Measuring the electric form factor of the neutron with recoil polarimetry (GEn-RP)

22nd STFC Nuclear Physics Summer School 2024

Andrew Cheyne
(a.cheyne.1@research.gla.ac.uk)
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Presentation Overview

- Introduction
- The GEn-RP Experiment
- Analysis
- Future Work

Introduction

An anomalous moment

The nuclear magneton is the spin magnetic moment of a Dirac particle.

$$\mu_N = \frac{e\hbar}{2m_p}$$

DISCUSSION

The now rather accurately known values

$$\mu_p = 2.78_5 \pm 0.02 \quad \mu_n = -1.93_5 \pm 0.02$$
$$\mu_d = 0.855 \pm 0.006$$

of the magnetic moments of proton, neutron and deuteron are of considerable interest for nuclear theory. The fact alone that μ_p differs from unity and μ_n differs from zero indicates that, unlike the electron, these particles are not sufficiently described by the relativistic wave equation of *Dirac* and that other causes underly their magnetic properties.

Figure 1: Alvarez and Bloch's measurement of the neutron. Stern's Proton

What is a Form Factor

Form factor is...

a scaling term that describes the deviation from point-like.

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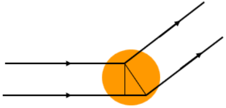
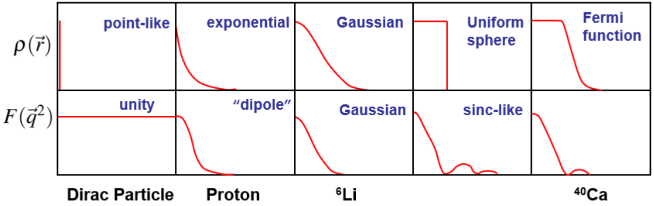


For example:



Method 1: Elastic Scattering Cross-section

Scattering cross section from a point-like proton

$$\frac{d\sigma}{d\Omega} = \underbrace{\frac{\alpha^2}{4E_1^2 \sin^4(\theta/2)}}_{\text{Rutherford}} \underbrace{\frac{E_3}{E_1}}_{\text{Proton recoil}} \left(\underbrace{\cos^2(\frac{\theta}{2})}_{\text{Electric/ charge scattering}} + \underbrace{\frac{q^2}{2M^2} \sin^2(\frac{\theta}{2})}_{\text{Magnetic term due to spin}} \right)$$

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$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E_1^2 \sin^4(\theta/2)} \frac{E_3}{E_1} \left(\frac{G_E^2 + \tau G_M^2}{(1+\tau)} \cos^2(\frac{\theta}{2}) + 2\tau G_M^2 \sin^2(\frac{\theta}{2}) \right)$$

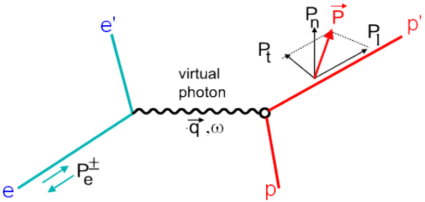
$$\text{where, } \tau \equiv \frac{Q^2}{4M^2} = -\frac{q^2}{4M^2}$$

How do they relate to the proton and neutron measurements?

The Sachs electric and magnetic form factors, G_E and G_M, describe electric and magnetic distribution.

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left[G_E^2 + \frac{\tau}{\epsilon} G_M^2\right] \frac{1}{(1+\tau)}$$

Method 2: Polarisation transfer



- P_l is mostly kinematic factors
- P_t is a combination of kinematic and electric *(think GEn)*

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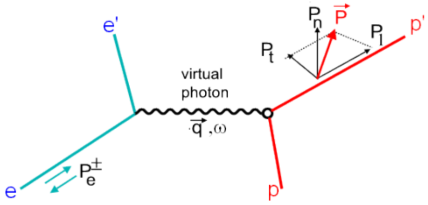


- P_l is mostly kinematic factors
- P_t is a combination of kinematic and electric *(think GEn)*

Polarisation transfer from incident photon to a neutron ($\vec{e}N \to e\vec{N}$)

$$\frac{P_t}{P_l} = \frac{1}{\sqrt{\tau + \tau(1+\tau)\tan^2(\frac{\theta_e}{2})}} \cdot \frac{G_E}{G_M}$$

But... P_l, cannot be measured easily.

