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Rejection of backgrounds from pileup alpha coincidences in the SNO+ detector

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Abstract. SNO+ is a multi-purpose neutrino detector with a number of physics goals, one of which is to investigate the existence of Neutrinoless Double Beta Decay. The potential rarity of this process means that other radioactive decays occurring in and around the detector can become major background sources. Two such backgrounds are the $\beta$ decays of $^{214}$Bi and $^{212}$Bi, which are followed by the $\alpha$ decays of their respective daughters: $^{214}$Po and $^{212}$Po. These daughters have relatively short half-lives, and so these $\beta$-$\alpha$ coincidences can form pileup events in the detector. Two methods are presented here for rejecting such pileup coincidence events.

1. Introduction

SNO+ is the successor to the Sudbury Neutrino Observatory (SNO), located 2km underground in Ontario, Canada. It consists of a 6-metre radius spherical volume of liquid scintillator surrounded by 7000 tonnes of ultra-pure water and observed by over 9000 photomultiplier tubes (PMTs) that detect the light from scintillation events (a more detailed description of the experiment is given in [1]). The detector’s location, with a 6000 m.w.e. rock overburden [2], provides shielding from cosmic particle flux, and the ultra-pure water reduces the number of backgrounds entering from the surrounding rock. However, there are still backgrounds present in the scintillator itself, including the $\beta$ decays of $^{214}$Bi and $^{212}$Bi, which are followed by the $\alpha$ decays of their respective daughters $^{214}$Po and $^{212}$Po. This $\beta$-$\alpha$ coincidence can occur completely within a single 400ns-wide trigger window due to the short half-lives of the Po daughters, making the coincidence a pileup event that appears very similar to a potential $^{130}$Te neutrinoless double beta decay ($\beta\beta_0\nu$) event.

The time residual, $t_{\text{res}}^i$ of a single triggered PMT in any given event is calculated by:

$$t_{\text{res}}^i = t_{\text{pmt}}^i - t_{\text{light}}^i - t_{\text{ev}}$$

where $t_{\text{pmt}}^i$ is the $i$th PMT’s trigger time, $t_{\text{ev}}$ is the reconstructed event time, and $t_{\text{light}}^i$ is the travel time through the varying materials between the event and PMT. Figure 1 shows the normalised $t_{\text{res}}$ distributions for $^{130}$Te $\beta\beta_0\nu$, $^{214}$Bi $\beta$ and $^{214}$Po $\alpha$ events (the distributions for $^{212}$Bi and $^{212}$Po look identical to their 214- counterparts).

2. Cumulative Time Residuals Method

The cumulative number of triggered PMTs up to a given value of $t_{\text{res}}$ is a reliable way of viewing the differences between $^{130}$Te $\beta\beta_0\nu$ and BiPo events. Figure 2 shows the cumulative fraction of triggered
The normalised distributions for $^{130}$Te $\beta\beta$0$\nu$, $^{214}$Bi $\beta$, and $^{214}$Po $\alpha$ events. The Te and Bi distributions are almost identical, but the Po distribution has a lower peak and longer tail, both resulting from the larger late-light component associated with scintillating $\alpha$’s.

PMTs as a function of $t_{\text{res}}$ for a typical BiPo pileup event (the fraction is used rather than the raw number of PMTs in order to correct for the slight variation in the raw number of PMTs per event).

A Kolmogorov-Smirnov test between the BiPo and CDF curves quantifies the difference, using:

$$\Gamma = \frac{1}{N_{\text{hits}}} \times \sum_{b} \left( x_{b}^{\text{ev}} - x_{b}^{\text{cdf}} \right)^2$$

where there are $b$ bins in each distribution, and $x_{b}$ is the normalized number of events in bin $b$. Figure 3 shows the distribution of $\Gamma$ for $^{130}$Te $\beta\beta$0$\nu$ and $^{214}$BiPo events.

The normalised cumulative fraction of triggered PMTs as a function of $t_{\text{res}}$ for $^{130}$Te $\beta\beta$0$\nu$ events (smooth curve, top) and a BiPo pileup event (double-shouldered curve, bottom).

The values of $\Gamma$ for $^{130}$Te $\beta\beta$0$\nu$ (left-side peak) and $^{214}$BiPo (low-level spread) events. $^{212}$BiPo events have an almost identical distribution to the latter. There is a very clear separation between the Te and BiPo events.

3. Log-Likelihood Difference Method

The log-likelihood of an event being $^{130}$Te $\beta\beta$0$\nu$ based on its $t_{\text{res}}$ distribution is given by:

$$\mathcal{L}_{\text{Te}} = \sum_{i=1}^{N} \ln \left( N_{\text{PMT}}(t_{i_{\text{res}}}) \right)$$

where $N$ is the number of triggered PMTs and $N_{\text{PMT}}(t_{i_{\text{res}}})$ is the probability of the $i^{th}$ PMT having the time residual $t_{i_{\text{res}}}$ based on the $^{130}$Te $t_{\text{res}}$ distribution in Figure 1. Similarly, using the Bi and Po $t_{\text{res}}$ distributions, the log-likelihood of the same event being a BiPo pileup is:
where \( A \) is the mean number of triggered PMTs in a Po \( \alpha \) event (different for \(^{214}\)Po and \(^{212}\)Po). The quantity \( \Delta t \) represents the delay before the \( \alpha \) emission, and is varied to maximize \( \mathcal{L}_{\text{BiPo}} \). This leads to a minimised difference:

\[
\Delta \mathcal{L} = \mathcal{L}_{\text{Te}} - \mathcal{L}_{\text{BiPo}}
\]

Figure 4 shows the distribution of \( \Delta \mathcal{L} \) for \(^{130}\)Te \( \beta\beta\)0\(\nu\) and \(^{214}\)BiPo pileup events.

4. Overall Bi-Po Rejection

Figure 5 shows the remaining BiPo pileup percentage as a function of the remaining \(^{130}\)Te \( \beta\beta\)0\(\nu\) percentage, where each point corresponds to a cut-value on either \( \Gamma \) or \( \Delta \mathcal{L} \). (The \(^{212}\)BiPo curves are limited by statistics.)

In both backgrounds, the Log-Likelihood Difference method performs better than the Cumulative \( t_{\text{res}} \) method. However, there are still a small number of BiPo events remaining. These events all have a very fast \( \alpha \), i.e. one that has been emitted <15ns after the Bi \( \beta \). In this situation, the BiPo \( t_{\text{res}} \) distribution looks identical to that of \(^{130}\)Te \( \beta\beta\)0\(\nu\), making discrimination impossible.

References
[1] SNO Collaboration 2000, *Nucl. Instrum. Methods* A 449 172-207
[2] Lozza V 2012 *J. Phys.: Conf. Series* 375 042050