Neutron detection with the Neutral Current Detectors

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PHYS 052

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Dear Dr. Berg,

Please find attached my work term report titled *"Neutron detection with the Neutral Current Detectors"*. This report is submitted as part of my Physics Co-operative Education Program and covers my PHYS-052 summer term at SNOLAB, an underground laboratory for rare-event physics experiments in Lively, Ontario. The report summarizes my contributions to developing neutron spectrometry techniques using helium-3 proportional counters repurposed from the Sudbury Neutrino Observatory.

The work focused on three main areas. First, I studied the associated electronics and background characteristics of the counters, identifying limitations from gamma sensitivity Second, I made a GEANT4 simulation to calculate the correction factors due to efficiency and energy cuts. Finally, I implemented and tested spectral unfolding algorithms (including Gravel and maximum entropy methods) to extend the counters' sensitivity from purely thermal neutrons to energies up to $\sim$11 MeV. To do so the response was calculated using GEANT4 simulations for each moderation case.

These methods provide a pathway to monitor underground neutron fluxes with improved accuracy, which is crucial for rare-event searches sensitive to neutron-induced backgrounds. The report presents the simulation framework, unfolding methodology, and experimental validations.

I thank my supervisors and colleagues at SNOLAB for their guidance and support throughout this term.

Sincerely,

Kishan

Kishan

Neutron detection with the Neutral Current Detectors

SNOLAB

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Abstract

This report summarizes my contributions during the Summer 2025 work term to the Neutral Current Detectors (NCD) project at SNOLAB, focusing on methods to detect thermal neutrons and fast neutrons in range 10^{-10} to 11 MeV by utilizing polyethylene moderation and unfolding algorithms. The goal was to prepare the method and analysis using GEANT4, to enable the conventional Helium-3 counters to detect high-energy neutrons. I studied the detection of thermal neutrons with NCDs, analyzed the associated electronics and background sources, and applied an unfolding method combined with GEANT4 simulations to extract the high-energy neutron flux. This work provides potential methods for monitoring neutron backgrounds for the low-background physics experiments at SNOLAB.

1 Introduction

SNOLAB is a world-class physics research center in Lively, Ontario, with facilities on the surface and 2 km underground. The underground facility offers a unique low-background environment, ideal for conducting highly sensitive neutrino and dark matter physics experiments.[1]

SNOLAB's underground Low Background Counting Facility provides services such as gamma counting using ultra-low background high-purity germanium detectors, passive radon emanation measurement, and X-ray fluorescence (XRF) spectrometry.(1) The facility provides background measurements from various samples (e.g., detector components) and develops strategies for reducing unwanted background radiation in sensitive experiments. This summer 2025 work term report includes my contribution to the Neutral Current Detectors Project. Henceforth, the Neutral Current Detectors will be referred to as NCDs for convenience.

1.0.1 Helium-3 counter and NCDs Introduction:

Helium-3(^3He) is a rare non-radioactive isotope, and among its many special properties, the neutron capture cross section makes it an excellent choice for detecting thermal neutrons. In a neutron capture event(see figure 1), a slow or thermal neutron interacts with the Helium-3 atoms, undergoes a nuclear transition(unstable Helium-4 state), then disintegrates into a proton and a triton. In this interaction, due to the negligible kinetic energy of the neutron, the reaction can be approximated as taking place at rest, and the Q value of 764 keV is distributed among triton and proton according to their mass; therefore, triton is released with 191 keV and proton with 573 keV, as shown in Figure 1.

Due to this property, Helium-3 gas detectors are conventionally used to count thermal neutrons. Technically, the cross section for neutron capture is higher for slower neutrons, but the thermal neutrons dominate the cold neutrons in typical environments with room temperature, hence the Helium-3 detectors practically

[1] https://www.snolab.ca/about/about-snolab/

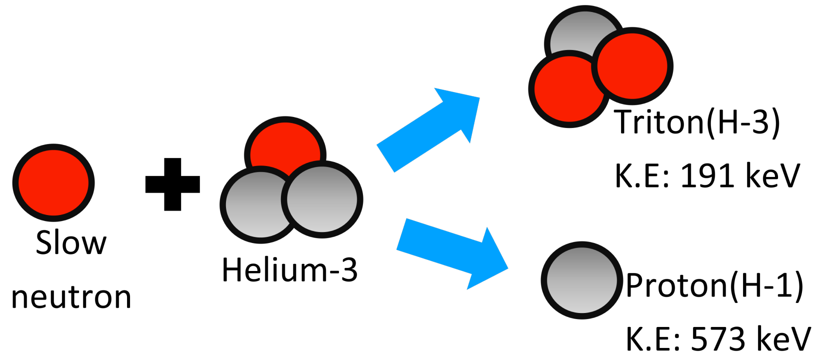


Figure 1: Neutron Capture event: A Thermal neutron interacts with a Helium-3 nucleus, resulting in a nuclear interaction with Q value of 764 keV

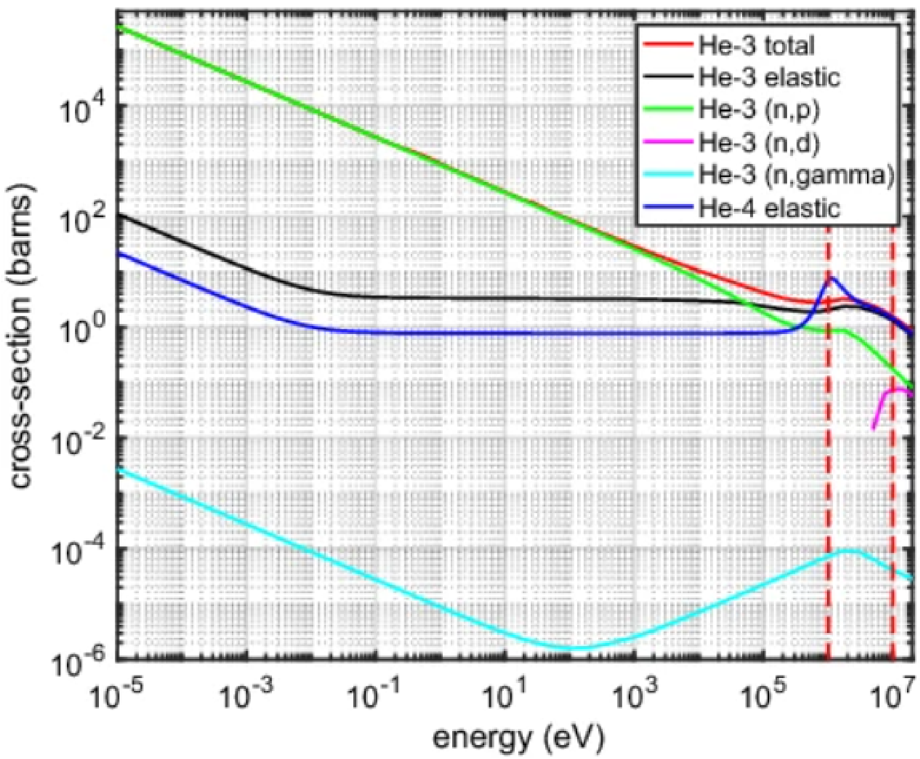


Figure 2: One study compared the fast neutron sensitivity in Helium-3 and Helium-4 gas. The He-3 (n,p) in green trail shows decreasing cross section for increasing neutron energies.(2)

end up detecting thermal neutrons. However, Helium-3 counters are unable to detect the fast neutron because of the dropping cross section of neutron capture and increasing Helium-3 recoil cross section with faster neutrons(see figure 2).

NCDs were custom-made cylindrical Helium-3 counters that were optimized for the SNO experiment(3). The physical parameters for the NCDs are in Figure 3.

