# Design and Performance of the Spin Asymmetries on the Nucleon Experiment

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Abstract

The Spin Asymmetries of the Nucleon Experiment (SANE) performed inclusive, double-polarized electron scattering measurements of the proton at the Continuous Electron Beam Facility at Jefferson Lab. A novel detector array observed scattered electrons of four-momentum transfer  $2.5 < Q^2 < 6.5 \text{ GeV}^2$  and Bjorken scaling 0.3 < x < 0.8 from initial beam energies of 4.7 and 5.9 GeV. Employing a polarized proton target which could be rotated with respect to the incident electron beam, both parallel and near perpendicular spin asymmetries were measured, allowing model-independent access to transverse polarization observables  $A_1$ ,  $A_2$ ,  $g_1$ ,  $g_2$  and moment  $d_2$  of the proton. This document summarizes the operation and performance of the polarized target, polarized electron beam, and novel detector systems used during the course of the experiment, and describes analysis techniques utilized to access the physics observables of interest.

### 1. Introduction

Deep-inelastic leptonic scattering has driven the study of nucleon spin structure as the cleanest probe available to hadronic physics. Inclusive spin asymmetry measurements at high x of-

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fer a particularly clear view of nucleon structure where the influence of sea quarks falls away. The Spin Asymmetries of the Nucleon Experiment (SANE) was devised to precisely measure inclusive double-spin asymmetries  $A_1^p$  and  $A_2^p$  in the deepinelastic region of final state invariant mass W and in a wide range of x, allowing direct access to spin structure functions  $g_1^p$  and the higher-twist dependent  $g_2^p$ , revealing trends as x approaches unity, and connecting spin structure function moments to lattice QCD calculations. Where a thorough exploration of these asymmetries with traditional, narrow-acceptance spectrometer techniques would be a protracted, expensive effort, SANE viewed a wide kinematic range using a novel, nonmagnetic, high-acceptance electron detector array. This array utilized the drift space between a Cherenkov detector and the electromagnetic calorimeter to create a "telescope" to isolate electron events of interest from the scattering chamber. To access both spin asymmetries in a model independent way, a polarized proton target was needed which could provide both longitudinal and the more challenging transverse target orientation components.

SANE was performed in Hall C of the Thomas Jefferson National Accelerator Facility from January to March of 2009. A polarized electron beam at energies of 4.7 or 5.9 GeV was incident on a solid, polarized proton target to produce spin asymmetries with the target polarized parallel to the beam, or nearly perpendicular (80°) to it. Scattered electrons were observed using Hall C's standard High Momentum Spectrometer (HMS), as well as a novel detector system, the Big Electron Telescope Array (BETA), resulting in a kinematic coverage of  $2.5 < Q^2 < 6.5 \text{ GeV}^2$  and 0.3 < x < 0.8. While BETA was built with SANE's primary aim in mind-accessing deep-inelastic double spin asymmetries-the HMS also allowed two additional, single-arm measurements to be performed opportunistically during the experiment. Measurements of spin asymmetries  $A_1^p$  and  $A_2^p$  were performed by the HMS in the resonance and low-W DIS regions, and the ratio of the electric to magnetic proton elastic form factors was measured using coincidences between the HMS and BETA as well as HMS single-arm data.

This document describes the design of SANE, with emphasis on its non-standard additions to Jefferson Lab's Hall C, as well as performance of each system during the experiment. We also give an overview of the analysis and corrections needed to produce spin asymmetries from BETA.

### 2. Polarized Electron Beam

Jefferson Lab's Continuous Electron Beam Accelerator Facility (CEBAF) consists of two linear accelerators, which at the time of this experiment, each accelerated electrons by roughly 600 MeV. Recirculating arcs connect these linacs, allowing a nominal 6 GeV maximum beam energy after 5 passes around the "race-track" [1]. Laser-excited, strained GaAs photocathodes provided a polarized electron source which switched helicity in 30 Hz pseudo-random batches.



Figure 1: Magnitude of hits the detector system versus the "fast" (left) and "slow" (right) raster positions, showing the raster patterns for a typical run.

### 2.1. Hall C Beamline

Upon entering Hall C, the beam was expanded from below  $100 \,\mu\text{m}$  in diameter to a  $2 \times 2 \,\text{mm}^2$  square by two air-core magnets roughly 25 m upstream of the target, producing the "fast raster" [2]. To further retard damage to the target polarization by radiation from the beam, an additional, circular "slow raster" was created by scanning the beam over a 2.0 cm diameter spiral pattern to better cover the 2.5 cm diameter target cell [3]. Figure 1 shows each raster pattern as observed from hits in the BETA detector versus the recorded raster amplitude.

To counteract the bending of the beam away from the target center while the target field was perpendicular, 5 T magnetic field, it was passed through two dipole chicane magnets, BE and BZ, which bent the beam down and then up towards the scattering chamber, respectively. Table 1 shows the deflection of the two chicane magnets for both energy settings used while the target was in its near perpendicular configuration. Any out of plane precession of the electron spins due to the chicane transport is canceled as the beam is subsequently bent in the opposite sense by the target magnet, so the beam polarization remains unaffected.

Beam E	BE Bend	BZ Bend	Target Bend
4.7 GeV	-0.878°	3.637°	-2.759°
5.9 GeV	-0.704°	2.918°	-2.214°

Table 1: Table of chicane parameters for  $80^{\circ}$  field for both beam energy settings. Negative angles indicate downward bends.

After passing through the target, the electron beam was again deflected downwards. Rather than using a second set of chicane magnets to direct the beam up to the beam dump, an 80-foot long helium bag was devised to transport the beam to a temporary beam dump on the experimental floor.

### 2.2. Beam Polarization Measurement

The beam polarization direction as it arrived in Hall C was not always 100% longitudinal due to the requirement to share polarization with the other experimental halls. The degree of longitudinal polarization was a function of both the polarization direction as the electrons left the injector, as set with a Wien filter, and the amount of spin precession through the accelerator before arrival in Hall C. The precession itself is a function of the number of passes through the accelerator, the overall beam energy, and the difference in energy between the two linear accelerators in the machine.

