IBD Selection for the 288kg Prototype SoLid Module

D Saunders, on behalf of the SoLid collaboration
IH Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol, United Kingdom
E-mail: dan.saunders@bristol.ac.uk

Abstract. The SoLid experiment aims to make a measurement of very short baseline neutrino oscillations using reactor antineutrinos. Key to its sensitivity are the experiment’s high spatial and energy resolution, combined with a very suitable reactor source and excellent background rejection. Placed on the surface at just 5 m from the reactor core, the cosmic flux and reactor output lead to a challenging environment. The fine segmentation of the detector, 5 cm cubes, allows the topology of events to be studied to previously unseen precision. This offers new and unexplored handles for tackling these backgrounds - a key requirement for SoLid physics aims. Using the most recent SoLid prototype (288 kg, 20% scale), we present the first selection to focus on IBD signals. This includes descriptions of SoLid signals and backgrounds, and demonstration that the segmentation can lead to gains in orders of magnitude in background rejection.

1. Introduction
The SoLid detector will perform an oscillation search for sterile neutrinos at a very short baseline of 5.5 m to 10 m using the BR2 reactor at SCK CEN [1]. The experiment aims to resolve the reactor anomaly, where all previous reactor based experiments have measured a deficit in the flux of anti-neutrinos from the reactor to a significance of 2.5 $\sigma$ [2]. One possible explanation is the existence of a fourth sterile neutrino.

The novel design of the SoLid detector aims to tackle the major challenges of performing experiments at the very short baseline. These include large backgrounds, of both cosmic origin as well as the reactor itself. There are also safety restrictions discouraging the use of flammable liquids. The detector will be composed of thousands of 5 cm Polyvinyl Toluene (PVT) cubes, with two sides lined with $^6$LiF:ZnS(Ag). The combination of these two scintillators allow the detection of both charged particles and neutrons [1]. The time scale of light emission varies significantly between these two types of scintillation, allowing the type of signal to be identified. Light is extracted from the cubes using wavelength shifting light fibres that are placed along two orthogonal grooves that are cut into the cubes. The fibres are read out using silicon photomultipliers.

A 288kg (20% full scale) prototype of the experiment was built and commissioned in early 2015. This used a single sheet of $^6$LiF:ZnS(Ag). This took a short three day run whilst the reactor was operational at 60 MW, prior to a one year long refit of the reactor itself, during which many long background runs were recorded. The reactor on run itself is too short to observe a statistically significant neutrino signal, although the two month long reactor off dataset allows for background studies. The results of a first selection to focus on the neutrino signal and reduce the backgrounds using this new detector technology are presented.
2. Signal and Backgrounds

The electron antineutrinos emitted from the reactor are detected using inverse beta decay (IBD) interactions, where a neutrino combines with a proton from the detector, giving rise to a positron and neutron. The positron, also known as the prompt $P$, scintillates in the PVT before annihilating into two photons (which had a negligible detection efficiency at the prototype). The delayed neutron $D$ is detector on average around 60 $\mu$s later once thermalised, typically within a distance of two cubes of the positron. The energy of the positron peaks near 2 MeV, and the segmentation of the detector allows the positron energy to be accurately estimated independently of the annihilation photons [1].

The signal is studied via simulation generated using Geant4 [4], which follows the IBD model found in [3]. Many detector effects such as the masking of channels, complete geometry of the prototype, light yield variations, and degeneracies due to 2D readout are also included in the simulation.

The background in the analysis can be split into two main categories:

- **Correlated Background, $B_{Cor}$**: the P and D signals are produced via the same mechanism, and correlated in time. Sources of this background include muon spallation and fast neutrons. This background is studied using the reactor off dataset (with other backgrounds subtracted).

- **Accidental Background, $B_{Acc}$**: the P and D signals are not correlated in time, and formed of random mismatches between EM and ZnS singles. This has two main parts: the environmental contribution when the reactor is not operational $B_{Acc,Environmental}$; and the additional contribution from the reactor itself when operational $B_{Acc,Reactor}$ [1]. Accidental backgrounds are studied using shifted time windows applied during the IBD reconstruction, using both reactor on and reactor off datasets.

3. IBD Reconstruction

The trigger conditions used for the prototype require multiple channels to be above a pre-set threshold in coincidence. At trigger, waveforms of length 4 $\mu$s are recorded for all above threshold channels. The prompt and delayed interactions are required to trigger separately. SoLid events
are formed of simultaneous signals found in these waveforms from multiple channels, which are coincident at the time scale of the time resolution $O(10)$ ns of the detector [1]. This allows the position of the interaction to be found, as well as other variables such as topological shape.

