

Proton Polarization Studies and Uncertainty Analysis for E08-027

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1 Introduction

The purpose of Hall A experiment E08-027 was to measure the proton spin dependant structure function, g_2 , in a Q^2 range of $0.02 - 0.2\text{GeV}^2$. For a measurement of g_2^p we required a proton target with spin polarization perpendicular to the electron beam axis, for this purpose we used a pre-irradiated ammonia target material which was placed in the scattering chamber shown in figure 1. Dynamic Nuclear Polarization (DNP) was used to achieve high proton polarization for the extended duration of the experiment, while high precision measurements of the polarization were done using Nuclear Magnetic Resonance (NMR).

The polarization, temperature, pressure, timestamp, and various other readings from the NMR system were collected roughly every 30 seconds using Labview software and stored in text files on the target lab computer. The offline polarizations were then calculated using Thermal Equilibrium (TE) measurements and the online NMR signals as described in section 4.

2 Target Material

The frozen ammonia beads used during the g_2^p experiment first went through a pre-irradiation process at the National Institute of Standards and Technology (NIST) in Gaithersburg, MD. The ammonia was divided into 10 different material samples and placed in a 14MeV electron beam for 120 min. introducing roughly $10^{17}\text{e}^-/\text{cm}^2$ to each sample. The pre-irradiation allowed for rapid initial polarization while in the Hall A beamline due to radicals already being present in the material for the DNP process.

While in the beamline the ammonia material was subject to a continuous

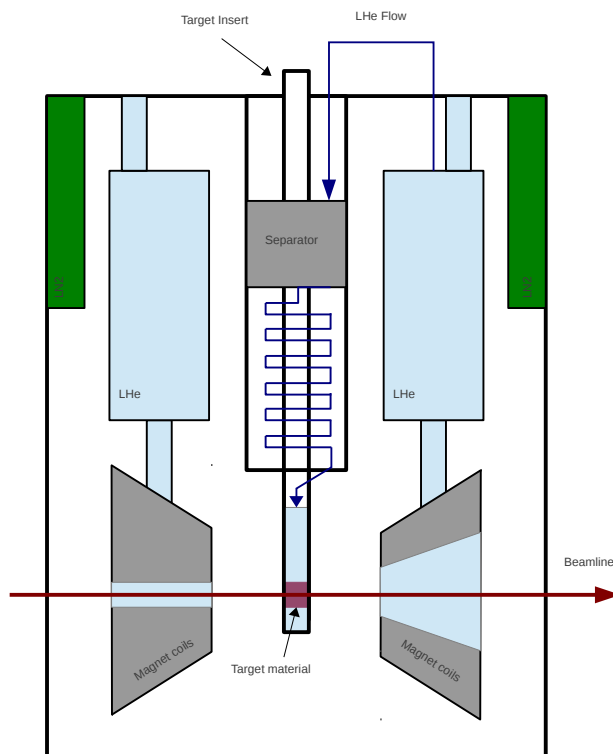


Figure 1: Rotatable scattering chamber layout with liquid helium flow. Target material shown in center along beamline.

100nA electron beam for the duration of the experiment. This acted to introduce additional radicals in the material which, in turn, decreased the relaxation time of the polarized proton material. To combat the decreasing relaxation time while in beam, anneals were performed several times per week in which the target material was heated up to 75 K for several minutes to recombine excess radicals in the material. After several cycles of this process annealing the material was no longer effective and a new sample was used.

3 Set Up

The ammonia target material was packed into the target insert while in a LN₂ bath to maintain a temperature of 77K. The target insert was then placed into the center of a 5T split pair superconducting magnet and cooled down to 1K in a LHe bath using a series of roots pumps. A horn connected to a microwave generator was also connected to the ladder for Dynamic Nuclear Polarization. A small coil used for the Nuclear Magnetic Resonance process

was also present in the target material cup.

