

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 this, we required a proton target with spin polarization oriented perpendicular to the electron beam axis. We used a pre-irradiated frozen ammonia target material placed along the beam line in the center of a 5T superconducting helmholtz coil as shown in Figure 1. To achieve the desired statistics and uncertainties for the experiment we required both a high proton polarization and an accurate method of measuring it. 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. This document describes the analysis methods used.

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

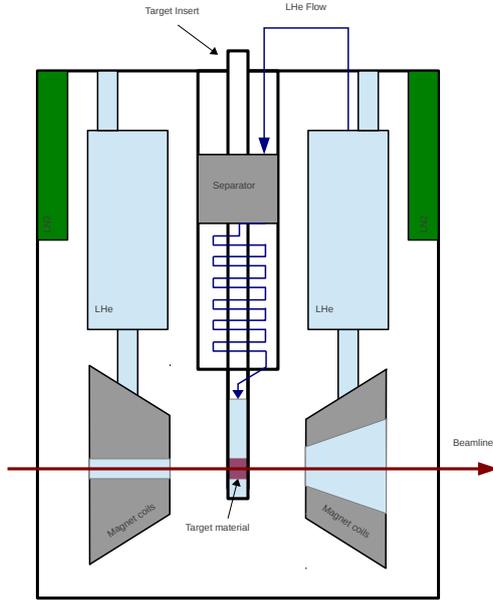


Figure 1: Rotatable scattering chamber layout with liquid helium flow. Target material shown in center along beamline.

material samples and placed in a 14 MeV electron beam for 120 minutes 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.

The ammonia material was subject to a continuous 50 nA 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 liquid N_2 bath to ensure the crystal beads did not melt. The target insert was then placed into the center of a 5T split pair superconducting magnet and cooled down to 1 K in a liquid He bath using an evaporation refrigerator connected to a series of large 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 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 electron-proton coupling by inducing a spin flip in the electron-proton pair using a microwave generator which emits microwaves at the $\nu_{EPR} - \nu_{NMR}$ frequency as seen in Figure 2. The electron has a spin relaxation time on the order of several milliseconds while the proton has a relaxation time on the order of tens of minutes. After the electron-proton pair align with the field, the electron will quickly relax and can be used to polarize a new proton. This process is called Dynamic Nuclear Polarization (DNP) and can be used to drive proton polarizations to levels far above the thermal equilibrium polarization.

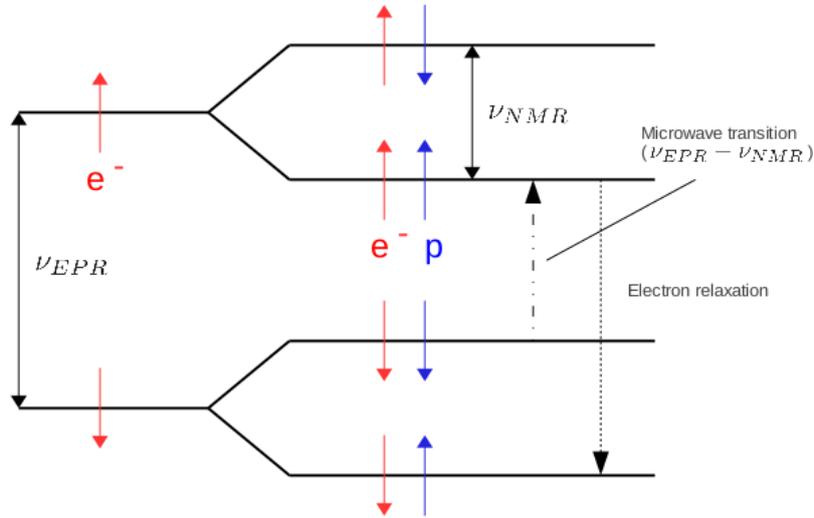


Figure 2: Electron-proton spin coupling interaction diagram.

