Pulse Shape Analysis Techniques in Liquid Scintillator for the Identification and Suppression of Radioactive Backgrounds to Neutrinoless Double Beta Decay

To cite this article: J Dunger and SNO+ Collaboration 2017 J. Phys.: Conf. Ser. 888 012083

View the article online for updates and enhancements.
Pulse Shape Analysis Techniques in Liquid Scintillator for the Identification and Suppression of Radioactive Backgrounds to Neutrinoless Double Beta Decay

J Dunger for the SNO+ Collaboration
Denys Wilkinson Building, Keble road, Oxford OX1 3RH, UK
E-mail: jack.dunger@physics.ox.ac.uk

Abstract. Spatial/temporal patterns of light produced in large scintillator experiments like SNO+ are sensitive to particle ID/count. Here we set out rules for choosing a test statistic for hypothesis testing based on timing and demonstrate two applications to the SNO+ [1] neutrinoless double beta decay ($0\nu\beta\beta$) experiment: constraining internal $^{60}$Co contamination, and suppressing the 2.6MeV $\gamma$ background created by $^{208}$Tl decay on the acrylic vessel.

1. Event Topology and Time Residuals

The emission time distribution of optical photons in large scintillation detectors depends on particle type and event topology. $O(1\text{MeV})$ $e^-$ tracks in liquid scintillator are just mm, but position resolution in typical large liquid scintillator experiments is typically $O(10\text{cm})$. Single-site (SS) electron events therefore appear point-like: light is isotropic with a time profile indistinguishable from that intrinsic to the scintillator (Figure 1).

Some events are multi-site (MS): more than one primary particle is created, or the particles created are only visible via a series of discrete interactions with the scintillator, e.g. $\gamma$. The MS response is the convolution of the SS response and the event’s energy deposition time profile. Nuclear $\beta\gamma$ decays create several vertices just ns apart, slightly spreading the emission out in time relative to SS events (Figure 1).

Of course, detectors observe photons as they trigger PMTs, not as they are emitted. To correct for time of flight we define a ‘time-residual’ for each hit $i$:

$$t^i_{\text{res}} = t^i_{\text{hit}} - t^i_{\text{flight}} - t_{\text{vertex}}$$

for $t^i_{\text{flight}}$ calculated flight time between PMT $i$ and the reconstructed vertex, reconstructed time $t_{\text{vertex}}$. Figure 1 shows example average time residual spectra from SNO+ Monte-Carlo.

Time residuals are representative of the photon emission profile that encodes PID information modulo detector response and light path calculation errors from scattering etc. that can be accounted for with Monte-Carlo simulation and/or calibration.

The picture is complicated further by the need to reconstruct a vertex under some hypothesis. If MS events are reconstructed as $e^-$ (as in in SNO+) then the time residuals are smeared by mis-calculated times of flight.
2. Hypothesis Testing

Typically, we observe a binned histogram of time residuals for an event (bin contents $\vec{t}$), and test it against two event hypotheses $H_0$, $H_1$ with mean time residual spectra $\vec{\mu}_0$, $\vec{\mu}_1$ using some test statistic $T$. The Neyman-Pearson lemma guarantees that the log-likelihood ratio test is the uniformly most powerful discriminator $LLR = \log(P(\vec{t}|H_0)/P(\vec{t}|H_1))$, but this is difficult to calculate in general.

If the PMT hits can be considered independent draws, then the LLR simplifies to a linear classifier: $\log(L_0/L_1) = \vec{w} \cdot \vec{t}$ with $w^i = \log(\mu_0^i/\mu_1^i)$. This assumption will approximately hold for well constructed SS events. However for MS events, variation in exact topology creates strong correlations between bins: unusually early or late hits tend to come in groups created by more distant vertices. Correlations also appear when there are distinct subsets of events in a class (e.g. the positrons that form ortho-positronium) or where accuracy of vertex reconstruction varies significantly.

The Fisher discriminant $(F)$ is an alternative that additionally uses the covariance matrices of the two hypotheses to form a linear classifier with $\vec{w} = (\Sigma_0 + \Sigma_1)^{-1}(\vec{\mu}_0 - \vec{\mu}_1)$. This is the linear classifier that maximises the separation of the two distributions $S = (\bar{F}_0 - \bar{F}_1)^2/(\text{Var}(F_0) + \text{Var}(F_1))$.