3.1 Dynamic Nuclear Polarization

Proton polarization in a magnetic field is given by Curie's Law as

$$P_{TE} = \tanh\left(\frac{\mu B}{kT}\right) \quad (1)$$

where B is the magnetic field and T is the material temperature, here P_{TE} is called the thermal equilibrium polarization. For a 2.5T magnetic field this results in a proton polarization on the order of 0.15% and an electron polarization on the order of 92%. To drive the proton polarization to values necessary for experimental data taking we exploit the spin-spin interaction of the proton and electron by inducing a spin flip using a microwave generator which emits microwaves at the $\nu_{EPR} - \nu_{NMR}$ frequency as seen in figure 2. The electron will then relax and can be used to polarize a new proton. This process is called Dynamic Nuclear Polarization and can be used to drive proton polarizations to levels far above the thermal equilibrium polarization for the duration of the experiment.

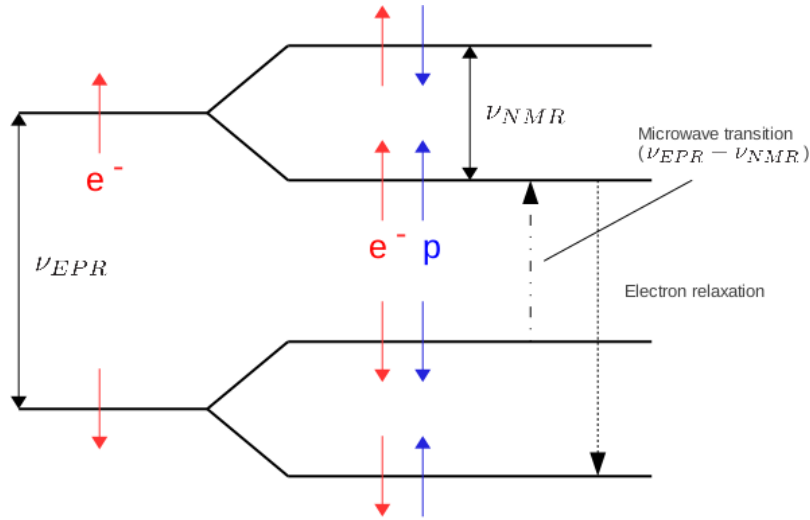


Figure 2: Electron-proton spin coupling interaction diagram.

3.2 Nuclear Magnetic Resonance

To measure the proton polarization we created an LCR circuit using a wire coil nested within the target material and an RF generator connected to a

Q-meter. The RF generator swept out a frequency around the proton Larmor frequency which induced a spin flip in the target material. The energy released or absorbed by the corresponding spin flip can then be measured and related to the proton polarization through a calibration constant calculated using thermal equilibrium polarization measurements.

4 Analysis

4.1 Thermal Equilibrium Measurements

During the g_2^p experiment 10 target materials were used. A material was considered ‘new’ if the target field was changed, the field orientation was rotated, or the material itself was replaced. For each target material a separate thermal equilibrium (TE) measurement had to be done to find material dependant calibration constants. During these measurements the microwave generator was shut off and the proton polarization was given time to thermalize. Thermalization times varied depending on the field value but took an average of 1 to 2 hours. After the polarization was thermalized the average area is calculated using the integrated NMR signal shown in figure 3 for each point in the TE.

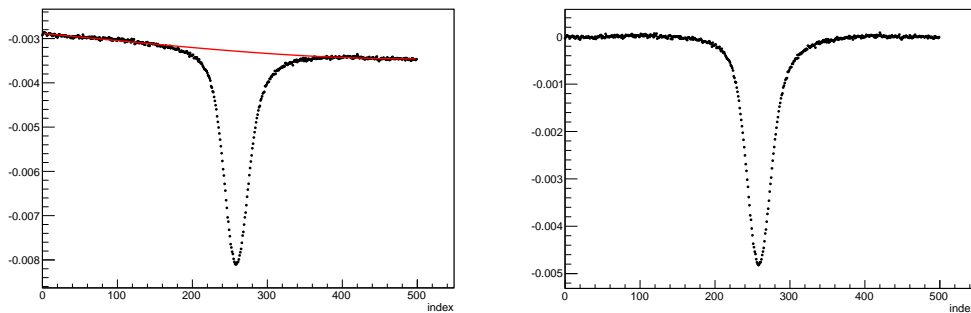


Figure 3: Third order polynomial fit to baseline subtracted data for an arbitrary TE measurement (left) and the final fit subtracted signal for Riemann sum integration (right).

