The g_2^p Experiment: A Measurement of the Proton's Spin Structure Function

Ryan Zielinski

Department of Physics, University of New Hampshire, Durham, NH 03824

July 23, 2013

Abstract

The g_2^p experiment was a spin structure function measurement in the resonance region at Jefferson Lab's Hall A. Longitudinally polarized electrons were scattered from transversely polarized protons at small forward angles and low momentum transfer. By measuring the polarized cross-section of this interaction, g_2^p can be extracted. The analysis of the experimental asymmetries and unpolarized cross-sections used to determine the polarized cross-sections is underway. This proposal will present my involvement in the experimental preparation and current analysis efforts. I also provide a timeline and plan for the future analysis, culminating in a Fall 2016 graduation.

1 Motivation

In 1933 Estermann and Stern found that the magnetic moment of the proton was roughly two times larger than predicted for a structureless spin- $\frac{1}{2}$ particle [1]. This anomalous magnetic moment first showed that the proton is not 'fundamental' in the same way as the point-like electron. Years later, high energy scattering experiments revealed that the proton is a composite system with a messy internal structure of quarks and gluons exhibiting complex many-body interactions. The inclusive electron scattering process, shown in Figure 1, characterizes this deviation from point-like behavior with four structure functions, each describing a particular aspect of the proton's compositeness. These four can be subdivided into smaller groups of two: the unpolarized $(F_1^p \text{ and } F_2^p)$ and spin-polarized $(g_1^p \text{ and } g_2^p)$ structure functions. Experimentally these structure functions are determined using polarized electron beams and proton targets. For the spindependent structure functions, the proton is also polarized. With the exception of g_2^p , the four structure functions have been measured over a wide kinematic range [2, 3].

The finite size of the proton, as characterized by its structure functions, plays an important role in quantum electrodynamics (QED) calculations of hydrogen-like systems. Developed by Feynman, Schwinger and Tomanaga, QED describes the interaction of all electromagnetically charged particles. It has produced highly accurate results, where measurements of the electron's anomalous magnetic moment agree with QED beyond 10 significant digits [4]. In the case of the hyperfine splitting of atomic hydrogen, the experimental result is orders of magnitude more precise than QED. The lack of data for g_2^p is a leading contributor to this theoretical uncertainty. Furthermore, the discrepancy between proton charge radius measurements in muonic and atomic hydrogen [5] could possibly be resolved with more complete proton structure function data. See Appendices A and B for further details on the hyperfine splitting calculation and the proton charge radius measurement.

2 Measuring Spin Structure Functions

The success of quantum electrodynamics makes the electromagnetic interaction a prime candidate to study the proton. To leading order in QED, electron-proton scattering is mediated by a single virtual photon, and the resolution of the electron probe is proportional to its energy through the de Broglie relations. If the electron wavelength is greater than the size of the proton, then it lacks sufficient energy to penetrate inside the proton. Corresponding experimental measurements at these electron energies give information on the collective behavior of the quark-gluon interactions and, in turn, how they relate to the finite size of the proton.



Figure 1: Leading order inelastic $ep \rightarrow e'X$ scattering.

2.1 Inclusive Electron Scattering

In the electron-proton scattering process shown in Figure 1, an electron with four-momentum $k^{\mu} = (E, \mathbf{k})$ interacts with the proton of four-momentum $p^{\mu} = (\epsilon, \mathbf{P})$ by exchanging a virtual photon. The electron is then scattered at an angle θ with four-momentum $k'^{\mu} = (E', \mathbf{k}')$. The space-like virtual photon has fourmomentum $q^{\mu} = (k - k')^{\mu} = (\nu, \mathbf{q})$ and $q^2 < 0$, where the four-momentum transfer squared is formally defined as $Q^2 \equiv -q^2$ and ν is the energy transfer. For inclusive interactions only the scattered electron is detected, but it is still useful to define the invariant mass of the hadronic system, $W = \sqrt{(p+q)^2}$.

In the laboratory frame of reference, where the proton is at rest, and assuming E and $E' \gg m_e$, so the electron mass can be neglected, the following kinematic relations describe the scattering process

$$\nu = E - E'$$

$$Q^{2} = 4EE' \sin^{2} \frac{\theta}{2}$$

$$W = M^{2} + 2M\nu - Q^{2}$$

$$x = \frac{Q^{2}}{2M\nu}$$
(1)

The scalar quantity x refers to the momentum fraction carried by the particle struck in the interaction. For protons, the scattering process can be either elastic or inelastic. In elastic scattering, the proton remains in the ground state, so W is equal to the mass of the proton and x = 1. Increases in momentum transfer lead to inelastic scattering and the resonant excitation of the proton. The first of the inelastic resonant states is the Δ -baryon, at W = 1.232 GeV and x < 1, as shown in Figure 2. The resonance region continues until $W \approx 2$ GeV ($Q^2 \approx 1$ GeV²). At this invariant mass, the energy of the electron probe is sufficient to scatter off quarks inside the proton. This kinematic region is referred to as deep inelastic scattering (DIS).



Figure 2: Inclusive cross section (arbitrary units) versus W for ep scattering at a single, constant Q^2 .

2.2 Structure Functions and Scattering Cross Sections

Making an analog to classical scattering [6], the inclusive electron-proton scattering system can be described in terms of the proton's constituents. The total scattering cross-section is just the sum of the cross-sections for scattering off each free constituent point-particle. Feynman originally named these constituents partons, but they are now known as the more familiar quarks and gluons. In Feynman's parton model, the proton's structure is defined in terms of its structure functions,

$$F_{1}(x) = \frac{1}{2} \sum_{f} e_{f}^{2} [q_{f}(x) + \bar{q}_{f}(x)]$$

$$F_{2}(x) = xF_{1}(x)$$

$$g_{1}(x) = \frac{1}{2} \sum_{f} e_{f}^{2} [q_{f}(x) - \bar{q}_{f}(x)]$$

$$g_{2}(x) = 0$$
(2)

where e_f is the charge of a quark of flavor f, and $q_f(x)$ [$\bar{q}_f(x)$] represents the distribution of quarks [antiquarks] inside the proton [2]. The second spin structure function, $g_2(x)$, describes quark-gluon interactions inside the proton and so is zero in the *free* parton model.

