SoLid Detector Technology

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SoLid Detector Technology

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Abstract. SoLid is a reactor anti-neutrino experiment where a novel detector is deployed at a minimum distance of 5.5 m from a nuclear reactor core. The purpose of the experiment is three-fold: to search for neutrino oscillations at a very short baseline; to measure the pure $^{235}$U neutrino energy spectrum; and to demonstrate the feasibility of neutrino detectors for reactor monitoring. This report presents the unique features of the SoLid detector technology. The technology has been optimised for a high background environment resulting from low overburden and the vicinity of a nuclear reactor. The versatility of the detector technology is demonstrated with a 288 kg detector prototype which was deployed at the BR2 nuclear reactor in 2015. The data presented includes both reactor on, reactor off and calibration measurements. The measurement results are compared with Monte Carlo simulations. The 1.6t SoLid detector is currently under construction, with an optimised design and upgraded material technology to enhance the detector capabilities. Its deployment on site is planned for the begin of 2017 and offers the prospect to resolve the reactor anomaly within about two years.

1. Introduction
SoLid is a short baseline reactor anti-neutrino experiment using a novel detector technology deployed at close distances, between 5.5 and 10 m from the BR2 nuclear reactor compact core at SCK•CEN in Mol, Belgium. The physics goal of the SoLid experiment is to resolve the reactor anti-neutrino anomaly [1] by searching for evidence of oscillation from the original electron neutrino state to a non-standard “sterile” state [2]. The experiment will perform a precise measurement of the anti-neutrino spectrum as a function of distance and energy thanks to a highly segmented, composite scintillator detector design (Sec.2). At the same time, it will provide one of the most precise measurements of a pure $^{235}$U anti-neutrino spectrum, which is an essential ingredient for the improvement of the reactor flux calculation [3].

The BR2 reactor offers a compact core with diameter < 0.5 m while providing a high anti-neutrino flux ($\sim 10^{19} \nu/s$) . It usually runs $\sim 60$ MW cycles lasting 3-4 weeks, running approximately 150 days per year. Although the BR2 reactor provides a relatively low background compared to other facilities, the environment close to such a nuclear reactor raises a number of experimental challenges. From the physics side, low overburden and close proximity to the reactor cause high rates of various background events. Cosmic ray muons can cause fast spallation neutrons which can mimic the signal produced by anti-neutrino events in the detector. However, the highly segmented detector allows most of these cosmic events to be reconstructed. The muon energy deposition distribution provides also a standard candle that can be used for channel and cube equalisation, and by comparison to simulation, the absolute energy scale

1 On behalf of the SoLid Collaboration
can be extracted (Sec.3). These events can also be used to monitor the timing stability of the detector. There are also backgrounds due to accidental time coincidences of randomly distributed background $\gamma$-rays with environmental neutrons. This background is increased by additional neutrons and $\gamma$-rays that can be emitted when the reactor is running. Technical constraints must also be taken into account: the limited available space and strict security requirements around a reactor core, impact on the size and admissible components of the detector, the accessibility and data handling infrastructure.

2. Detection Principle

The detection of reactor anti-neutrinos is based on the inverse beta decay (IBD) $\bar{\nu}_e + p \rightarrow n + e^+$ in which an anti-neutrino ($E_{\nu} > 1.805$ MeV) creates a positron and a neutron when interacting with a proton of the fiducial volume (Fig.1). The active volume of the SoLid detector consists of highly segmented proton-rich 5 cm $\times$ 5 cm $\times$ 5 cm polyvinyl toluene (PVT) cubes coupled with neutron-sensitive $^6$LiF:ZnS(Ag) tiles. The positron emitted from the IBD event causes the PVT to scintillate, before it annihilates with an electron in the detector, emitting a pair of 511 keV $\gamma$ rays. The neutron from the IBD thermalises in the PVT and has approximately 50% probability to be captured by a $^6$Li atom in the neutron-sensitive layer within $\sim$ 15 cm from the interaction point, resulting in the interaction: $n + ^6$Li $\rightarrow \alpha + ^3$H + 4.78 MeV.

Each voxel is wrapped into a reflective Tyvek sheet to optically isolate the detector segments. The scintillating light is guided out of the detection volume by a 2D orthogonal (horizontal and vertical) array of wavelength shifting (WLS) fibres, instrumented with a $3 \times 3$ mm$^2$ silicon photomultiplier (SiPM) at one end. A mirror is coupled at the other end of each fibre to increase the light collection.

The signal collected from an IBD event is a combination of two very different features. The positron yields a prompt and sharp pulse (Fig.2-top) while the neutron captured on $^6$Li induces a slowly decaying pulse (Fig.2-bottom) in the ZnS(Ag) scintillator. The time delay between both signals corresponds to the thermalisation time of the neutron.

![Figure 1. Detection of a IBD process in the SoLid detector.](image1)

![Figure 2. Typical IBD signal. Prompt positron pulse (top) followed by the slowly decaying neutron pulse (bottom).](image2)

Because of the high level of segmentation, the positron pulse gives a good precision on the position of the IBD interaction and the energy of the anti-neutrino. Moreover, the separation of true IBD events from background [7] not only benefits from the time information but, unlike conventional neutrino detectors, from the spacial configuration – $e^+$ and $n$ can possibly be detected in neighbouring cubes – of the IBD event candidate as well, allowing some possible direction reconstruction.

3. Performances of the SM1 prototype

A full-scale test module (Fig.3), named SubModule 1 (SM1), was constructed in 2014 and commissioned in 2015. SM1 consists of 9 detector planes, each containing 16 by 16 PVT cubes,
resulting in a total of 2304 cubes weighing 288 kg. These cubes are read out by 288 WLS fibres coupled to as many SiPM sensors. The collected signal is amplified and digitised with a 14 bit resolution at a sampling rate of 65 MHz using custom electronics. The module is surrounded by a 9 cm thick polypropylene neutron shield, and 8 muon-veto scintillator panels used as active shielding. The SM1 prototype demonstrated the scalability of the detection technology and was used to test production methods and commissioning procedures[4]. From February to August 2015, SM1 took data at the BR2 reactor site. The stability and performance of the SM1 prototype was monitored by detecting muons crossing or decaying in the fiducial volume [5]. Calibration measurements were performed with several neutron and gamma sources (AmBe, $^{60}$Co, $^{252}$Cf) and validated with dedicated simulations (Fig.4). These measurements demonstrated the high-quality background reduction of this novel neutrino-detector technology.

4. Present and Future: SoLid phase 1

The phase 1 of SoLid has started during Summer 2016 with the development and gradual building of a 1.6 tonne detector. The system will be subdivided in 5 modules of 10 planes, holding 12800 PVT cubes equipped with two neutron tiles. 3200 read-out channels will be equipped with double-clad fibres, enhancing the light collection and therefore the energy resolution [6].

The installation of the first modules at BR2 is planned for February 2017. The full detector and readout electronics will be placed in a cooled container to reduce the SiPM dark count rate. The container will be surrounded with passive water shielding to diminish the rate of fast neutrons in the active detector volume. Based on the first IBD analysis performed with the SM1 prototype [7], and the development of neutron identification methods on the full data stream and extended triggering, a detection efficiency of around 30% is expected, resulting in several hundreds of neutrinos that will be recorded every day. The combination of the detection rate and the excellent background rejection ($\sim 100$ for accidental and $\sim 10$ for cosmic) will provide a stringent test of the reactor anti-neutrino anomaly within a few years of operation [8].

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