Light yield studies for SoLid phase I.

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Abstract. The SoLid experiment is searching for sterile neutrinos at the BR2 nuclear research reactor. Anti-neutrinos are detected through 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 temporal signature: polyvinyl-toluene cubes (PVT) to detect the positrons and $^6\text{LiF:ZnS}$ sheets to detect the neutrons. 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 ($\sim$ 1.6 t) is now finished and data taking has started. To improve the energy resolution of SoLid phase I, we have tried to increase the light yield studying the PVT scintillator design. To study the positron light yield on the PVT, we have built a test bench with a $^{207}\text{Bi}$ source. We have improved the design of the cubes, their wrapping or the type and the configuration of the fibers. After its construction, the SoLid detector has been calibrated with a $^{22}\text{Na}$ source and preliminary results seem to show that the light yield has increased by a factor 3 compared to SM1 so it should improve the energy resolution of the positron from 21% for SM1 down to 12% for SoLid.

Introduction
Different experiments have seen anomalies in the neutrino flux which could be explained by the oscillation into a new sterile neutrino [1]. To test this hypothesis, the SoLid experiment will look for neutrino oscillations at very short baseline ($\sim$6-9 m) [2]. It is a reactor neutrino experiment at SCK•CEN (Mol, Belgium) which will search for oscillations to sterile neutrinos, measure precisely the $^{235}\text{U}$ flux and spectrum, and demonstrate the ability of a neutrino detector to monitor reactors. The oscillations to sterile neutrinos should be visible both as a change in the anti-neutrino flux with the distance and as a distortion of their energy spectrum. For SoLid phase I, we wanted to optimize the light yield compared to SM1 to get a better energy resolution. It would also allow us to lower the detection threshold to get a more efficient neutron trigger and improve the background rejection. Furthermore we wanted to have a better detector uniformity.

1. The SoLid detector
The SoLid experiment detects neutrinos through inverse beta decay: $\nu_e + p \rightarrow e^+ + n$. The detector is highly segmented with cubes of $5 \times 5 \times 5$ cm$^3$. The phase I detector will consist of 50 frames of $16 \times 16$ cubes. 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. They also give us a measurement of the anti-neutrino energy. Neutrons, after thermalization, can capture on the $^6\text{LiF:ZnS}$ sheets (slow scintillation signal) put on each PVT cube. The cubes are wrapped in Tyvek reflective coating and wavelength shifting fibers bring the scintillating light
to silicon photomultiplier (SiPM) whose pulses are digitised (40 MHz). Mirrors were placed at the end of the fibers which do not have a SiPM. An efficient pulse shape analysis allows us to distinguish the signals from neutrons in $^{6}$LiF:ZnS and positrons in PVT [3]. These delayed coincidences sign a $\nu_{e}$ interaction. To reduce backgrounds, SoLid can take advantage of its time, spatial topology and energy measurements.

2. The PVT test bench
In order to improve the energy resolution, we have built a test bench to study the positron light yield in the PVT (Fig. 1). We use a $^{207}$Bi source which produces conversion electrons with a peak energy of 1 MeV by decays through electron capture to excited states of $^{207}$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. 2) 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 %.

Figures

Figure 1. The PVT test bench with the external trigger composed of two PMTs and the SoLid type detector unit above it.

Figure 2. Distribution of the SiPM charge signal in PA on the test bench. We fit in red the 1 MeV peak from $^{207}$Bi.

3. 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. Examples of light yield improvements found with the PVT test bench for a cube located at the center of the fibers.

| Detector component | SM1 | SoLid phase I | Gain |
|--------------------|-----|---------------|------|
| Wrapping of the cubes | Tyvek of 75 g·m$^{-2}$ | Tyvek of 105 g·m$^{-2}$ | +10% per cube |
| Number of ZnS sheets | 1   | 2             | -4 per cube % |
| Optical fibers      | single-clad fibers | double-clad fibers | +15 % per fiber |
| Mirrors             | aluminium mirror   | aluminised mylar mirror | +10 % per fiber |
| Number of fibers    | 2 fibers           | 4 fibers           | +40% per cube |
To get an idea of the increase in light yield expected for SoLid phase I compared to SM1, we have done measurements with one cube in the closest setup as possible to the 2 detectors. We have also measured the attenuation length of the different fibers used to extrapolate this one cube measurement to a whole plane (16 × 16 cubes).

![Image](image1.png)

**Figure 3.** Detector plane light-yield maps for SM1 and SoLid Phase 1 extrapolated from our light-yield and attenuation measurements. The average light-yield are 18.9 and 52.3 PA/MeV for SM1 and SoLid Phase 1 respectively. The maximal cube difference is only 4 % for the Phase 1 compared to 43 % for SM1.

We expect thus an increase in light yield of 180% for SoLid phase I compared to SM1.

4. **Calibration of the SoLid detector**

After their construction, each frame of the SoLid detector (16 × 16 cubes) has been calibrated with $^{22}$Na, $^{252}$Cf and AmBe sources. An automated system has been used to move the sources and qualify all the cubes in a frame. The $^{22}$Na source emits gammas at 511 keV and 1270 keV in coincidence. While one of the two 511 keV gammas was used to start the external trigger, the Compton edge of the 1270 keV gamma interaction in the cubes of the detector could be fitted to measure the light yield (Fig. 4).

![Image](image2.png)

**Figure 4.** The $^{22}$Na energy spectrum measured in a cube of the SoLid detector. The first peak around 200 ADC is due to the 511 keV gammas and the compton edge around 500 ADC corresponds to the 1270 keV gammas.
All the frames are very uniform in light yield (Fig. 5). A preliminary light yield of 73 PA/MeV/cube was detected in average after cross-talk substraction which should lead to an energy resolution of 12%. This is an increase of the light yield by a factor three compared to SM1 which is better than expected. This bigger increase compared to test bench measurements may be due to the different electronics used for the test bench or to light leaks to the neighbouring cubes which can be collected in the detector while we use only one cube on the test bench.

Conclusion
With the test-bench measurements, we have found improvements to increase the light yield by changing the wrapping, the type and number of optical fibers, mirrors and cube design. These changes have improved the uniformity of the SoLid detector and according to preliminary results it seems that the light yield has been multiplied by 3 from SM1 to SoLid phase I. This should improve the energy resolution for SoLid phase I down to 12 % at 1 MeV which is very promising for its sensitivity to the reactor anomaly.

References
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