For an unpolarized proton in the parton model, the inclusive scattering cross-section is a sum over all possible electron and proton spins. In terms of the proton structure functions $F_1(x)$ and $F_2(x)$, the crosssection is

$$\frac{d^2\sigma}{d\Omega dE'}(\downarrow\Uparrow +\uparrow\Uparrow) = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left(\frac{2}{M}F_1(x,Q^2)\tan^2\frac{\theta}{2} + \frac{1}{\nu}F_2(x,Q^2)\right),\tag{3}$$

where the Mott cross-section describes a relativistic electron scattering from a point-like Dirac particle [7]. Polarization of the proton introduces two additional degrees of freedom, which are parameterized by the spin-dependent structure functions $g_1(x)$ and $g_2(x)$. The polarized proton's spin $\uparrow [\Rightarrow]$ can be parallel [perpendicular] to the two possible electron spin states: \uparrow or \downarrow . The polarized cross-sections are then described by [3]

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

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

where, due to kinematic factors, the parallel cross-section difference $(\Delta \sigma_{\parallel})$ is dominated by contributions from $g_1(x)$ and the perpendicular cross-section difference $(\Delta \sigma_{\perp})$ is dominated by contributions from $g_2(x)$.

3 The Experiment

The g_2^p experiment used inclusive electron-proton scattering to measure the proton's spin-dependent crosssections. The g_2^p structure function can be explicitly solved for in terms of the polarized cross-sections as

$$g_2^p = \frac{MQ^2}{4\alpha^2} \frac{y^2}{2(1-y)(2-y)} \left(-\Delta\sigma_{\parallel} + \frac{1+(1-y)\cos\theta}{(1-y)\sin\theta} \Delta\sigma_{\perp} \right),$$
(5)

where $y = \frac{\nu}{E}$ [8]. The experiment focused on the resonance region at a momentum transfer of $0.02 < Q^2 < 0.16 \text{ GeV}^2$. To achieve these Q^2 values, the incident electrons ranged in energy from E = 1.2 to 3.4 GeV and were scattered at $\theta = 5.69^{\circ}$. The electron beam current ranged from 50 to 100 nA. The full kinematic range of the experiment is shown in Figure 3.



Figure 3: Kinematic coverage of the g_2^p experiment. Masses of the proton and pion production threshold are marked. The right-hand side vertical axis is the extrapolation to constant Q^2 .

The experiment used the electron beam facility at Jefferson Lab to scatter longitudinally polarized electrons from a transversely polarized ammonia (NH₃) target in Hall A. At the lower beam energies, a larger magnetic field would have increased the scattering angle of the detected electrons, limiting access to the low Q^2 values. This effect can be seen in Figure 3, noting that higher values of W indicate lower-energy scattered electrons. The magnetic field strength used to polarize the proton target was divided between 5.0 T and 2.5 T running to limit the effect the field had on the scattered electron trajectories.

The scattered electrons were detected using a pair of high-resolution momentum spectrometers (HRS), which each consisted of quadrupoles and a dipole magnet to transport the electrons from the target to the detectors. Physical constraints limit the scattering angle of the spectrometers to a minimum of 12.5° . In order to to reach the lowest possible momentum transfer, a pair of septa magnets were installed in front of the HRS entrance. The magnets horizontally bent electrons scattered at 5.69° into the spectrometers, which were located at 12.5° .

3.1 The Electron Accelerator

The Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab produces polarized electron beams up to 6 GeV in energy. The electrons are created by using a laser to stimulate photoemission from a phosphorus doped gallium arsenide (GaAsP) cathode [9], and are organized into as many as three 499 MHz bunches [10]. These photo emitted electrons are accelerated to 45 MeV prior to injection into the first superconducting linac, as presented in Figure 4. After reaching energies of 400 MeV, magnets steer the accelerated electrons through a recirculation arc, where they enter an identical second linac and are again accelerated. Now, the bunches can either be separated and sent to the experimental halls or they can enter another recirculation arc to reenter the first linac. Any particular bunch can make up to five orbits before it enters a hall.



Figure 4: CEBAF facility. Reproduced from [10].

The electron beam helicity $(\vec{S} \cdot \hat{p})$ is controlled by passing the injector laser through a voltage-controlled wave plate. By changing the sign of the voltage applied to the wave plate, the polarization of the incident photon is switched. This causes the emission of an electron of opposite spin. The flipping occurs pseudorandomly at 1kHz, to limit time-dependent systematic effects. The beam helicity can also be flipped using an insertable half-wave plate. This wave plate allows for the study of helicity-dependent systematic effects and was flipped every few hours.

3.2 Experimental Hall A

The layout of Hall A along the beamline is shown in Figure 5. Two beam current monitors (BCMs) are the first pieces of equipment along the Hall A beamline. These monitors are resonant cavities tuned to the beam frequency of 1497 MHz [10]. The output voltage of the cavity antenna is proportional to the beam current. Each BCM is calibrated using a tungsten calorimeter.



Figure 5: Experimental Hall A for the g_2^p experiment.

Located in between the BCMs and tungsten calorimeter are the fast and slow raster. The beam is rastered to minimize radiation damage and depolarization of the target material. The fast raster increases the initial 200 μ m beam profile [10] to a 4 mm x 4 mm square beam spot. The circular slow raster pattern then ensures the beam moves over the full 1 inch diameter target cup. Each raster consists of a time-varying magnetic dipole field controlled by a function generator.

Polarization of the electron beam is measured using the Møller polarimeter, which uses the electron polarization dependence of the Møller process to determine the beam polarization [10]. Two dipole chicane magnets are located after the Møller polarimeter. The magnets adjust the electron beam trajectory to compensate for the 5.0 and 2.5 T transverse target magnetic field and ensure the beam strikes the center of the target, as shown in Figure 6. The 5.0 T transverse target field also makes it impossible for the unscattered electrons to continue along the beam path after the target and reach the standard Hall A beam dump. A local tungsten dump collects the beam upon leaving the target scattering chamber.



