The SoLid experiment

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Abstract. The SoLid experiment is a short-baseline project, probing the disappearance of reactor antineutrinos using a novel detector design. Installed at a very short distance of \( \sim 5.5 - 10 \) m from the BR2 research reactor at SCK-CEN in Mol (Belgium) it will be able to search for active-to-sterile neutrino oscillations, exploring most of the allowed parameter region. SoLid will make use of a highly segmented detector, built from 5 cm PVT cubes, interleaved with \(^6\)LiF:ZnS(Ag) screens, and read out by optical fibers and Silicon Photomultipliers (SiPMs). The detector granularity allows for the localization of the positron and neutron signals from antineutrino interactions and the robust neutron identification capabilities, offered by the \(^6\)LiF:ZnS(Ag) inorganic scintillator, provide background suppression to an unparalleled level.

This paper reviews the experimental layout and current status of SoLid. Emphasis is put on the challenges one faces towards this measurement, focusing on the decisions and strategy adapted by the SoLid collaboration. The analysis scheme and the details of the oscillation framework are also presented, highlighting the sensitivity contour and physics potential of SoLid. Finally, other physics topics, such as, reactor monitoring or measurement of the \(^{235}\)U spectrum are also covered.

1. Experimental layout

The recent observation of the Reactor Antineutrino Anomaly has revived the interest in short-baseline experiments probing the disappearance of electron neutrinos and antineutrinos [1]. The SoLid experiment is a reactor project that aims to resolve the anomaly using a novel detector design. SoLid will employ a long and segmented detector, installed at a very short distance of \( \sim 5.5 - 10 \) m from the BR2 research reactor at SCK-CEN (Mol, Belgium) and it will scan the allowed parameter region through the detection of low-energy \( \bar{\nu}_e \). Furthermore, it will be able to conduct a precise measurement of the \(^{235}\)U flux and spectrum, and also demonstrate the ability to perform reactor monitoring on surface.

The SoLid detector is made of \( 5 \times 5 \times 5 \) cm\(^3\) polyvinyl-toluene (PVT) cubes that are aggregated in planes of 16\( \times \)16 cubes. The cubes are hold together by an aluminum frame and they are optically separated using Tyvek wraps. Wavelength shifting fibers are threaded through grooves on the PVT cubes, in two orthogonal directions, and the light produced by charged particles is guided through the optical fibers and read out by Silicon Photomultipliers (SiPMs), Fig. 1 (left).

With this design, one can have precise information on the energy and position of antineutrinos interacting in the detector. Additionally, sheets of \(^6\)LiF:ZnS(Ag) are interleaved inside the cubes to enhance neutron tagging, through the pulse discrimination capabilities offered by this inorganic scintillator.

The SoLid detector, envisaged for the first phase of the experiment (Phase I), will be composed of 50 planes and it will have an active mass of 1.6 tons, Fig. 1 (right). To improve the energy
resolution, the light will be collected by two optical fibers in each direction. Furthermore, in one cube face inside the Tyvek wrap, two $^6\text{LiF:ZnS(Ag)}$ sheets will be placed to increase the neutron detection efficiency. The detector will be installed inside a steel container where the temperature will be lowered and controlled with great accuracy. This condition allows to reduce significantly the dark counts rate of the SiPMs. A detailed review of the SoLid detector technology can be found in Ref. [2].

2. Antineutrino flux from BR2

The BR2 reactor at SCK-CEN is highly enriched in $^{235}\text{U}$ and it is only used for scientific research. It operates for about 150 days per year, at a nominal thermal power of $\sim 60$ MW. The compact core of the BR2 reactor (diameter smaller than $\sim 1$ m) ensures that the neutrino oscillations, those predicted by the reactor anomaly, are not washed out by the spatial extension of the source. The SoLid site is ideal for performing such an experiment since the background from the reactor is small compared to other sites. Furthermore, the large space availability inside the BR2 building allows to probe a large baseline with a long detector.