After the SNO experiments, these counters were removed and moved to the HALO experiment, which utilizes the neutron capture events to detect charged current and neutral current interactions of supernova neutrinos with lead(Pb). Later, the low background facility took four NCDs from HALO to detect thermal neutrons in various underground locations at SNOLAB.

The Neutral Current Detectors project at Low Background Lab aims at measuring the thermal(low-energy neutrons:0.025 eV) and high-energy neutrons(up to 11 MeV) separately. The work term report's method is split into two parts to express sufficient information to the reader about the methods used. Moreover, the second part builds on the first part and involves the novel method of using moderators and unfolding methods together to find high-energy neutron counts for a neutron source.

In the first method section, the approach is to describe the detector physics of NCDs and the electronics, and lastly, it finishes with a practical use of GEANT4 simulation to introduce a correction factor.

In the second method section, the report begins by introducing a method to detect the fast neutrons by solving a linear algebra problem using the response of the detector setups. Then the GEANT4 simulation toolkit is utilized to make six simulations which can calculate the response for moderation cases. Then, the unfolding algorithm GRAVEL is introduced for solving the convolution matrix equation for the unknown source spectrum.

Then, in the analysis and results section, the two methods in the methods section are tested separately and compared to the reference expected values.

The discussion section includes some suggestions to improve the accuracy of the methods used and their potential.

Physical parameters of the NCDs

Outer diameter	5.08 cm
Wall thickness (nominal)	370 μm
Wall thickness (measured)	305 − 533 μm
Lengths	200, 227, 250, 272, 300 cm
Anode wire diameter	50 μm
Gas pressure	2.5×10^5 Pa (2.50 ± 0.01 atm)
Gas mix (by pressure)	85%:15% ^{3}He:CF_4 or ^{4}He:CF_4
Weight	525 g/m

Figure 3: The physical parameters for the four NCDs. The 200 cm (length) NCDs were used.

NCD id	Preamplifier id	Amplifier id	Gain	Shaping time(μ seconds)	Output
J1(Input 1)	q3xx	ORTEC 572	60	6	Universal
J8 (Input 2)	q300	CANBERRA Amplifier 2022	36	4	Bipolar
S5 (Input 3)	q206	ORTEC 572	60	3	Universal

Table 1: Updated NCD electronics

2 Methods

2.1 Part 1: Thermal neutron detection

2.1.1 Experimental setup

Originally, the experimental setup comprised two NCDs, each paired with a Pre-Amplifier and ORTEC Amplifier, allowing for the separate processing of signals. The initial calibration was conducted with the central wire in each NCD operating at 1900 volts, which generated an inverse radius electric field.

As the project progressed, a third NCD was incorporated into the setup, increasing the total number of NCDs to three. Following this addition, a thorough assessment of available amplifiers was conducted to calibrate the pulse height distribution of the newly integrated NCD.

The two existing NCDs were equipped with ORTEC 572 Amplifiers, and given the identical characteristics of the NCDs, the only variable that could influence calibration processes was the pre-amplifiers. Despite an extensive search, a third ORTEC 572 Amplifier could not be sourced to facilitate uniform calibration among all three NCDs. Fortunately, Ian Lawson provided a CANBERRA 2022 Amplifier, which shares similar internal resistance, gain setting options, and pulse timing characteristics with the ORTEC amplifiers. This substitution was deemed suitable for maintaining calibration accuracy.

Then, a new setup was made for which all the NCD's preamplifier, amplifier and settings were changed. The new settings are shown in table 1.

The setup was still calibrated at 1900 V, but the neutron capture's 764 keV peaks were calibrated to align with 764 ADC channel using MAESTRO software in a computer that was dedicated to NCD measurements.

The detection principle of each NCDs is as follows(see figure 4):

1. Thermal neutrons are captured by Helium-3 nuclei based on their cross section.
2. This reaction produces a triton and a proton, which ionize the Helium-3 gas.
3. Ionized charges drift toward the central wire under a 1900 V field, multiplying near the wire due to the strong electric field.
4. The charges are converted to an electrical signal by a pre-amplifier.

5. The signal is then amplified and shaped into pulses.

6. The NCD computer analyzes the pulse shape and applies energy cuts to count neutrons.

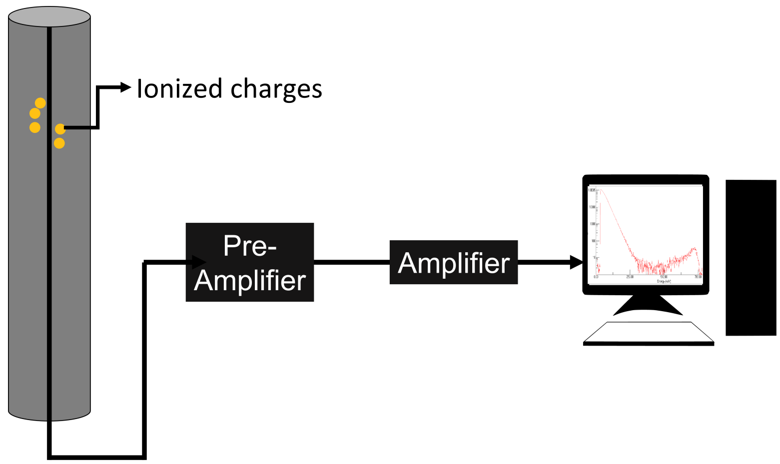


Figure 4: Simplified slow neutron detection principle for NCD using standard electronics.

2.1.2 Energy Cuts:

The NCDs were designed for neutron detection in SNO's low background environment with a limited ambient gamma background. However, when using them for ambient neutron measurements, the background interferes with the neutron capture energy depositions. For example, a moderated AmBe source measurements using the J8 NCD is shown in figure 5.

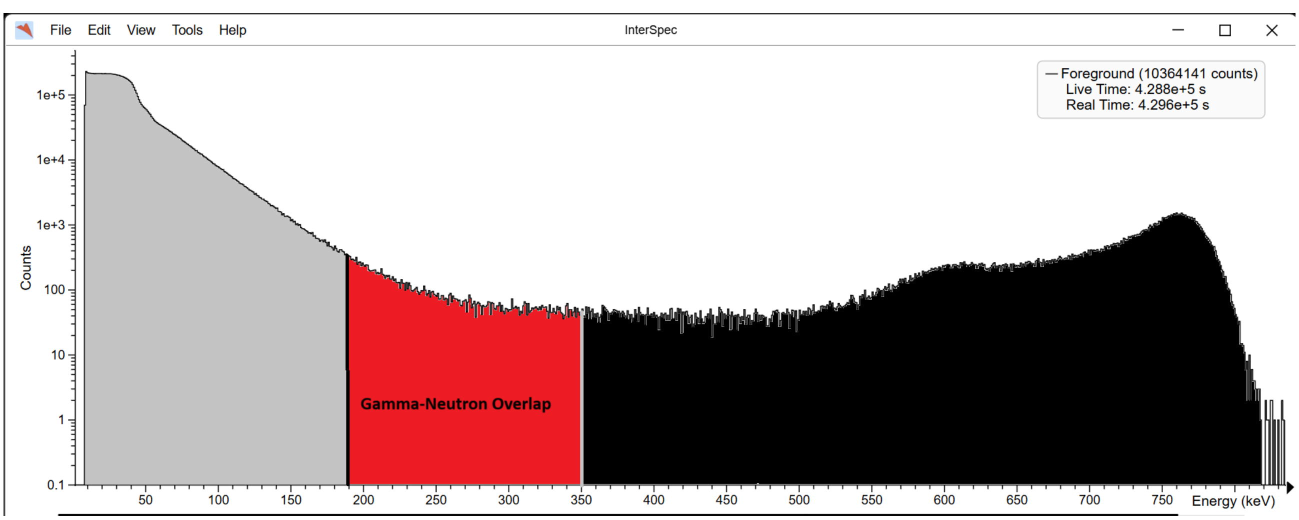


Figure 5: Updated electronics: Experimental ambient neutron measurements in the Low Background Facility using J8 NCD. The region of interest for neutron capture covers 180 to 800 keV. However, the Gamma background from the lab interferes with the 180 to 350 keV region of interest.