Figure 6: Chicane magnets correct for beam deflection due to the target's transverse magnetic field.

The beam position and direction is measured using two beam position monitors (BPMs). Each BPM

has four wire antennas that run along the beam direction. Passing electrons induce a signal on the wires, which is inversely proportional to the distance from the electron beam. Two wire scanners (super harps) are used to calibrate the BPMs. Moving the super harp's wires across the beam leads to a shower of detectable particles. The absolute position of the super harps is determined from survey data [10].

Located at the entrance to the high resolution spectrometers are the two horizontal dipole septa magnets. The current and thus field strength of the magnets can be adjusted for different electron energies to keep the scattering angle at a constant 5.69°.

3.3 Solid Polarized Ammonia Target

The g_2^p proton target consisted of frozen ammonia (¹⁴NH₃), which was polarized using dynamic nuclear polarization (DNP) in a 5.0 or 2.5 T magnetic field at around 1 K. In DNP, a microwave field is used to polarize protons through the hyperfine interaction of free electrons and the proton. The large target magnetic field and low temperature initially creates polarization in the ammonia as the electrons and protons align themselves with the field. This thermal equilibrium polarization is 99.8% [12] for the electron but less than 1% for the proton ($\mu_p \approx \frac{\mu_e}{660}$). Microwaves tuned to the spin-dependent hyperfine energy levels (see Figure 7) can induce the proton's spin to flip along with the spin of the electron. The small relaxation time of the electron means the same electron can polarize many protons, while the large relaxation time of the proton leads to polarization greater than 90% [13] for a 5.0 T magnetic field. The nitrogen contribution to the target polarization is discussed in Appendix C.



Figure 7: Microwaves transition a paired spin state, $e_{\downarrow}p_{\downarrow} \rightarrow e_{\uparrow}p_{\uparrow}$. Based on a figure from [14].

The proton polarization was measured using nuclear magnetic resonance (NMR). A coil embedded in the

target material carries a small magnetic field, which can cause a proton to spin flip as it emits or absorbs energy interacting with the field. The energy is proportional to the polarization of the target material. The known thermal equilibrium polarization was used to initially calibrate the NMR.

The target magnetic field was provided by two superconducting Helmholtz coils. The target material was suspended in the uniform field region of the coils using a target insert. The microwave and the NMR fields were carried along the approximately 1.5m long insert via waveguides to the target material cups at the bottom of the insert. A liquid helium evaporation refrigerator kept the ammonia at about 1K. This entire system was housed within an evacuated scattering chamber, which was kept at low pressure using mechanical pumps.

3.4 High Resolution Spectrometers

Hall A contains two nearly identical magnetic spectrometers known as the high resolution spectrometers. Each spectrometer, referred to as HRS-L and HRS-R, consists of three superconducting quadrupole magnets and one superconducting dipole magnet in a QQDQ configuration as shown in Figure 8. The quadrupoles focus the transported electrons, while the dipole determines the electron momentum that reaches the detector stack. The momentum resolution is at the 10^{-4} GeV level [10], and the momentum acceptance is $\pm 4\%$ around the central value.



Figure 8: The high resolution spectrometer magnet configuration. Reproduced from [10].

3.5 HRS Detector Package

The electron detector stack for the HRS-R is shown in Figure 9. Scattered electrons first pass through a pair of vertical drift wire-chambers (VDCs). The electrons ionize the gas inside the wire chambers and timing information from the ionization trail determines the position and angle of the trajectory. Next the electrons pass through a pair of segmented plastic scintillators (s1 and s2m), which form the data acquisition trigger. Particle identification is provided by a gas Čerenkov detector and a two-layer electromagnetic calorimeter (Preshower and Shower). The gas Čerenkov uses the production of Čerenkov light in CO_2 to distinguish electrons from other negatively charged particles. The calorimeters use a collection of lead glass blocks to induce a cascade of pair production and bremsstrahlung radiation from energetic particles. With the exception of the VDCs, the detector signals are read out using photomultiplier tubes.



Figure 9: Frontal view of the lead glass blocks and side-view of the HRS-R detector stack. The HRS-L stack only differs in the layout of its electromagnetic calorimeters.

3.5.1 Data Acquisition and Trigger

The main data acquisition trigger was a logical AND of the s1 and s2m scintillator planes. The logic pulse for each scintillator was formed from the logical sum of the coincidence of corresponding left and right scintillator segments. A secondary trigger was used to determine the efficiency of the main trigger. The efficiency trigger required a hit in either one of the scintillators, but not both, and the gas Čerenkov. The first requirement excluded main triggers while the second defined events that should have been been detected by both scintillator planes. No coincidence was required between the triggers on the left and right spectrometers. Each spectrometer had its own identical, but independent, data acquisition system.

After the triggers were formed they were sent to the trigger supervisor (see Figure 10), which acted as



Figure 10: The data acquisition process

the main control point for the data acquisition system (DAQ) [15]. This VME-standard module served as a link between the trigger system and the front-end analog-to-digital converters (ADCs) and time-to-digital converters (TDCs) used to read out the detectors. The trigger supervisor decided whether or not the DAQ recorded an event. If the event was accepted, then gates and stops were issued for the Fastbus ADCs and TDCs. The detector data was organized event by event and recorded to disk. Scaler-counter information was also injected into the data stream parallel to the ADC and TDC information

The ability of the trigger supervisor to accept events is highly dependent on the event rate; the data acquisition system cannot accept new events if it is still processing an old one. It is useful to define a quantity called the DAQ deadtime, which is the ratio of triggers received to triggers accepted. The DAQ deadtime can be decreased through prescaling the events. With prescaling, the trigger supervisor only accepts one of every *ps* events, where *ps* is the (integer) prescale factor. A prescale factor can be applied individually to each trigger. The deadtime (DT) is determined from the livetime (LT) with DT = 1 - LT, and the livetime is the ratio of accepted triggers to total triggers adjusted by the prescale factor such that

$$LT = \frac{ps_i T_i^{acc}}{T_i^{tot}},\tag{6}$$

where *i* represents the different trigger types. The main and efficiency triggers were i = 1 [i = 3] and i = 2 [i = 4] for the HRS-R [HRS-L], respectively.

