LIP-STUDENTS-24-2

Background analysis in recent SNO+ data

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Abstract. A study of the ^{210}Bi activity during the second phase of the SNO+ experiment (2022-2024), which contained an organic liquid scintillator as the active medium, was performed. Furthermore, data as been separated into two sets, before and after the addition of a secondary wavelength shifter. The rate of ^{210}Bi decays as a function of time as well as its spectral shape was studied in different fiducial volumes with the help of Monte Carlo simulations.

KEYWORDS: ACTIVITY, RADIOACTIVE DECAY, NEUTRINO

1 Introduction

1.1 The SNO+ experiment

The SNO+ experiment is the succeeding step of the SNO (Sudbury Neutrino Observatory) experiment, which ran between 1999 and 2006, and used water (H_2O or D_2O) as the target medium. The SNO+ experiment has three different phases, characterised by the target medium used inside the acrylic vessel (AV). Firstly, light water (H_2O) was used, followed by a organic liquid scintillator phase, which was subsequently divided in two, PPO and bis-msb. This is the current phase of the experiment and the one discussed in this paper. Finally, the detector will be filled with tellurium in order to search for neutrinoless double beta decay, a not yet observed process that will allow to study the nature of neutrinos (Dirac vs Majorana)

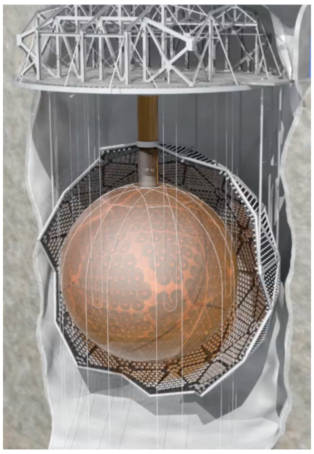

Figure 1. Artistic impression of the SNO+ detector. The AV is surrounded by the PMTs in the PSUP and held down by a system of ropes

1.2 The SNO+ detector

The experiment is located two kilometers underground in a mine in Canada. The flat rock overburden, reduces the number of comics muons reaching the detector by several order of magnitude. The SNO+ detector consists on a 6 m radius acrylic vessel with a thickness of 5.5 cm, which is surrounded by a structure (PSUP) that holds the photomultiplier tubes (PMTs), approximately 8.5 m from the center of the detector. The majority (9362) are inward-facing PMTs, while the other 91 face outwards to detect light from muons and other sources exterior to the PSUP. The entire detector is located in a cavity excavated in the rock and the volume between the AV and the PSUP is filled with ultra-pure water (UPW), to prevent the external radiation (originated in the PSUP and the cavity walls) from reaching the AV. Finally, as the SNO+ liquid scintillator has a lower density than the surrounding water, a system of ropes was developed to hold the AV in place.

1.3 The ^{210}Bi decay

Despite the high radiopurity of the materials selected for SNO+, the liquid scintillator itself, the PSUP, the external water and the cavity walls are a source of radioactive decays. Moreover, the mine air contains ^{222}Rn, which is part of the ^{238}U decay chain, see Figure 2, which can contribute to the radioactive background. Although there are several mechanisms to stop radon ingress in the AV, some ^{222}Rn can still enter the detector, eventually decaying into ^{210}Bi. Furthermore, the AV surface contains a high level of ^{210}Pb (a daughter of ^{222}Rn and parent of ^{210}Bi), which deposited during the construction period of SNO and the transition phase between the SNO and SNO+, when no shield was in place. The ^{210}Bi decays via a beta minus decay, emitting an electron and an antineutrino in the process. This electron can have energies between 0 MeV and 1.2 MeV and is the particle that is detected. This decay corresponds to one of the largest backgrounds at low energies in SNO+ and affects the measurement of low energies solar neutrinos. Therefore, it is the utmost importance to study these events and investigate the detector response accordingly. The analysis in this paper will focus on the data of the ^{210}Bi decay obtained in phase two of the experiment.

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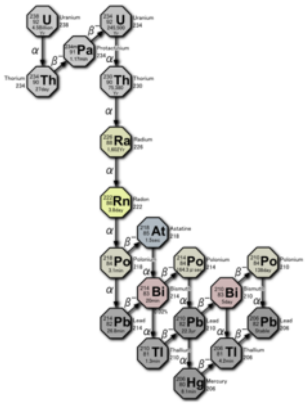

Figure 2. ^{238}U decay chain (Wikipedia. Retrieved from https://en.wikipedia.org/wiki/Radon-222#/media/File:Decay_chain(4n+2,_Uranium_series).PNG.

