Radon Monitoring Analysis and Bubble Detector Spectrometer Simulations

Kishan Chaudhary

Student ID: 200465153

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Physics Co-op Coordinator
Department of Physics
University of Regina
Regina, SK

Dear Physics Co-op Coordinator,

Please find attached my work term report titled *”Radon Monitoring Analysis and Bubble Detector Spectrometer Simulations”*. This report is submitted as part of my Physics Co-operative Education Program and covers my PHYS-051 summer term at SNOLAB, an underground research laboratory in Lively, Ontario. The report is based on my contribution to two projects in the Low Background Facility underground: Radon Monitors Test and Bubble Detector Spectrometer.

The first project, Radon Monitoring, is about testing 36 Radon Monitors available in Canada. This is a continuing joint project between Health Canada and SNOLAB, and the primary purpose is to recall radon monitors with considerably bad accuracy. The 36 Radon Monitors were tested against AlphaGUARD Radon Detector, and 24 Radon Monitors passed the accuracy test according to the cumulative average within the 25% range with respect to AlphaGUARD’s cumulative average.

The second project, Bubble Detector Spectrometer, aims to calculate the neutron flux in the 10 keV to 20 MeV energy range in the Low Background Facility underground. The report focuses on the update to the GEANT4 simulation, whose primary aim is to simulate the neutrons detected inside the BDS due to radioactive neutron sources surrounding it. The report includes the result of the simulation run for testing how putting the BDS inside a 12-inch Lead(Pb) castle interferes with the neutron energies emanating from the radioactive sources surrounding the BDS. The GEANT4 simulation is still a work in progress as the future students involved in the projects will contribute to the simulation.

It is recommended that the reader goes through the report project-wise, meaning reading the material one project at a time is ideal for understanding both projects.

I thank Ian Lawson, Alexander Lemieux, Dimpal Chauhan, Steffon Luoma, Alexander Vicol, and Rishi Patni for their guidance and support throughout this term.

Sincerely,

Kishan

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Radon Monitoring Analysis and Bubble Detector Spectrometer Simulations

SNOLAB

Creighton Mine #9, 1039 Regional Road 24, Lively, ON P3Y 1N2

Kishan Chaudhary

Student ID: 200465153

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Summary

This summer 2024 work term report includes my contribution to two projects at SNOLAB's Low Background Counting Division: the Radon Monitoring Project and the Bubble Detector Spectrometer(BDS) project.

The first project, the Radon Monitoring Project, involved testing 36 radon monitor in partnership with Health Canada to evaluate their accuracy in the underground environment. This report briefly describes the data collection methods used by three students and the final analysis methods I used to compare the cumulative average of 36 Radon Monitors to a professional Radon Detector, AlphaGUARD PQ-2000. Additionally, a response test was performed on particular monitors to determine their reaction to a sudden change in radon levels. In conclusion, 24 of the 36 monitors performed acceptably within the 25% accuracy range from the AlphaGUARD's radon value, with the RadonEye monitors performing excellently in the response test.

The second project, Bubble Detector Spectrometer (BDS), involved using Bubble Detectors in the Low Background Facility underground to evaluate neutron flux in the 10 keV to 20 MeV energy range. This report focuses on the changes to the BDS GEANT4 simulation to make the results more reliable. Brief methods for updating the geometry, physics list, gun particle, tracking, and analysis plots are included, and the simulation was explicitly tested with neutron spectra inside the BDS detectors. The results of the updated simulation focus on the effect of Lead (Pb) shielding material on the neutron energies detected in the BDS Bubble Detectors. In conclusion, the data from the simulation run indicated that the Pb castle considerably affected the neutron spectra in the 10 keV to 20 MeV energy range detected inside the BDS bubble detectors.

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 (particularly Radon) in sensitive experiments. This work term report details two active projects at the facility: the Radon Monitoring Project and the Bubble Detector Spectrometer.

1.0.1 Radon Monitoring Introduction:

Radon(see Appendix A) is a significant lung health hazard, and Health Canada operates an active Radon Research Facility dedicated to assessing the radon threat to Canadians. Traditionally, radon monitors required at least three months of data collection to determine cumulative radon levels. However, advancements in technology and materials science have enabled modern radon monitors to detect radon levels over much shorter periods. Despite these advancements, the accuracy of unverified radon monitors remains to be determined. Health Canada's Radon Monitoring Project aims to evaluate various radon monitors available in Canada and potentially recall underperforming monitors from the market. Health Canada's Ottawa office houses a laboratory where radon monitors are tested in a controlled environment using professional reference devices.

In 2024, SNOLAB's Low Background Counting Facility partnered with Health Canada to test 12 radon monitor in the underground environment, comparing them against two professional reference devices: the Alpha Track Radon Detector and the AlphaGUARD PQ-2000. The Alpha Track method is a traditional long-term approach that requires post-collection analysis to determine the cumulative radon average. In contrast, the AlphaGUARD uses an ionization chamber to record radon levels hourly. This report focuses on the accuracy of total of 36 radon monitors compared to the AlphaGUARD professional monitor. For a radon monitor's results to be deemed acceptable, each monitor's cumulative average must fall within 25% of AlphaGUARD's cumulative average for the same period.

Students from the Low Background Counting Facility were responsible for collecting data from the radon monitors, compiling it into a database and producing plots and accuracy tables under the super-

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

vision of Dimpal Chauhan, scientific support at SNOLAB. The radon monitor testing was completed on June 15th, and a detailed analysis report was submitted to Health Canada by the end of the summer term. The technical report was co-authored by three students under the guidance of Dimpal Chauhan and Ian Lawson, and reviewed by Stephen Sekula, Research Group Manager at SNOLAB. This work report presents the final analysis results and the methods employed.