Two questions of interest

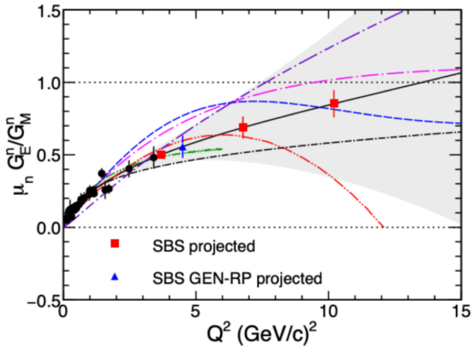


Figure 2: GEn world data

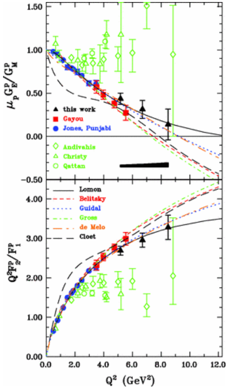
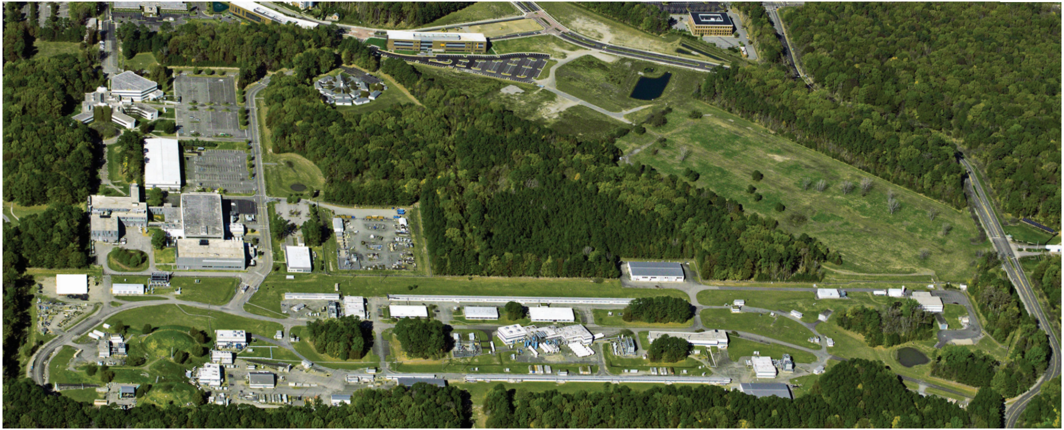


Figure 3: Cross section vs polarimetry methods

The GEn-RP Experiment

Jefferson Lab - One of the world's most powerful telescopes

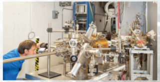


CEBAF AT JEFFERSON LAB

Jefferson Lab's Continuous Electron Beam Accelerator Facility (CEBAF) enables world-class fundamental research of the atom's nucleus. Like a giant microscope, it allows scientists to "see" things a million times smaller than an atom.

AT JEFFERSON LAB, NUCLEAR PHYSICISTS STUDY FOUR FUNDAMENTAL AREAS:

- Quark Confinement – Addressing one of the great mysteries of modern physics – why quarks exist only together and never alone.
- The Physics of Nuclei – Illuminating the role of quarks in the structure and properties of atomic nuclei, and how these quarks interact with a dense nuclear medium.
- Tests of the Standard Model – Studying the limits of the theory that describes fundamental subatomic particles and their interactions.
- The Fundamental Structures of Protons and Neutrons – Mapping in detail the distributions of quarks in space and momentum, culminating in a picture of the internal structures of protons and neutrons.