The beam polarization was monitored in nine dedicated Møller polarimeter measurements [4] covering each nominal beam energy and polarization setting. Periods of beam energy instability during this experiment meant that the degree of spin precession through the machine was not constant at a given energy setting, yielding more variation in the beam polarization with time than is typically expected. Therefore, the nine polarization measurements were used to interpolate the beam polarization throughout the experiment via a fit with three degrees of freedom: the intrinsic polarization of the beam at the source  $P_{\text{source}}$ , the energy imbalance of the north and south linear accelerators, and a small global correction to the overall beam energy  $F_{\rm corr}$ . In addition, the beam polarization had been found to depend to some degree on the quantum efficiency of the photcathode, which can be described by a correction,  $F(\epsilon_a)$ , based on fits to data from the preceding experiment, GEp-III [5]. The beam polarization in Hall C  $P_B$  could then be expressed as a function of the Wien angle  $\theta_w$ , quantum efficiency of the photocathode, and half wave plate status  $n_{hwp}$ , as

$$P_B = (-1)^{n_{\text{hwp}}} P_{\text{source}} F_{\text{corr}} F(\epsilon_q) \cos(\theta_w + \varphi_{\text{precession}}), \quad (1)$$

where  $\varphi_{\text{precession}}$  is determined by following the spin precession through each bend in the accelerator.

Using the Wien angle, quantum efficiency and half wave plate status recorded over the course of each data-taking run, the beam polarization over time was calculated using this fit. By averaging this data over the charge accumulated on the target from beam current measurements at each moment in time, a charge-averaged beam polarization was then produced for each run. Figure 2 shows the achieved electron beam polarization for each experimental run for the entire experiment. Of note is the rather low beam polarization near run 72400, which came from non-optimal setting of the Wien filter at the injector. The increase in polarization that follows results from optimizing the Wien angle.

#### 3. Polarized Proton Target

SANE utilized the University of Virginia polarized solid target, which has had extensive use in electron scattering experiments at SLAC [6, 7, 8] and Jefferson Lab [9, 10, 11], and is shown in Figure 3. Polarized protons were provided in the form of solid ammonia NH<sub>3</sub> beads held in one of two 2.5 cm diameter, 2.5 cm long cells (*top* or *bottom*) held in the "nose" of a helium evaporation refrigerator providing roughly 1 W of cooling power at 1 K. This nose was located at the center of an Oxford Instruments NbTi, 5 T superconducting split pair magnet, which allowed beam passage parallel or perpendicular to the field. This magnet provided better than  $10^{-4}$  field uniformity in the  $3 \times 3 \times 3$  cm<sup>3</sup> volume of the target scattering cham-



Figure 2: Electron beam polarization per data-taking run.

ber. While the magnet allowed beam passage perpendicular to the field, the geometry of the coils did occlude the acceptance of BETA when oriented at  $90^{\circ}$ , so in practice  $80^{\circ}$  was used. The field's alignment in Hall C to its nominal values were to within 0.1 degree.

Polarized target nuclei were provided via dynamic nuclear polarization (DNP) of ammonia (<sup>14</sup>NH<sub>3</sub>). DNP employs high magnetic fields ( $B \approx 5$  T) and low temperature ( $T \approx 1$  K) to align spins in a target medium, using microwave radiation to drive polarizing transitions of coupled electron–nucleus spin states [12]. These techniques offer excellent polarization of protons—exceeding 95%—in a dense solid and can maintain this polarization under significant flux of ionizing radiation, such as an electron beam.

At magnetic field B and temperature T, the polarization of an ensemble of spin 1/2 particles is calculable by Boltzmann statistics as  $P = \tanh(\mu B/(kT))$ . At 5 T and 1 K, this creates a high polarization of electron spins (99.8%), but quite low polarization in protons (0.5%). In DNP, microwave energy is used to transfer this high electron polarization to the proton spin system, which is accomplished via several mechanisms, the simplest of which to explain is the solid-state effect [13, 14]. By taking advantage of coupling between free electron and proton spins, microwave radiation of frequency lower or higher than the electron paramagnetic resonance by the proton magnetic resonance ( $v_{EPR} \pm v_{NMR}$ ) drives flip-flop transitions  $(e_{\perp}p_{\perp} \rightarrow e_{\uparrow}p_{\uparrow})$  to align or anti-align the proton with the field. The electron's millisecond relaxation time at 1 K means that the free electron will relax quickly to become available to perform a polarizing flip-flop with another proton. While the protons take minutes to relax, they will frequently perform energy-conserving spin flip transitions via dipole-dipole coupling with other neighboring protons. This allows the transport of nuclear polarization away from the free electron sites-a process called "spin-diffusion" which tends to equalize the polarization throughout a material [15].

### 3.1. Target polarization measurement

The proton polarization was measured via nuclear magnetic resonance measurements (NMR) of the target material, employ-



Figure 3: Cross-section of UVa polarized target cryostat, refrigerator, and scattering chamber.

ing a Q-meter [16] to observe the frequency response of an LCR circuit with the inductor embedded in the target material. An RF field at the proton's Larmor frequency induces spin flips as the proton spin system absorbs or emits energy. By integrating the real portion of the response as the circuit is swept through frequency, a proportional measure of the sample's magnetic susceptibility, and thus polarization, is achieved [17].

NMR "Q-curve" signals contain the frequency response of both the material's magnetic susceptibility, and the circuits own background response. To remove the background behavior of the NMR electronics, a *baseline* signal is recorded, while the proton NMR peak is shifted away from the frequency sweep range with a magnetic field shift. To produce a final NMR signal, this baseline is subtracted, seen in a) of Figure 4, and a



Figure 4: a) Raw NMR signal and baseline in arbitrary units. b) Final NMR signal, with baseline and residual signals subtracted, showing the integrated signal area.



Figure 5: Calibration constants for each target material sample used during the experiment. The calibration constant used to calculate the final target polarization is an average of one or more values from all the thermal equilibrium measurements taken for that sample. Errors shown are statistical only.

polynomial fit to the wings of the resulting curve is performed, allowing the subtraction of any residual background shifts in the Q-curve, as seen in b) of Figure 4. The degree of polarization is then proportional to the integrated area under this backgroundsubtracted signal.

