Background Analysis for the SNO+ Experiment

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Abstract. SNO+ aims to conduct a world leading search for neutrino-less double beta decay of ^{130}Te with a 5 year half-life sensitivity of 1.9×10^{26} years using 3.9 tonnes of natural Tellurium isotropically loaded in 780 tonnes of liquid scintillator. The total background budget within 0.5σ to 1.5σ of the $0\nu\beta\beta$ energy is 13.4 events per year, dominated by ^{8}B solar neutrinos. We discuss SNO+ analysis strategies to measure the residual Uranium and Thorium chain backgrounds through the timing coincidence of short half-life components ^{214}Bi – ^{214}Po and ^{212}Bi – ^{212}Po. We show that these so-called Bi-Po events can be rejected from the $0\nu\beta\beta$ region of interest (ROI) with 99.995% efficiency and minimal (<2%) signal sacrifice. Pure samples of Bi-Pos can also be created to accurately measure the rates of Uranium and Thorium decays in-situ. In a fraction of decays, the Polonium alpha decay will occur within the same trigger window as the beta, resulting in a higher energy 'pile-up' event. Separate classifications based on the hit timing structure efficiency reject these events with minimal (<1%) signal loss. A final class of background events results from the pile up of higher frequency low energy backgrounds with events such as $2\nu\beta\beta$, which would not otherwise contribute to the ROI. We present a final set of of event classifiers developed specifically to reject these events and show that their contribution to the double beta analysis can be reduced to negligible levels.

1. Introduction

The SNO+ experiment[1] will search for neutrino-less double beta decay ($0\nu\beta\beta$) of ^{130}Te using 3.9 tonnes of natural Tellurium isotropically loaded in 780 tonnes of LAB-PPO liquid scintillator. The total background budget within the energy region of interest (the ROI, defined as $0.5\sigma - 1.5\sigma$ around the $0\nu\beta\beta$ Q-value, 2.53 MeV) is 13.4 events per year. Whilst solar ^{8}B neutrino and $2\nu\beta\beta$ backgrounds can only be reduced by improving energy resolution, we can apply both purification and analysis techniques to reduce other background contributions. These proceedings discuss the analysis algorithms developed to measure and reduce the contributions of ^{238}U chain (target level $< 1.3\times10^{-15}$ g/g in the scintillator cocktail) and ^{232}Th chain (target level $< 4.9\times10^{-16}$ g/g in the scintillator cocktail) decays and also techniques to reject random pile-up background.

2. Delayed Coincidences

The naturally arising 238-Uranium and 232-Thorium decay chains both contain short-lived isotopes of Bismuth. Fortunately, these short-lived decays follow the highest energy beta emission steps in the chains that are most likely to contribute to the $0\nu\beta\beta$ ROI. In the Uranium chain ^{214}Bi beta decays (beta endpoint energy = 2.25 MeV) with a branching fraction of >99% to ^{214}Po that subsequently alpha-decays with a half-life of 164 μs, and in the Thorium chain

^{212}Bi beta decays (beta endpoint energy = 3.27 MeV) with a branching fraction of 64% to ^{212}Po that subsequently alpha-decays with a half-life of 0.30 μs. In both cases the delayed coincidence of the alpha can be used to tag and reject the proceeding beta decay. We have developed rejection criteria based on the timing between the alpha and beta candidate events, $\Delta T_{\beta-\alpha} < 24 \times T_{1/2}^{214Po}$, the number of hits in the alpha candidate event, Nhits$_\alpha > 50$, and the reconstructed spatial separation of the beta and alpha, $\Delta R_{\beta-\alpha}$ <1.5 m (this latter cut is not applied if $\Delta T_{\beta-\alpha}$ <500 ns). These criteria are found to reject 99.9975% of all ^{214}Bi events and 99.999% of all ^{212}Bi events within the 3.5 m analysis fiducial volume when the alpha is emitted ≥400 ns after the beta. The Nhits and ΔR cuts are required to limit signal sacrifice, which can occur if a true signal event is incorrectly tagged by a different low energy background event, mistaken for the Polonium alpha decay. This effect is dominated by ^{14}C and ^{210}Po and ^{210}Bi, Radon daughters that have accumulated on the acrylic vessel (AV) that can leach into the scintillator during data taking. We conservatively predict the rate of all background events above 50 Nhits, R_{bg}, to be 190 Hz and calculate the probability of mistagging true signal (sacrifice) to be 1.2% with equation 1.

$$P_{\text{mistag}} = 1 - \exp\left(-R_{bg} \times dT \times \left(\frac{dR}{R_{AV}}\right)^3\right) \tag{1}$$