Pulse data analysis suggests that the 180 to 800 keV data are ideally the neutron capture ionization events. However, the gamma backgrounds interfere with the neutron capture pulse data in the 180-350 keV region.

There were some choices to deal with the gamma-neutron interference/overlap, for example:

- Consider making a lower energy cut of 350 keV instead of 180 keV and losing some efficiency.
- Use the 180 to 800 keV, but do background measurements with shielding to stop all neutrons, find the gamma counts per second in the 180 to 350 keV, and subtract the gamma counts from the ambient experimental data run for some time t.
- Plotting the rise time vs energy of proportional counter events, it's possible to separate the gamma-induced events from the neutron events.

All choices are viable, but for saving time, the first choice, to use 350 to 800 keV, was used. Also, using lead(Pb) castle appears as a sound idea to remove gamma backgrounds; however, it affects the ambient neutron counts.

2.1.3 GEANT4 simulation

Despite a high neutron capture cross-section for thermal neutrons, the intrinsic detector efficiency still needs to be determined for calculating the thermal neutron flux through the NCDs.

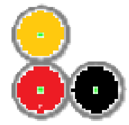
Experimentally calculating neutron detection efficiency using neutron beams and collimators is expensive; therefore, a GEANT4 simulation was used. This enables calculating correction factors, which can be applied to the experimental data to improve accuracy; moreover, it would also take into account the neutron cuts resulting from the 350 keV lower energy cut in the previous section.

Previously, Student Cody had attempted to make a GEANT4 simulation for 2 NCDs; however, the material composition and event tracking lacked robustness. Instead of updating Cody's simulation, a new GEANT4 simulation was created, which utilized the physics list from my previous work term's (Summer 2024) neutron attenuation simulation.

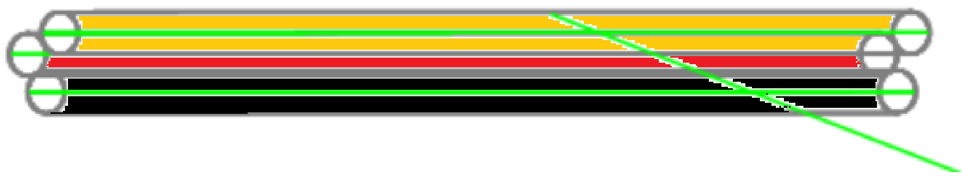
The previous term's simulation included the following physics list:

HadronElasticPhysicsHP, G4HadronPhysicsQGSP BIC HP, G4IonPhysicsXS, G4StoppingPhysics, ElectromagneticPhysics, GammaNuclearPhysicsLEND(LEND GND1.3 ENDF.BVII.1), G4DecayPhysics, and G4RadioactiveDecayPhysics.

These physics list enables high precision neutron transport for 0-20 MeV neutrons, the elastic scattering, ionization, decay physics and complementary gamma physics libraries, which were more than enough for the NCD interactions.



(a) Three NCDs front view geometry: The yellow, red and black are NCDs



(b) Three NCDs isometric view geometry

Figure 6: GEANT4 NCD geometry

A brief summary of the simulation components:

1. Detector Construction: To save time, Cody's geometry files were edited and used as the geometry for the new simulation. The geometry was changed as follows: updated to three 200 cm length NCDs(see figure 6), updated Helium-3 gas composition and added a simplified cuboid room geometry.

2. Gun particle: The General Particle Source(GPS) was utilized to use a point radioactive source. The location of the source was the same as the AmBe source location for experimental measurements.

3. Tracking and Analysis: Instead of allocating a sensitive detector to each NCD, the NCDs were made with the same physical volume, and this physical volume was used as a sensitive detector. The experimental measurements analyzed electronics separately, the neutron counts were summed, then the flux was calculated using the time period and surface area of the three NCDs. The simulation's sensitive detector included the interactions in all three NCDs for every event, and then the triton particle was counted for every event. Since one neutron capture event results in one triton and a proton, the number of tritons produced corresponds to the neutron captures in the NCDs. The fStopAndKill command was utilized in the sensitive detector class to immediately stop tracking after triton detection, to save computational time.

The GEANT4 simulation was implemented using a C++ object-oriented approach. All the changes and simulations were used on a special computer at SNOLAB, reserved for the Low Background Facility's computational purposes.

After the simulation was created, they were validated. This is important since the correction factor is to be applied to the experimental data, and relevant simulation interactions are required. The bridge that closes the gap for such comparison is the energy deposition. Experimentally, the energy deposited from neutron capture events produces ionized charges, which are detected using standard detector electronics. In simulation, there are no electronics; however, energy deposition can be tracked with very high resolution. To compare the experimental and simulation data, the simulation's energy deposition was Gaussian perturbed to add artificial electronic noise and binned in wider bins to decrease effective resolution.

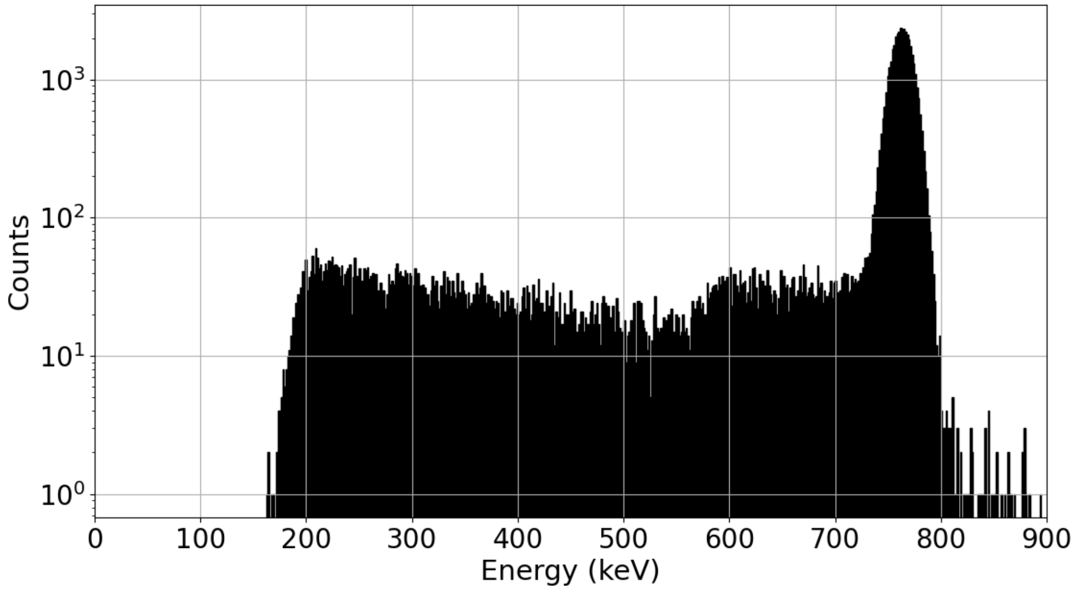
The figure 7 compares the simulation's data(top) to a robust low background Helium-3 counters energy deposition study(bottom). The data was binned into 1200 bins and a 10 keV Gaussian perturbation to mimic electronic noise. The primary region of interest in the plots is the 180-800 keV energy range. The results validated the simulation interactions since the wall effect was accounted for with sufficient accuracy. The wall effect is a result of the geometry of the Helium-3 counters: The triton and proton don't always deposit the Q value of 764 keV inside the gas. Due to conservation of energy and momentum, during neutron capture, the triton and protons are released in opposite directions with their respective energies, and if the capture event is close to the detector's outer cylindrical wall, at least one particle collides with the walls and results in partial energy deposition of the Q value. Another effect of interest is the edge effect, which is due to an inconsistent electric field around the dead region(near edges) of the detectors, resulting in a mild energy deposition. Despite adding Gaussian noise to mimic experimental data, the simulation only accounts for energy deposition and hence is unable to reproduce the edge effect.