The method used to find NMR area was to fit a third order polynomial to the wings of the raw NMR signal and subtract to remove backgrounds from the Q-meter circuit. The remaining fit subtracted signal is integrated using a Reimann sum method to find the NMR area. Using this area and the calculated thermalized polarization from equation 1 the calibration constant

is calculated using

$$CC = \frac{P_{TE}}{A_{TE}} \quad (2)$$

where P_{TE} is the thermalized polarization and A_{TE} is the thermalized NMR area. The number of TE's done on a target material varied depending on available time but ranged from 1 to 8 measurements. A complete list of target material, TE measurements, and online reported calibration constants is seen in Table 1.

Table 1: Target Materials

| Material | TE measurement | Online CC | |
|----------|----------------|------------|------------|
| 7 | 11 | -1.734839 | |
| | 13 | -1.753021 | |
| | 15 | -1.6698 | |
| | 19 | -1.7417065 | |
| | 21 | -1.7435 | |
| | 23 | -1.72013 | |
| | 25 | -1.65485 | |
| | 8 | 12 | -1.5207665 |
| 8 | 14 | -1.4936905 | |
| | 16 | -1.5108 | |
| | 17 | -1.7414075 | |
| | 20 | -1.463427 | |
| | 22 | -1.400362 | |
| | 24 | -1.386324 | |
| | 11 | 29 | -1.7541085 |
| | 12 | 34 | -1.5466705 |
| 13 | 47 | -1.5102705 | |
| 14 | 48 | -1.8436115 | |
| 17 | 51 | -1.4249 | |
| 18 | 52 | -1.7233 | |
| 19 | 53 | -1.596351 | |
| | 55 | - | |
| | 59 | -1.582325 | |
| 20 | 54 | -1.862160 | |
| | 56 | -1.650683 | |
| | 60 | - | |

4.2 Calibration Constant Uncertainties

From equation 2 there are two main factors to consider for each calibration constant uncertainty measurement; the uncertainty in the third order polynomial fit of the raw NMR signal and the uncertainty in the magnetic field and temperature reading which contribute to the TE polarization calculation. For the uncertainty in the fit a gaussian of known area was generated, then the variance in the area between the integrated signal and the gaussian area was the uncertainty in the fit area, δ_A . This uncertainty varied largely based on the quality of the NMR signal, but was never larger than 3%.