3.2 Nuclear Magnetic Resonance

To measure the proton polarization, we create an LCR circuit, called a Q-meter, which uses a wire coil nested within the target material and a variable capacitor for tuning the circuit frequency. An RF generator connected to the Q-meter circuit sweeps out a frequency around the proton Larmour frequency, which induced a spin flip in the target material within the coil. The energy released or absorbed by the corresponding spin flip can then be measured. The measured energy is directly proportional to the target polarization. To find the constant of proportionality we perform this same process (called NMR) at thermal equilibrium conditions, or without microwaves, where the real polarization is well known from Equation 1. This process is called a thermal equilibrium measurement. The ratio between the NMR signal and the thermal equilibrium polarization then gives the constant of proportionality to be used with the enhanced signal.

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 the material dependant calibration constant. 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.

Once the material was relatively thermalized we began taking our TE measurement. This involved sweeping the NMR circuit over the proton resonant frequency once every few seconds for anywhere from tens of minutes to several hours, depending on the available time for such an intrusive measurement. Each sweep produced a resonance peak as shown in Figure 3.

To find the energy absorbed or released from the proton spin flip, the NMR signal has to be integrated. Before this can be done several backgrounds have to be subtracted from raw signal. The first to be subtracted is a general background signal, or baseline. The baseline is measured by decreasing the magnetic field slowly until the NMR signal can no longer be seen. The remaining curve contains background information about the Q-meter that is then subtracted from the signal. The second background is obtained by fitting a third order polynomial to the wings of the resulting signal. Sub-

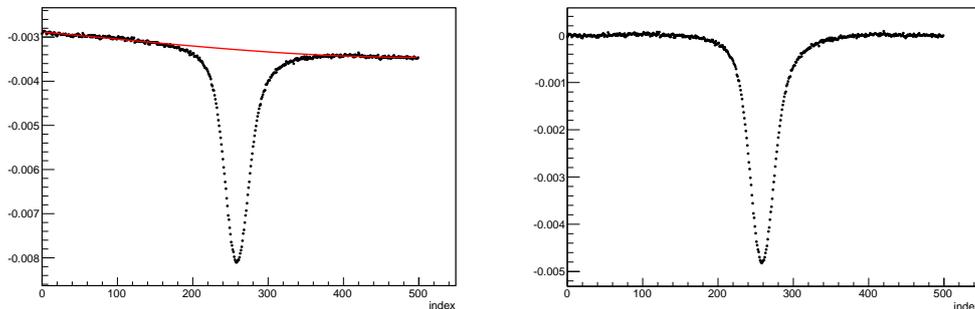


Figure 3: Third order polynomial fit to baseline subtracted data for an arbitrary TE measurement (left) and the final fit subtracted signal for Riemann sum integration (right).

tracting this fit removes any remaining background due to noise from the Q-meter circuit and drifting of the signal.

The raw NMR signal and baseline/fit subtracted signals for all TE measurements during g_2^p are listed in Appendix B. The final fit subtracted signal is integrated using a Riemann sum method to find the area. Using this area and the calculated thermalized polarization from Equation 1, the calibration constant is calculated using the ratio

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

where P_{TE} is the thermalized polarization and A_{TE} is the final integrated area. Each TE measurement contains anywhere from ten to several hundred calibration constants, depending on the length of the TE. To find the final CC for a TE measurement the statistically weighted average of all points is taken.

The number of TE's done on a target material varied depending on available time and ranged from 1 to 8 measurements. A complete list of target material, TE measurements, and online reported calibration constants is provided in Table 1. Calibration constants for all of the 2.5T settings were reported as exactly twice what is listed due to a problem with the online polarization analysis code. This led to online target polarizations being reported as twice that of the actual value for those settings.

4.2 Calibration Constant Uncertainties

From Equation 2, there are two main factors to consider for each calibration constant uncertainty; the uncertainty in the third order polynomial fit

Table 1: Target Materials

Material	TE measurement	Online CC
7	11	-1.734839
	13	-1.753021
	19	-1.7417065
	21	-1.7435
	23	-1.72013
8	12	-1.5207665
	14	-1.4936905
	16	-1.5108
	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
20	54	-1.862160

of the raw NMR signal which enters directly into A_{TE} , and the uncertainty in the magnetic field and temperature reading, which enter into P_{TE} . 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%.

