The SoLid reactor anti-neutrino detector

N C Ryder, for the SoLid Collaboration
Department of Physics, University of Oxford, Keble Road, Oxford, OX1 3RH

Abstract. The SoLid collaboration has developed a highly segmented, composite scintillator anti-neutrino detector which will be deployed between 6 and 9 m from the BR2 research reactor in the coming months. The detector is designed to perform anti-neutrino oscillation searches, anti-neutrino energy spectrum measurements and demonstrate the capability for reactor monitoring. Some results from a 288 kg prototype deployment in 2015 are presented, along with details of the upgrades being used in the full 2 t detector that is currently being constructed.

1. The SoLid detector technology

The SoLid collaboration are building a compact anti-neutrino detector for deployment between 6 and 9 m from the center of the BR2 reactor core at SCK·CEN in Mol, Belgium. The aims of the collaboration are to probe the reactor anti-neutrino anomaly [1] by performing a very short baseline oscillation search, to provide precise measurement of the anti-neutrino energy spectrum from a highly enriched reactor core and to demonstrate the capability of using a small anti-neutrino detector for reactor monitoring purposes.

Deploying an anti-neutrino detector within 10 m of a research reactor comes with a number of challenges. At such a close proximity to the reactor core the detector must be compact, with minimal shielding in addition to the low level of over burden provided by above ground deployment in the reactor building. This requires detectors that are carefully designed to distinguish between anti-neutrino events and the significantly higher rate of background events. In particular, background signatures whose rates are correlated with the reactor power must be minimised to simplify the use of reactor off data periods for background estimations. Deploying any system so close to the reactor requires careful assessment of safety risks the equipment introduces, limiting choices of detector materials and electronics while ensuring minimal potential for any liquids to leak from the detector.

The SoLid detector is designed around having a robust, trigger level neutron identification method [2]. This allows collection of a rich data set from many channels of the highly segmented detector around the neutron signal. Data is collected over a time window large enough to include the positron candidate signals as well as additional signals for classifying background events.

The SoLid detector technology is built up from a large number of optically isolated composite scintillator elements. Each element couples a polyvinyl toluene (PVT) cube with a number of \( ^6\text{LiF:ZnS(Ag)} \) sheets. The PVT cube acts both as the anti-neutrino target and as a scintillator to detect the positron resulting from the inverse beta decay interaction. The \( ^6\text{LiF:ZnS(Ag)} \) screens have a high capture cross section for thermal neutrons on the lithium-6 nuclei. The interaction, \( ^6\text{Li} + ^1_0 \text{n} \rightarrow ^4_2 \alpha + ^3_1 \text{H} + 4.78 \text{MeV} \), results in an energetic alpha particle and triton, which deposit their energy in the ZnS(Ag) inorganic scintillator.
The two different scintillators provide optical emissions with dramatically different time signatures, as shown in figure 1. The PVT emits a single pulse, lasting of order nanoseconds, shown in the lower waveform. The emission from the ZnS(Ag) is a much slower decay over microseconds, an example of which is shown in the upper waveform. The distinctly different time signatures allow the light to be collected from both scintillators using the same optical collection system and be categorised by analysis of the waveform.

Each detector element has one or more $^6$LiF:ZnS(Ag) sheets on orthogonal edges of the $5 \times 5 \times 5$ cm$^3$ PVT cube, all wrapped in a Tyvek layer to optically isolate each cube from its neighbours. Grooves in edges of the cubes house wavelength shifting (WLS) optical fibres that are used to collect the scintillation light. The detector is constructed from $16 \times 16$ arrays of composite scintillator elements, with each row or column of 16 cubes coupled to one or two WLS fibres. The combination of signals on vertical and horizontal fibres allows the cube emitting the scintillation light to be identified.

2. Deployment of a 288 kg prototype at BR2
The collaboration deployed a 288 kg prototype detector module at the BR2 reactor in 2015. The prototype module was constructed as 9 planes of 16 by 16 cubes. A single $^6$LiF:ZnS(Ag) screen was coupled to each cube. A single WLS fibre read out each row or column of cubes, with a silicon photomultiplier (SiPM) at one end and a reflective surface at the other end. The detector took data for a few days before the BR2 reactor shut down for an extended maintenance period. Following this the detector collected reactor off data for months before being exposed to various radioactive sources.

The data taking campaign was impacted by poor performance of the analog electronics, which introduced large amplitude sinusoidal noise on all channels. In particular this required raising the trigger threshold such that there was a low efficiency for triggering on the low amplitude neutron signals. Despite this limitation, the detector performed well at distinguishing scintillation signals from the ZnS(Ag) and PVT scintillators using a neutron ID parameter based on the ratio of the waveform’s integral to its maximum amplitude, as shown in figure 2. In this plot the neutron signals are identified as those having a particle-ID (PID) parameter $\geq 12$. The effectiveness of this ID method is clear when the two AmBe neutron source runs are compared to the reactor on/off runs. The additional high rate of neutron captures significantly increases the rate of events identified as being neutron captures in the $^6$LiF:ZnS(Ag), with minimal impact on the
PVT signal region. The AmBe source data was also used to validate the simulation models of neutron capture by comparing the measured and simulated time differences between PVT signals and neutron captures, as shown in the plot on the right of the same figure.