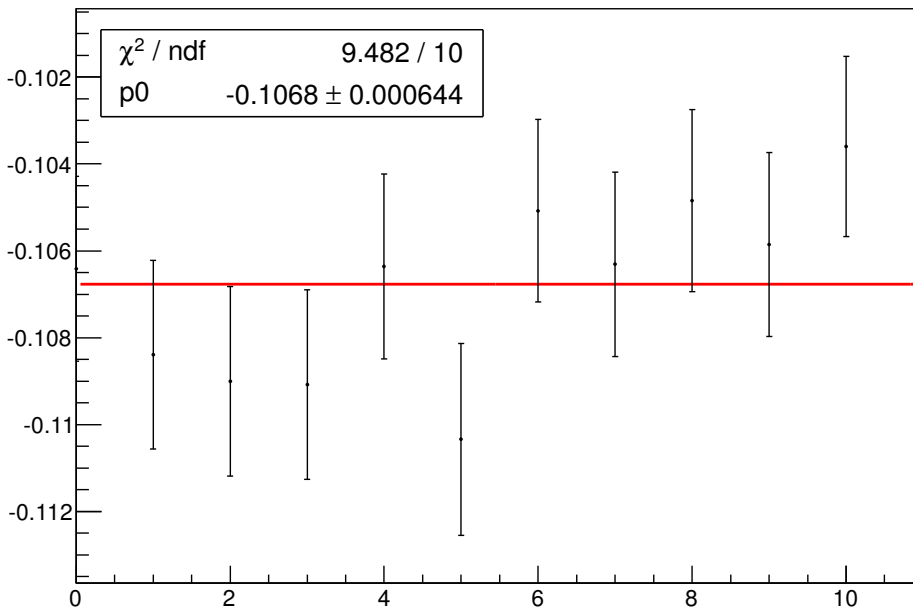


Figure 4: Zero order polynomial fit to the contributing points for TE 15. The reduced χ^2 and fit result (average integrated area) are shown in the legend.

The TE polarization uncertainty had 2 main contributors. The target field reading was provided as having a relative uncertainty of 2% dictated by the precision of the magnet power supply. The temperature was measured using both a He₃ and He₄ manometer that measured the pressure in the target nose and converted it to temperature. The variance in the two readings was then the uncertainty in temperature. The TE polarization uncertainty was

then calculated as

$$\delta_{TE_{pol}} = \frac{\mu B}{kT} \sqrt{\left[\left(1 - \tanh \left(\frac{\mu B}{kT} \right)^2 \right) \frac{\delta_B}{B} \right]^2 + \left[\left(1 - \tanh \left(\frac{\mu B}{kT} \right)^2 \right) \frac{\delta_T}{T} \right]^2} \quad (3)$$

Using $\delta_{TE_{pol}}$ and $\delta_{TE_{area}}$ the calibration constant uncertainty for each point in the TE is then propagated using

$$\delta_{CC} = \frac{P_{TE}}{A_{TE}} \left(\frac{\delta_{TE_{pol}}}{P_{TE}} + \frac{\delta_{TE_{area}}}{A_{TE}} \right) \quad (4)$$

for offline analysis. The average calibration constant for each material TE is then chosen by fitting a zero order polynomial to each TE measurement (shown in figure 4) and minimizing the reduced chi-squared to find contributing points. The final uncertainty in the average calibration constant is calculated as the standard deviation of the mean. Final offline calibration constants and uncertainties are shown in table 2.

Table 2: Material Calibration Constants

| Material | Offline CC | CC Uncertainty | % Uncertainty |
|----------|------------|----------------|---------------|
| 7 | -1.813134 | 0.056163 | 3.09 |
| 8 | -1.48743 | 0.079499 | 5.34 |
| 11 | -1.882293 | 0.094091 | 4.99 |
| 12 | -1.639794 | 0.026468 | 1.61 |
| 13 | -1.6070 | 0.0278 | 1.73 |
| 14 | -1.96990 | 0.06553 | 3.32 |
| 17 | -1.469568 | 0.018018 | 1.22 |
| 18 | -1.79844 | 0.01718 | 0.95 |
| 19 | -1.575523 | 0.128217 | 8.13 |
| 20 | -1.753275 | 0.078435 | 4.47 |

4.3 Run Polarizations

The offline run polarizations were calculated for each NMR point during production runs using the equation

$$P = A \times CC \quad (5)$$

Where A is the integrated NMR area which is found by fitting a third order polynomial to the raw NMR signal, similar to the method of finding A_{TE}

in section 4.1, and CC is the corresponding material calibration constant calculated in section 4.2.

The final run polarization plots were fitted with an exponential decay and the fit average was used as the run averaged polarization. The uncertainty in the polarization of each run was propagated from the calibration constant in the usual way and averaged together. Final production run polarizations for 5T and 2.5T settings are shown in figure 5. The average offline polarization is 15% and 70% for 2.5T and 5T settings, respectively.

