nucleon. To describe the scattering process, four structure functions, F_1, F_2, g_1 and g_2 are used. 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). 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 2 and 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

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

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

$$\Delta\sigma_\perp = \frac{d^2\sigma}{d\Omega dE'}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2\sin\theta}{MQ^2}\frac{E'^2}{\nu^2 E}\left[\nu g_1(x,Q^2) - 2Eg_2(x,Q^2)\right] \tag{3}$$

In equations 1, 2, and 3, ν is the difference between the incoming (E) and scattered (E') electron energy, Q^2 is the 4-momentum transfer squared, θ is the scattering angle, 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. The model describes a nucleon as made up of different kinds of point particles, called partons, which were later recognized as quarks and gluons. In the Bjorken limit, as Q^2 and ν go to infinity, constituent partons are considered to be semi-free and point like. In this way, the structure functions can be written in terms of quark distribution functions. However, in the infinite momentum frame, longitudinal momentum dominates, so there is no transverse contribution, leaving us with a value of zero for g_2. In g_2, transverse spin is important; to get a non-zero value for g_2, we must include transverse momentum, which is neglected here.

$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \bar{g}_2(x,Q^2) \tag{4}$$

The first term of equation 4, g_2^{WW}, is known as the Wandzura-Wikczek relation;[1] 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 measurements at JLab, the only dedicated experiment to measure g_2 was SLAC E155x,[2] which shows consistency with the g_2^{WW} prediction. The function g_2^n has been measured extensively in Hall A at JLab,[3] 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.[4] 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.[5] More recently, the g_2^p experiment took data covering the low Q^2 region.

The 0th moment of g_2 (no x-weighting) provides a test of the Burkhardt-Cottingham sum rule, shown in equation 5. 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 Fig. 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 arrises 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 Jefferson Lab 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.

$$\Gamma_2(Q^2) = \int_0^1 g_2(x, Q^2)dx = 0 \tag{5}$$

The 2nd moment of g_2 provides insight to the generalized spin polarizabilities γ_0 and δ_{LT} (equations 6 and 7), which offer a benchmark test of Chiral Perturbation Theory (χPT). For the quantity γ_0, the difficulty in these calculations is in how to included the resonances, specifically the Δ resonance, which usually dominates.

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

$$\delta_{LT}(Q^2) = \frac{16\alpha M^2}{Q^6} \int_0^{x_0} x^2 \left[g_1(x, Q^2) + g_2(x, Q^2) \right] \tag{7}$$
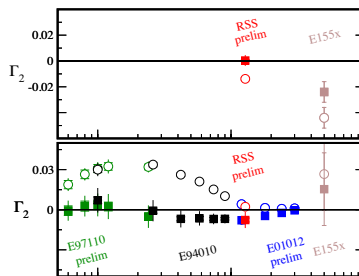

Fig. 1. Current results for the BC sum rule. The top plot is for the proton and the bottom plot is for the neutron. Open circles represent the measured data, while black diamonds show the total integral with low-x and elastic contributions included. Reproduced from Ref. 3.
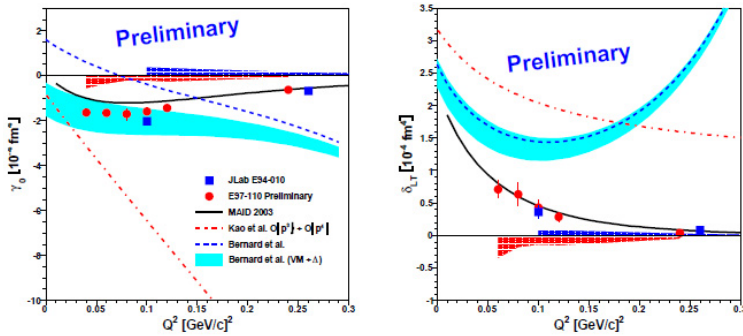
Fig. 2. On the left are the current neutron results for the generalized spin polarizability γ_0, and on the right are neutron results for δ_{LT}. The blue squares represent published data from E94010, while the red circles are preliminary data from E97110. Reproduced from Ref. 6.

The neutron results for the generalized polarizabilites are shown in Fig. 2. Shown alongside the data for γ_0 is the relativistic baryon χPT 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 χPT due to its insensitivity to the Δ resonance.[7–9] In this case, as seen in Fig. 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}.[10] 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 $0.02 < Q^2 < 0.2$ 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 Fig. 3.

This experiment required a large scale installation in Hall A (see Fig. 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
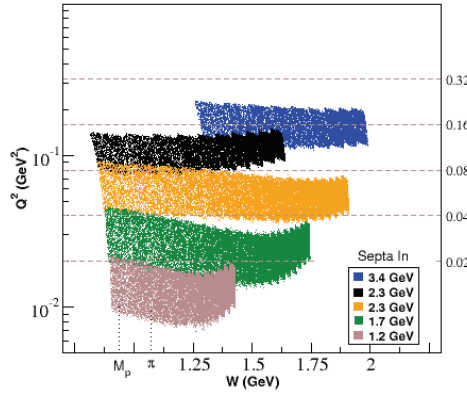
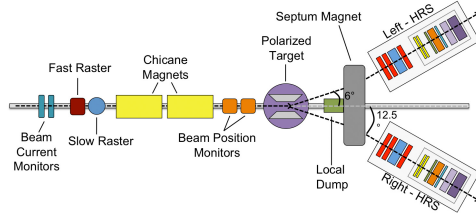Fig. 3.   Kinematic coverage of the g_2^p experiment.

Fig. 4.   Hall A beamline for the g_2^p experiment.

beam position and beam current, were required due to the low beam current (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 (HRSs) were used with a detector stack containing two pairs of vertical drift chambers (VDCs), 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 $\sim$2m apart, provide the trigger for the data acquisition system. Sandwiched between the scintillator planes is a gas Cherenkov counter, which contains CO_2. Finally, two layers of lead glass form an electromagnetic calorimeter; 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 to tracking analysis, including analysis of multi-track
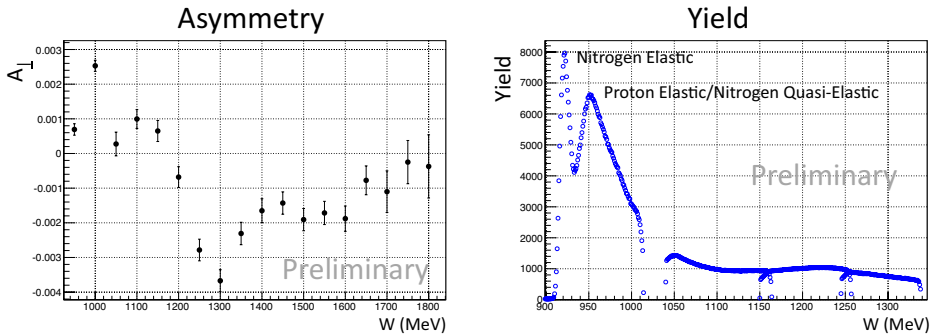
Fig. 5. Preliminary reults for the g_2^p experiment. On the left are asymmetry results (normalized by beam and target polarizations) and on the right are yield results.

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 ∼70% and ∼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 and right HRS with target field on have been finished. Beam position and raster size calibrations were recently completed. 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 Fig. 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 ∼3-6 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 χPT 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 region. 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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