The coefficient of proportionality used to calculate the polarization from the integrated signal is known as the calibration constant (*CC*) and is determined by NMR measurements without the application of DNP. These thermal equilibrium (*TE*) measurements give a signal area  $A_{\text{TE}}$  at a known polarization  $P_{\text{TE}}$ , calculated from the given field *B* and temperature *T*:

$$P_{\rm TE} = \tanh\left(\frac{\mu B}{kT}\right).$$
 (2)

An enhanced polarization P can then be calculated from a signal area A during DNP:  $P = A(P_{\text{TE}}/A_{\text{TE}})$ . The calibration constant  $P_{\text{TE}}/A_{\text{TE}}$  depends on the geometrical arrangement of the target material beads in the cell and the magnetic coupling of the NMR pickup coil to those beads, so in general a single constant may be applied to a target sample throughout its use in the experiment. When they were possible, multiple thermal equilibrium measurements for a given target material sample were averaged to be applied to all the target polarization data for that sample.

Figure 5 shows each calibration constant taken during the experiment, and the final averaged constants used to calibrate the NMR signal area for each target material sample. Samples number 10 and 11 have drastically different calibration constants due to the different orientation of the NMR coil to the field after the magnet was rotated; they are physically the same target samples as materials 8 and 9.

### 3.2. Material Preparation and Lifetime

Ammonia ( $^{14}NH_3$ ) offers an attractive target material due to its high polarizability and radiation hardiness, as well as its favorable dilution factor — ratio of free, polarizable protons to total nucleons. Ammonia freezes at 195.5 K, and can be



Figure 6: The change in microwave frequency used to polarize during SANE as radiation dose from the beam is accumulated. Positive polarization points are shown in blue and show a roughly linear decrease, while the negative polarization points in green exhibit a curving increase.

crushed through a metal mesh to produce beads of convenient size, allowing cooling when the material is under a liquid helium bath [18].

Before dynamic polarization is possible, the material must be doped with paramagnetic radicals, which provide the necessary free electron spins throughout the material. For SANE, the ammonia target samples were radiation doped at a small electron accelerator, the Medical-Industrial Radiation Facility at NIST's Gaithersburg campus. Free radicals were created by 19 MeV electrons at a beam current between 10 and 15  $\mu A$ , which was incident upon the frozen ammonia material held in a 87 K liquid Ar<sub>2</sub> bath, until an approximate dose of  $10^{17}$  e<sup>-</sup>/cm<sup>2</sup> (100 Pe/cm<sup>2</sup>) was achieved.

While proton polarizations exceeding 95% are possible after irradiation doping of ammonia, the experimental beam causes depolarization. The first depolarizing effect, of order 5%, is due to the decrease in DNP efficiency due to excess heat from the beam [19]. A longer term depolarization effect comes from the build up of excess radicals under the increasing dose of ionizing radiation. While the maximum achievable polarization falls as continued radiation dose is accumulated, the optimal microwave frequency needed to reach the highest polarization will also shift as the free electrons come under the dipole–dipole influence of more free electron neighbors, broadening the electron spin resonance peak. Figure 6 shows the microwave frequency chosen by the target operator during the experiment to maximize the target polarization, displaying the shift in microwave frequency as dose from the beam is accumulated.

By heating the target material to between 70 to 100 K certain free radicals can be recombined. This "anneal" process will often allow the polarization to achieve its previous maximal values. With subsequent anneals, however, the build-up of other radicals with higher recombination temperatures will result in the increased decay rate of the polarization, until the material must be replaced [20].

Figure 7 shows the lifetime of a typical target material used



Figure 7: Polarization of a typical target material sample versus charge accumulated during data taking, with vertical yellow lines showing when anneals were performed.

during SANE, and illustrates several artifacts common during beam taking conditions. Vertical yellow lines depict anneals. The build-up of radicals in beam can be seen at 0 and  $6 \text{ Pe/cm}^2$  as polarization actually increases with dose accumulated. Small spikes in polarization seen throughout are the result of beam trips, when the polarization improves as the temperature drops with the loss of heat from the beam. Other hiccups in operation apparent in the plot are a poorly performed anneal, just after  $2 \text{ Pe/cm}^2$ , resulted in starting polarization below 60%, and the loss of liquid helium in the target cell at approximately 3 and  $11 \text{ Pe/cm}^2$ .

# 3.3. Offline Corrections

Several corrections were necessary to the online NMR signal analysis that was performed as the experiment ran. Because the scale of the thermal equilibrium signals is two orders of magnitude smaller than that of the enhanced polarization signal, different amplification gains are used for the two measurements. Differences between the nominal and actual gains of the amplifiers results in a correction of approximately 1%.

During the running of the experiment, the superconducting magnet experienced a damaging quench which necessitated repairs. While 5 T operation of the magnet was restored, a slight current leak while in persistent mode was seen due to minute electrical resistance [21]. While the change in magnet current was only about 0.05% per day, this resulted in a significant shift in the NMR signal peak. The wings of each signal—after baseline subtraction— are used to perform a polynomial fit to remove residual Q-curve movement, so the shifting peak created poor fits as it approached the edge of the sweep range. The resulting fits, such as the one seen in a) of Figure 8, were poor. This effect was corrected by varying the size of the wings used in the polynomial fit for each signal, ensuring that only the background portion of the signal was included in the fit, as seen in b) of Figure 8.



Figure 8: Effect of the magnetic field drift on the polynomial residual fit.



Figure 9: Charge averaged target polarization achieved for each SANE data-taking run.

### 3.3.1. Target Polarization Performance

During SANE, a total of  $122.2 \times 10^{15}$  e/cm<sup>2</sup> of radiation dose was accumulated on the 11 different ammonia material samples. Anneals were performed 26 times, and 23 thermal equilibrium calibration measurements were taken. Figure 9 shows the polarization for each experimental run, with indications for the orientation of the target during that period. Despite considerable unforeseeable difficulties in the operation of the target during SANE, the total charge-averaged proton polarization achieved was 68%.