3.5.2 Scintillator Trigger Efficiency

The scintillator efficiency is formally defined as

$$\epsilon_{\rm trig} = \frac{T_1}{T_1 + T_2} \,, \tag{7}$$

where T_1 and T_2 are the total number of trigger counts for the main and efficiency triggers respectively on the right spectrometer. A similar expression exists for the left spectrometer. The trigger counts are corrected for both prescale and deadtime. Cuts are also made to select only electron events. For both spectrometers,



Figure 11: Trigger efficiencies for the g_2^p experiment. HRS-L is on the left and HRS-R is on the right.

the trigger inefficiency correction is less than a 1% effect, as seen in Figure 11.

3.6 Spectrometer Optics

A set of optics matrix elements are used to reconstruct the detected electrons back to the location of the electron-proton interaction at the target. The matrix is determined using elastic scattering (with no beam raster) from a thin carbon foil target and a sieve slit collimator placed in front of the entrance to the high-resolution spectrometers. The survey of the thin target allows for determination of the interaction vertex, while the sieve slit defines the electron's trajectory.



Figure 12: The detector coordinate system top view (left) and side view (right). The x-y origin is given by the intersection of the 184th wires of the U1 and V1 planes.

3.6.1 Coordinate Systems

The vertical drift chambers define the detector coordinate system shown in Figure 12. The detected electron's trajectory is given by a pair of angular and spatial coordinates for the dispersive and non-dispersive axes. The dispersive axis runs along the length of the VDC and the electron's position is given by x_{det} , while the tangent of the angle made by its trajectory is θ_{det} . The non-dispersive axis runs parallel to the width of the

VDC and the corresponding detector variables are y_{det} and ϕ_{det} . The focal plane coordinates, which are used to determine the optics matrix, are calculated by taking into account the off-set between the spectrometer central ray (defined as a trajectory passing through the center of the spectrometer) and the origin of the detector coordinate system [16].

The optics matrix elements relate the focal plane coordinates to the target coordinates (θ_{tg} , ϕ_{tg} , x_{tg} , y_{tg}) defined from the target coordinate system shown in Figure 13. The z-axis is defined from a line passing perpendicular through (and towards) the central sieve slit hole. The x-axis is parallel to the sieve slit surface and points vertically down; the y-axis is parallel to the sieve slit surface in the transverse plane [16]. The tangent of the in-plane and out of plane angles with respect to the central ray trajectory are given by ϕ_{tg} and θ_{tg} respectively. The central scattering angle of the spectrometer is represented by θ_0 .



Figure 13: The target coordinate system top view. Reproduced from [10].

3.6.2 Optics Matrix

The optics matrix relates focal plane coordinates to the target coordinates and, to first order, can be expressed as

$$\begin{pmatrix} \delta \\ \theta \\ y \\ \phi \end{pmatrix}_{\rm tg} = \begin{pmatrix} \langle \delta | x \rangle & \langle \delta | \theta \rangle & \langle \delta | y \rangle & \langle \delta | \phi \rangle \\ \langle \theta | x \rangle & \langle \theta | \theta \rangle & \langle \theta | y \rangle & \langle \theta | \phi \rangle \\ \langle y | x \rangle & \langle y | \theta \rangle & \langle y | y \rangle & \langle y | \phi \rangle \\ \langle \phi | x \rangle & \langle \phi | \theta \rangle & \langle \phi | y \rangle & \langle \phi | \phi \rangle \end{pmatrix} \begin{pmatrix} x \\ \theta \\ y \\ \phi \end{pmatrix}_{\rm fp}$$

$$(8)$$

and the relative momentum of the particle is defined as

$$\delta = \frac{P - P_0}{P_0} \tag{9}$$

where P is the particle's measured momentum and P_0 is the spectrometer central momentum determined by the dipole magnetic field. At higher orders, the optics matrix becomes a tensor. Each optics element is determined from a χ^2 minimization process, which compares reconstructed events at the sieve plane to the actual surveyed sieve slit positions. In the process, only elastically scattered focal plane events corresponding to sieve slit holes are optimized. These events are selected using a series of graphical cuts. The results for the optimization of θ_{tg} and ϕ_{tg} for the right spectrometer are shown in Figure 14. The middle sieve plot is before optimization, using an initial optics matrix. In this plot, the arrows point to which hole these events actually came from, determined using the graphical cuts. The right-most plot is the optimized sieve pattern, using the new matrix generated from the optimization. This optimization is just for a single beam energy and target field configuration; there will be a separate optics matrix and optimization for each kinematic setting. There is also a separate optimization for δ and y_{tg} .



Figure 14: Angular optimization for HRS-R. Each cross represents the location of a sieve slit hole, and the bigger holes are circled in red. The actual sieve slit is on the far left.

4 Experimentally Determining g_2^p

For the g_2^p experiment, asymmetries and cross-sections were measured for polarized electron scattering from polarized NH₃.

4.1 Electron Asymmetries

The electron asymmetries are defined as the ratio of the difference in polarized cross-sections to the sum of the polarized cross-sections such that

$$A_{\parallel} = \frac{\frac{d^2\sigma}{d\Omega dE'}(\downarrow \Uparrow - \uparrow \Uparrow)}{\frac{d^2\sigma}{d\Omega dE'}(\downarrow \Uparrow + \uparrow \Uparrow)},$$

$$A_{\perp} = \frac{\frac{d^2\sigma}{d\Omega dE'}(\downarrow \Rightarrow - \uparrow \Rightarrow)}{\frac{d^2\sigma}{d\Omega dE'}(\downarrow \Rightarrow + \uparrow \Rightarrow)}.$$
(10)

The direction of the target polarization (\Uparrow or \Rightarrow) with respect to the electron beam helicity (\uparrow and \downarrow) define the parallel and transverse asymmetries. The cross-section normalization is the same for the numerator and denominator in (10), so each asymmetry is proportional to the ratio of the difference of the raw electron events corresponding to the electron's positive or negative helicity state,

$$A = \frac{1}{f \cdot P_t \cdot P_b} \left(\frac{N_+ - N_-}{N_+ + N_-} \right) \,, \tag{11}$$

where P_t and P_b are the target and beam polarization respectively, and f is the dilution factor. The dilution factor accounts for scattering from unpolarized material in the ammonia target, such as nitrogen, helium and the aluminum caps on the target cups. The raw electron counts, N_+ and N_- , must also be corrected for false asymmetries related to the charge and deadtime. Charge asymmetries occur when unequal numbers of electrons corresponding to each helicity state scatter off the target, and deadtime asymmetries occur if one helicity state is preferentially accepted by the trigger supervisor.