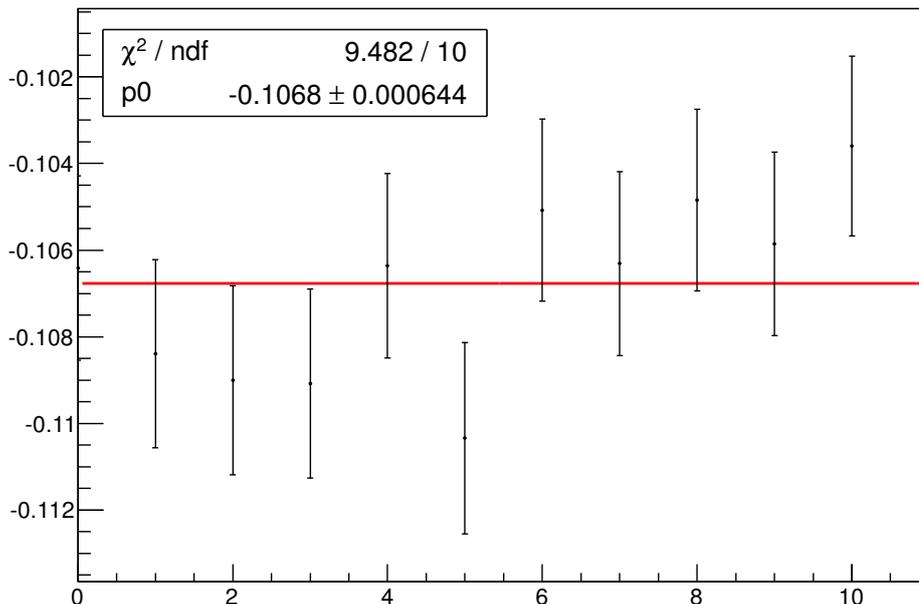


Figure 4: Fit to the contributing points for TE 15. The reduced χ^2 and fit result (average integrated area) are shown in the legend.

Equation 1 shows that the only two contributions to the systematic uncertainty in the TE polarization are the measurements of the magnetic field and temperature. 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 ^3He and ^4He 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

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

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

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

The length of the TE is chosen by fitting a straight line to the data within an online recorded start and stop time, shown in Figure 4, and adding (or removing) additional measurements while minimizing the reduced chi-squared to find the maximum ‘good’ number of points. The final value of the calibration constant is taken as the uncertainty weighted average of all contributing points. For materials 7, 8, 19 and 20 multiple TE’s were done. In these instances all calibration constants associated with one material are averaged again, further reducing the final uncertainty. Final offline calibration constants and uncertainties are shown in Table 2.

Table 2: Material Calibration Constants

Material	Offline CC	CC Uncertainty	% Uncertainty
7	-1.77329035	0.017186281	0.97
8	-1.44326238	0.013504229	0.94
11	-1.8061799524	0.0604883812	3.35
12	-1.5991123591	0.0478660027	2.99
13	-1.5018451533	0.0669351503	4.46
14	-1.8399628478	0.0675719182	3.67
17	-1.4470309781	0.0298793421	2.06
18	-1.7519990637	0.0250878914	1.43
19	-1.6209860752	0.0154156676	0.95
20	-1.8679436844	0.0482384082	2.58

4.3 Run Polarizations

The offline run polarizations were calculated for each NMR point, recorded roughly every 10 seconds, during production runs using the equation

