Light yield and energy resolution studies for SoLid phase 1

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Abstract. The SoLid experiment is searching for sterile neutrinos at a nuclear research reactor. It looks for inverse beta decays (producing a positron and a neutron in delayed coincidence) with a very segmented detector made of thousands of scintillating cubes. SoLid has a very innovative hybrid technology with two different scintillators which have different light emissions: polyvinyl-toluene cubes (PVT) to detect the positrons and $^{6}$LiF:ZnS sheets on two faces of each PVT cube to detect the neutrons. It allows us to do an efficient pulse shape analysis to identify the signals from neutrons and positrons. The 288 kg detector prototype (SM1) took data in 2015. It demonstrated the detection principle and background rejection efficiency. The construction of SoLid phase I (∼1.5 t) has now started. To improve the energy resolution of SoLid phase I, we have tried to increase the light yield studying separately the two scintillators: PVT and ZnS. A test bench has been built to fully characterize and improve the neutron detection with the ZnS using an AmBe source. To study the positron light yield on the PVT, we have built another test bench with a $^{207}$Bi source. We have improved the design of the cubes, their wrapping or the type and the configuration of the fibers. We managed to increase the PVT light yield by about 66 % and improve the resolution of the positron energy on the test bench from 21 % to 16 % at 1 MeV.

1. Introduction
Different experiments have seen anomalies in the neutrino flux which could be explained by the oscillation into a new sterile neutrino (Giunti et al, 2013). To resolve these anomalies, the SoLid experiment will look for neutrino oscillations at very short baseline (5.5-10 m). It is a reactor neutrino experiment at SCK·CEN (Mol, Belgium) which will search for sterile neutrinos, measure precisely the $^{235}$U flux and spectrum, and demonstrate the ability of a neutrino detector to monitor reactors. For SoLid phase I, we want to optimize the light yield compared to SM1 to get a better energy resolution. It will allow us to lower the detection threshold to get a more efficient neutron trigger and improve the background rejection. We also want to have a better detector uniformity.

2. The SoLid detector
The SoLid detector detects neutrinos through inverse beta decays: $\nu_e + p \rightarrow e^+ + n$. The detector is highly segmented with cubes of $5\times5\times5$ cm$^3$. It has an innovative technology as it is composed of two scintillators with different time response. Positrons (fast scintillation signal) are detected in cubes made of PVT. Neutrons (slow scintillation signal) are detected in the $^{6}$LiF:ZnS sheets put on each PVT cube, after thermalisation in the detector. The cubes are wrapped in
Tyvek reflective coating and wavelength shifting fibers bring the scintillating light to silicon photomultiplier (SiPM) whose pulses are digitised (65 MHz). We put mirrors at the end of the fiber which does not have a SiPM. An efficient pulse shape analysis allows us to distinguish the signals from neutrons in $^6\text{LiF}:\text{ZnS}$ and positrons in PVT (Vercaemer, PoS(EPS-HEP2015)083). These delayed coincidences sign a $\nu_e$ interaction.

3. $^6\text{LiF}:\text{ZnS}$ neutron screen
A good light yield is essential for achieving high neutron detection efficiency. A test bench has been built to determine the most efficient neutron screen. The amount of light detected from neutron absorptions in $^6\text{LiF}:\text{ZnS}$ screens depends on the thickness of the screen, the ratio of the $^6\text{LiF}$ to ZnS and the light collection efficiency.

![Figure 1: Distribution of PMT signal charge from 5 MeV alphas absorbed on the opposite side of different $^6\text{LiF}:\text{ZnS}$ screens.](image1.png)

To achieve the best efficiency, 225 $\mu$m thick screens with $^6\text{LiF}:\text{ZnS}$ mass ratio of 1:2 are used in SoLid (Fig. 1). We have shown with the test bench that in SM1, the neutron efficiency was low mostly due to a high trigger threshold (Fig. 2). In phase I, this issue will be solved by identifying the neutrons on a dedicated neutron trigger directly implemented on the field-programmable gate array (FPGA) electronics.

4. The PVT test bench
We have also built a test bench to study the positron light yield in the PVT (Fig. 3). We use a $^{207}\text{Bi}$ source which produces conversion electrons with a peak energy of 1 MeV by decays through electron capture to excited states of $^{207}\text{Pb}$. An external trigger with two photomultiplier tubes (PMTs) and a 110 $\mu$m scintillator triggers in coincidence on the 1 MeV conversion electrons only and reject the source gamma background. Above this external trigger, we put a SoLid type detector unit composed of one or several cubes with optical fibers and SiPM. We can change the wrapping of the cube, the number of ZnS sheets, the number and type of fibers and their mirrors or the cube position along the fiber. Using the single photo-avalanche (PA) peaks in the spectrum, we can convert the charge of the SiPM pulses in PA (Fig. 4) and compare the position on the 1 MeV peak for different configurations to measure the improvements. We have measured a systematic error of 5 % and a statistical error of 0.2 %.

5. Results of PVT light yield studies
After testing several materials and configurations for the SoLid detector, we have found the improvements shown in Table 1. Adding a second ZnS layer reduces the light yield but it also
increases the neutron detection efficiency and reduces its capture time (to reduce background).

Table 1: Light yield improvements found with the PVT test bench

| Detector component | SM1        | SoLid phase I | Gain      |
|--------------------|------------|---------------|-----------|
| Wrapping of the cubes | Tyvek of 75 g·m$^{-3}$ | Tyvek of 105 g·m$^{-3}$ | +30%      |
| Number of ZnS layers | 1          | 2             | -10%      |
| Optical fibers     | single-clad fibers | double-clad fibers | +38%      |
| Mirrors            | aluminium mirror | aluminised mylar mirror | +20%      |
| Fibers configuration | 2 fibers with 1 SiPM/fiber | 4 fibers with 1 SiPM/fiber | PA per fiber: -40% PA per cube: +43% |

Figure 3: The PVT test bench with the external trigger composed of two PMTs and the SoLid type detector unit above it.

Figure 4: Distribution of the SiPM charge signal in PA on the test bench. We fit in red the 1 MeV peak from $^{207}$Bi.

Figure 5: From test bench measurements: calculation of the number of PA/cube for 1 MeV deposited in a plan of SM1 (left) and in a plan of SoLid phase I (right) taking into account the fiber attenuation. Red boxes without numbers indicate SiPM positions.

In the end we have increased the light yield by 66 % on the PVT test-bench (from 22.4 for SM1 configuration to 37.2 PA/cube/MeV for SoLid phase I configuration, see Figs. 5a and 5b). This improves the energy resolution ($\sigma_E = \frac{1}{\sqrt{N_{PA}}}$) on the test bench from 21 % to 16 % at 1 MeV and the largest relative variation of the detector ($\Delta_{PA} = \frac{P_{PA_{max}}-P_{PA_{min}}}{P_{PA_{max}}}$) from 98 % to 7 %. We will also improve the amount of light detected by increasing the SiPM overvoltage and reducing temperature to get a 14 % energy resolution for SoLid phase I.