1.0.2 Bubble Detector Spectrometer(BDS) Introduction

The Bubble Detector Spectrometer or BDS (see Appendix B) is a Neutron spectrometer method for neutron kinetic energies ranging from 10 KeV to 20 MeV. Generally, nuclear industries use the BDS package to calculate neutron dose and flux for radioactive sources. Still, SNOLAB's Low Background Counting team decided to use the BDS underground to calculate the neutron flux in the 10 KeV and 20 MeV. 24 Bubble detectors for each energy threshold[2] of the BDS, meaning 144 BDS bubble detectors(see figure 1) were brought underground. The 144 BDS were situated on the Lower Background Facility's upper floor, and the BDS run was initiated in January 2021.

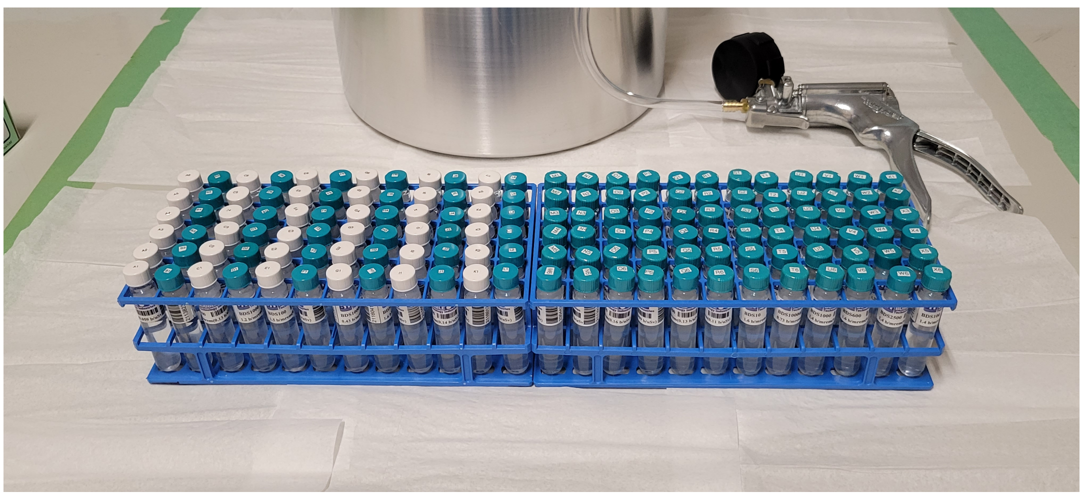


Figure 1: The 144 Bubble Detectors were distributed in two Trays. These trays were put into a thin pressure Aluminium Chamber.

Previously, the Low Background Counting team measured the neutron flux from the radioactive rocks in the SNOLAB underground facility, and this data provides an opportunity to test the neutrons detected in 10 keV to 20 MeV from the BDS detectors. Typically, the BDS detectors are used in relatively high neutron flux fields, and BDS calculation for neutron spectrometers requires about 100 Bubbles in each detector tube for sufficient error calculations. Being 2 km underground, the rock burden on the top stops most neutrons from the surface or cosmic events; moreover, most of the scarce neutrons from the surrounding radioactive rock underground are primarily in between 0 to 3 MeV,

[2] There were six energy thresholds.

and slower neutrons will stop considerably quickly in the high-pressure air underground. The initial data of bubble formation frequency in the Bubble Detectors indicated that at least two years' worth of data is required for the "unfolding" calculation from BTI to provide good statistics. To improve and utilize the BDS, the Low Background Facility decided to investigate the BDS and develop a separate method to calculate Neutron Flux in the Lab, thus avoiding the high statistics issue with the BTI's "unfolding" program.

Because the BDS detects neutrons through the physical interaction of the neutrons with the Gel[3] material, the BDS can only detect the neutrons that interact with the individual Bubble Detectors according to their bubble formation threshold, sensitivity, and mean cross-sections. Hence, a GEANT4(see Appendix C) simulation was made to observe the neutrons detected in the BDS Gel from known neutron energy emitted from the facility's wall surface.

Every term, one student is assigned to assist the BDS project lead, Steffon Luoma, in investigating the BDS to get better neutron flux. In the Winter 2024 term, the BDS pressure chamber [4] and surrounded by a 12-inch thick Lead(Pb) castle. This was done to study whether the lab's gamma flux affects the bubble formation, because Pb is a known shielding material to stop gamma particles.

During the Summer Term, the primary goal assigned by Steffon was to upgrade the SLBDS[5] simulation according to the given instructions and compare the effect of adding the Pb castle to the different neutron energies from the wall. This report includes a brief description of the methods and results of the updated simulation, which tested how adding Pb castle affected the neutrons travelling from the walls to the BDS.

2 Methods

2.1 Radon Monitoring Data Collection Method

There were 12 unique Radon Monitor brands, and each of the unique brand monitors had three monitors. Hence, a total of 36 monitors were distributed for monitoring(see Figure 2). The AlphaGUARD detector required a licensed Bertin Pro DataView software for data collection and analysis. The monitors were divided into two parts for data collection: App and Manual (see Table 1). The app monitors took data automatically and only required to be synced; however, the manual monitors' data was recorded using a phone that would take photos of these monitors every 24-hour intervals. The main

[3]Gel is the Freon superheated material that vaporizes on interaction with specific energy neutrons, forming bubbles

[4]The BDS detector's sensitivity and cross-sections were calculated at atmospheric pressure and 20 degrees Celsius. To ensure these factors are still intact underground, the 144 Bubble Detectors were put inside a cylindrical pressure chamber with an air pump to reduce the pressure to 1 atm

[5]Name of the GEANT4 simulation for Bubble Detector Spectrometer.

reason for distributing them into the two groups was that the App monitors took data more frequently than the manual monitors. The manual monitors were set to cumulative Radon Level mode and recorded the cumulative Radon levels from the beginning of the project; hence, there was no need for frequent measurements.