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

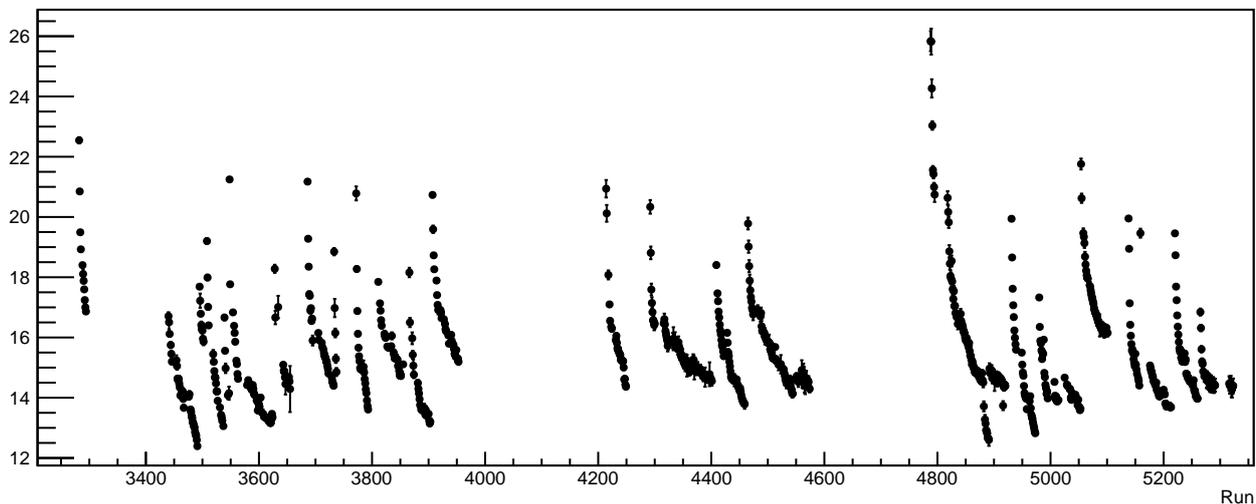
where A is the integrated NMR area, found using the fitting method as described in Section 4.1, and CC is the corresponding material calibration

constant calculated in Section 4.2.

The final run polarizations were fit 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 listed in Appendix A. The average offline polarization is 15% and 70% for 2.5T and 5T settings, respectively.

A Offline Polarizations

Offline Right Arm 2.5T Polarizations



Offline Left Arm 2.5T Polarizations

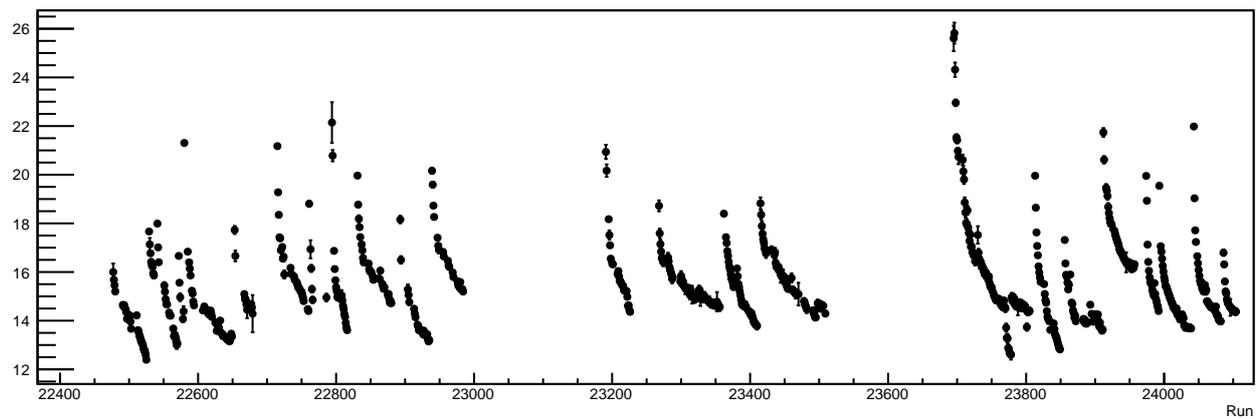


Figure 5: Final 2.5T Right/Left arm polarizations for all runs.