2.1.4 Determining correction factor for thermal measurements

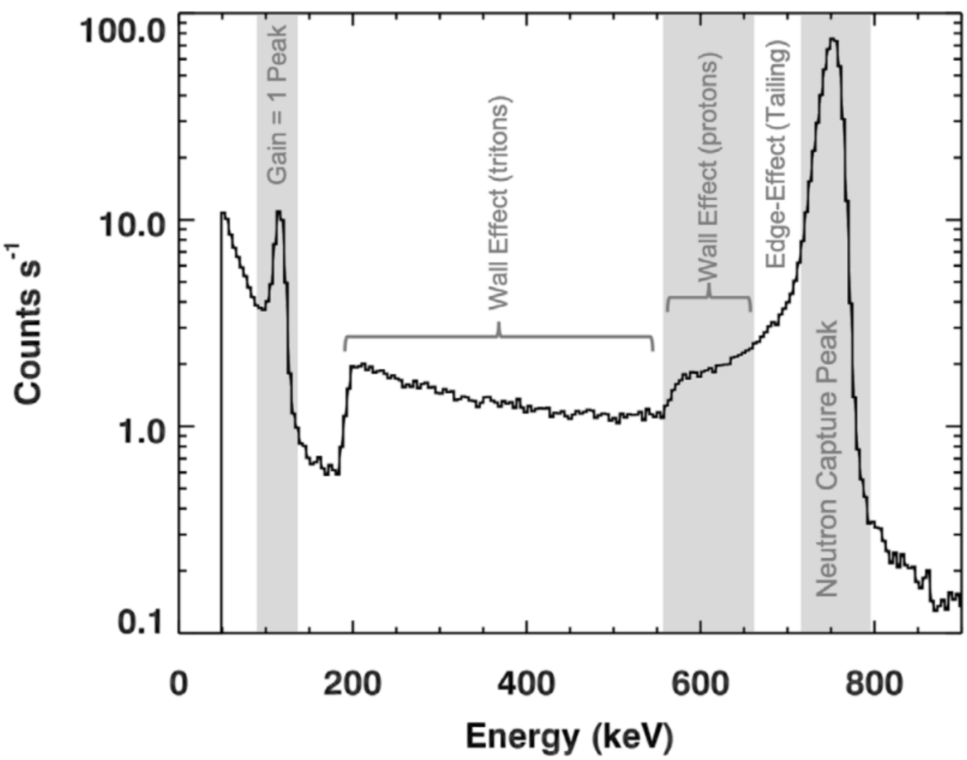
To account for efficiency loss due to the lower-end energy cut in section 2.1.2, the GEANT4 simulation was utilized to find a correction factor to account for the efficiency lost.

The lost efficiency factor can be calculated by comparing the count rate between the experimental and simulation results for the same setup and neutron source. This efficiency is simply the ratio of the neutron capture rate detected in the experimental setup over the simulation's neutron capture rate. The activity of the AmBe source, along with the number of events, was used to determine the time period for a certain number of events in the simulation.

The activity of the AmBe source used for the experimental setup was about 63 neutrons per second, and the simulation was run for 10 million events. The time can be approximated as: $t = \frac{10000000}{63} \approx 158730.2$ seconds. During the 10 million AmBe source run, the simulation's sensitive detector counted 365,467 neutron captures. Using Poisson uncertainty, $365\,000 \pm 600$ Neutron captures. Then the simulations count per second is simply:



(a) NCDs GEANT4 simulation: 1200 binned and 10 keV Gaussian noise



(b) Experimental data from NASA's Helium-3 counter studies(4)

Figure 7: Comparison between NCD simulation and a low noise experimental data.

$\frac{365467 \pm 60 \ neutron\ capturecounts}{158730.2\ seconds} \approx 2.3024 \pm 0.0004$ counts per second

Next, the experimental setup was run for an average time of 6524 seconds for the same setup. In total, the NCDs detected 7619 neutron capture counts. Using Poisson uncertainty, it's 7620 +/− 90 neutron captures. The experimental counts per second are:

$\frac{7620 \pm 90\ neutron\ capturecounts}{6524\ seconds} \approx 1.17 \pm 0.01$ counts per second.

The efficiency factor of interest is:

$\frac{Experimental\ CPS}{Simulations\ CPS} = \frac{2.3024 \pm 0.0004}{1.17 \pm 0.01} \approx 0.509 \pm 0.004$

This efficiency factor can correct the experimental data for energy cuts and efficiency.

This efficiency factor is not robust, more in the discussion section at the end of the report.

2.2 Part 2: Fast neutrons

2.2.1 Fast neutron detection method

Due to their low cross section for fast neutrons, the NCDs cannot detect them directly. Instead, many studies have used their high cross section for slow neutrons to infer fast neutron counts by placing moderators around the detectors.

Hydrogenous materials are particularly effective moderators (5). Because hydrogen nuclei are light, they efficiently remove energy from neutrons through scattering. With each collision, neutrons lose energy and change direction randomly, gradually becoming thermalized.

Before this project, five moderation setups were used with the NCDs: bare (no moderator), 1" polyethylene, 2" polyethylene, 3" polyethylene, and 12" water boxes. The combination of 3" polyethylene and water boxes stopped most ambient neutrons, except those above about 8 MeV. However, moderation complicates analysis: neutrons may scatter away before reaching the detector, making it harder to deduce the fast neutron flux.

This challenge can be framed as a convolution/de-convolution problem with three components: the detected counts, the source neutron spectrum, and the detector response. The convolution is expressed by the Fredholm integral of the first kind:

$$C_m = \int_{E_i}^{E_f} R_m(E)\, S(E)\, dE \quad \text{for } m = 1, \ldots, n \tag{1}$$

Here, C_m is the measured count rate for configuration m, $R_m(E)$ is the detector response to a neutron of energy E, and $S(E)$ is the source spectrum. Intuitively, the source emits neutrons with spectrum S; the moderator and detector response R modifies this spectrum; and the convolution of R and S produces the measured counts C. The response function is a conditional probability density (not normalized), incorporating source geometry, scattering, attenuation, and detector efficiency. Importantly, it does not sum to one since many neutrons are never detected.

The goal is to recover the source spectrum $S(E)$. After applying correction factors (Section 2.1.4), the measured counts C are known, and the response R can be determined. However, solving for S directly is not possible: the problem is ill-posed, R is non-analytical, and multiple mathematical solutions for S may exist, many of which are unphysical.

To address this, physicists discretize each integral into a matrix equation. For n shielding configuration and j energy bins, the the matrix equation is:

$$C = RS \tag{2}$$

Here, C is a column vector with n rows , R is the response matrix with n rows and j columns and, S is the binned source spectrum with j rows. The resolution is limited by the number of moderation setups or n, since the problem is underdetermined if R has more columns than rows.

Because measuring R experimentally is impractical, the GEANT4 toolkit was used to calculate it.

2.2.2 Determining response matrix R:

The experimental setup included five moderation configurations, each created as a separate GEANT4 simulation to save time. The response was initially assessed for these configurations using 29 energy bins ranging from 0.1 MeV to 11 MeV. A mono-energetic neutron source was run with 1 to 10 million events, depending on the shielding thickness.