### 4. Detector Systems

The centerpiece of SANE's inclusive measurement of deep inelastic electron scattering was the Big Electron Telescope Array (*BETA*)<sup>1</sup>, a large acceptance, non-magnetic detector package situated just outside the target vacuum chamber, seen installed in Hall C in Figure 10. Electrons scattered in the target passed though a small tracking hodoscope for position information, a threshold Cherenkov detector for electron discrimination, and a second, large hodoscope, before finally producing



Figure 10: Photograph of BETA from above, showing the support structure for the calorimeter at left, lucite hodoscope in yellow at center, Cherenkov tank in red, and target platform at right.

a shower in the calorimeter. BETA occupied a large, 0.2 sr solid angle at 40° to the beam direction, and provided pion rejection of 1000:1, energy resolution of better than  $10\%/\sqrt{E}$ , and angular resolution of approximately 1 mr. Figure 11 shows renderings of a Geant4 simulation of BETA with an example electron track.

#### 4.1. BigCal

BETA's big electromagnetic calorimeter, *BigCal*, consisted of 1,744 TF1-0 lead-glass blocks; 1,024 of these were  $3.8 \times 3.8 \times 45.0 \text{ cm}^3$  blocks contributed by the Institute for High Energy Physics in Protvino, Russia. The remaining 720, from Yerevan Physics Institute, were  $4.0 \times 4.0 \times 40.0 \text{ cm}^3$  were previously used on the RCS experiment [23]. The calorimeter was assembled and first utilized by the GEp-III collaboration [24]. The Protvino blocks were stacked  $32 \times 32$  to form the bottom section of BigCal, and the RCS blocks were stacked  $30 \times 24$  on top of these, as seen in Figure 12. The assembled calorimeter had an area of roughly  $122 \times 218 \text{ cm}^2$ , which, placed 335 cmfrom the target cell, made a large solid angle of approximately  $0.2 \text{ sr at a central scattering angle of <math>40^\circ$ .

BigCal was the primary source for event triggers for BETA, and a summation scheme was used to simplify triggers and reduce background events, as seen in Figure 12. While each lead-glass block had its own FEU-84 photomultiplier tube and ADC readout, the smallest TDC readouts consisted of groups of 8 blocks in one row. These TDC groups then formed 4 timing columns, which were summed and discriminated for another TDC readout. The 8 block TDC signals were also summed into larger timing groups of 64 blocks, 4 rows by 8 columns (designated by color in Figure 12), which were overlapped to avoid split events. Finally, timing groups were summed into four trigger groups to form the main DAQ triggers [24].

#### 4.2. Gas Cherenkov

The Cherenkov counter held dry  $N_2$  radiator gas at near atmospheric pressure, and employed eight  $40 \times 40$  cm<sup>2</sup> mirrors to focus Cherenkov photons onto 3 inch diameter Photonis

<sup>&</sup>lt;sup>1</sup>The original BETA design was conceived by Glen Warren [22].



Figure 11: Two renderings of BETA from the Geant4 simulation, showing at top a simulated electron event originating in the target, creating Cherenkov showers in the gas Cherenkov and lucite hodoscope, and depositing its energy in the upper section of the calorimeter. The lower diagram shows the dimensions of each components, and their distances from the target.



Figure 12: Layout of BigCal's 1,744 lead-glass blocks, showing upper RCS and lower Protvino sections, as well as trigger and timing groups. An example 8 block TDC channel and 64 block timing group are show in hatched areas [25].

XP4318B photomultiplier tubes. Nitrogen's index of refraction of 1.000279 gave a momentum threshold for Cherenkov emission by pions of 5.9 GeV, allowing effective rejection of pions, given a maximum beam energy of 5.9 GeV. The 8 mirrors, 4 spherical and 4 toroidal, were positioned to cover the full face of BigCal, effectively dividing BigCal into 8 geometric sectors each corresponding to one mirror. Due to the proximity of the Cherenkov tank to the target magnetic field,  $\mu$ -metal shields enclosed each photomultiplier tube, and additional iron plating was situated between the tank and magnet. The design and performance of the SANE Cherenkov is discussed in detail in reference [26].

# 4.3. Hodoscopes

Two tracking hodoscopes provided additional position information and background rejection. Mounted between BigCal and the Cherenkov tank, the lucite hodoscope consisted of 28 lucite bars of  $3.5 \times 6.0 \times 80.0$  cm, curved with a radius equal to the distance from the target cell, giving a normal incidence for participles originating in the target. With an index of refraction of 1.49, Cherenkov radiation was produced from the passage of charged particles above  $\beta_{\text{threshold}} = 0.67$ . The effective threshold increases to 0.93 when Cherenkov photons are detected simultaneously at both ends of the lucite bar, because these photons propagate through total internal reflection. The Cherenkov angle must be above critical angle for lucite  $(42^\circ)$  to allow normal incidence in this case. Photonis XP2268 photomultiplier tubes coupled to the each end of each bar collected the Cherenkov light, allowing the determination of the position of the hit along the bar using timing information from both tubes.

A smaller, front tracking hodoscope consisted of three planes of  $3 \times 3$  mm Bicron BC-408 plastic scintillator bars positioned just outside the target scattering chamber, 48 cm from the target cell. This hodoscope provided tracking information on particles as they were still under the influence of the target's magnetic field. By combining tracking information close to the target with final positions in BigCal, any discernible curve in the particles trajectory would allow differentiation of positively and negatively charged particles, allowing positron rejection.

### 4.4. Hall C HMS

The standard detector system in Hall C, the High Momentum Spectrometer (HMS), was utilized in a supporting role throughout the experiment. The HMS is made up of three superconducting quadrupole magnets and one superconducting dipole, which focus and bend charged particles into a detector package with two gas drift chambers, four hodoscopes, a gas Chereknov tank and a lead-glass calorimeter. During SANE, the HMS was positioned at 15.4°, 16.0° and 20.2°, accepting proton and electron scattering events from the target. In addition to the calibration and support of BETA, events from the HMS were used to produce independent analyses on the proton electric to magnetic form factor ratio [27] and spin asymmetries and structure functions [28].

### 4.5. Data Acquisition

Data collection was coordinated by a trigger supervisor [29], which received triggers from BigCal, Cherenkov and HMS TDCs. If not busy, the trigger supervisor accepted triggers from readout controllers, sending gate signals to ADCs and start signals to TDCs. Readout controllers then read out signals, to be assembled by an event builder and saved to disk. To monitor events missed due to the data acquisition being in a busy state, the dead-time was monitored with scalers on the discriminator output which wrote to the data stream every 2 seconds.