1.4 Efficiency

In order to separate the ^{210}Bi from the rest of the backgrounds, cuts in energy and position have been applied. Consequently, the efficiency of the cuts has been calculated using Monte Carlo simulations. The efficiency was obtained as the number of events that passed the cuts with respect to the number of events simulated. The resulting efficiencies can be seen in Figure 3.

	FV 6000	FV 5000	FV 4000	FV 2500
Efficiency PPO (%)	10.3666	6.25635	3.2161	0.790491
Efficiency bismsb (%)	2.57426	2.06215	1.01384	0.2064

Figure 3. Efficiencies for the Bi-210 events in the 2.2 g/L PPO and the Bis-MSB phase for various FV

It is expected that the efficiency scales as FV (Fiducial Volume) ratio unless there is an effect that removes events for larger radii. This can be seen as being the case of the 6000 to 5000 mm radius in the bis-msb case, contrary to the PPO case. If the efficiency followed the volume ratio, the 6000 mm value would have been 3.42%, instead of the obtained 2.57%. The difference might be due to the strong radial dependence of the nhits (energy) above 5000 mm, see Figure 4 for the case of ^{214}Bi, a beta decay of the same U chain. This effect is not perfectly modeled in the MC, requiring a different tuning for large radii.

2 The ^{210}Bi spectrum

2.1 2.2 g/L PPO phase

Figure 5 shows the energy spectrum of the PPO phase. Since our goal is to study the activity of the ^{210}Bi the region of interest that was chosen was between 0.6 MeV and 0.9 MeV. This corresponds to the region where the decay is dominant.

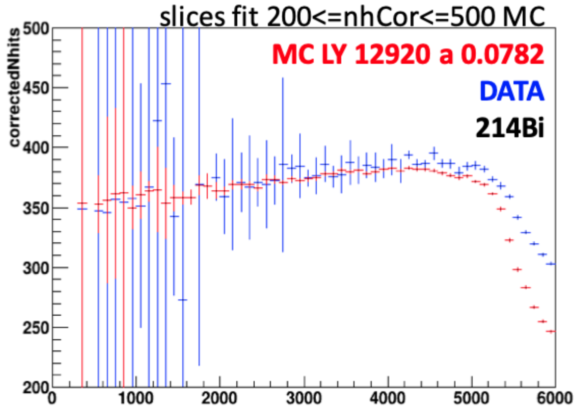

Figure 4. Plot of the dependence of the corrected Nhits with radius for the Bi-214 decay in the U-chain for both data and MC.

In this region, however, there is a disagreement between the data and the MC simulations for energies closer to 0.9 MeV. Instead of a downward trend, a plateau is observed. This region is still under investigation.

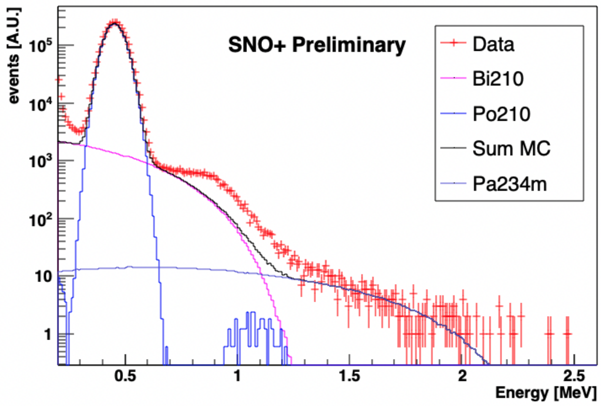

Figure 5. Example of the energy spectrum of the SNO+ scintillator during the 2.2 g/L PPO phase

The next step after defining the region of interest, is to plot the number of events for a selected number of days and verify if there is any significant fluctuation. To do this, three plots for the fiducial volumes of 2500 mm (6), 5000 mm (7) and 6000 mm (8), were made. Since, not every day had the same number of runs and each run corresponds to one hour, in order to compare the various periods, the events were normalized to 23 hours.

From this initial plots, some preliminary conclusions can be made. First it is possible to notice that the later dates have a higher rate, independently of the volume. This indicates that a possible contamination happened around the month of February. This is especially noticeable in the plot for the FV of 2500 mm where the rate around the middle of February (2023-2-11 and 2023-2-19) rises above the rest. Furthermore, all the other dates fluctuate, more or less, between the same (lower) values.