The results for both bare and full (3-inch polyethylene + 12-inch waterboxes) configurations were nearly linear with small values, complicating the future S matrix calculations. However, decreasing shielding would lower resolution due to reduced bins. After discussions with supervisors, it was suggested to acquire more moderators for better configurations and resolution. This report focuses on a trial involving six setups: Bare (no moderation), 1" to 5" polyethylene. These simulations aimed to evaluate the response (see Figure 8). Equation 2 is still very general, and to determine S, R has to be the probability of neutrons emitted from the source being detected in the three NCDs. The response values were computed based on the ratio of triton counts to total events, reflecting neutron captures detected by our electronics.

No validation was necessary for these simulations, as they were based on a previously established framework. The next step is to determine S, given known values of C and R.

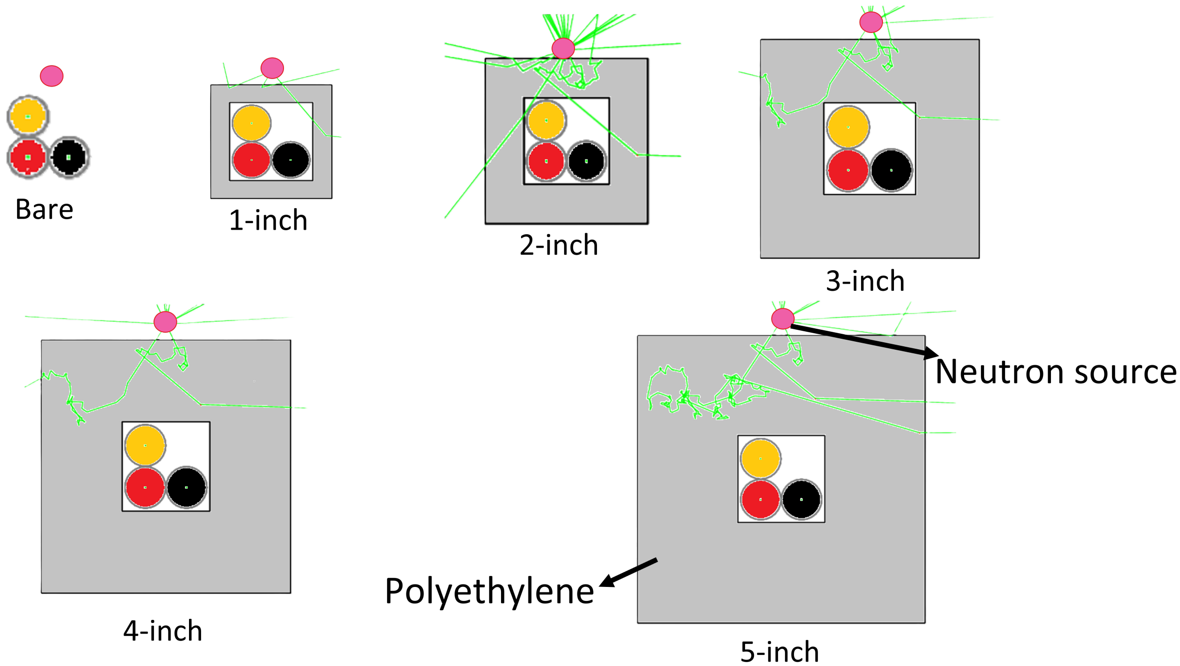


Figure 8: This figure shows the six moderation cases geometry. The silver box is the polyethylene, and the red, black and yellow are the three NCDs

2.2.3 Unfolding algorithms:

At first glance, the direct approach to solve for S is to find inverse R matrix, however, though mathematically valid, the solutions are non-physical. To check the inverse solutions, an attempt solving for S using a known AmBe source, but some solution values were negative. This is due to ill-conditioned problem.

Many authors have utilized moderation for slow neutron detectors, and one promising method in particular involves unfolding algorithms(6). This report involves using the GRAVEL algorithm, which was developed around the 1970s, as an updated version of the SAND-2 algorithm. The code is available in the UMG package, however, its private. Thanks to Tyler Dolezal, whose Neutron-Unfolding github repository[2] includes the GRAVEL PYTHON-based algorithm for public access. The PYTHON code was modified to

[2]https://github.com/tylerdolezal/Neutron-Unfolding.git

take the input response in a different format. The governing equations for the algorithm are:

$$S_j^{(k+1)} = S_j^{(k)} \exp\left(\frac{\sum_i W_{ij}^k \ln\left(\frac{C_i}{\sum_l R_{il} S_l^k}\right)}{\sum_i W_{ij}^k}\right), \tag{3}$$

$$where,\ W_{ij}^k = C_i \frac{R_{ij} S_j^k}{\sum_l R_{il} S_l^k}, \tag{4}$$

$$J^k = \frac{\sum_i \left(C_i - \sum_j R_{ij} S_j^k\right)}{\sum_i R_{il} S_l^k}. \tag{5}$$

The GRAVEL code also requires an initial guess spectrum and a tolerance value. The algorithm in equation (3) refines the initial guess spectrum using a weight factor based on equation (4), and entropy-based iterations continue until a tolerance value is satisfied for the relative error between C and $R \times S$ as seen in equation (5).

3 Analysis & Results

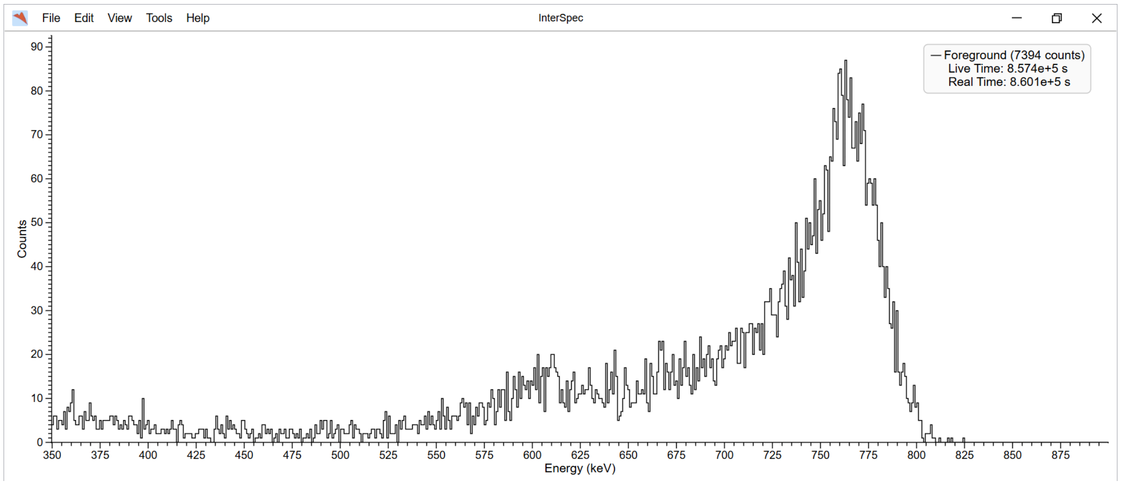
3.1 Thermal neutron detection test

Previously, a ambient thermal neutron measurement using NCDs was performed at SNOLAB from the SNO collaboration. The measured ambient thermal neutron flux was 4144.9 ± 49.8 ± 105.3 neutrons/m^2/day (7). Here the first error is statistical and second is systematic.