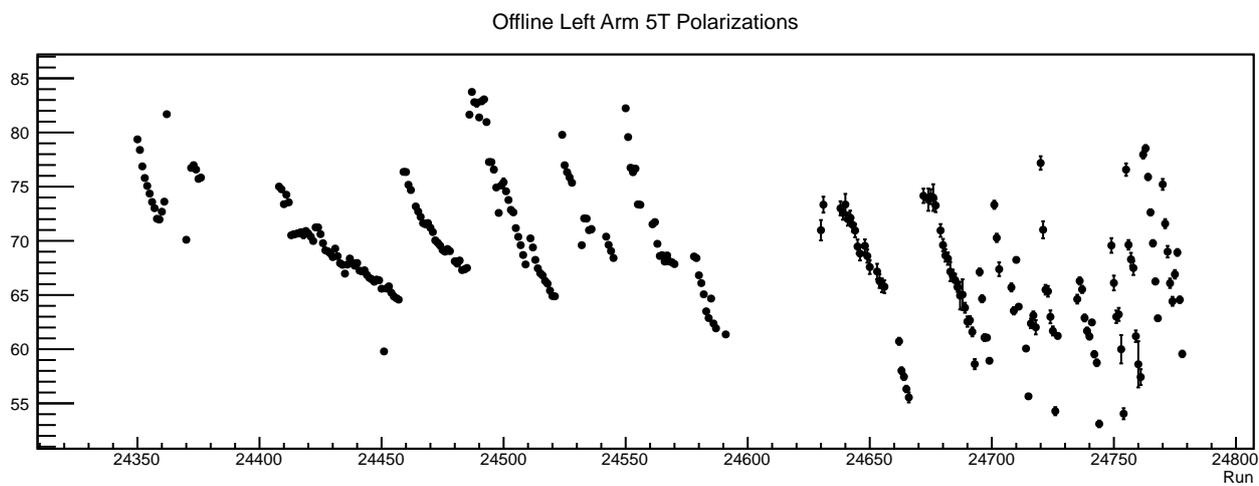
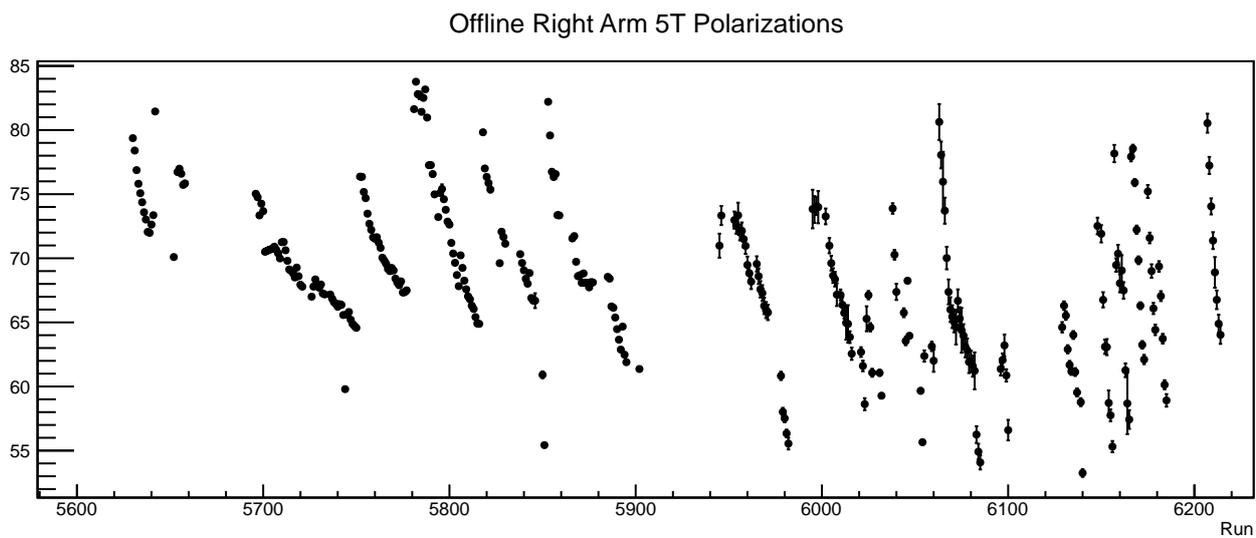


Figure 6: Final 5T Right/Left arm polarizations for all runs.