Figure 2: This figure shows the Radon Monitoring setup for the period of the operation of this project

Manual Monitors	App Monitors
Funny Kitchen (FK)	Airthings Wave Plus (WP)
CRADTEC Smart (CRAD)	Airthings View Plus (VP)
Ecosense EcoBlu (EB)	Ecosense EcoQube (EQ)
Hanchen Home (HAN)	Ecosense RadonEye (RE)
Life Basis (LB)	Life Basis Intelligent (LCA)
Airthings Corentium Home (CH)	
Safety Siren Pro Series 4 (PS4)	

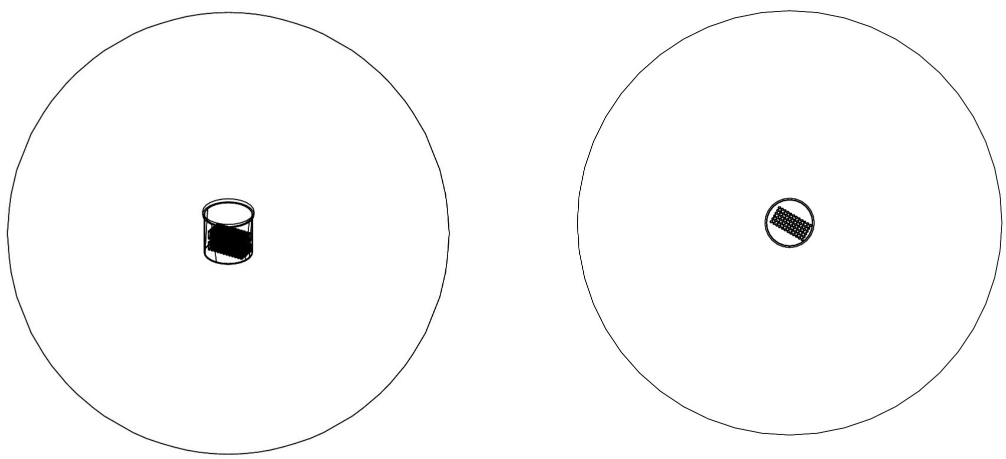
Table 1: Radon Monitor according to collection method. Press the monitors name for more details

Specifically, the RadonEye(RE), EcoQube(EQ), and Life Basis Intelligent(LCA) app monitors recorded hourly-based Radon measurements, which made them ideal for comparing their responses with the AlphaGUARD hourly Radon levels.

With the help of two other students, Rishi Patni and Alexander Vicol, the data from each monitor was recorded in separate CSV files before the end of July.

2.2 Bubble Detector Spectrometer (BDS) Simulation method:

Steffon Luoma provided the original SLBDS simulation, and it is important to understand the operations of that simulation to see how changes were made. A brief description of the vital components(concerning this report) of the SLBDS simulation is listed below:



(a) Geometry view

(b) Geometry View: Top

Figure 3: The Original SLBDS Geometry

1. Detector Construction: The Figure 3 shows the Geometry View. For simplification, the walls were spherical(World Volume), and the pressure chamber(cylindrical) and the 144 BDS tubes were situated at the center of this Sphere. The Pressure Chamber and BDS tube material were used according to the molecular composition of each material which BTI provided. Figure 3b shows the top view; the individual tubes were distributed in two trays, and each tray holds 72 Bubble detectors (12×6). One tray was placed on top of the other tray inside the pressure chamber.

2. Gun particle: The simulation generated the particles with random angular distribution from the surface of the Sphere, which is ideal since the rock walls project neutrons in an isotropic manner. The gun particles for a single run were monoenergetic.

3. Tracking and Analysis: The Gel material inside the individual BDS tubes was the "SensitiveDetector" material. Ntuples analysis was initialized to store counts of particles vs Post-Step-energy histograms for the Sensitive Detector at every Step for every event.

The Bubble Detector Spectrometer GEANT4 simulations were 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.

The original SLBDS simulation counted every particle's post-step energies[6] for counts, causing a large amount of unwanted entries in analysis plots[7]. To avoid this pitfall, the new simulation created from the SLBDS version had updated "SensitiveDetector" tracking and analysis, in which the particle's TrackID and EventID were used to avoid multiple entries of the same particle. To implement such tracking, two new private members in the "SensitiveDetector" class were introduced, which would keep track of the EventID and TrackID of particles in the Gel. Then, using an "if" statement, the tracker was instructed only to record the energy values for particles with a new EventID or new TrackID. Moreover, using the particle name, the particles were distinguished and individual spectra for Neutron, Gamma and Alpha according to their ParentID[8] was obtained.

To compare the simulation results, the new and old SLBDS simulations had the same Physics Lists: HadronElasticPhysicsHP, G4HadronPhysics QGSP BIC HP, G4IonPhysics XS, G4IonPhysics XS, G4StoppingPhysics, ElectromagneticPhysics, GammaNuclearPhysics LEND, G4DecayPhysics and G4RadioactivePhysics.

Initially, in the new simulation, monoenergetic neutron(gun particle) energies of 10 KeV, 100 KeV, 1 MeV, 5 MeV and 10 MeV were used in separate simulation runs to observe how the neutron energies were affected while going through the Pb castle. However, Steffon advised implementing Neutron Flux instead of separate monoenergetic runs. Thus, a new simulation named "SLBDS Neutron Flux" was created, which could use neutron spectra for the gun particle instead. Implementing complete spectra enables the simulation for Pb and Non-Pb castle cases to be compared directly, and it makes the simulation one step closer to the actual BDS environmental conditions.

To project neutron spectra, the G4GeneralParticleSource was initialized instead of the previous G4GunParticle. Then, a macro file[9] was used to instruct GEANT4 with user interface commands to project neutrons

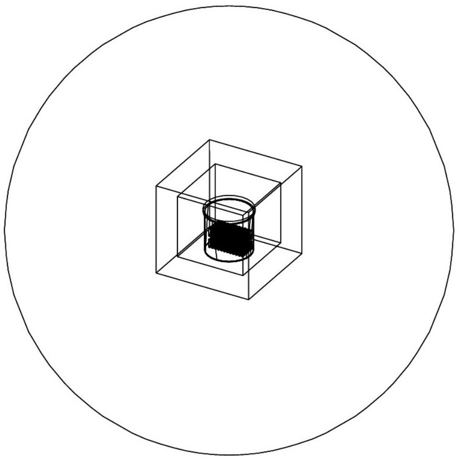
[6] During the interaction of particles(steps), the pre-step energy is the energy of particle before interaction and post-step energy is the energy of particle after the interaction

[7] In GEANT4 every gun particle or primary particle has ParentID, StepID, EventID and TrackID which can help distinguish among the particles. But a gun particle can go through several steps(like scattering), and produce secondary particles with their separate steps. Counting for every step particle involves multiple counting of the same particle until it goes out of the SensitiveDetector or stops through interactions.