4.2 Unpolarized Electron-Proton Cross-Sections

The unpolarized raw cross-section is defined according to

$$\sigma_{\rm raw} = \frac{d\sigma_{\rm raw}}{d\Omega dE'} = \frac{psN}{N_{\rm in}\rho LT\epsilon_{\rm det}} \frac{1}{\Delta\Omega\Delta E'\Delta Z},$$
(12)

where:

- N is the number of scattered electrons recorded in the detectors defined by acceptance/detector cuts
- ps is the prescale factor
- $N_{\rm in}$ is the number of incident electrons determined from the total BCM charge accumulated over a run
- ρ is the target density
- LT is the DAQ livetime correction factor
- ϵ_{det} is the product of all hardware and software detector efficiencies

- ΔZ is the target length seen by the spectrometer
- $\Delta E'$ is the scattered electron energy spread
- $\Delta\Omega$ is the angular acceptance of the spectrometer

It is instructive to write the unpolarized raw cross-section in terms of the contributions from scattering of polarized and unpolarized target material

$$\sigma_{\rm raw} = \sigma_+ + \sigma_- + \sigma_{\rm unpol} \,, \tag{13}$$

where σ_+ represents the scattering cross-section of polarized protons from positive helicity electrons (\uparrow) and σ_- represents the scattering cross-sections of polarized protons from negative helicity electrons (\downarrow). The proton cross-section is then

$$\sigma_{\text{proton}} = (\sigma_{+} + \sigma_{-} + \sigma_{\text{unpol}}) \cdot f ,$$

$$f = \frac{\sigma_{+} + \sigma_{-}}{\sigma_{+} + \sigma_{-} + \sigma_{\text{unpol}}}$$
(14)

where f is the same dilution factor defined for the asymmetries.

A raw ammonia yield plotted versus the invariant mass is shown in Figure 15 for three dipole momentum (E') settings. This yield only uses very rough detecter and optics calibrations. It was defined as follows

$$Y = \frac{ps_i N_i}{N_{\rm in} LT \epsilon_{det}},\tag{15}$$

which is a cross-section without acceptance corrections. The nitrogen and proton elastic peaks are clear and the Δ -resonance is roughly where it should be. There is also a nitrogen quasi-elastic peak corresponding to elastic scattering of the nitrogen constituents. The gaps in the yield are related to the rough optics calibration. Tight cuts were placed on the matrix reconstructed variables to ensure a good electron sample. A more complete optics analysis would have increased the overlap between momentum settings.

4.2.1 Spectrometer Acceptance

The spectrometer solid angle acceptance, $\Delta\Omega$, is not a purely geometrical quantity. The fields created by the spectrometer magnets create an acceptance that depends on the electron's trajectory, momentum and interaction vertex. The acceptance will have to be determined using a Monte Carlo simulation. This work is in progress.



Figure 15: Experimental yield, arbitrary units, for HRL-L at $E = 2.2 \text{ GeV}, \theta_0 = 5.69^{\circ}$

4.2.2 Radiative Corrections

The electron-proton scattering process is not as simple as depicted in Figure 1. The incoming electron can internally radiate giving rise to higher order Feynman diagram contributions. The electron can also externally radiate a photon through bremsstrahlung and ionization processes before (and after) interacting with the target. Both internal and external radiative corrections need to be applied to the experimental asymmetries, cross-sections, and cross-section differences to correctly describe the physics of the interaction.

4.3 Polarized Cross-Sections

The polarized cross-section used to extract g_2^p is found by taking the product of experimental asymmetries and unpolarized cross sections,

$$\Delta \sigma_{\parallel(\perp)}^{\exp} = \sigma_{+} - \sigma_{-} = 2 \cdot A_{\parallel(\perp)}^{\exp} \cdot \sigma_{0}^{\exp}, \qquad (16)$$

where $A_{\parallel(\perp)}^{\exp}$ is the parallel (perpendicular) asymmetry dependent on the direction of the target polarization, and σ_0^{\exp} is the experimental cross section. Comparing (11) and (14) to (16), the dilution factors cancel when computing polarized cross-sections. The experiment will mostly rely on previous results [17] for the parallel component to g_2^p . Data for the parallel polarized cross section was measured for one beam energy setting as a cross-check on this data.

5 Analysis Progress

The g_2^p experiment ran from March to May in 2012 and the analysis effort is currently underway. This next section will discuss my involvement in the experimental preparation, and the current and future analysis efforts as part of the g_2^p collaboration.

5.1 The g_2^p Data Acquisition System

In the lead up to the experiment, my focus was to get the data acquisition system ready for the run-period. This included cabling the trigger logic, organizing the detector read out and verifying that the detectors were in working order. The main portion of my DAQ work centered around decreasing the deadtime of the system. This was achieved by integrating an additional Fastbus crate into the DAQ.