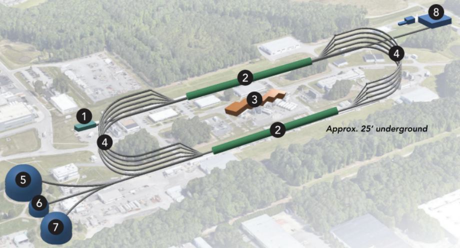


1 INJECTOR

The injector produces electron beams for experiments.

2 LINEAR ACCELERATOR

The straight portions of CEBAF, the linacs, each have 25 sections of accelerator called cryomodules. Electrons travel up to 5.5 passes through the linacs to reach 12 GeV.



8 EXPERIMENTAL HALL D

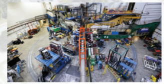
Hall D is configured with a superconducting solenoid magnet and associated detector systems that are used to study the strong force that binds quarks together.

3 CENTRAL HELIUM LIQUEFIER

The Central Helium Liquefier keeps the accelerator cavities at -456 degrees Fahrenheit.

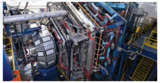
4 RECIRCULATION MAGNETS

Quadrupole and dipole magnets in the tunnel focus and steer the beam as it passes through each arc.



5 EXPERIMENTAL HALL A

The BigBite and Super BigBite spectrometers precisely measure the inner structure of nucleons. Hall A will also be used for the Measurement of a Lepton-Lepton Electroweak Reaction (MOLLER) experiment and a group of experiments using the



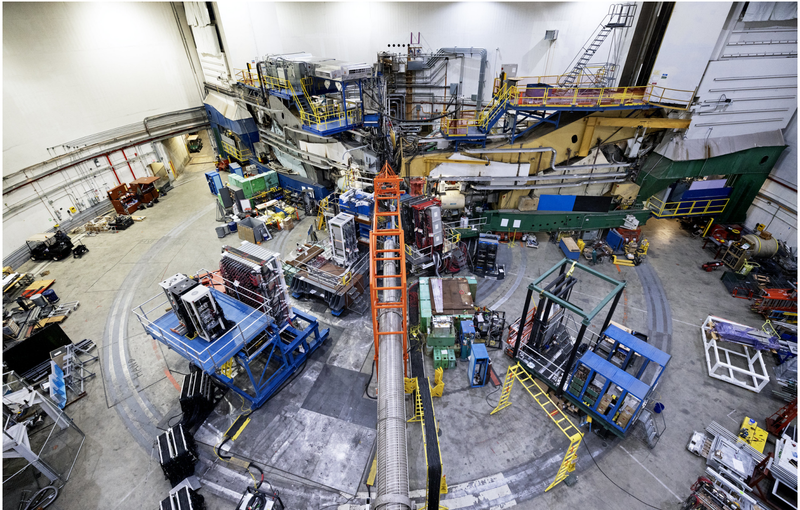
6 EXPERIMENTAL HALL B

The CEBAF Large Acceptance Spectrometer surrounds the target, permitting researchers to simultaneously measure many reactions over a broad range of angles.

7 EXPERIMENTAL HALL C

The Super High Momentum Spectrometer and High Momentum Spectrometer precisely measure the inner structure of protons and nuclei. Hall C is also used for experiments with the Neutral Particle Spectrometer and other unique, large-installation experiments.