SANE utilized 8 trigger types, representing triggers and coincidences from the detectors, of which 2 were used in the final analysis. The BETA2 triggers were the result of coincident hits in the Cherenkov and BigCal, representing a candidate electron event. PI0 triggers required two BigCal hits in different quadrants of the detector, representing vertically separated two photon events from neutral pions.

#### 5. BETA Commissioning and Calibration

SANE's initial commissioning and calibration plans were hampered early on by unanticipated target magnet failure and subsequent repairs. Due to these delays, plans were scrapped that would have calibrated BigCal with elastic e-p scattering in coincidence with a proton detected in the HMS. This plan required running at lower energies and included scanning the position of the elastic events in the calorimeter by varying the target magnet current and orientation. Furthermore, in order to optimize data collection for the proposed beam energy and target configurations while accommodating the accelerator run plan, BETA began commissioning detectors with transverse target polarization.

BETA's BigCal calorimeter was calibrated in real-time using neutral pion events from the target, allowing drifts in gain to be observed throughout the experiment. The Cherenkov photomultiplier tube ADC channels were calibrated before the experiment to roughly 100 channels per photo-electron, as discussed in detail in reference [26]. The Lucite hodoscope used only TDC data to record the position of hits, calculable from propagation of the electron's Cherenkov light to photomultiplier tubes at each end of the bar.

# 5.1. Cluster Identification

To reconstruct the final energy and position of particle hits in the calorimeter, a simple algorithm was used to group signals originating from one shower in neighboring calorimeter blocks into clusters for each event. The block with the largest signal was selected as the cluster seed, and blocks within a  $5\times5$  grid of this centroid were included in the cluster, unless detached from the group. The next cluster was formed by finding the next highest signal block, excluding those already included in a cluster, and this process was repeated until all blocks above a chosen threshold, roughly were used.

Once clusters were identified, they were characterized for use in the analysis. We assigned each cluster a pre-calibration energy  $E_c = \sum_i c_i A_i$  for block number *i*, ADC values  $A_i$  and block calibration constants  $c_i$ , where final  $c_i$  are the end goal of the calibration. In the first pass of analysis, each ADC channel was assumed to be 1 MeV, based on adjustments before the experiment using cosmic ray events. The moment of the cluster is then an energy weighted average of position

$$\langle x \rangle = \sum_{i} \frac{c_i A_i}{E_c} (x_i - x_{\text{seed}}),$$
 (3)

and similarly for  $\langle y \rangle$ , so that the cluster position on the face of BigCal was taken to be  $(x_{seed} + \langle x \rangle, y_{seed} + \langle y \rangle)$ . The second moment gave the position standard deviation.

### 5.2. $\pi^0$ Calibration

The large number of  $\pi^0$  background events incident on the calorimeter from the target allowed reliable calibration of a majority of the calorimeter, as well as effective, real-time gain monitoring throughout the experiment. Neutral pions produced in the target decay to two photons at a 98.8% branching probability with a mean lifetime of  $8 \times 10^{-17}$  seconds, so that most pions have decayed to photons before exiting the target. By measuring the separation angle of the photons  $\alpha$ , we can determine the relative energies of the incident photons  $E_{1,2}$  from the pion mass  $m_{\pi^0}^2 = 2E_1E_2(1 - \cos \alpha)$ .

Unfortunately, the PIO trigger was unable to populate all calorimeter blocks with events because the trigger required two of the four trigger groups ( $T_{1-4}$  shown in Figure 12) to fire in coincidence. The reach of the events was limited by the energy thresholds for each trigger groups' discriminator which was set to roughly 400 MeV. For example, to populate the upper-left most block with a photon shower requires relatively low energy  $\pi^0$  decays so that the angle between the two photons is large enough to trigger  $T_3$  and  $T_4$ . If the  $\pi^0$  is too energetic the angle isn't big enough to use smaller trigger groups to form the PIO trigger.

To supplement the  $\pi^0$  calibration and improve the energy calibration of blocks at the edges of the calorimeter, a calibration was done by looking at the energy spectra measured in each block. A GEANT simulation of the experiment was run with events weighted by the inelastic cross section [30]. The energy spectra for each block is dominated by inelastic electrons in the high energy tail. The energy gain coefficients for a block were set so that the measured energy spectra for each block matched the GEANT simulated energy spectra in the high energy tail region for W < 2.0 GeV. These energy gain coefficients where used as the starting values for determining the final gain coefficients in the  $\pi^0$  calibration method.

Events from the PIO trigger were chosen and cuts were placed to include only clusters which were 20 cm to 80 cm apart, excluding pairs produced outside the target, and to exclude events that gave triggers in the Cherenkov, such as electrons. To calibrate a given block, we formed a histogram of the invariant mass results for all the clusters which pass the cut and include that block. Normalizing this invariant mass result to the known pion mass  $\pi^0 = 134.9$  MeV, a new calibration constant was obtained for the block. Once new constants are produced for all blocks, this process is repeated, and iterated many times until all block results converge on the pion mass, as seen in Figure 13.



Figure 13: Plot of neutral pion mass reconstruction after block calibration. The energy resolution of this peak is directly proportional to the energy resolution of the clusters in the calorimeter.



Figure 14: The difference of electron energies reconstructed from elastic protons detected in the HMS and the measured energies in BETA. The measured data (black) are compared to the simulation results (red).

# 5.3. Neural Networks and Track Reconstruction

### 5.3.1. Photon Position Corrections

Particles incident on the calorimeter farther away from the center of its face arrived at more oblique angles to the surface, so that the depth of the shower had an increasing effect on the resolved cluster moment. Photons hitting the calorimeter at the top or bottom enter the face of the calorimeter at angles far from normal incidence. Therefore the electromagnetic shower's longitudinal development will have the same directional bias. The x and y moments for these types will result in a shift that depends on the incident angle (which for photons is easily mapped to its position). In order to correct for this, a neural network was trained to provide the reconstructed x-y coordinates of where

the photon crossed the face of the calorimeter. The neural network provided the correction values  $\delta_x = x_{\text{face}} - x_{\text{cluster}}$  and  $\delta_y = y_{\text{face}} - y_{\text{cluster}}$ , the difference between the position on the face of BigCal where the particle entered and centroid of the cluster created in BigCal.