5.1.1 DAQ Deadtime

In a simple single-trigger, non-prescaled system the DAQ deadtime is approximately

$$DT \approx D_r + D_c \,, \tag{17}$$

where D_r is the readout deadtime and D_c is the conversion deadtime [18]. The conversion deadtime is correlated with the time it takes for a frontend ADC (TDC) module to complete an analog (time)-to-digital conversion, while the readout deadtime is correlated with the time it takes to transfer data out of the frontend modules. The two deadtimes are not entirely independent because first the front end conversion occurs and then all the modules are read. Using Poisson probability theory, the two deadtime components can be broken down into two infinite sums:

$$D_{c} = \sum_{n=1}^{\infty} \frac{\mu_{c}^{n} e^{-\mu_{c}}}{n!} ,$$

$$D_{r} = \sum_{n=1}^{\infty} \frac{\mu_{r}^{b+n} e^{-\mu_{r}}}{(b+n)!} ,$$
(18)

where $\mu_c = R\tau_c$, $\mu_r = R(\tau_r - \tau_c)$, R is the trigger rate, τ_c is the conversion time, τ_r is the readout time and b is the buffer factor [18]. The buffer factor is a feature of the trigger supervisor that allows it to store converted events in a buffer before read out. Provided the buffer is not full, new events can be processed while older events are being read out, decoupling the conversion and readout deadtimes. The conversion time is fixed and module dependent. The readout time depends on the number of modules being readout. When running the DAQ at low to moderate rate in buffered mode, b = 8, the buffer factor reduces the the readout contribution to the overall deadtime. The deadtime is then dominated by the conversion time. As the rate increases the probability of a full buffer also increases and readout begins to dominate the deadtime.

5.1.2 Improving Deadtime

To limit the error deadtime corrections introduce into the cross-section normalization, experiments typically aim for a maximum of 20% deadtime [19]. In the past, this translated into a maximum non-prescaled acceptable DAQ rate of 4 kHz. To increase the rate, a third Fastbus crate was added to both spectrometer DAQs. The read out of each crate is done in parallel so by distributing the module population throughout the three crates, the readout time of each was decreased. This resulted in an improvement of the DAQ rate from 4 kHz to 6 kHz while maintaining comparable deadtime. More information on the read out of the Fastbus crates can be found in Reference [15].



Figure 16: Deadtime for both HRS during commissioning with the model prediction given by 18.

Rate (kHz)	DT (%)	Crate	$\tau_c \ (\mu s)$	$\tau_r(\mu s)$	Rate (kHz)	DT (%)	Crate	$\tau_c \ (\mu s)$	$\tau_r(\mu s)$
14.2	49	TS		36	19.5	60	TS		44
7.3	29	Fastbus	12	90	7.4	31	Fastbus	12	100
6.5	24				5.7	25			
5.3	20				4.4	20			
4.2	15				<u></u>				
3.2	12								

Table 1: HRS-L deadtime is on the left and HRS-R deadtime is on the right. Included are the conversion and readout times used in the model in Figure 16, measured with cosmic ray data. Note: The TS crates cannot be buffered. The busy time listed for these components is the total busy time and is labeled as the "readout" time.

5.1.3 Deadtime Testing

The updated DAQ system was initially tested during commissioning for the experiment in December 2011. During the test, the HRS-L DAQ consisted of three Fastbus crates and a trigger supervisor (TS) crate that included scalers. The total deadtime is a sum of the contributions from the TS crate and slowest Fastbus crate. The data simulated experimental conditions, using an electron beam incident on a carbon-foil target. The results in Table 1 highlight the 6 kHz improvement. The model from (18), plotted in Figure 16, compares favorably with the experimental data. In addition, two-crate performance was tested on the HRS-R because its third crate had not yet been installed.

5.2 Current Analysis

The analysis procedure for the experiment is outlined in Figure 17 and highlighted in red is what I am currently responsible for. The optics work is divided between two other graduate students and myself. We have optimized spectrometer optics data for the no target field settings for both the left and right spectrometers. This initial optimization removed the added complexity of the target field and allowed for an optics calibration focusing on the septa and HRS magnets. The 0 T field matrices are used as the initial input for the 2.5 T and 5.0 T optimization. Work has shifted to repeating the same analysis but with a longitudinal target field. My results for HRS-R longitudinal angular optimization are shown in Figure 14. Our next step is to analyze the optics data taken with a transverse target field at both 2.5 T and 5.0 T.



Figure 17: The analysis flow for g_2^p . Farm production represents creating usable data files from the raw data using the ROOT analysis software package.

The optics optimization relies on BPM information to reconstruct the electron beam to the target. The BPM analysis package is currently set up to reconstruct events for runs with no-raster and no-target field. There is a preliminary calibration for no-raster and a longitudinal 5.0 T target field. The next step in the calibration is to include raster reconstruction and transverse target fields.

The helicity decoder package and BCM calibrations are also complete, but the target analysis is still ongoing. This analysis includes determining the target polarization for each run which is needed for the asymmetry calculation.

Spectrometer detector efficiencies are needed as a correction to the measured cross section. A first round calibration of the HRS detectors is now complete. This includes particle identification (PID) calibrations on the gas Čerenkov and lead glass on both spectrometer arms. Detector and cut efficiency analysis on the PID detectors is also finished. My role was to calculate the s1 and s2m trigger scintillator efficiency. The results of the calculation are shown in Figure 11. The trigger efficiency for all good production runs is above 99%.

During the run period I set up a MySQL database for the experiment. Information about each run was automatically uploaded into the database at the end of the run, and included things such as beam energy, dipole momentum and beam current. Each spectrometer had its own table in the database. After the experiment finished, I used these tables as a basis to construct a more complete g_2^p database. The new analysis tables include information on run type and run quality, as well as a more accurate calculation of fields included in the original tables. The run-type field in the database sorts through the different calibration, optics, and production runs from the run period and each run is assigned a quality factor. The quality factor sorts through junk runs, runs that have potential problems, and good runs. These analysis tables also provide a central location for the cross-section normalization variables and the good-electron cuts. I have created both a web-interface for the database and a C++ library that can be used with the ROOT analysis software. More information on the MySQL database can be found in Reference [20].