Hall A



Experiment setup

- 15cm LD2 target (mostly)
- Polarised Electron Beam
- Electron Arm
- Hadron Arm

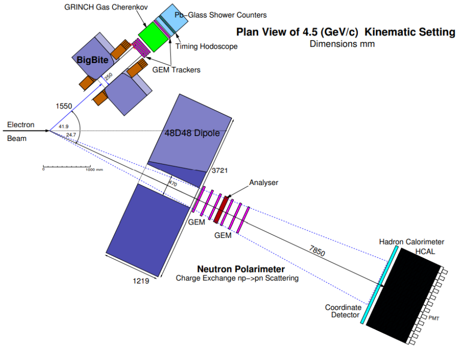
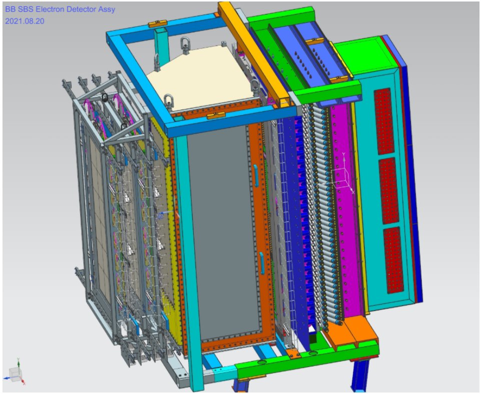


Figure 5: Experimental setup for GEn-RP.

Electron Arm

The electron arm is used for:

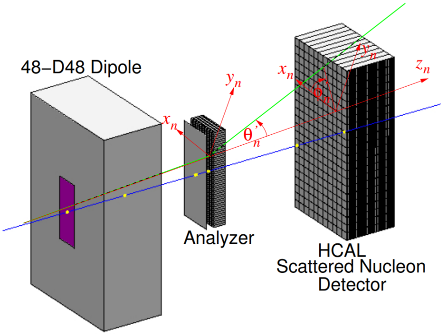
- Coincidence timing
- Momentum reconstructions
- Target vertex reconstruction
- Pion rejection

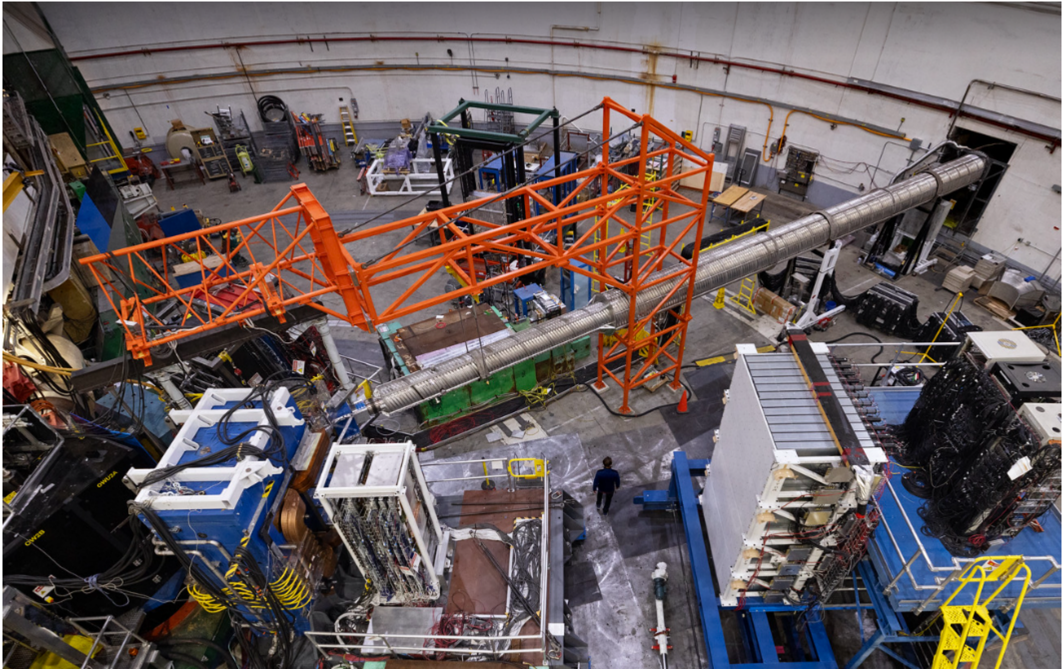


Super Bigbite Spectrometer (SBS) Hadron arm

The hadron arm has:

- The Dipole magnet for:
  - separation protons and neutrons
  - low momentum charged particles rejection
  - spin-precession
- Hadron Calorimeter (HCal) and Cordinate detector
- More GEMs for tracking
- The steel polarisation analyser...