The photon position correction neural network followed the BFGS training method [31], using a sigmoid activation for all nodes, and was trained with 1 million uniformly thrown photon events in the Geant4 simulation with the detectors, magnetic field and target geometries. Quantities characterizing the cluster, such its mean position, standard deviation, skewness and kurtosis, were used as input neurons. The strongest neuron weights for the  $\delta_y$  correction were connected to the *y* position input neuron indicating that the further the position is from the calorimeter center, the larger the correction needed to fix the oblique angle of incidence, as expected. Figure 15 shows the performance of the neural network for the *y* position correction.



Figure 15: The performance of the network correction on the cluster *y* position (in cm). The blue histogram shows the simulation input data used to train the network. The black histogram shows the network result and the red histogram shows the difference between the nominal (blue) and output (black) network results.

### 5.3.2. Electron Reconstruction

Using the hits in BETA and knowledge of the target's 5 T field, the trajectory of the scattered electron was reconstructed to allow the determination the kinematics of each event. While naïve, straight-line tracks from x and y calorimeter hits to the target gave initial physics scattering angles  $\theta$  and  $\phi$ , corrections were made to take into account the angle of incidence in the calorimeter and, more importantly, the bending of the electron in the magnetic field. A Geant4 simulation with a detailed description of the geometry and an extended target field map were used to generate the events used in training each neural network. Roughly 1 million events, of uniformly distributed angle and energy, originating uniformly from the target volume, were simulated.

Three neural networks were constructed for this analysis: (a) BigCal position correction, which determined the x-y coordi-

nate where the track crosses the calorimeter face, as discussed in subsection 5.3.1; (b) a network to calculate the corrections to the angle of incidence; and (c) a network to get the scattered momentum vector at the target which corrected for the deflection of charged tracks as they propagated through the target magnetic field. Each neural network was trained for each particle type (electron, positron, and photon) and target field/beam energy configuration.

The BigCal x-y position correction neutral network (a) for photons is shown in Figure 15 and very similar networks were constructed for electrons and positrons. The neutral network for calculating the angle of incidence, (b), gave the momentum direction at the face of BigCal. Network (b) is only needed for electrons and positrons because they are deflected in the target's magnetic field, whereas photons follow a straight line. This network was useful for computing the *physics scattering angles* (the scattering angles and momentum at the target) when propagating the charged particle backwards towards the target with the initial momentum and position at BigCal as the inputs. However, this method was only used as a check of the final neural network (c), which was trained to produce the physics scattering angles  $\theta$  and  $\phi$ . Figure 16 shows the network performance for the physics scattering angle  $\theta$ .



Figure 16: The performance of the network correction to calculate the physics scattering angle  $\theta$  (in radians). The red histogram shows the simulation input data used to train the network. The blue histogram shows the trained network result and the black histogram shows the difference between the nominal (red) and network output (blue) results .

### 6. Asymmetry Analysis

Because BETA was a new detector configuration, we discuss here the analysis framework required for its inclusive spin asymmetry measurements, leaving HMS analysis details to other works [32, 33]. Deep-inelastic scattering electron events detected in BETA were reconstructed, separated into kinematic

bins, formed into yields based on the beam helicity, and corrected to produce physics asymmetries at each target field angle. These asymmetries take the form

$$A = \frac{1}{f P_B P_T} \frac{N_+ - N_-}{N_+ + N_-},\tag{4}$$

for dilution factor f, beam and target polarizations  $P_B$  and  $P_T$ , and corrected electron yields for each beam helicity  $N_{\pm}$ . Here the target and beam polarizations are applied as a single, charge averaged value for all events in each experimental run, while the dilution factor and the yields are functions of the kinematics of each event.

### 6.1. Event Selection

#### 6.1.1. Binning

Electron yields were separated first into broad  $Q^2$  bins to catch any large scale  $Q^2$  evolution in the results, then tight bins in x or W were formed based on the energy resolution of the detectors. A fit to the measured energy resolution as a function of energy of the form

$$\delta E'(E') = \frac{C_0}{\sqrt{E'}} + C_1,$$
 (5)

with fit constants  $C_0$  and  $C_1$ , allowed the production of a set of E' bins such that

$$E'_{i+1} = E'_i + \delta E'(E'),$$
 (6)

with bounds above and below this abscissa by  $\delta E'/2$ . For the production of clearer plots, these minimally sized bins were later recombined with their neighbors based on their statistical significance.

### 6.1.2. Event Selection

To minimize backgrounds and ensure that good electron events are counted in the yields, events were rejected if they did not meet the following criteria. For asymmetry yields, only single cluster events in BigCal with a corresponding Cherenkov hit were taken. A cut was placed on the Cherenkov hit geometry, ensuring that the position in the calorimeter matched a hit in the correct Cherenkov sector. To exclude charged pion events which were unlikely to occur above 500 MeV, only clusters of energy greater than 0.9 GeV were accepted.

#### 6.2. Asymmetry Measurements

To extract physics spin asymmetries, SANE directly measured double-spin asymmetries with the target's magnetic field anti-parallel and at 80° to the beam. Reconstructed electron event yields from each helicity  $n_{\pm}$  were used to form raw asymmetries  $A_{180^{\circ}}$  and  $A_{80^{\circ}}$ , as a function of their x and  $Q^2$  kinematic bins:

$$A_{\rm raw}(x,Q^2) = \frac{n_+(x,Q^2) - n_-(x,Q^2)}{n_+(x,Q^2) + n_-(x,Q^2)}.$$
(7)

These raw asymmetries must be first corrected for the effects of dead time in the data acquisition system, unequal total electron

events in each helicity, and the dilution of the target by material other than the protons of interest.

### 6.2.1. Charge Normalization and Live Time Correction

Although the 30 Hz, pseudo-random helicity flips of the beam produce nearly equal number of positive and negative helicity incident electrons, any imbalance in the beam charge between the two helicity states will introduce a false asymmetry. This effect is corrected by normalizing the asymmetry using total charge accumulated  $Q_+$  and  $Q_-$  from each helicity. The beam charge was measured by a cylindrical cavity which resonates at the same frequency as the accelerator RF in the transverse magnetic mode as the beam passes through the cavity. The RF power of the resonance is converted by antennae in the cavity into an analog voltage signal. This analog signal is processed into a frequency which is then counted by scalers which are gated for beam helicity. A special set of data was taken to calibrate the beam current measured in the hall relative to the beam current measured by a Faraday cup in the accelerator injector at various beam currents. The scalers were injected into the datastream every two seconds, and experimental data was used only if the beam current was between 65 and 100 nA.