To improve the accuracy and better understand what is happening around the dates where the number of events

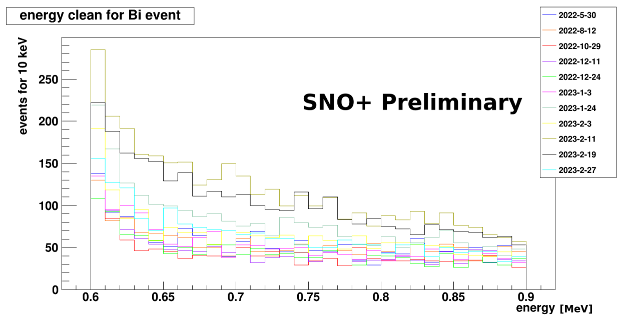

Figure 6. Energy plot of the bismuth 210 decay for the a FV of 2500 mm

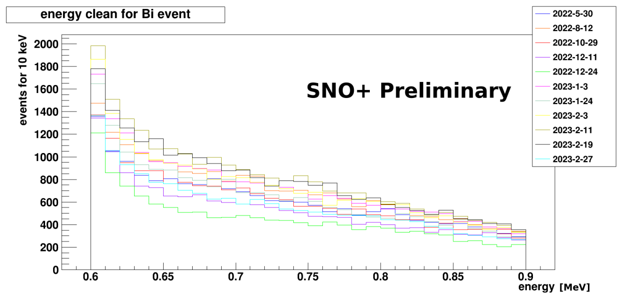

Figure 7. Energy plot of the bismuth 210 decay for the a FV of 5000 mm

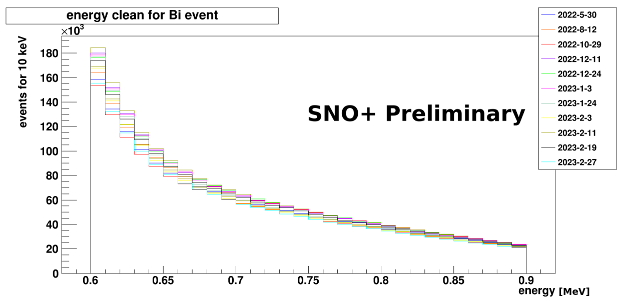

Figure 8. Energy plot of the bismuth 210 decay for the a FV of 6000 mm

deviates substantially from the average, a few more runs were analysed, doubling the statistics. Starting from the number of events, the daily activity was calculated.

This is done by dividing the number of events by the respective efficiency and by livetime. The results are plotted in Figure 9.

Figure 9 shows that the activity in the 6000 mm FV is much larger than the rest. As mentioned in section 1.3 Radon atoms attached to the surface of the AV mainly during the SNO construction period. While the ^{222}Rn has decayed away, its long lived daughter ^{210}Pb ($T_{\frac{1}{2}} = 22.2$ years), which is also the parent of the ^{210}Bi, is still here, leading to higher surface activity when compared to the bulk of the scintillator (smaller FVs). Additionally, for the bulk of the scintillator, in the beginning (June/July 2022) and at the end (January/February 2023) the activity

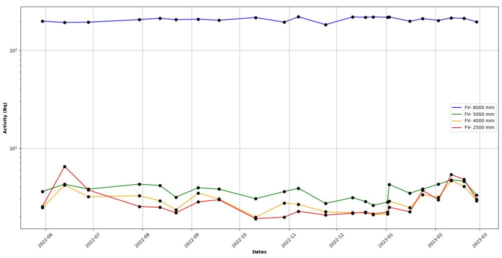

Figure 9. Bismuth 210 activity for the 4 different FV during the 2.2 g/L PPO phase

is much higher than average. We suggest that these deviations are due to some external contamination that might have entered the detector. Moreover, it is possible that these contaminations are connected since their magnitude is almost the same.

The average values for the various fiducial volumes (except 6000 mm) are shown in Figure 12

2.2 bis-msb

During the period between March and December 2023 a secondary wavelength shifter was added to the AV with the objective of shifting the scintillator light to longer wavelengths reducing the absorption emission by PPO and increasing the detected light yield by a factor of about 1.6. This should enhance the event separation between fiducial volumes and improve the final activity results. An analysis of the bis-msb phase data was therefore performed with the goal of comparing the results between the two phases.

For this analysis a cut in the corrected hits was performed between the values of 350-520 Nhits (see Figure 10). The energy spectrum could not be used as a proper energy calibration was not yet available. The region was selected with the help of the ^{210}Bi simulation to identify the region where it dominated.