How can we measure the polarisation of the neutron?

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- N-N scattering depends on the spin-orbit interaction and producing an azimuthal modulation of the scattering cross section.

$$\sigma(\theta'_n, \phi'_n) = \sigma(\theta'_n)\left[1 + A_y(\theta'_n)\left\{P^n_x \sin\phi'_n + P^n_y \cos\phi'_n\right\}\right]$$

- $\sigma(\theta'_n)$ is the unpolarised differential cross section
- $A_y(\theta'_n)$ is the analysing power of the scattering process
- P^n_x and P^n_y are the incident nucleon polarisations

Asymmetry

If we...

- keep the electron and nucleon detection angles constant
- flip the beam helicity and dipole polarity
- Count

we can make linear combinations of these...

$$F(\phi'_n) = C\{1 \pm |P^*_x| \sin\phi'_n \pm |P^*_y| \cos\phi'_n\}.$$

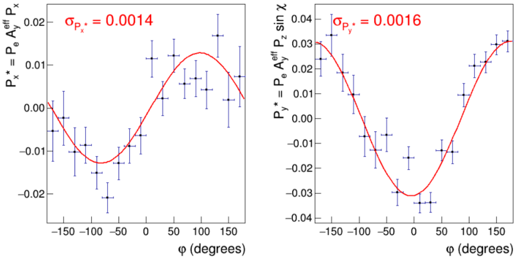

Figure 6: Simulations of the scattering asymmetry

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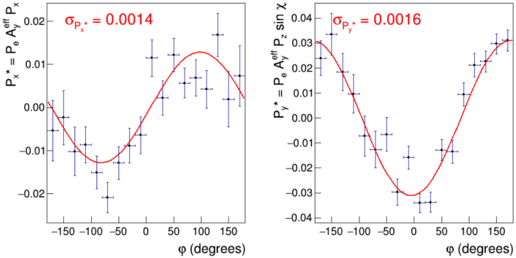


Figure 6: Simulations of the scattering asymmetry

$$\frac{P_t}{P_l} = \frac{1}{\sqrt{\tau + \tau(1+\tau)\tan^2(\frac{\theta_e}{2})}} \cdot \frac{G_E}{G_M}$$

Data Taking summary

University of Glasgow

Run summary

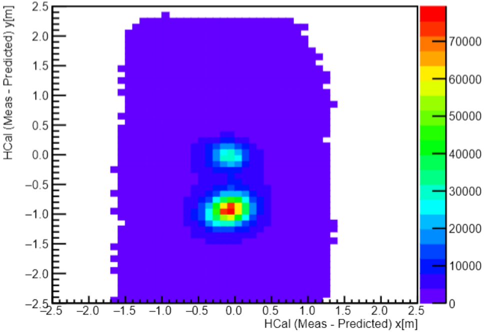
- 16th of April and 14th of May 2024.
- Beam current 10-12 μA on LD2
- 3 hours per day on LH2
- Data acquisition rate 3-4KHz
- Data rate 1-1.2 GB/s
- 12C of charge.

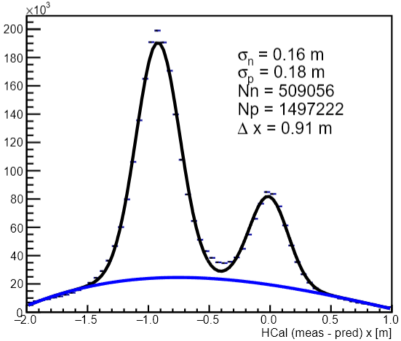
Problems

- Rates too high on forward GEMs, limited to 12μA.
- Some initial data-acquisition problems (1.3 GB per second).