5.3 Future Analysis

My future analysis plan is outlined in Table 2. By the end of this summer I plan to have finished the optics calibration. The remaining tasks for this are described in Section 5.2. After optics, I plan to focus on calculating raw cross-sections. A key component of this will be determining the spectrometer acceptance. Depending on my level of involvement with the acceptance simulations, I can also use this time to become familiar with the machinery to do the radiative corrections. After the acceptance analysis is finished, then I can move to determining the raw cross-sections. Combining another students asymmetry analysis with my cross-section analysis will provide a preliminary measurement of g_2^p . With an experimental value for g_2^p , I

Date	Milestone
Summer 2013	Finish optics analysis
Summer 2014	Unpolarized raw cross-sections
Summer 2015	Radiative corrections to cross-sections
Spring 2016	Preliminary g_2^p measurement
Summer 2016	g_2^p contribution to finite size effects
Fall 2016	Graduate

can determine its contribution to hyperfine structure and the proton charge radius puzzle.

Table 2: Analysis timeline. The finite size effects refer to hyperfine structure and the charge radius puzzle.

6 Conclusion

Due to their fundamental nature, knowledge of the proton structure functions is key for a complete understanding of the nucleon. The complexity of the scattering interactions means that these quantities cannot be determined analytically from the theory of the quark and gluon interaction: quantum chromodynamics. Instead, they are determined experimentally. With the exception of g_2^p , the four structure functions have been experimentally measured over a wide kinematic range. The g_2^p experiment will help fill in this gap by measuring g_2^p in the resonance region. Low Q^2 data for g_2^p is critical for a full understanding of the simplest bound atomic systems like the hydrogen atom. It can also help clarify discrepancies between different methods of determining the proton charge radius. It is by addressing these issues that my thesis will help complete our understanding of the nucleon structure.

A Hydrogen Hyperfine Structure

The interaction of the proton's magnetic dipole moment with the electron's magnetic dipole moment results in a shift of the energy levels of hydrogen based on the total angular momentum of the atom. Experimental measurements of this hyperfine splitting (the shift is on the order of $\frac{m_e}{m_p} \simeq 2000$ smaller than the fine structure correction) of the hydrogen ground state are accurate at the 10^{-13} MHz level, but theoretical calculations of the same splitting are only accurate to $\sim 10^{-6}$ MHz. Proton structure corrections, $\Delta_p^{\text{structure}}$, are the main theoretical uncertainty [21].

The theoretical hydrogen hyperfine splitting can be written as

$$\Delta E_{\rm hfs} = (1 + \Delta^{\rm R} + \Delta^{\rm small} + \Delta^{\rm QED} + \Delta_p^{\rm structure}) E_F^p, \qquad (19)$$

where \mathbf{E}_{F}^{p} [22] is the magnetic-dipole interaction energy, and Δ^{small} includes corrections due to the muonic and

hadronic vacuum polarizations and the weak interaction. The contributions due to recoil effects and radiative quantum electrodynamics, represented by Δ^{R} and Δ^{QED} respectively, are known to high accuracy. This contrasts with the proton structure dependent correction, $\Delta_p^{\text{structure}}$, which has the largest uncertainty [21].

Experimentally measured ground state and excited state properties of the proton are needed to fully characterize $\Delta_p^{\text{structure}}$. Elastic scattering is used to determine the ground state properties, while the resonance structure of inelastic scattering is useful for the excited state properties. The structure dependent correction is usually split into two terms,

$$\Delta_p^{\text{structure}} = \Delta^Z + \Delta^{\text{pol}}, \qquad (20)$$

where Δ^{Z} is the ground state term, first calculated by Zemach [23]. The excited state term, Δ^{pol} , can be further split into two additional terms,

$$\Delta^{\text{exc}} \propto \left(\Delta_1 + \Delta_2\right),\tag{21}$$

where Δ_1 involves F_2^p and g_1^P , but Δ_2 is solely dependent on g_2^p . Theorists have ample data to determine Δ_1 but are forced to rely heavily on models to calculate Δ_2 since there is little data for g_2^p . The models are poorly constrained with such few precision data points, but this experiment's error budget is expected to be better than 10% so current published errors will be improved by an order of magnitude for both Δ_2 and Δ^{exc} .

B Proton Charge Radius Puzzle

First measured by W.E. Lamb and R.C. Retherford in 1947 [24], the Lamb shift is the small difference between the $2S_{1/2}$ and $2P_{1/2}$ energy levels in atomic hydrogen. The existence of the shift can be explained by quantum electrodynamics (QED); the main contributor to the energy split is the electromagnetic field of photonic vacuum fluctuations. The fluctuations, permitted by the uncertainty principle, smear out the position of the electron, causing less of its charge to experience the strongest Coulomb potential closest to the proton nucleus. The *S* states have a greater probability of being close to the nucleus, so they have the greatest reduction in electron binding energy. This causes their energy level to shift slightly higher than that of the corresponding *P* state.

The muon is about 200 times heavier than the electron. In muonic hydrogen, where the valence electron is replaced by a muon, the Bohr radius is then 200 times closer to the proton nucleus. This leads to significant overlap in the muon and proton wave functions, which makes muonic hydrogen far more sensitive to the distribution of charge and magnetic moment of the proton [25]. As a result, the Lamb shift is also enhanced by a factor of 200, so experimental measurement of the shift can be used to precisely determine the charge radius of the proton, $\langle R_p \rangle$.

$r_p \ (\mathrm{fm})$	Unc. (fm)	Method
0.84184	0.00067	μ H Lamb Shift [5]
0.897	0.018	e-P scattering [26]
0.8768	0.0069	eH Lamb Shift [27]

Table 3: Values of the proton charge radius. The muonic hydrogen result is 10 times more precise than the atomic hydrogen result but 5.0σ smaller; it's 26 times more accurate than the result from e-P scattering experiments but 3.1σ smaller.

Researchers at the Paul Sherrer Institute (PSI) obtained a value for $\langle R_p \rangle$ using the Lamb shift in muonic hydrogen that differs by 5.0 standard deviations [5] from a similar measurement in atomic hydrogen [27]. The results, along with the value extracted from e-P scattering, are shown in Table 3. The main uncertainty in the PSI measurement originates from the proton polarizability, which is determined from an integral of the spin structure functions.