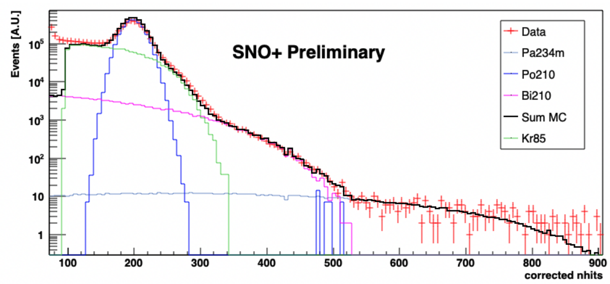

Figure 10. Example of the PMT hit (proportional to energy) corrected nhits spectrum of the SNO+ scintillator during the Bis-MSB phase

Following the sames steps as before, a plot of the activity, as well as its average value for the three smaller fiducial volumes was made (see Figures 11 and 12).

Looking at the average values it is possible to see that they are higher compared to the PPO phase. The possible

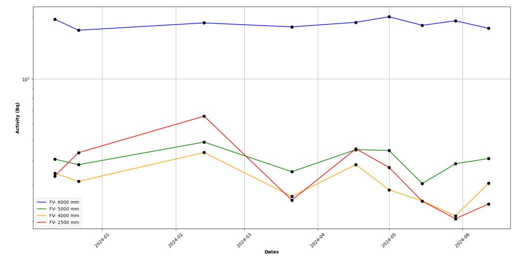

Figure 11. Bismuth 210 activity for the 4 different FV during the Bis-MSB phase

	Average PPO (Bq)	Average bismsb (Bq)
FV 5000	3.65	4.02
FV 4000	2.89	3.11
FV 2500	2.92	3.56

Figure 12. Average of the activity for the smaller three FV during the PPO and the bis-msb phase

cause for this is a contamination that entered during the detector operations for the bis-msb addition. Furthermore, when comparing the activity for the fiducial volume of 5000 mm and the activity for the fiducial volume of 4000 mm in both plots (PPO-9, MSB-11) it was anticipated that the deviation between them would be lower in the bis-msb plot. The reason being that in this latter phase it was expected a better energy and position resolution, leading to a better separation between the fiducial volumes. As a result, events from the surface should have a lower impact on the 5000 mm FV, reducing the activity for this fiducial volume (when compared to the PPO case). However, these results diverge for the observed ones (consult Table 12). This indicates that, not only might there still be a contamination for bigger fiducial volumes after the detector operations, but also that a re-calibration of the position should be done.

Additionally, to better understand the source of the two peaks in the fiducial volume of 2500 mm it was decided to divide the AV in its top an bottom parts. To do it a cut was performed in the z variable and the efficiency was calculated accordingly, following the same method mentioned in 1.4. The results obtained are shown in Figure 13. Notice the results were calculated by subtracting the lower part to the upper part and therefore if a value is positive it means that the majority of the activity was present in the lower hemisphere.

By comparing this data with the one already obtained it was possible to gather more information about the contamination periods. For instance in February 2024 the contamination seems to be coming from the bottom of the AV.

	2023-12-12	2023-12-22	2024-02-13	2024-03-21	2024-04-17	2024-05-01	2024-05-15	2024-05-29	2024-06-12
FV 6000	3.24	1.44	3.62	0.09	3.69	3.26	2.54	3.63	3.37
FV 5000	-0.08	-1.12	1.47	-1.22	1.67	1.08	0.36	0.57	0.74
FV 4000	0.21	-0.85	1.18	-0.86	1.61	0.87	0.71	0.07	0.89
FV 2500	-0.01	-1.98	0.45	-0.64	0.66	0.67	0.42	0.32	0.56

Figure 13. Activity difference between the lower and upper parts of the AV during the bis-msb phase

3 Conclusions and future steps

During this analysis a study of the energy and Nhits spectrum of the ^{210}Bi was made for the two periods of the SNO+ scintillator phase. A region of interest was defined and the corresponding cut efficiencies were calculated. Finally, the activities of the two periods were calculated and compared. The conclusions reached were that a possible contamination happened in the periods of June 2022 and February 2023, for the PPO phase and that during the addition period of the bis-msb a possible contamination entered the detector and lead to the spike in activity seen in February 2024 (for the 2500 mm FV).

Throughout this study some unexpected results were obtained and in order to better understand them it is important that a further analysis is performed. For instance, the analysis done for the second phase should be repeated, using the energy spectrum, instead of the Nhits spectrum. The plateau region in the PPO period should be better investigated as well. Finally, a continuous contamination was observed in the lower hemisphere. As such, a further analysis should be done to check if a minimum has been reached or if this contamination disappears in the future.

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