Analysis

Reconstruction of quasi-elastic scattering



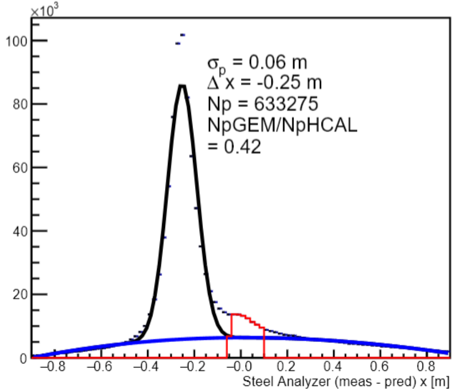


Charge exchange event selection

If we require:

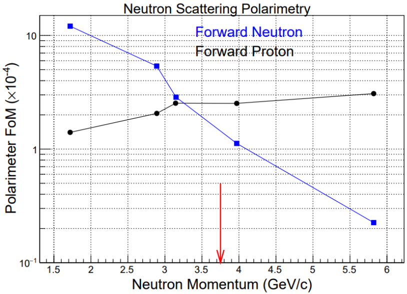
- Quasi-elastic scattering
- No track entering the anlyser
- A track leaving the analyser

We can isolate charge-exchange events.



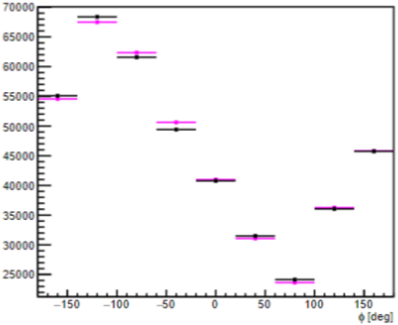
Why Charge-Exchange?

Neutron polarimeter figure of merit as a function of incident neutron momentum for two styles of polarimeter within the SBS apparatus using preliminary data from the recent Dubna measurement



A very bad example of asymmetry

Event without GEM tracking, calibrations, proper cut implementation and timing corrections we can still see some asymmetry peeking through.



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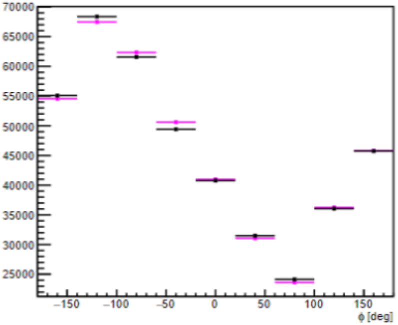


Time to do some calibrations for the next few months (year).