C Nitrogen Polarization in ¹⁴NH₃

In the nuclear shell model (see Figure 18), the spin-one ¹⁴N nucleus has six sets of nucleons in the 1s and $1p_{3/2}$ shells and an additional unpaired proton and neutron in the $1p_{1/2}$ energy shell [28]. These unpaired nucleons carry the spin of the nitrogen nucleus and are in an isospin triplet. Only the unpaired nucleons can be polarized, so it is useful to look at the angular momentum decomposition of the $1p_{1/2}$ shell to determine the nucleon polarization with respect to the nitrogen nucleus. The free nucleons can be separated into substates of the intrinsic spin (s = 1/2) and the orbital angular momentum of the p-shell (l = 1).



Figure 18: Shell model energy levels for the 14 N nucleus. The number following the orbital notation is the multiplicity of that energy level.

Consider the $|I = 1, I_3 = 1\rangle$ isospin triplet state. Both the proton and neutron must have $m_j = 1/2$ to account for this value of the nitrogen spin [29], and looking up the Clebsch-Gordan coefficients for $1 \bigotimes \frac{1}{2}$

yields the following for one of the nucleons:

$$\left|\frac{1}{2}, \frac{1}{2}\right\rangle = \sqrt{\frac{2}{3}} \left|1, 1\right\rangle \left|\frac{1}{2}, -\frac{1}{2}\right\rangle - \sqrt{\frac{1}{3}} \left|1, 0\right\rangle \left|\frac{1}{2}, \frac{1}{2}\right\rangle \tag{22}$$

where the decomposition is of the form $|J, m_j\rangle = \text{CG} |l, m_l\rangle |s, m_s\rangle$. By comparing values of m_j and m_s in (22), it is clear that the nucleon spin is aligned anti-parallel to the nitrogen spin a net 1/3 of the time. The result is the same for the $|I = 1, I_3 = -1\rangle$ state, noting that both the proton and neutron must have $m_j = -1/2$. There is no contribution from the $I_3 = 0$ state because the proton and neutron are aligned/antialigned in equal measure.

There are three free protons for every nitrogen nucleus in ammonia and the nitrogen only polarizes up to one sixth of the corresponding hydrogen polarization [14, 30]. The net contribution of the polarized protons in nitrogen to the measured target polarization (and spin asymmetry) is $1/3 \times 1/3 \times 1/6 \approx 2\%$. For example, a 90% target polarization corresponds to approximately 88.2% proton-ammonia polarization and 1.8% proton-nitrogen polarization. The measured asymmetries must be corrected for both the dilution factor (see Section 4.1) and also for the unwanted nitrogen polarization.

References

- [1] I. Estermann, O.C. Simpson and O. Stern, Phys. Rev. 52, 535 (1937).
- [2] J. Beringer *et al.*, Phys. Rev. D86, 234 (2012).
- [3] E. W. Hughes and R. Voss, Annual. Review. of. Nuclear. and. Particle. Science 49, 303 (1999)
- [4] R. Feynman, "QED: The Strange Theory of Light and Matter," Princeton. University. Press (1988).
- [5] R. Pohl *et al.*, Nature **466**, 213 (2010).
- [6] J.D. Jackson, "Classical Electrodynamics. 3rd ed," New York: Wiley, 1999. 461-462.
- [7] F. Halzen and A. Martin, "Quarks Leptons: An Introductory Course in Modern Particle Physics," New York: Wiley, 1984. 172-182.
- [8] A. Camsonne, J. P. Chen, D. Crabb, and K. Slifer *et al.*, "A Measurement of g₂^p and then Longitudinal-Transverse Spin Polarizability", http://hallaweb.jlab.org/experiment/g2p/docs/PAC33/dlt.pdf
- [9] T. B. Humenesky et al., Nucl. Instrum. Meth. A521, 261 (2004).
- [10] J. Alcorn *et al.*, Nuc. Instrum. Meth. **A522**, 297 (2004).

- [11] Jefferson Lab Tungsten Calorimeter webpage, http://hallaweb.jlab.org/experiment/LEDEX/ camsonne/webpage_calorimeter/page_principale.html.
- [12] T. D. Averett *et al.*, Nucl. Instrum. Meth. A427, 440 (1999).
- [13] D. G. Crabb *et al.*, Phys. Rev. Lett. **64**, 2627 (1990).
- [14] D. G. Crabb and W. Meyer, Annual. Review. of. Nuclear. and. Particle. Science 47, 67 (1997).
- [15] E. Jastrzembski et al., The Jefferson Lab Trigger Supervisor System, https://www.jlab.org/div_ dept/admin/publications/papers/99/PHY99-13.pdf.
- [16] N. Liyange, JLab-TN-02-012, Jefferson Lab, http://hallaweb.jlab.org/publications/Technotes/ technote.html
- [17] JLab Run Group EG4, M. Battaglieri, R. De Vita, A. Deur, M. Ripani spokespersons. http://www. jlab.org/expprog/proposals/03/PR03-006.pdf
- [18] R. Michaels, private conversation
- [19] R. Michaels, http://hallaweb.jlab.org/equipment/daq/dtime_faq.html.
- [20] R. Zielinski, The g_2^p wiki, https://hallaweb.jlab.org/wiki/index.php/G2pmysql
- [21] A. V. Volotka, V. M. Shabaev, G. Plunien and G. Soff, Eur. Phys. J. D 33, 203 (2005).
- [22] E. Fermi, Z. Phys. **60**, 320 (1930).
- [23] A. C. Zemach, Phys. Rev. **104**, 1771 (1956).
- [24] W. E. Lamb and R. C. Retherford, Phys. Rev. 72, 241 (1947).
- [25] K. Pachucki, Phys. Rev. A. 60, 3593 (1999).
- [26] I. Sick, Phys. Lett. B. 576, 62 (2003).
- [27] J. P. Mohr, N. B. Taylor and B. D. Newell, Rev. Mod. Phys. 80, 633 (2008).
- [28] W. W. True, Phys. Rev. **130**, 1530 (1963).
- [29] B. Adeva et al., Nucl. Instrum. Meth. A419, 60 (1998).
- [30] O. A. Ronodon, Phys. Lett. C. 60, 035201 (1999).