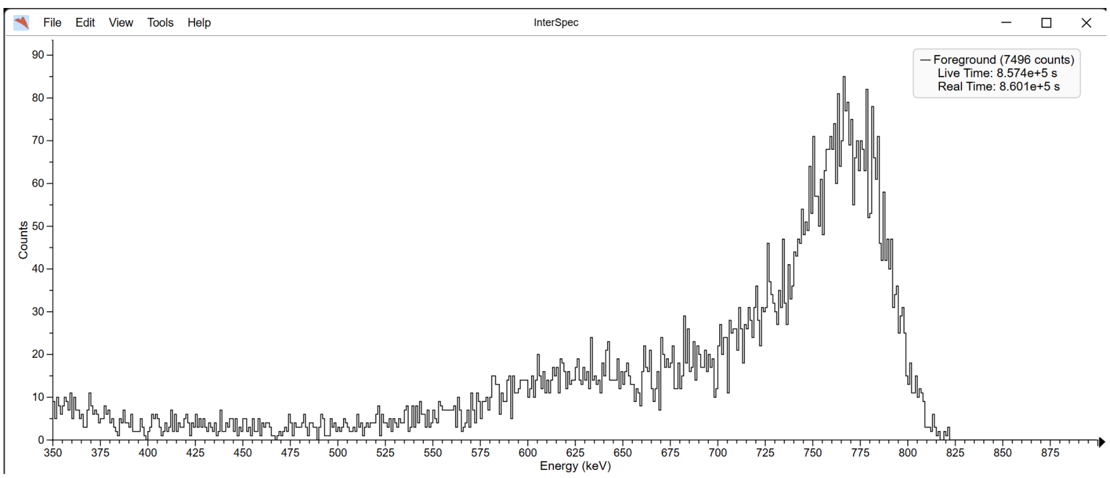
One way to test our method for detecting thermal neutron using correction factor was to take a background data with no moderation, use the methods developed in 2.1 section, and compare it with the SNO's measured data.

The correction factor determined in our report was taken using a very short experimental data and the geometry of the active volume of He-3 is still not precisely known, hence we didnt expect the calculated flux to be neck close to the expected SNO results.

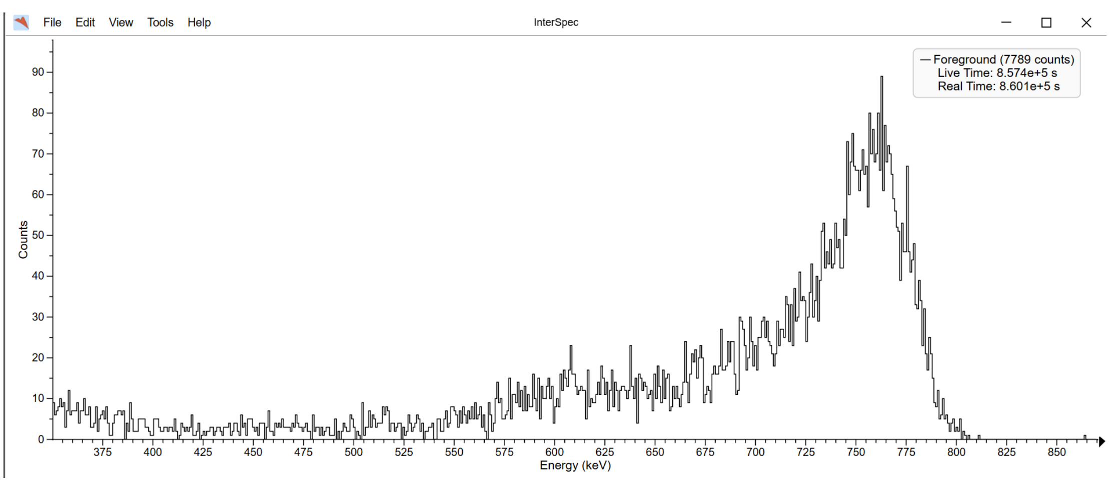
The three NCD setup with no moderation was placed in the J-Drift, and the setup took data for about 10 days. Then, the data was stored in ASCII channel file and using interspec software, the x-axis linear scale was adjusted so that the 764 keV peaks are aligned. To do so, 0.89, 1 and 0.85 linear corrections were applied to the input 1, input 2 and input 3 NCD data's x-axis respectively. Next, the 350-900 keV energy cuts were applied. The resulting plots for the three NCDs is shown in figure 9. In the plots, the peak near 764 keV is due to the full energy deposition from triton and proton that ionize the gas, the region lower than 764 keV until 350 keV includes the wall effect. Its also visible directly, that the majority of counts are



(a) Input-1 J-Drift data



(b) Input-2 J-Drift data



(c) Input-3 J-Drift data

Figure 9: Thermal ambient neutron data in the J-drift for the NCDs

in the 500 to 825 keV range. Ideally more data would be nicer for statistics, however the data was taken during PNP period, and there was limited access for underground shifts. The plots were consistent among the NCDs, and the data was used to measure a test ambient thermal neutron flux through the NCDs. The surface area of the NCDs(summed) was calculated as 0.9966 m^2 from the inner tube volume of the NCD geometry in the GEANT4 simulation. It is expected that the effective surface area should be slightly smaller than this value since the Helium-3 gas doesnt occupy the full inner tube volume. However, it was still decent for a test flux calculation.

According to the methods, the steps used for calculating the test flux were:

1. First the counts for the active period from each NCDs were summed, since we were interested in flux thorugh the NCDs as one effective detector. The total counts: 22679 $\pm$ 151 counts

2. The correction factor from section 2.1.4 was applied to the total counts from step 1. The corrected counts: 44556 $\pm$ 5400 counts

3. The live time, which takes into account the dead time for each NCDs were averaged. The effective time for measurement was: 857394 seconds(negligible uncertainty) or 9.92354 days

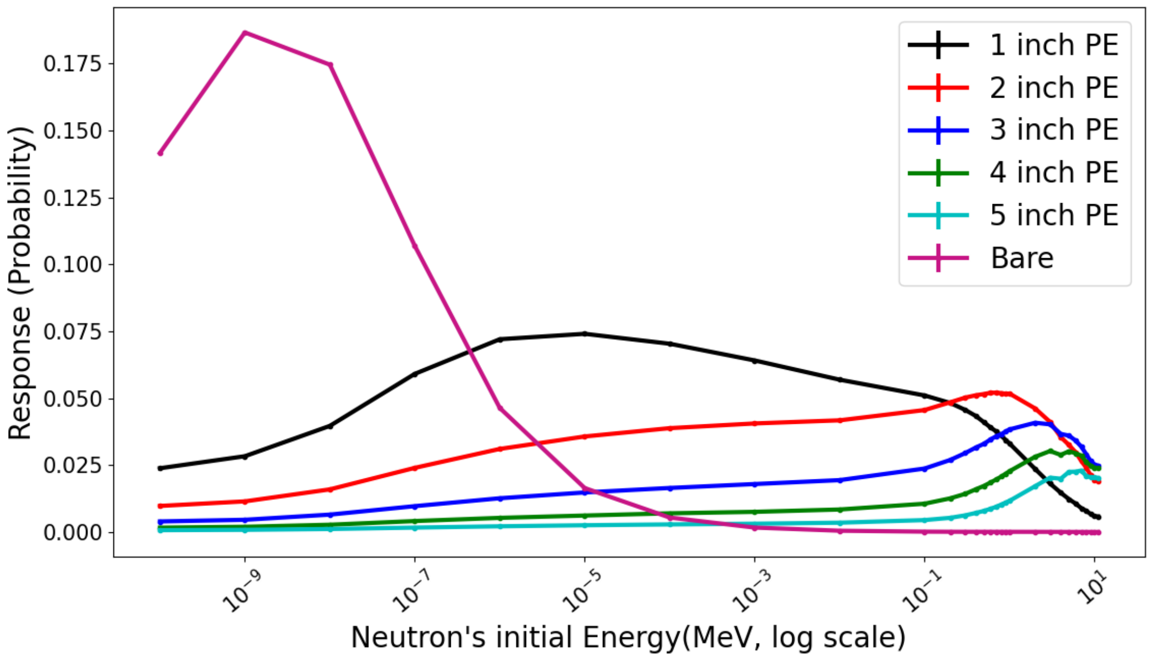
4. The corrected counts per days is corrected counts by effective time: 4490 $\pm$ 540 counts per day.