In the special case that the hits are completely independent and the observed $\vec{t}$ varies due to Poisson fluctuations only, the Fisher discriminant reduces to the Gatti parameter $w^i = (\mu_0^i - \mu_1^i)/(\mu_0^i + \mu_1^i)$. However, under such circumstances the optimal likelihood is simple to calculate. Therefore, far from being generally optimal, the Gatti parameter should be avoided.

In the presence of strong correlations, the Gatti parameter looses by ignoring them and without them a tractable likelihood ratio performs better.

If even with bin-bin correlations accounted for the two hypotheses are not Gaussian, one might be able to do better still with non-linear machine learning algorithms, or a parameterisation of the time residual shape.

3. Constraining $^{60}$Co Contamination

Unstable $^{60}$Co is created by cosmogenic neutron spallation on Te. Its dominant decay produces two $\gamma$ with total energy of 2.5MeV and a low-energy $e^-$. $^{60}$Co decay in SNO+ would sit almost exactly in the region of interest around the $^{130}$Te $2\nu\beta\beta$ decay endpoint. With $t_{1/2} = 5.3$ yr and a production mechanism that scales with Te mass it poses a unique challenge. Underground purification will completely remove any internal $^{60}$Co, but a discovery claim requires in-situ measurement of the contamination level. The characteristic broadening shown in Figure 1 can be used to statistically separate background from signal with a Fisher discriminant. Figure 2 shows the separation achievable with SNO+ filled loaded with tellurium diol to 0.5% Te by mass, and with the same detector fitted with 1ns FWHM transit time spread and Hamamatsu r5912 quantum efficiency PMTs (currently prototyping at Hamamatsu).
Entries 11613
Mean 0.1559
RMS 0.5152

Figure 2. Fisher discriminant distributions for $0\nu\beta\beta$ and $^{60}$Co events $r$/$mm < 4200, 2.49 < E/MeV < 2.65. SNO+ phase I (left) and SNO+ with fast high QE PMTs

Figure 3. Timing based Fisher discriminant (left) and spatial log-likelihood (right) for $0\nu\beta\beta$ and $^{208}$Tl AV events $r$/$mm < 4200, 2.49 < E/MeV < 2.65

4. Suppressing 2.6MeV $\gamma$ from the Acrylic Vessel
The SNO+ scintillator is encased in a 5cm thick acrylic vessel (AV). Naturally occurring $^{208}$Tl on/in the acrylic will decay, emitting a 2.6MeV $\gamma$, low energy $\gamma$ and $e^-$. A small fraction of these 2.6MeV $\gamma$ can penetrate into the detector centre and appear as $0\nu\beta\beta$ candidates, limiting the active detector mass.

The small amount of energy deposited close to the AV by lower energy particles, the several ns delay created by the 2.6MeV $\gamma$ flight into the centre and its multiple scatters give these decays a characteristic timing signature (see Figure 1) that can be used to suppress them. The bin contents $t_i$ are strongly correlated for $^{208}$Tl events so a Fisher discriminant is used to separate the two event classes (non-linear classifiers give no further improvement). Figure 3 shows the separation achievable in a 0.5% loaded SNO+ detector.

Additional rejection can be achieved using the position of early hits. In $^{208}$Tl AV events these hits will be concentrated around the area of the AV where the decay occurred, but will be isotropic for $0\nu\beta\beta$ events. We can deduce the location of the decay using the fact that, statistically speaking, the 2.6MeV $\gamma$ will have travelled radially inwards to reach the detector centre (other paths are exponentially suppressed) and the detector will reconstruct a vertex close to its first scatter.

Therefore early hits $-20 < t_{res}$/ns $<-2$ will concentrate around the direction to the reconstructed vertex, i.e. $\cos(\theta) = \frac{(\vec{r}_{PMT} - \vec{r}_{vertex}) \cdot (\vec{r}_{vertex})}{|\vec{r}_{PMT} - \vec{r}_{vertex}| |\vec{r}_{vertex}|}$ is peaked forwards. Figure 3 shows the separation achievable using PDFs in $\cos(\theta)$ and a likelihood test statistic calculated assuming hits are independent.

References
[1] S. Andringa et al. Advances in High Energy Physics, vol. 2016, 6194250
[2] E.Gatti and F. De Martini, Nuclear Electronics, vol .2, pp. 265-276, IAEA Wien (1962).