Bigbite pion rejection

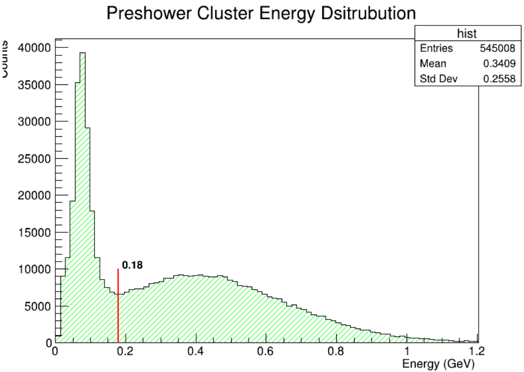


Figure 7: Locating the pion peak to be removed

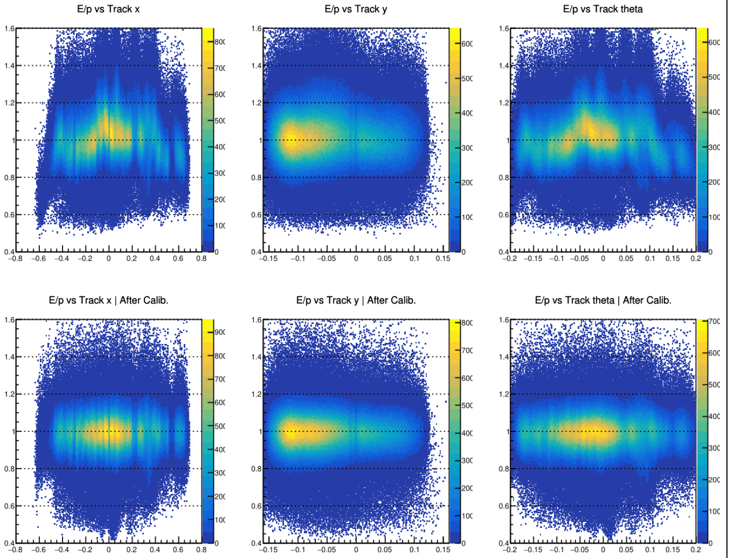


Figure 8: Energy resolution alignment.

Future Work

Future work

- Calibate the remaining detectors (Timing hodoscope, Hadron Calorimeter) and rerun the data processing with new calibrations.
- Resolve some timing issues with hadron calorimeter.
- Tune event selection to isolate charge-exchange events.
- Get an asymmetry..?

Thanks for listening

A very special thank you to:

- My supervisors, Rachel Montgomery & David Hamilton.
- The Hall A SBS group
- The GEn-RP analysis team (Andrew Puckett, Jiwan Poudel, Bogdan Wojtsekhowski, Michael Kohl, Will Tireman, and Saru Dhital).
- Kate Evans, Bhasitha Dharmasena, and Gerry Penman for always being willing to help.
- Everyone who took shifts during the run.
- The Glasgow Nuclear and Hadron group.

Polarimetry

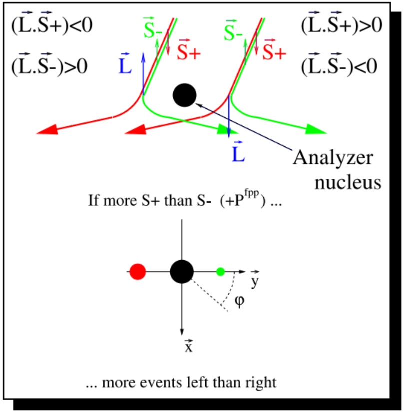
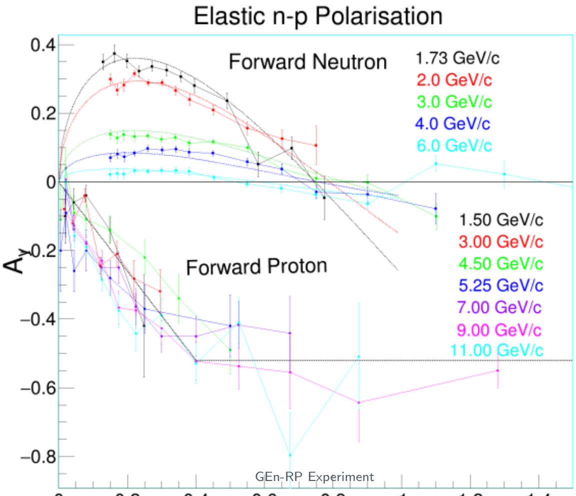