![Figure 2. Neutron identification in the prototype module was performed using an identification parameter based on the ratio of waveform integral to maximum amplitude (left plot). The time delay between EM and neutron capture signals were used to validate the neutron transport and capture simulations (right plot).](image)

The low neutron efficiency and short reactor on data period means that the detector did not have a good sensitivity to anti-neutrinos. However the reactor on and off periods were analysed to study the various background categories and develop event classification techniques. The relative topology and timing between the prompt positron candidate and delayed neutron capture proved to be very powerful, as can be seen in the distributions in the top row of figure 3. In addition to the standard timing cut, requiring the positron candidate and neutron to be within a distance of 2 cubes of each other is very efficient for the IBD events while greatly reducing the background significantly. This cut reduces the rate of accidental combinations of unrelated PVT and neutron capture signals by more than an order of magnitude, whilst also significantly reducing the correlated PVT and neutron capture signals (such as those from a fast neutron causing a proton recoil and then going on to be captured). The impact of the topological cuts used as well as cuts on the multiplicity of signals coincident with the positron candidate is shown in the bottom of figure 3, where the signal:background ratio is increased two orders of magnitude. It is expected that the upgraded trigger scheme to be used in the full scale experiment will allow a significant improvement upon these techniques as the additional signals used in the topology and multiplicity cuts will not need to independently cause threshold based triggers, but will be collected merely due to their spacial and temporal proximity to a neutron signal.

3. Planned deployment of a 2 t detector at BR2
A 2 t version of the SoLid detector, containing 6 modules (60 detection planes), is currently under construction. A shipping container houses the detector, the read-out electronics, a calibration source robot and a cooling system, visible in figure 4. The temperature within the container will be maintained at approximately 5°C. The container will be surrounded by water filled plastic bricks that act as shielding to reduce the neutron related background signals.

Compared to the prototype detector, the full sized detector has a number of upgrades. The water shielding around the detector will reduce both the neutron and gamma-ray based background signals. The number of neutron sensitive sheets per cube has been increased from one to two. This increases the probability that the neutron from an IBD event is captured
**Figure 3.** Event classification in the prototype module was based on the topology between positron candidates and the neutron capture (top left), the time delay of the neutron capture (top right) and as well as the positron candidate energy and the multiplicity of signals coincident with the positron candidate. The relative efficiency of these selection criteria on simulated IBD events and measured background signals is shown in the lower plot.

**Figure 4.** The full SoLid detector will be deployed inside a shipping container at BR2.
improved compared to the prototype detector. The major upgrade for the full scale detector is a customised trigger system designed for high efficiency of selecting IBD event data. In this data collection scheme, each channel’s data is buffered on-detector with low threshold zero suppression. Data read out is triggered by the identification of a ZnS(Ag) scintillation signal in one or more channels. Due to the data buffering, each neutron signal can trigger data read out from a volume of the detector around the signal in a suitable time window to include the prompt positron signal from the potential IBD event.

The neutron trigger is based on identifying the ZnS(Ag) signals containing single or multi-photon peaks detected over order microseconds. As shown in figure 5, ZnS(Ag) scintillation signals have a high rate of such peaks, that can be distinguished from the background of PVT signals combined with fluctuations in the dark count photon rate. Initial studies of the new trigger scheme show that it performs significantly better than the threshold based trigger followed by offline neutron waveform identification used in the prototype detector.

![Figure 5. The neutron trigger is based on counting low amplitude peaks down to the single pixel avalanche level. The scintillation signals from the neutron sensitive $^6$LiF:ZnS(Ag) have a high rate of peaks over a microsecond scale.](image)

The modular design of the SoLid detector will allow for a phased deployment at the BR2 reactor over the course of the spring and summer of 2017. Detector modules consisting of 10 planes are capable of operation either independently or as part of the full detector. The 6 modules of the full detector are currently in production and will be deployed over the summer, during periods where the reactor is not running.

4. Conclusion

The SoLid collaboration have developed a novel, highly segmented, composite scintillator anti-neutrino detector. A prototype 288 kg module of this detector took data in 2015 and demonstrated the capability for classifying waveforms as coming either from the PVT or the neutron sensitive $^6$LiF:ZnS(Ag) scintillators. Combining the event topology and hit multiplicity with the standard prompt signal to neutron capture time difference allowed the background event rate to be reduced by orders of magnitude. The collaboration is currently constructing a full scale 2 t detector for deployment between 6 and 9 m from the BR2 core in the coming months. The upgraded detector will have a bespoke anti-neutrino event trigger scheme which will collect a rich data set expected to significantly improve the event classification methods.

References

[1] Mention, G. et al., *Reactor antineutrino anomaly*, Phys. Rev. D **83**, 073006 (2011)
[2] Vacheret, A. et al., *A novel segmented-scintillator antineutrino detector*, arXiv:1703.01683 (2017)