The prediction of the antineutrino flux from the BR2 reactor, is performed using detailed simulation packages. To obtain the number of fissions, the thermal power of the reactor is needed. This is an important quantity for the operation of BR2, and it is measured by the reactor authorities with a good accuracy ($\sim$1-2 %). The number of fissions as a function of time is then calculated employing reactor simulation codes like MURE [3] or MCNPX/CINDER90 [4, 5]. For this task several information is needed from SCK-CEN. This include the core geometry, the neutron flux and the initial fuel composition. The spectrum and flux of $\bar{\nu}_e$ is then calculated using the neutrino yields provided by the so-called conversion method [6, 7].

The $\bar{\nu}_e$ from BR2 interact on free protons in PVT through the inverse beta decay (IBD) channel, $\bar{\nu}_e + p \rightarrow e^+ + n$. This is an interaction that has high cross-section but an energy threshold at 1.8 MeV. The positron thermalization and annihilation gives a prompt signal in PVT, and the subsequent neutron capture on $^6\text{Li}$ provides a second, delayed signal. The time and space correlation of the prompt and delayed signals offer a neat way to identify IBD events. Fig. 2 shows the energy distribution of $\bar{\nu}_e$, for 150 days of running with the Phase I detector, overlapped with the expectation using the Daya Bay spectrum. For this analysis a value of 30% was assumed for the IBD efficiency ($\epsilon_{\text{IBD}}$) and the energy resolution was set to $14\%/\sqrt{E}$, where $E$ refers to the visible energy. On the bottom panel of Fig. 2 we show the ratio between the two spectra. In particular, SoLid will be able to probe the bump seen by reactor experiments if this originates from the $^{235}\text{U}$ spectrum.
3. Sensitivity to sterile neutrinos

The sensitivity of SoLid to sterile neutrinos was estimated using a $\chi^2$ analysis with pull terms. The spectrum was binned in visible energy ($E$) and distance ($L$) from the core center. 16 bins between 1.0 - 7.4 MeV were used in $E$ and 25 bins between 5.0 - 8.0 m in $L$. The exact formula of the $\chi^2$ employed in the analysis was:

$$
\chi^2 = \sum_{i,j} \left( \frac{S_{ij} - (1 + \alpha + \alpha_b + a_E + a_L)T_{ij} - B_{ij}}{\sigma_{iE}^2 + (\sigma_{2iB}T_{ij})^2 + (\sigma_{2bB}B_{ij})^2} \right)^2 + \frac{\alpha^2}{\sigma_\alpha^2} + \frac{\alpha_b^2}{\sigma_{\alpha_b}^2} + \sum_i \left( \frac{a_i^j}{\sigma_{iE}} \right)^2 + \sum_j \left( \frac{a_j^i}{\sigma_{iL}} \right)^2.
$$

The index $i$ corresponds to the energy bins and $j$ to the distance bins. $S_{ij}$ refers to the data expectation assuming no oscillations, and $T_{ij}, B_{ij}$ to the theoretical antineutrino prediction and background.

$\sigma$ and $\sigma_b$ account for the uncertainties of the signal and background normalization and they were set equal to 100% and 10% respectively. The uncertainties on the neutrino energy spectrum ($\sigma_{iE}^2$) and position reconstruction ($\sigma_{iL}^2$) were equal to 10% and 1%. Finally, 1% uncorrelated bin-to-bin errors were assumed for the signal and background. Fig. 3 shows the exclusion contour (blue) of Phase I for 150 days of data taking, overlapped with the allowed regions of the Reactor and Gallium anomalies, together with the global fit region from Ref. [8]. For this plot we assumed a simple oscillation model with three active and one sterile neutrino. One could see that the Phase I configuration can exclude the global best fit at 95% with only 150 days of running. Extending the data taking period will of course improve the sensitivity reach of SoLid.

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