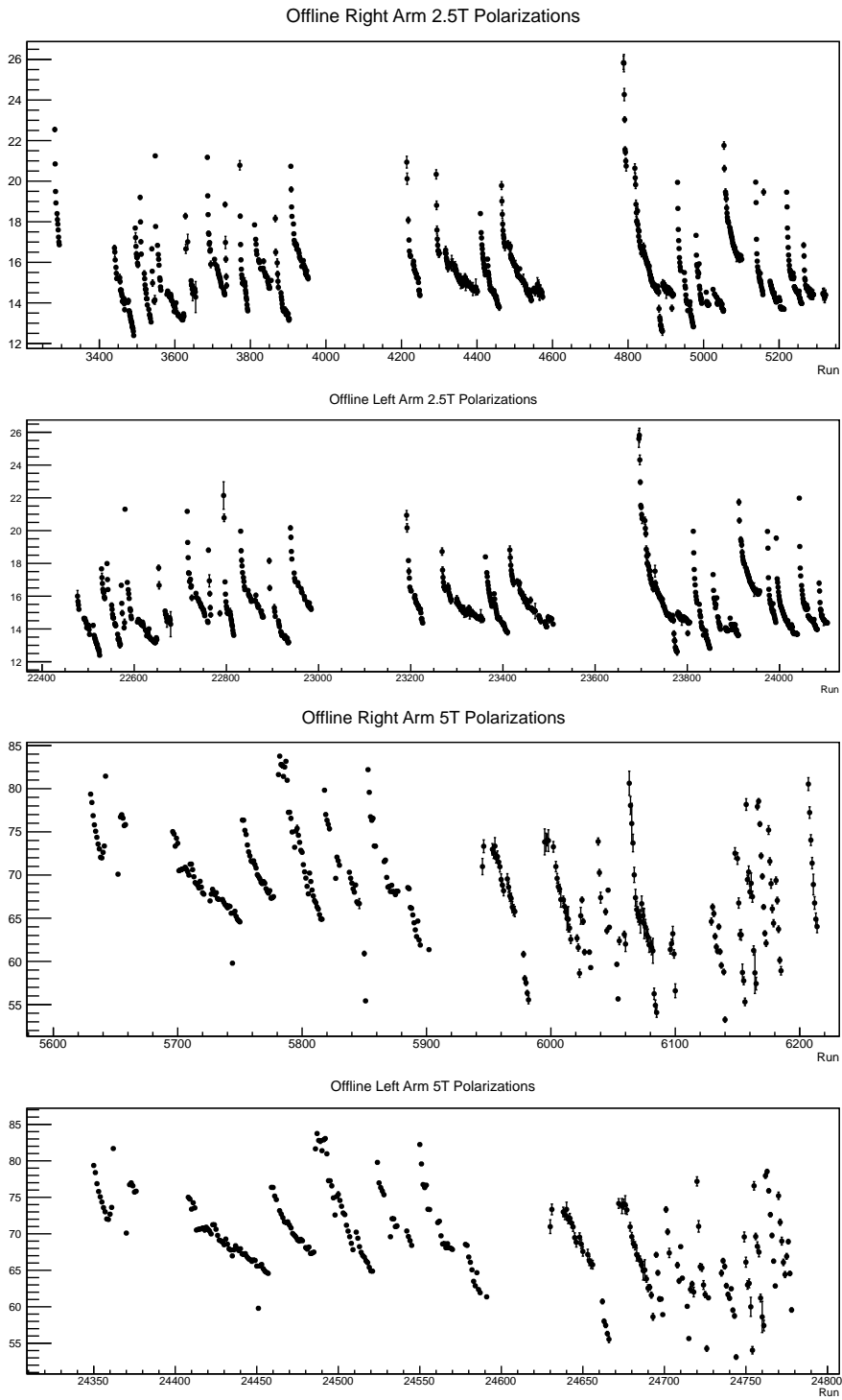


Figure 5: Final 2.5T Right/Left arm polarizations (1st/2nd) and final 5T Right/Left arm polarization (3rd/4th)