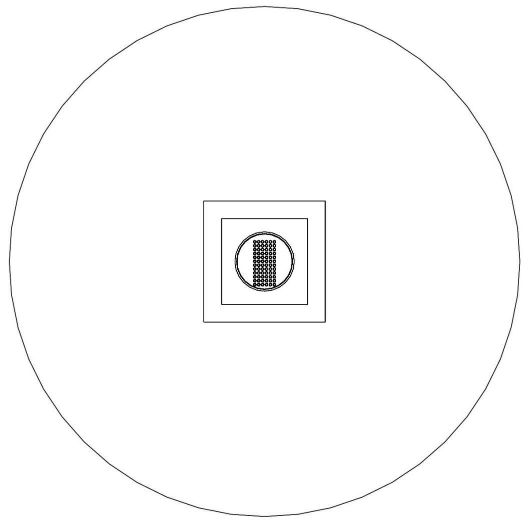
[8] Every primary particle's ParentID=0, whereas every secondary particle's ParentID$\neq$0

[9] Macro text file is usually used in GEANT4 to implement the gun particles outside the source code(the C++ simulation code). This allows using multiple gun particle sources, each of which will have a separate macro file with commands to set the properties of the gun particle.

isotropically[10] from a spherical surface just smaller than the world volume. The "Arb" [11] energy type was set, a spectrum file[12] with the respective energies, and their relative intensities were used for "Spline" interpolation. This interpolation assigns the gun neutron energies based on the interpolation curve, which is based on the relative intensities for each neutron energy in the file. The SLBDS Neu-



(a) Geometry view



(b) Geometry View: Top

Figure 4: The Pb castle SLBDS Geometry

tron Flux simulation was primarily built to introduce efficiency or correction factors for the neutrons travelling from the Lab walls to the BDS Gel. Then, the Pb castle was added to the simulation geometry to compare the neutrons detected for the same number of events with and without the Pb castle. Figure 4 shows the visualization for the updated geometry used in this new simulation.

3 Analysis & Results

3.1 Radon Monitors Data Analysis

PYTHON programming language was selected to perform the final data analysis due to its wide variety of data analysis libraries and easy data handling capabilities. Firstly, the data was checked to ensure that the correct parameters(for example, data intervals, units, weighted values if required) were to be compared among all the monitors. The monitors had different ways to record data; for example, one Radon Monitor took 1-hour Radon Levels and counted time in terms of the number of hours

[10]Isotropic angular distribution means random distribution. This is ideal for radioactive nuclei since they emit products or particles in random angular directions. The neutron source for the SNOLAB walls is essentially the radioactive materials in the rock.

[11]The "Arb" energy type enables user instructed energies spectra

[12]For the spectrum file, a previous Neutron flux text file with neutron energies and respective flux was fed to a PYTHON algorithm. The PYTHON code used the ratio of respective flux to cumulative flux to assign the Relative intensity for each energy.

passed from the beginning, and another Radon Monitor took a 2-hour Radon level with time in date time format. Some monitor's Radon Levels were weighted to ensure ideal data handling in case their time intervals were changed during the active period. Thanks to student Rishi Patni, whose previous PYTHON analysis helped build the Final Analysis code quickly.

The PYTHON code, which handled the data and analysis, performed the following operations:

1. Read the 37 CSV files(including AlphaGUARD) and make separate DataFrames for each monitor.

2. Parse the string time values from the DataFrames in identical datetime format for every monitor.

3. Individual plots for monitors that took data on 1-hour intervals against AlphaGUARD.

4. Two cumulative plots comparison with AlphaGUARD for app and manual monitors.

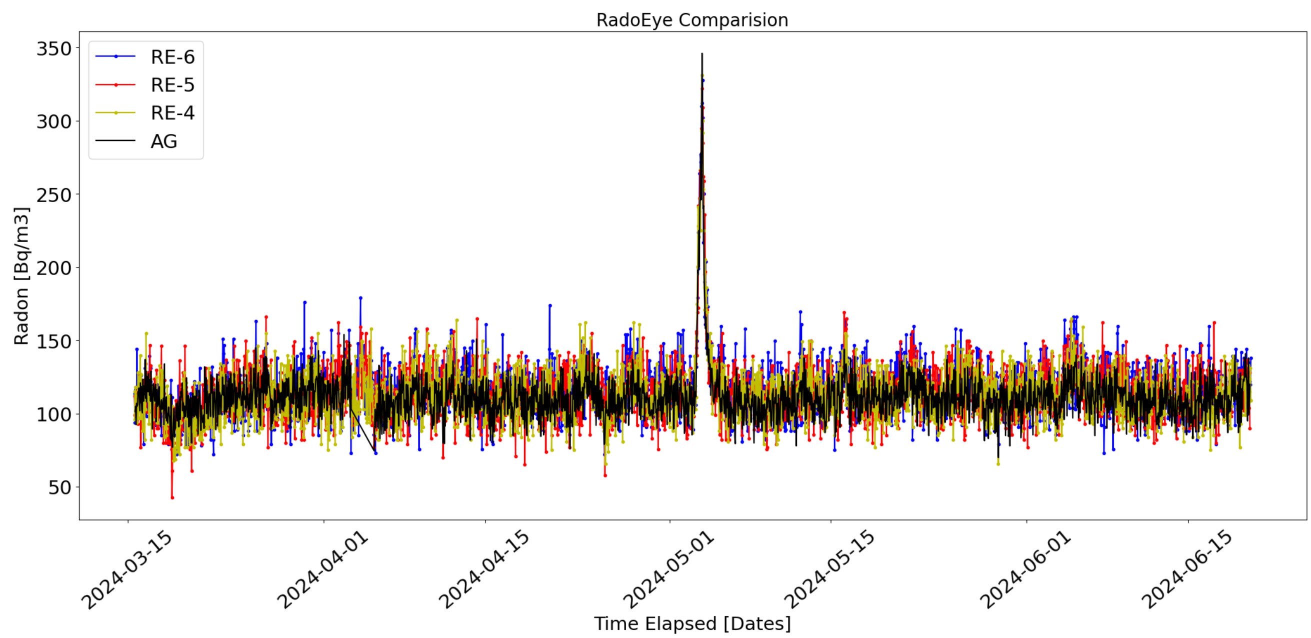


Figure 5: This figure shows the RadonEye comparison to AlphaGUARD throughout the project.

Multiple plots were made to compare the app monitor data with the AlphaGUARD, but this report only includes two of these plots. The plots were made in such a manner that the AlphaGUARD's data should overlap the Radon monitors data in case of ideal accuracy. Due to air ventilation malfunction around 3^{rd} May, the Radon Levels went as high as 350 Bq/m3. But this "Radon Peak" also offered a response test for the specific app monitors which took hourly Radon Levels.

Figure 5 shows the RadonEye monitors plot in comparison with the AlphaGUARD data. The fact that the black AlphaGUARD trail overlaps the RadonEye monitors suggests that the RadonEye monitors performed excellently. They also responded well around the "Radon Peak".

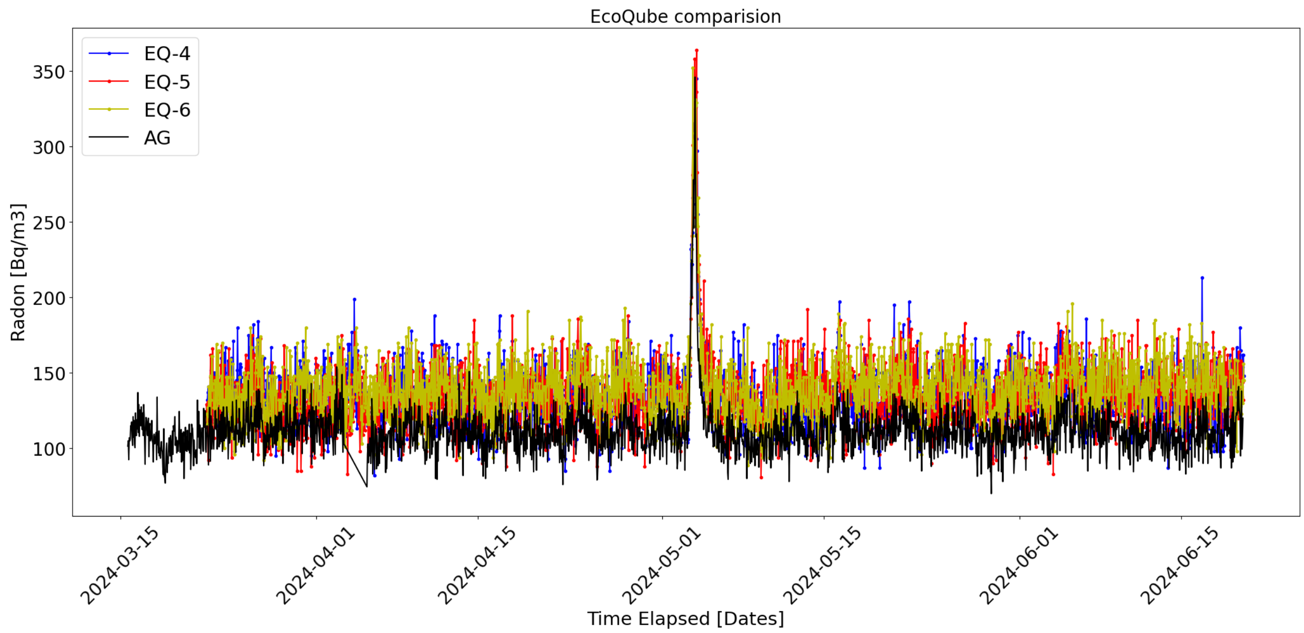


Figure 6: This figure shows the EcoQube comparison to AlphaGUARD throughout the project.

Figure 6 shows the EcoQube monitors plot in comparison with the AlphaGUARD data throughout their active period. The EcoQube monitors Radon Levels were consistently higher compared to the AlphaGIUARD's Radon Levels throughout their active period.

Then, the following methods for the statistical analysis were performed for Final Analysis:

1. Accuracy: It is defined as the relative percent error between the average radon concentration measured by different radon monitors and the reference radon concentration from AlphaGuard and is given as:

$$\text{Monitor's Accuracy} = \frac{\text{Monitor's mean} - \text{AlphaGUARD's mean}}{\text{AlphaGUARD's mean}} \times 100\%, \tag{1}$$

2. Coefficient of Variation: It is defined as the relative standard deviation for the result measured by the tested radon monitors and is given as:

$$\text{Monitor's C.V.} = \frac{\text{Monitor's Radon Level Standard deviation}}{\text{Monitor's measured mean}} \times 100\%, \tag{2}$$

   where the Standard deviation is obtained from the radon data of individual radon monitors. The C.V. was calculated for all the app monitors only because they had many data points to provide a good standard deviation.

3. Response: The Radon Level of a monitor with ratio to AlphaGUARD's Radon Level at a particular time.

$$\text{Monitor's Response} = \frac{\text{Monitor's Radon value}}{\text{ALPHAGUARD's value}} \times 100 \tag{3}$$

in our case, the Response is explicitly measured at May 3^{rd}, 2024 during the Radon Peak. The Response was only calculated for the RE, EQ and LCA monitors since they responded to Radon Levels on an hourly basis.