Figure 9: Enter Caption

Figure of Merit Study



RF cavity

Figure 10: RF accelerator cavity

Frame Title

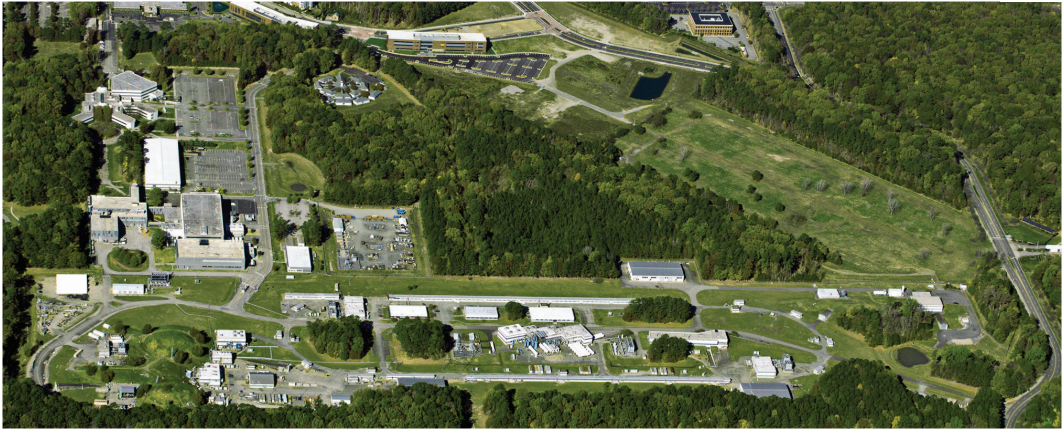


Figure 11: Enter Caption

More asymmetry stuff

University of Glasgow

The unpolarised distribution C (background), and the separated x and y polarised distributions can be obtained as the following linear combinations of these flipped beam helicty and dipole polarity distributions.
The polarimeters measure the full azimuthal distribution plots of the different counts in F_x and F_y are then fitted with sine and cosine functions, allowing the extraction of $P^*_{x,y}$ from equation **??**. These effective polarisations measured by the polarimeter, $P^*_{x,y}$, are then projected back to the target as,

$$P^*_x = A^{eff}_y P_e P_x$$
$$P^*_y = A^{eff}_y P_e P_z \sin\chi.$$

where A^{eff}_y is the analysing power χ is the precession angle.

Magnetic Field study

One complication is that the precession angle, χ, depends on the path the nucleon took through the magnetic field since,

$$\chi = \frac{2\mu_n}{\hbar c \beta_N} \int_L B.dl$$

where β_N is the neutron velocity and B is the magnetic field through which it being precessed. Thus the ratio,

$$\frac{P_x}{P_y} = \frac{P_x^*}{P_y^*} \cdot \sin\chi,$$

allowing the extraction of $\frac{G_E^n}{G_M^n}$ from equation 19. One of the advantages of using this ratio method is that the resulting ratio is independent of Analysing power.

Magnetic field analysis

- Simulation analysis at 100% SBS coil current of 2100A which gives:
- a $\int B\Delta l$ of 1.47 Tm and for a neutron momentum of $3.2GeV/c$ $(Q^2 = 4.4(GeV/c)^2)$ gives
- $\sin\chi = 0.81$.

The Big Bite Calorimeter

- BigBite calorimeter is made of two parts, Shower (SH) and PreShower (PS).
- SH detector is composed of 189 modules, each composed of a 8.5x8.5x37cm lead-glass blocks readout by a PMT. The 189 modules are laid out in 27 rows of 7 blocks all facing the spectrometer z-axis.
- Similarly, PS detector is composed of 52 modules laid out in 26 rows of 2 blocks all facing the spectrometer z-axis. Each PS module is made of 9x9x37cm lead-glass block readout by a PMT.

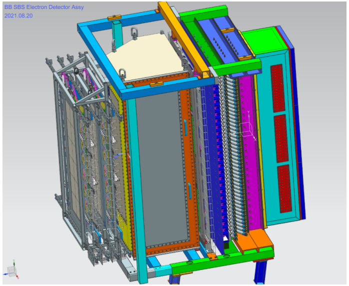


Figure 12: CAD drawings from Chris Soova dated Aug 20, 2021

Coordinate systems

Hall

- +z is down the beam axis
- +y is up (away from gravity)
- +x makes RH coodinate system (so L looking down beamline)

Detector

- +z is down particle central axis in particle direction
- +x is down to the floor
- +y makes RH coordinate system.