Electromagnetic events (e.g. positrons, muons), and ZnS(Ag) events (e.g. neutrons) are separated from each-other using pulse shape discrimination. Given the significantly slower scintillation emission rate of the ZnS(Ag) scintillator, the ratio of integral to amplitude $I/A$ of waveforms is a powerful discriminator [1]. In practice, since ZnS(Ag) events are localised to a single cube, a selection is applied to the sum of the two values of $I/A$ from the vertical and horizontal waveforms, and an identification efficiency and purity $> 95\%$ can be achieved.

IBD candidates are found by searching for time correlations between ZnS(Ag) and EM events at the neutron thermalisation timescale $O(100)\mu s$. The time difference between these kinds of events, $\Delta t = t_D - t_P$ is shown in figure 1. Two main components can be observed: a correlated population at the timescale of the neutron thermalisation, which corresponds to $B_{Cor}$. This sits on-top of a large flatter contribution, corresponding to the non-correlated population $B_{Acc}$. IBD interactions inside the detector are indistinguishable from correlated background using $\Delta t$ alone.

A selection is applied in $\Delta t$ to initially form IBD candidates: $0 < \Delta t < 220\mu s$. This retains 91\% of all correlated candidates (such as IBDs). An example candidate is shown in figure 1. As well as $\Delta t$, other IBD features are extracted, including the spatial separation between the Pa and De event in the $x$, $y$, and $z$ directions (in practice, the separation in the $xy$ plane $\Delta xy^2 = (x_D - x_P)^2 + (y_D - y_P)^2$ is used due to symmetry), and the multiplicity (i.e. number of channels forming the event) of the prompt event.

4. IBD Selections

$E_{Prompt}$: The energy of the IBD prompt for signal and backgrounds is shown in figure 2 (after the application of other selections). All backgrounds are found at lower energies than the IBD signal, with the accidental background dominating. Given the steepness of all the backgrounds, a harsh cut is placed in energy: $E_{Prompt} > 1.5$ MeV. This has a signal selection efficiency of $\approx 73\%$, and reduces the remaining background by a factor of 4. An upper energy cut, which has $> 99\%$ signal efficiency, is also placed at 8 MeV to remove muons.

$\Delta xy$: The distributions of the radial separation between the prompt and delayed events in the $xy$ plane is show in figure 2. The signal is well contained at low separations, with 90\% of signal P...
Figure 3. Signal and background rates for the sequential application IBD selections. The topological features are highlighted in blue.

and D events separated by two or fewer cubes. Given the backgrounds are distributed at higher values, they are reduced by a factor of 5.7. This selection is particularly effective at tackling $B_{\text{Acc}}$, giving a reduction in over a factor of 10.

$\Delta z$: The signal is boosted such that the neutron is on average found further from the reactor than the positron. This is due to the kinematics of the IBD interaction, and the $^{6}\text{LiF:ZnS(Ag)}$ screen being placed on the face of the cube that is farthest from the reactor. Conversely, the backgrounds are more isotropic. The selection $0 \leq \Delta z \leq 2$ is applied, which has a signal efficiency of 94% whilst reducing the remaining background by a factor of 2.

*Prompt multiplicity:* Prompt events from $B_{\text{Cor}}$ often trigger many more channels (e.g. muons and proton recoils) than signal. By only selecting prompt event where energy is deposited in one or two touching cubes, the correlated background can be reduced by 30%.

5. Summary and Outlook
The effect of these selections on the signal and background rates are shown in figure 3. For an overall signal selection efficiency of approximately 57%, the total background $B$ can be reduced by a factor of around 180. Of this, the topological selections (if applied after the others) provide an additional factor of 20 in background reduction, and are especially effective in tackling the accidental backgrounds, giving a reduction of over two orders of magnitude.

The construction of full 1500 kg experiment is currently underway [1]. Informed by these studies, the design is being updated to tackle the remaining sources of background, of which correlated background dominates. This will include passive shielding with 50 cm water around the entire detector, and a completely new trigger scheme, expected to be more efficient for both neutrons and positrons. The light yield of the cubes will also be increased, and should allow for better discrimination between signal and backgrounds.

[1] N. Ryder et al. (SoLid), First results of the deployment of a SoLid detector module, EPS 2015.
[2] G. Mention et al, Reactor antineutrino anomaly, Phys. Rev. D 83 073006.
[3] P. Vogel and J. F. Beacom, Angular distribution of neutron inverse beta decay, Phys. Rev. D60 (1999) 053003.
[4] S. Agostinelli, Geant4 - a simulation toolkit, Nucl. Instrum. Methods in Phys. Res. A, 506, 3.