Monitors	Cumulative Average(Bq/m3)	Accuracy%	C.V.%	Response % at the Radon Peak
AlphaGuard	111.1	0	14.9	100
CRAD-4	114	2.6	-	-
CRAD-5	108	-2.8	-	-
CRAD-6	110	-1.0	-	-
RE-4	113	1.8	17.1	96
RE-5	115	3.3	17.4	93
RE-6	117	5.1	16.9	95
HAN-4	103	-7.3	-	-
HAN-5	102	-8.2	-	-
HAN-6	116	4.4	-	-
PS4-4	121	8.9	-	-
PS4-5	118	6.2	-	-
PS4-6	118	6.2	-	-
EB-4	125	12.5	-	-
EB-5	114	2.6	-	-
EB-6	123	10.7	-	-
CH-5	91	-18.1	-	-
CH-6	85	-23.5	-	-
CH-7	91	-18.1	-	-
LB-6	91	-18.1	-	-
LB-5	120	8.0	-	-
LB-4	74	-33.4	-	-
EQ-4	135	21.5	15.9	94
EQ-5	136	21	16.3	90
EQ-6	139	25.1	15.2	96
LCA-4	81	-26.9	18.0	71
LCA-5	92	-17.2	21.5	76
LCA-6	93	-16.2	19.3	81
VP-4	82	-26.2	24.3	-
VP-5	79	-28.9	22.9	-
VP-6	83	-25.3	21.7	-
WP-5	73	-35.2	20.1	-
WP-6	83	-26.2	30.2	-
WP-7	83	-26.2	22.6	-
FK-4	49	-55.9	-	-
FK-5	50	-55.0	-	-
FK-6	50	-55.0	-	-

Table 2: Radon Monitors Statistical Analysis. See Table 1 for individual monitor's detail link

Table 2 shows the complete statistical analysis performed for the Radon monitors. The accuracy column suggests that 24 Radon Monitors were under the 25% mark around AlphaGUARD's average, making their data acceptable. The Airthings monitor performed acceptably on the surface environment, but their accuracy was unacceptable underground, most likely due to the environmental change. However, despite being precise among themselves, the Funny Kitchen monitors performed poorly underground, and they were not working properly.

3.2 BDS GEANT4 Simulation Results

Figure 7 shows the neutron spectra of the General Particle Source implementation with 5 million events. To get better statistics for the neutrons in the SensitiveDetector(gel) material, the World Volume's (Sphere) radius was reduced.

In reality, the BDS package is only capable of detecting neutrons in the 10 KeV to 20 MeV, thus the neutron detection inside the BDS Gel(SensitiveDetector) was enabled for neutron energies higher than 10 KeV. Therefore, the results will only include neutrons detected with energies more than 10 KeV.

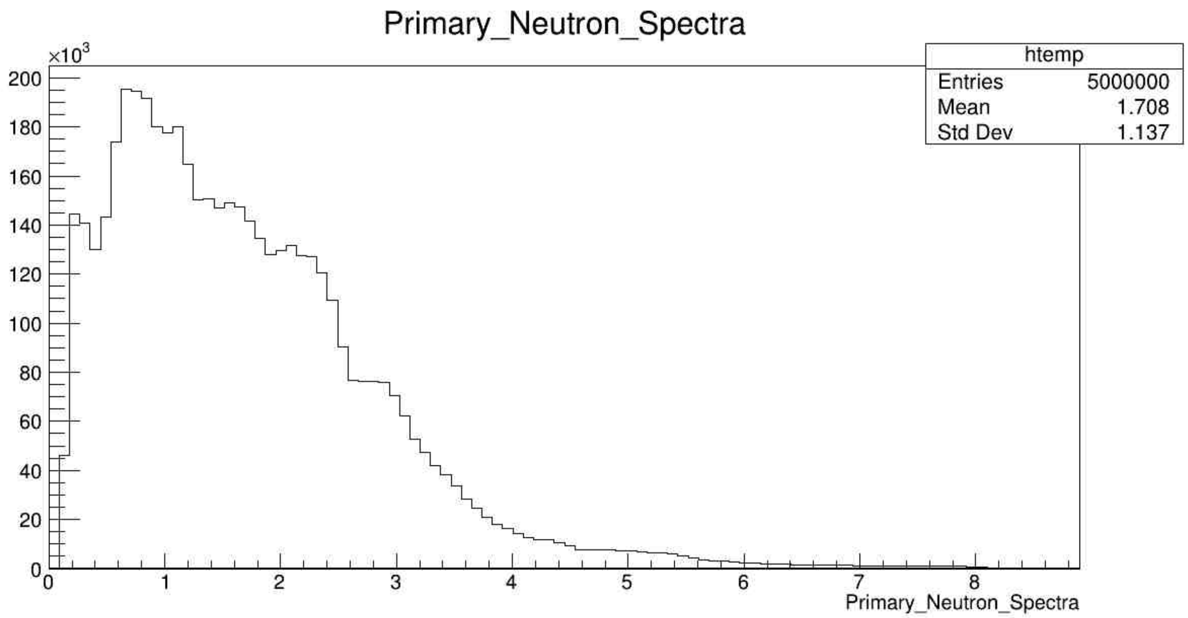


Figure 7: This figure shows the Ntuple for the counts(y-axis) vs neutrons energies (x-axis; binned) that were emitted from the walls in a 5 Million event run.

Then, two simulations were used to generate neutron spectra with and without the Pb castle. In both simulations, 5 million events or wall neutrons were projected so that the results could be compared. The following results show the total neutron spectra, meaning it includes both the primary and secondary neutron particles.