5. The flux in units required is counts per days by the surface area of NCDs: 4510 $\pm$ 540 counts $/day/m^2$

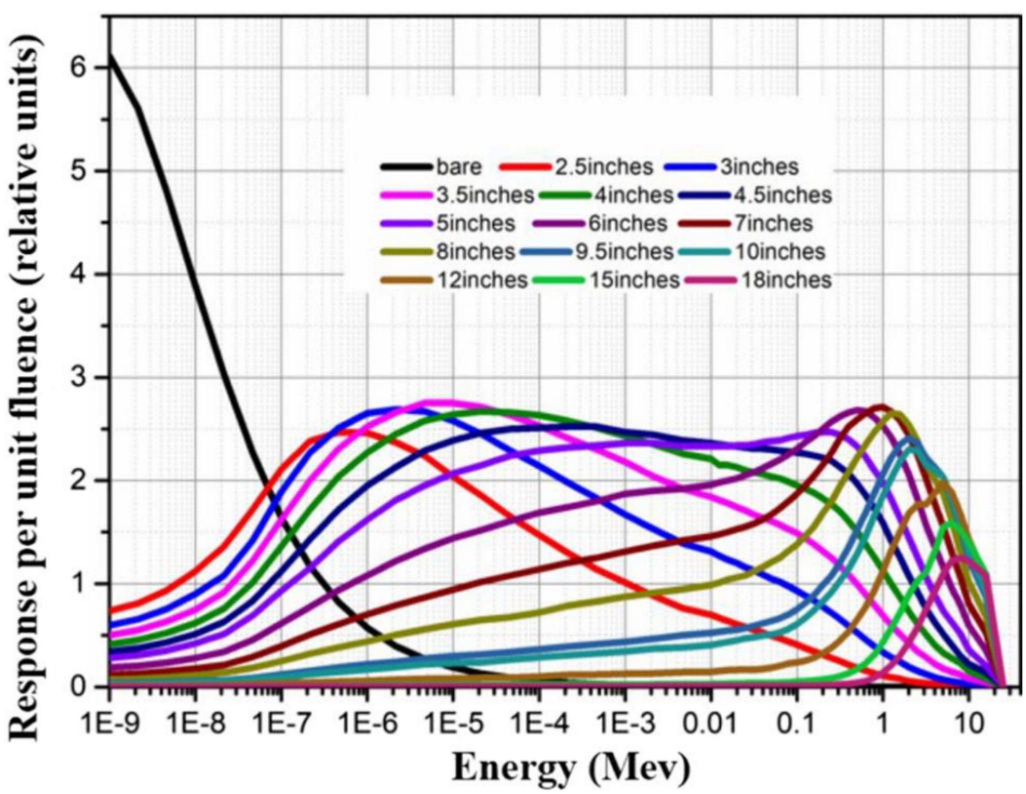
Despite simplified models, the flux in step 5 agrees with the SNO's neutron flux. Also, the measurement was taken in a different area, and closer to the walls, so the measurement shouldn't be expected to be very close to the SNO's value.

3.2 Simulative fast neutron detection test:

Testing the fast neutron counting was more time consuming, and to save time and energy, the test was taken in the GEANT4 simulation itself. First, it was decided to test the fast neutron counting method in the range 10^{-10} to 11 MeV range. The six moderation cases at the end of section 2.2.2 were used, and the response matrix was determined for 29 energy values in our region of interest. The figure 10, shows the comparison of the NCDs test response matrix(figure a) with a robust response analysis values for Bonner Sphere Detectors, which are Helium-3 filled Spherical detectors. In figure a, the reducing response with increasing polyethylene thickness seems clear, which is a consequence of the nature of neutrons scattering. Also, the BSS study used fifteen detectors, each with its own separate moderation(total 15 moderation cases), hence the response peaks are more stable than our case. Ideally, evaluating response for more energies in our region of interest



(a) The NCDs response



(b) BSS response for 15 detectors and 15 moderation(8)

Figure 10: Response comparison of the the NCDs and BSS from Yang-Yang laboratory

would be ideal, however, the simulations were time consuming; in fact the 5 inch polyethylene simulation ran for about 50 hours.

Then the response values were binned into six energy bins in the region of interest, to make the solutions more stable. In particular, the six bins were: 10^{-10} to 10^{-6} MeV(slow neutrons), 10^{-6} to 0.1 MeV(epithermal neutrons), 0.1 to 2 MeV, 2 to 4 MeV, 4 to 7 MeV and 7 to 11 MeV.

Then, a reference AmBe spectrum was used to test the methods. AmBe spectrum are well known fast neutron source, whose neutrons are primarily in the 0.1 to 10 MeV range. The count matrix C was determined using the AmBe reference source for the six moderation cases for 10 million events each.

The equation 2 in the six binned form for the case was:

$$\begin{bmatrix} 367 \\ 178956 \\ 365467 \\ 351517 \\ 268617 \\ 185942 \end{bmatrix}_{6\times1} = \begin{bmatrix} 0.0704 & 0.0302 & 0.0122 & 0.0051 & 0.0021 & 0.0531 \\ 0.0517 & 0.0451 & 0.0232 & 0.0103 & 0.0043 & 0.00017 \\ 0.0387 & 0.0515 & 0.0346 & 0.0188 & 0.0090 & 0.000061 \\ 0.0208 & 0.0436 & 0.0404 & 0.0404 & 0.0186 & 4.74E-05 \\ 0.0125 & 0.0325 & 0.0355 & 0.0294 & 0.0216 & 2.61E-05 \\ 0.0070 & 0.0220 & 0.0220 & 0.0254 & 0.0209 & 1.32E-05 \end{bmatrix}_{6\times6} \cdot \begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{bmatrix}_{6\times1}$$

The reference AmBe source spectra is well known, and its actual S matrix for the bins was calculated with high accuracy. The idea was to assume S is unknown, then use the GRAVEL algorithm to find a numerical solution for predicted S, then compare it with the actual S matrix from reference AmBe.

The S matrix includes the neutron counts emitted from the source in the six energy bins of interest. The primary objective of the test was to accurately predict the fast neutrons that were emitted from the AmBe source, and secondary objective was to predict the initial energies from the six energy bins of interest.

Then the GRAVEL algorithms used the R and C input, an initial guess spectrum of [0,0,1,1,1,1] (for stable solutions) and a tolerance value of 0.0001. The comparison of GRAVEL's predicted S matrix with actual S matrix(also see figure 11):

$$S_{GRAVEL} = \begin{bmatrix} 0 \\ 0 \\ 2116115 \\ 2309272 \\ 2934946 \\ 2700566 \end{bmatrix}_{6\times1} \quad and \quad S_{AmBe} = \begin{bmatrix} 0 \\ 0 \\ 2151240 \\ 2838782 \\ 3478108 \\ 1531870 \end{bmatrix}_{6\times1}$$