Typically, scalers measure the total number of accepted triggers,  $n_{\pm}^{\rm acc}$ , and the total trigger events,  $n_{\pm}^{\rm trig}$ , for each helicity. To account for the computer livetime from either helicity due to event triggers that arrive while the data acquisition is busy, the corrected yield is divided by the computer livetime:  $L_{\pm} = n_{\pm}^{\rm acc}/n_{\pm}^{\rm trig}$ . Together, the charge normalization and livetime corrections result in corrected yields

$$N_{\pm} = \frac{n_{\pm}}{Q_{\pm}L_{\pm}},\tag{8}$$

for raw counts  $n_{\pm}$  of electron yields of each helicity, for each run, and as a function of kinematic bin.

Unfortunately, during SANE the total positive beam helicity trigger events from the scalers were not measured and therefore a direct measure of  $L_+$  was not made. The total negative beam helicity trigger events were, however, recorded by the scalers, as were the accepted trigger events for both helicities. The livetime for the negative helicity was calculated for each run from the scaler data. Given the trigger rates of the experiment, the livetime can be approximated as  $1 - \tau R^{\text{trig}}$  where  $R^{\text{trig}}$  is the rate of triggers and  $\tau$  is the computer deadtime of the data acquisition system. For each run,  $\tau$ , was determined from the negative helicity data and the livetime for each helicity,  $L_{\pm}$ , was calculated as  $1 - \tau R_+^{\text{trig}}$ . A plot of the livetime for the negative helicity events for all the runs in the experiment is shown in Figure 17. For most of the experimental data, the livetime measurement is consistent with  $\tau \approx 160 \,\mu \text{sec.}$  But the experimental data taken with the perpendicular target at beam energy of 4.7 GeV, shows large variations in the livetime with only small variation in trigger rate. This means that  $\tau$  must have been fluctuating, but the cause of this effect is not fully understood.

To check the effectiveness of the charge and livetime corrections to the data, a measurement of the false asymmetry can be done using the trigger asymmetry,  $A_{p,n}$ , as measured with pos-



Figure 17: The computer livetime for negative helicity events as a function of negative helicity trigger rate.



Figure 18: The false asymmetry for pairs of run groups with opposite sign of  $P_BP_T$  versus run number.

itive (p) or negative (n) combinations of beam,  $P_B$ , and target,  $P_T$  polarizations. The false asymmetry is calculated as

$$A_{\text{false}} = \frac{C_p A_n - C_n A_p}{C_p - C_n},\tag{9}$$

and  $C = P_B P_T$ , with the p(n) indicating the sign of C. In Figure 18, the false asymmetry is plotted as a function of run number.

### 6.2.2. Packing Fraction

The ammonia target samples consisted of irregular beads roughly 2 mm in diameter, cooled in a liquid helium bath and held with aluminum foil windows. Each sample differed in the amount, size and shape of the beads used. To determine what portion of the target cell was ammonia, called the packing fraction  $p_f$ , experimental yields from each sample were compared with yields taken throughout the experiment on a carbon disk target of known thickness. The electron yield is a linear function of the packing fraction  $Y(p_f) = mp_f + b$ , where m and b



Figure 19: Packing fractions for all target material samples used during SANE, showing averaged value and error.

depend on the beam current, acceptance, partial densities and cross sections.

Using this linear relation, we can determine the packing fraction of a given sample by interpolating between two reference points on the line, as determined from a Monte Carlo simulation. The simulation used was the Hall C HMS single arm MC, based on an empirical fit of inelastic cross section [30, 34], and contained realistic HMS, target and field geometries. By running the MC with reference points of 50% and 60% packing fractions, simulated yields provided the necessary two points on our line. The HMS experimental yield from a target sample is then used to interpolated the sample's packing fraction. Figure 19 shows the calculated packing fractions for all SANE target material samples.

### 6.2.3. Dilution Factor

The dilution factor f is a kinematics dependent correction to the measured asymmetries to account for contributions of unpolarized nucleons in the target. Essentially a ratio of the crosssections of the polarized protons to the nucleons of all other materials in the target cell, the dilution factor was calculated for each experimental run as

$$f(W, Q^2) = \frac{N_1 \sigma_1}{N_1 \sigma_1 + N_{14} \sigma_{14} + \Sigma N_A \sigma_A}$$
(10)

for number densities  $N_A$  of each nuclear species present in the target of atomic mass number A, and radiated, polarized crosssections  $\sigma_A(W, Q^2)$  [35]. This factor covers not only the protons (1) and nitrogen (14) in the ammonia sample, but must also include other materials such as helium (4) and aluminum (27). Substituting numeric values for this specific target, the dilution factor is expressed in terms of these cross sections and the packing fraction  $p_f$  as

$$f = \left(1 + \frac{\sigma_{14}}{3\sigma_1} + 0.710 \left[\frac{4}{3p_f} - 1\right] \frac{\sigma_4}{3\sigma_1} + \frac{0.022}{p_f} \frac{\sigma_{27}}{3\sigma_1}\right)^{-1}.$$
 (11)

Cross sections for each species needed for equation 11 were calculated from empirical fits to structure functions and form factors, and included all radiative corrections used later in the analysis. The dilution factor for a typical run is shown in Figure 20 in x bins.



Figure 20: The dilution factor calculated for run 72925 as a function of x, showing the increasing contribution from the elastic tails at lower energies (i.e. lower x). Each color represents a different  $Q^2$  bin.

### 6.2.4. Target Radiation Thicknesses

The thickness of each radiator in the scattering chamber was required for the calculation of external radiative corrections. Table 2 shows the radiation thickness for all materials traversed by the beam passing through the target, for a nominal packing fraction of 0.6, as well as the percentage of radiation length  $\chi_0$ .