Figure 9 shows the neutron spectra detected in the BDS Gel without the Pb castle in the 5 Million

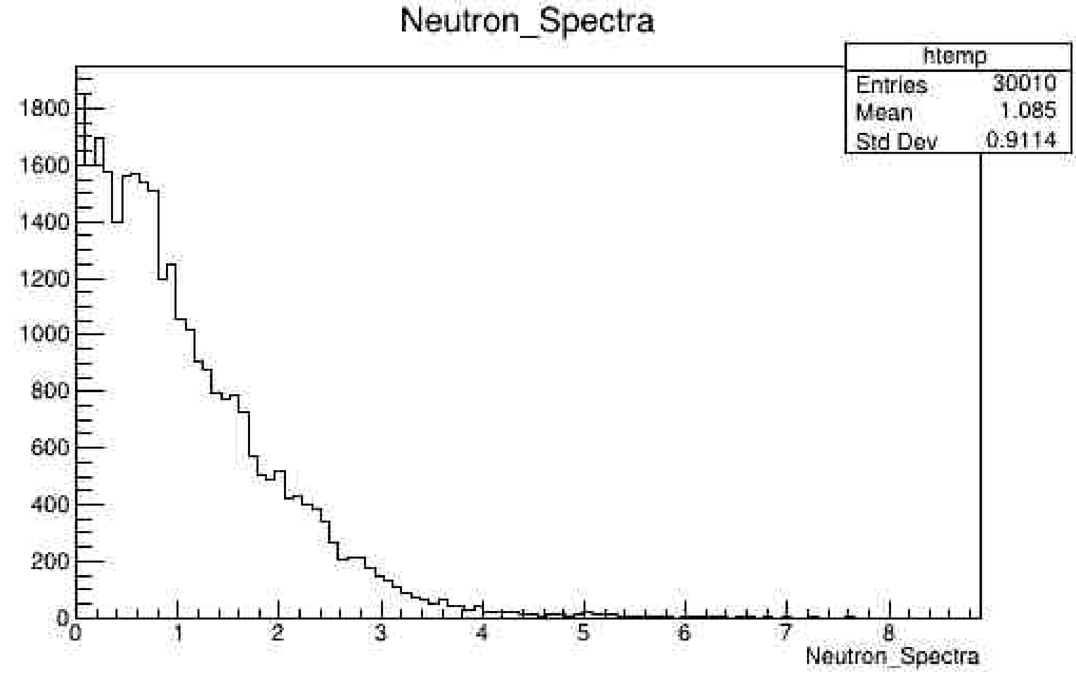


Figure 8: This figure shows the Ntuple for the counts(y-axis) vs neutrons energies (x-axis; binned) that were detected in the BDS Gel with the Pb castle around the BDS.

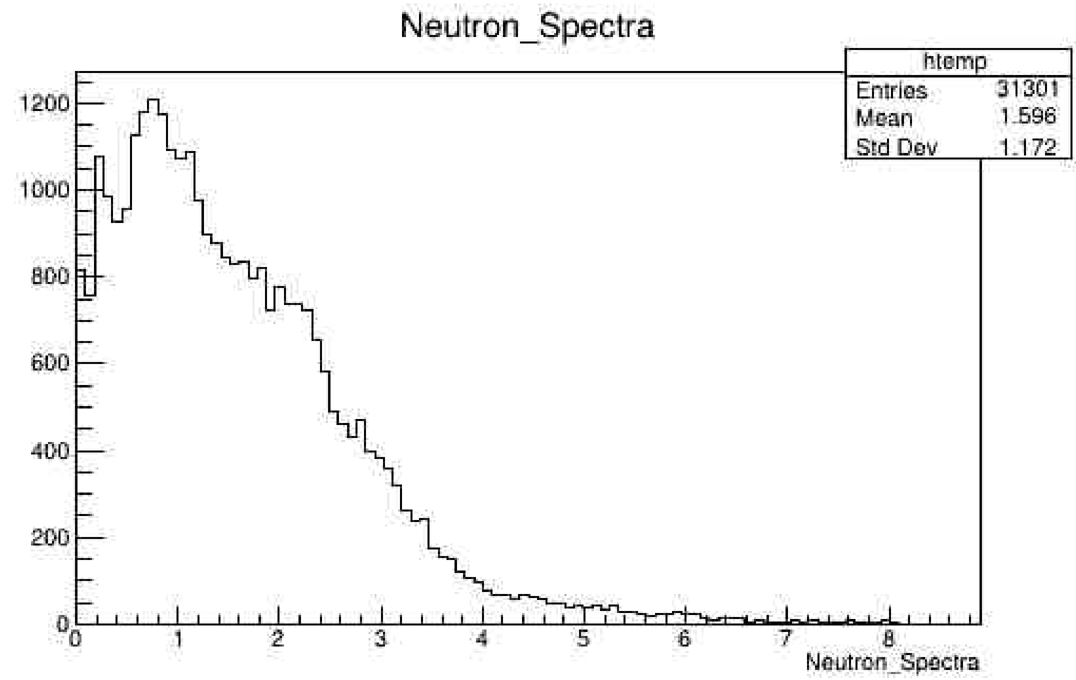


Figure 9: This figure shows the Ntuple for the counts(y-axis) vs neutrons energies (x-axis; binned) that were detected in the BDS Gel without the Pb castle

event run. Compared to figure 7, the neutron energies are lower since the neutrons interact with the pressure Chamber, Air and BDS tube materials on the way, but the spectra shape was still acceptable.

Figure 8 shows the neutron spectra in the BDS Gel with the Pb castle, and apparently, the Pb castle lowers the neutron energies, and the spectra shape is different compared to the wall's neutrons. By investigating the primary and secondary neutrons, it was noted that with the Pb castle, secondary neutrons due to Pb neutron interactions were detected in the 0-2 MeV region. These neutrons pose a threat to the BDS Lab neutron Flux calculations.

4 Conclusion

4.1 Radon Monitoring Conclusion:

Out of the 36 radon monitors tested at SNOLAB, 24 were found to be accurate within a 25% range compared to the AlphaGuard PQ-2000. The Airthings and Funny Kitchen radon monitors showed lower cumulative radon averages. The RadonEye and CRAD monitors demonstrated good agreement with expected radon levels, with the RadonEye being especially responsive to high radon exposure on May 3rd. The responsiveness of manual monitors to changing radon levels is yet to be determined due to their cumulative averaging. A more consistent data collection strategy is needed to draw conclusions about their responsiveness to radon level fluctuations.