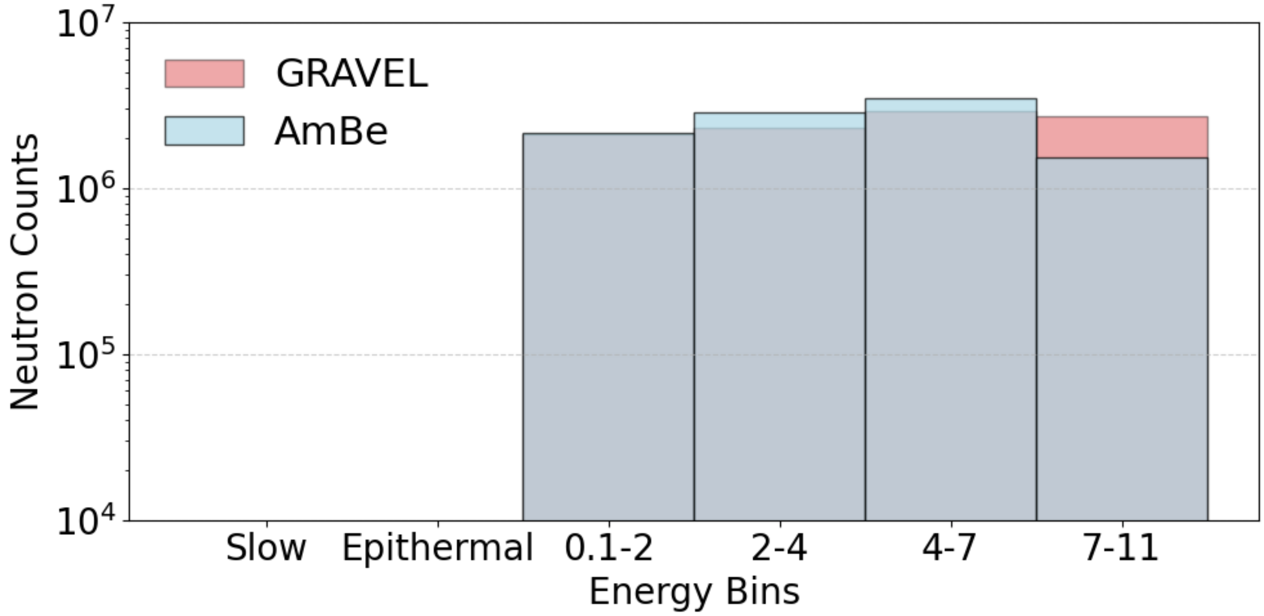


Figure 11: Comparison between the reference AmBe and predicted GRAVEL spectrum

The results for the first two bin is zero, since the AmBe has no slow and epithermal neutrons. Moreover, the later bin's results are sufficient considering the nature of unfolding.

For primary test, the total fast neutrons predicted was simply the sum of the elements in the S_{GRAVEL}, and it was 10060899 predicted fast neutrons, whereas the actual AmBe emitted 10000000 fast neutrons. The relative absolute was about 99.4%, which is accurate for the problem.

For secondary objective, the 0.1 to 2 MeV bin(third element in S matrix) was the most accurate for fast neutron range and the accuracy is lowest for the 7 to 11 MeV range bin.

4 Conclusion

The report introduced potential methods which involved utilizing GEANT4 simulation, for thermal measurement and fast neutron counting using the Neutral Current Detectors(NCDs). The methods were inspired by the pioneering research papers from experts in neutron detection studies.

The thermal neutron method was tested by measuring and calculating a test ambient thermal neutron flux in the J-drift, and the resulting value of 4510 $\pm$ 540 counts $/day/m^2$ was within the range of the SNO collaboration's ambient thermal neutron measurement.

The fast neutron method was tested in the energy range of 10^{-10} to 11 MeV range with six energy bins: 10^{-10} to 10^{-6} MeV(slow neutrons), 10^{-6} to 0.1 MeV(epithermal neutrons), 0.1 to 2 MeV, 2 to 4 MeV, 4 to 7 MeV and 7 to 11 MeV. The primary test for accurately predicting the fast neutrons indirectly by utilizing moderation, convolution matrix equation and GRAVEL unfolding algorithm was successful with a relative accuracy of about 99.4 %. The secondary objective to predict the initial energy of the neutrons for the six bins was sufficient considering the nature of unfolding.

These two methods have promising potential to utilize the Neutral Current Detectors to calculate the neutron flux in the 0 to 11 MeV range.

5 Discussion

Neutron detection is critical in the nuclear industry, but detection methods are still being researched. While moderation and unfolding methods are often used in underground labs with Bonner Sphere Detectors, unfolding is a challenge.

The simulation geometry for NCDs is simplified. The inner volume in simulations assumes coverage of only the inner tube, whereas actual NCDs have a dead region, suggesting a higher efficiency factor than 0.509 and a slightly lower final flux value. Additionally, potential background counts from epithermal or fast neutrons may affect results.

For fast neutron unfolding, energy bins are limited by moderation cases. While the unfolding algorithm can handle more than six bins, it leads to unstable spectra. The experimental setup uses 1", 2", and 3" polyethylene, with thicker polyethylene requiring more time for a proper count matrix. Due to the low neutron flux at SNOLAB, it may take at least eight days of data for no moderation cases, and weeks for thicker polyethylene.

The unfolding results can be more accurate if the moderation polyethylene cases and energy bins are optimized according to the response.

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A GEANT4 Beginners Guide

GEANT4 is a simulation toolkit for the passage of particles through matter. It can simulate particles in energies ranging from 250 eV to several TeV, with various detailed detector geometries, tracking and visualization settings. GEANT4 is a repository with detailed Monte Carlo simulation data from the worldwide collaboration of Physicists and Software Engineers. It is implemented with a C++ object-oriented approach, and the wide variety of detailed process libraries allows for the simulation of electromagnetic, hadronic, and optical physics interactions. (9)

During simulation interactions, GEANT4 differentiates between the gun particles(primary particles) and newer particles created due to interactions and radioactivity(secondary particles). Due to various detailed tracking features and individual cross-sections for multiple interactions, GEANT4 is primarily used in Medical, Particle, Nuclear and Astrophysics experiments. In addition, a more detailed Physics List, depending on energy scale and interactions, can be used according to the needs of the simulation.

GEANT4 simulations can be made by implementing the mandatory User Actions through the C++ language and using the G4RunManager class to communicate the information to GEANT4. The basic User Actions required to make a simulation using GEANT4's C++ approach are:

1. Detector Construction[3]: All the detector components inside the world are defined, initialized or used from prepared libraries in the Detector Construction implementation. A known material can be used from a library, or a new material can be created using a combination of defined atoms. A logical volume needs to be made first to make the volume of material inside the GEANT4. Then, this Logical Volume can be placed throughout the GEANT4 World according to relative coordinates to the "World Volume". World Volume or mother volume is the first and the largest volume, and it should include all the materials or detector components inside. Then, the Detector or Child Volumes can be placed inside the World Volume using their Logical Volumes. At the end of this section, "SensitiveDetector" can be assigned to particular material. A "SensitiveDetector" material is the primary material of interest whose interaction results are of interest.

2. Physics List: GEANT4 allows custom usage of Physics processes[4], which can be done by using particular Physics Lists based on the simulation requirement. The GEANT4 collaborators have already made several Physics List libraries suited for specific interactions and modes, thus only proper initialization is required.

[3] https://geant4-userdoc.web.cern.ch/UsersGuides/ForApplicationDeveloper/html/Detector/detector.html
[4] https://geant4-userdoc.web.cern.ch/UsersGuides/ForApplicationDeveloper/html/TrackingAndPhysics/physicsProcess.html

3. Action Initialization[5]: Action Initialization includes the actions that the GEANT4 should perform during the simulation. The most important action is the "Gun" initialization, which requires choosing the type, energy or momentum and angular distribution of the "primary particle" which will cause the interactions of interest. Then, additional actions for analysis and tracking during the Run, Events, Tracks or Steps can initialized separately for tracking particle information.

After the basic User Actions, many additional features or Actions, such as Visualization, Hits, Scoring, General Particle Source, Production Cuts, etc., can be used for more complex simulations.

[5] https://geant4-userdoc.web.cern.ch/UsersGuides/ForApplicationDeveloper/html/UserActions/mandatoryActions.html#user-action-initialization