Component	Material	Thickness (mg/cm <sup>2</sup> )	$\chi_0$ (%)
Target Material	<sup>14</sup> NH <sub>3</sub>	1561	3.82
Target Cryogen	LHe	174	0.18
Target Coil	Cu	13	0.10
Cell Lid	Al	10	0.04
Tail Window	Al	27	0.12
Rad Shield	Al	7	0.03
N Shield	Al	10	0.04
Beam Exit	Be	24	0.04
Vanue Windowa	Be	94	0.14
vacuum windows	Al	139	0.58
	80° Total, Before Center		2.98
	80° Total, After Center		2.36
	180° Total, Before Center		2.54
	180° Total, After Center		2.36

Table 2: Table of component thicknesses for radiative corrections. Total thicknesses before and after the center of the target are given for each magnet orientation configuration.

### 6.2.5. Polarized Nitrogen Correction

While the dilution factor correction accounts for scattering from material other than protons, it does not take into account the effect of any polarization of such material in the asymmetry. Nitrogen, in particular, provides a third of the polarizable nucleons in ammonia. During usual DNP conditions, the polarization of the spin-1/2 protons  $P_p$  and spin-1 nitrogen  $P_N$  in <sup>14</sup>NH<sub>3</sub> are related as

$$P_N = \frac{4 \tanh((\omega_N/\omega_p) \operatorname{arctanh}(P_p))}{3 + \tanh^2((\omega_N/\omega_p) \operatorname{arctanh}(P_p))},$$
(12)

where  $\omega_N$  and  $\omega_p$  are the <sup>14</sup>N and proton Larmor frequencies [36]. At maximum proton polarizations of 95%, the nitrogen polarization will be only 17%. In addition, in nitrogen a nucleon's spin is aligned anti-parallel to the spin of the nucleus one third of the time [37]. These effects together result in a maximum polarization of anti-parallel nitrogen nucleons of roughly 2%, which results in an added systematic error to the asymmetries of less than half a percent.

#### 6.2.6. Pair-symmetric background subtraction

At some kinematics, significant background contributions arose from electrons and positrons mistaken for DIS electrons after being produced in pairs from  $\pi^0$  events. Single electrons or positrons produced from conversions of  $\pi^0$  decay  $\gamma$ 's in material between the target and BigCal, or from Dalitz decays of  $\pi^0$ 's in the target, could arrive in BETA with the other of the pair deflected away by the target's strong magnetic field. The dilution  $f_{BG}$  and contamination  $C_{BG}$  of the measured asymmetries  $A_m$ by the pair-symmetric background enter as linear corrections

$$A_b = A_m / f_{\rm BG} - C_{\rm BG}.$$
 (13)

Simulations of the background were employed to determine the size of the contribution as compared to fits of existing data to inclusive charged pion asymmetries [38]. A FORTRAN routine to model inclusive pion production by J. O'Connell [39] was updated using cross section data from the Yerevan Physics Institute [40] to improve the cross section reproduction to better than 15% in the kinematics of interest.

The correction for an experiment using a magnetic spectrometer is

$$C_{\rm BG} = \frac{1 - RA_{\rm pair}/A_{\rm raw}}{1 - R} \,, \tag{14}$$

where  $R = n_{\text{pair}}^{e+}/n_{\text{dis}}^{e-}$  and  $A_{\text{pair}}$  is the positron asymmetry. However BETA simultaneously detected both positrons  $(n_{\text{pair}}^{e+})$  and electrons  $(n_{\text{pair}}^{e-})$ , so the ratio needed is  $R_{\text{BETA}} = 2R = 2n_{\text{pair}}^{e+}/n_{\text{dis}}^{e-}$ . The pair symmetric background ratio shown in Figure 21 is defined as

$$r = \frac{n_{\text{pair}}^{e^+}}{n_{\text{total}}^{e^-}} = \frac{R}{1+R} \,. \tag{15}$$

#### 6.3. Beam and target systematic errors

Table 3 shows an overview of SANE systematic error contributions from the beam and target systems, which enter equation



Figure 21: Simulations results for the pair symmetric background ratio defined in (15) as a function of the scattered electron energy. The lower curve is the ratio with the Cherenkov ADC window which removes the background contributions from pairs converted in material outside of the target cell.

4 as kinematics independent normalizations, and the kinematics dependent dilution factor. The error in the target polarization is the single largest contribution, and stems from the NMR polarization measurements. The NMR can be affected by minute shifts in the material beads over time and topological differences in dose accumulation around the coils embedded in the material. The thermal equilibrium measurements on which the enhanced NMR signals are calibrated also add error, with the temperature measurement of the material contributing significantly. Looking at the differences in the TE measurements over the experimental life of any given material gives an indication of the error. For example, material four's 3 TE measurements had a standard deviation of 8% around their mean, while material five had the same number of TE's with a 2% standard deviation. A detailed discussion of error in DNP targets from the SMC collaboration can be found in reference [41].

Global error in the beam polarization measurements contributes 1%, while the fit used to apply the measurements at varied beam energies will add another half percent. The dilution factor's uncertainty is based on statistical error in the measurement of the packing fraction and from the simulation.

Source	Error on Asymmetry
Beam polarization	1.5%
Target polarization	5.0%
Nitrogen correction	0.4%
Dilution factor	2.0%
Combined	5.6%

Table 3: Table showing systematic errors from the polarized beam and target.

### 7. Conclusion

Through a combination of a novel, wide-acceptance electron arm, and a rotatable, solid polarized proton target, the Spin Asymmetries on the Nucleon Experiment has significantly expanded the world's inclusive spin structure data for the proton. By taking spin asymmetry measurements with the target oriented at parallel and near perpendicular, model-independent access to virtual Compton asymmetries  $A_1^p$  and  $A_2^p$  on the proton was possible with the only input being the well measured ratio of longitudinal to transverse unpolarized cross sections  $R_p$ . The only other sources of model independent proton  $A_1$  measured in the same experiment are SLAC's E143 at 29 GeV [42] and E155 at 48 GeV [7], and the JLab's RSS [10]. SANE's kinematic coverage (shown in Figure 22) represents a crucial improvement to the world's data of inclusive proton scattering, particularly with a perpendicular target, filling in gaps in x coverage to allow integration for moments of structure functions, such as  $d_2$ . Forthcoming letters will present the physics results of these efforts.



Figure 22: The kinematic coverage of SANE events, before cuts, with target oriented parallel (top) and at  $80^{\circ}$  to the beam (bottom). Red points represent 5.9 GeV beam energy coverage, while blue points show 4.8 GeV.

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