Some radon monitors displayed lower levels compared to AlphaGUARD, possibly due to the underground air being filtered, which may affect the testing environment. The absence of radon progeny might be causing some measurements to register lower radon levels than expected. Health Canada has suggested a radon progeny test using an Alpha-Beta counter to provide a more comprehensive analysis of radon levels, accounting for environmental factors like temperature and humidity.

4.2 Bubble Detector Spectrometer Simulation Conclusion:

The previous GEANT4 simulation for the BDS simulation was successfully updated for improved tracking, physics list, geometry, and gun initialization to project spectra based upon the BDS.

The neutron spectra results indicated that the Pb castle considerably affects the neutron energies emitted from a particular Neutron Flux and creates new background secondary neutrons, which can affect the BTI's "unfolding" calculations. Due to the simulation results, it was concluded that the Pb castle is to be removed since its cons outweigh its pros.

Thus, according to the simulation, the Pb castle geometry considerably affects the neutron energies and creates unnecessary neutrons, which can affect the neutron spectrometer calculations.

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A Radon

A.0.1 What is Radon?

The best introduction is available in Wikipedia as follows:

> Radon is a chemical element; it has the symbol Rn and atomic number 86. It is a radioactive noble gas and is colorless and odorless. Of the three naturally occurring radon isotopes, only radon-222 has a sufficiently long half-life (3.825 days) for it to be released from the soil and rock where it is generated. Radon isotopes are the immediate decay products of radium isotopes. The instability of radon-222, its most stable isotope, makes Radon one of the rarest elements. Radon will be present on Earth for several billion more years, despite its short half-life, because it is constantly being produced as a step in the decay chain of Uranium and Thorium(mostly present in rock and minerals), each of which is an extremely abundant radioactive nuclide with an average half-life of thousands of years.(2)

There are many methods to detect Radon, such as Scintillation devices, Radon emanation boards, Sample Analysis, Radon Progeny Integrating Sampling Unit and more, but in general, most commercially available Radon Monitors use Ionization Chambers or photo-diode Alpha Spectroscopy since they are efficient.

A.0.2 Why is Radon a potential health threat?

The following quote about Radon Cancer lung threat is from the Canadian Cancer Society:

> The International Agency for Research on Cancer (IARC) classifies Radon as a known cause of cancer. Exposure to radon gas increases your risk of lung cancer. This risk depends on how much Radon you are exposed to and for how long, as well as if you are a smoker.
>
> Health Canada estimates that about 16% of lung cancer deaths are related to being exposed to Radon in the home. Radon exposure is the leading cause of lung cancer in non-smokers, and it's estimated that in Canada, there are more than 3,300 lung cancer deaths related to Radon each year. If you smoke, you are at an even higher risk of developing lung cancer if you are exposed to radon(3).

A.0.3 Radon is a major background threat in underground low-background Physics experiments. Why?

Underground Physics experiments like those at SNOLAB require sensitive detectors and this requires reducing environmental factors which can affect the experiments. These unwanted environmental factors are often called "background". Air particulate backgrounds can be controlled by proper air ventilation. Most heavy solid molecules and unwanted electromagnetic radiation (especially high energy gamma and X-ray) can be stopped by shielding materials, but radioactive gases like Radon are more challenging to remove directly. The Radon produced as radioactive decay from the rocks around the detector will eventually decay into its products, but many of its products are metals that can stick to the detector's surface. A particular decay product is Lead-206, which is considerably stable and poses a significant background threat to the detector. The ideal solution to reduce this whole chain of background is to prevent Radon from being near the detectors.

B Bubble Detector Spectroscopy(BDS)

Bubble Detector Spectrometer(BDS) is a bubble detector package from Canada's Bubble Technology Industries(BTI). The BDS package includes numerous bubble detector tubes which act as neutron detectors with different sensitivities and six energy threshold ranges: 10, 100, 600, 1000, 2500 and 10000 KeV(4). These bubble detector tubes perform neutron spectrometry from 10 keV to 20 MeV +/- 10% for most neutron fields. The BDS bubble detectors are lightweight and compact, and they are widely used in Nuclear Industries and Space Stations(5). Individual BDS detector tubes contain microscopic superheated[13] droplets maintained in a continuous meta-stable liquid state. These droplets are dispersed throughout a clear, elastic polymer and can detect neutrons through the formation of bubbles resulting from physical neutron interactions with the droplets (6). The gel polymer enables dispensed bubbles in the detectors, which can be seen by the eye. Still, a calibrated bubble detector optical device with proper calibration can provide more details for the counts and bubble size.

The BDS detectors are reusable as the bubbles can be pressurized back to a liquid state using pressure pumps; thus, the BDS can be used for at least nine months in typical neutron fields as long as the neutron-sensitive droplets avoid physical damage and chemical structure alteration due to contaminations. The tube of each bubble detector is made from low radioactive materials like Acrylic glass, which are thick enough to stop unwanted ions like Alpha.

BTI provides an "unfolding" calculation spreadsheet which performs the neutron spectrometer cal-

[13] Wikipedia Superheating: https://en.wikipedia.org/wiki/Superheating

Figure 10: The six energy threshold BDS Detectors.

culation, with the only required information being the number of bubbles in the separate tubes or detectors. The "unfolding" calculation requires good statistical data (at least 100 bubbles for every tube or detector) since the mean cross sections for energy ranges are used in combination with statistical approximations.

C GEANT4 Beginners Guide

GEANT4 is a simulation toolkit of 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. (7)

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 Medial, 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 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[14]: 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[15], 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. Action Initialization[16]: 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.

[14] https://geant4-userdoc.web.cern.ch/UsersGuides/ForApplicationDeveloper/html/Detector/detector.html
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