3. Characterising the U and Th levels in the Scintillator

A more stringent version of the rejection criteria, presented in the previous section, have been developed to select pure samples of ^{214}Bi-Po and ^{212}Bi-Po events in order to characterise the contribution of the Uranium and Thorium chain backgrounds within the scintillator volume. The selection is applied over a slightly larger, 4 m fiducial volume with $\Delta T < 12 \times T_{1/2}^{214Po}$ and $\Delta R < 2$ m and more stringent cuts on the Nhits of both the Bismuth and Polonium candidate events in order to reduce the contamination due to the ^{14}C and ^{210}Po and ^{210}Bi backgrounds mentioned above. This analysis has been conducted for the pure pre-Te-loaded scintillator phase and found to provide a >99% pure sample of ^{214}Bi-Po with 16.5% efficiency, and a 63% pure sample of ^{212}Bi-Po with 7.5% efficiency allowing 7% precision in the measurement of the ^{238}U background contribution and 41% measurement precision on the ^{232}Th background contribution within 3 months at the expected background levels. The lower precision on the Thorium chain background is due to the lower expected rate of ^{212}Bi events (including the lower branching fraction to ^{212}Po), and also a higher contamination of this sample due to greater overlap in Nhits distributions of the ^{212}Po and ^{212}Bi events with ^{210}Po and ^{210}Bi backgrounds.

4. Bi-Po Pile Up

Due to the exponential nature of radioactive decay, there will naturally be cases where the Polonium decays very promptly after the beta such that the beta and alpha event pile up in the same event time window (the SNO+ trigger window is 400 ns) without any second trigger. In these cases, the combined energy of the two decays is recorded, which results in a higher relative contribution of this class of event to the ROI. We have developed a series of analysis classification algorithms, based on the residual hit time distribution[1], to identify and reject these 'Bi-Po pile-up' events. The first algorithm is based on the expected step in the cumulative hit time residual distribution at the point where the alpha decay occurs as shown in figure 1. Two other algorithms apply a likelihood method also taking into account the expected energy deposit of the alpha and the fact that alpha decays produce scintillator pulses with a slightly higher contribution of late light as shown in figure 2.

[1] The time residuals are calculated from the hit time for a given PMT with respect to the event trigger time, taking into account the expected photon flight time direct from the reconstructed event position to that PMT.

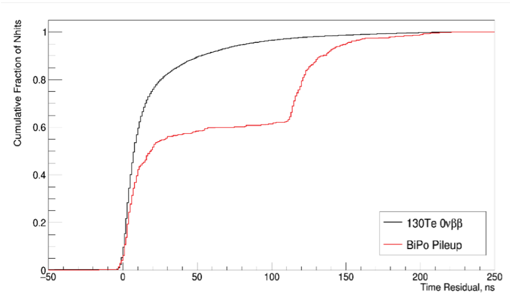

Figure 1. Cumulative timing classifier for Bi-Po pile-up events[2]. Signal events exhibit a smooth curve, but pile-up events show a step when the alpha decay occurs.

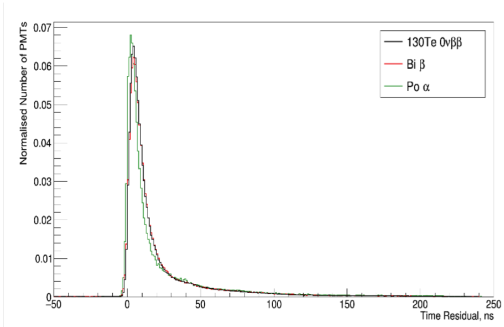

Figure 2. Likelihood difference for time residual PDFs for beta, alpha and $0\nu\beta\beta$ signal events.[2]

We have simulated a scintillator cocktail formed of LAB-PPO and 0.3% loading of natural Tellurium using a PRS surfactant, and when applying all these classification algorithms together, we achieve a factor of 38 rejection of ^{212}Bi-Po pile-up events, and a factor of 49 rejection of ^{214}Bi-Po pile-up events, with only 3.3% signal sacrifice. It should be noted that the SNO+ collaboration is continuing with scintillator cocktail R&D to achieve a higher initial loading of 0.5% and differences in the optical model and improved light yield will have an impact on these predictions. Hence an updated analysis is in progress.

5. Random Pile Up

There is a chance that two or more events within the detector will occur within the same 400 ns trigger window and contribute to the same event. The resulting 'pile-up' event will be reconstructed as a single event with a greater combined energy than either of the individual components. Thus, potentially high frequency, low energy decays such as ^{14}C, ^{210}Bi and ^{210}Po, could pile up with higher energy events like ^{130}Te $2\nu\beta\beta$ decay, causing events that would otherwise be below the $0\nu\beta\beta$ Q-value to contribute to the analysis ROI. However, due to both the spatial and timing separation of the composite decays, it is possible to identify and reject the majority of these events. Algorithms based on the spatial distribution of hits (for single events an isotropic distribution is expected) and timing distribution of hits can be applied and are shown to reduce the expected 36.3 pile-up events per year to 0.23 events per year, with only 1% signal sacrifice.

6. Summary

We have presented analysis techniques that significantly reduce the contributions of ^{238}U and ^{232}Th chain and pile-up events to the SNO+ $0\nu\beta\beta$ analysis, such that they contribute only a small fraction of the 13.6 event per year expected background in the energy region of interest.

Acknowledgments

This research was supported by the European Unions Seventh Framework Programme FP7/2007-2013, under the European Research Council (ERC) grant agreement 278310.

References

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