PROCEEDINGS OF SCIENCE

Analysis framework for sensitivity studies of the SoLid experiment

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The observation of the Reactor Antineutrino Anomaly, at the beginning of this decade, has revived the interest in short-baseline experiments that probe the disappearance of electron antineutrinos. In addition, the recent evidence for a distortion in the reactor antineutrino energy spectrum, seen by some of those short-baseline experiments, has questioned our current models even more.

The SoLid experiment is a reactor neutrino experiment, located at the BR2 reactor site of the SCK • CEN in Belgium, that aims to resolve the anomaly and perform a precise spectral measurement using a novel detector design.

To fulfil its challenging goals, the SoLid collaboration needs to perform detailled reactor calculations and develop a dedicated analysis framework. These proceedings aim to review the simulation chain and analysis techniques needed to predict the measured antineutrino rates and spectra, to build the detector response matrix and to determine the experimental sensitivity and confidence limits using several fitting methods.

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1. Introduction

The observation of the Reactor Antineutrino Anomaly [1], at the beginning of this decade, has revived the interest in short-baseline experiments that probe the disappearance of electron antineutrinos. In addition, the recent evidence for a distortion in the reactor antineutrino energy spectrum, seen by some of those short-baseline experiments [2, 3, 4], has questioned our current models even more.

The "Search for oscillations with a ^{6}Lithium detector" (SoLid) experiment is a reactor neutrino experiment that aims to resolve the anomaly and perform a precise spectral measurement using a novel detector design. Installed at a very short distance of $\sim$ 6 - 10 m from the BR2 research reactor at SCK • CEN in Belgium, it will be able to search for sterile neutrino oscillations through the detection of low energy $\bar{\nu}_e$. It will also exploit the high purity in ^{235}U of the BR2 reactor fuel, to increase our knowledge on reactor flux models and trace the origin of the spectral distortion. The first phase of SoLid has reached one year of data taking and the experiment will soon be able to present some initial results.

To fulfil its challenging goals, the SoLid collaboration needs to perform detailed reactor calculations and develop a dedicated analysis framework. These proceedings aim to review the simulation chain and analysis techniques needed to predict the measured antineutrino rates and spectra, to build the detector response matrix and to determine the experimental sensitivity and confidence limits using several fitting methods.

2. SoLid detection principle

The SoLid experiment uses a new segmented detector technology based on small detection cells that consist of a cube of polyvinyltoluene (PVT) scintillator for the detection of electromagnetic (EM) interactions and two thin sheets of ^{6}LiF:ZnS(Ag) for neutron capture. Figure 1 illustrates how a reactor antineutrino interacts in part of the detector volume, resulting in an inverse beta decay (IBD) reaction in which a positron and a neutron are created.

The positron annihilates in the PVT, giving a fast and sharp scintillation pulse; the neutron first thermalizes by scattering through the detector material and is then captured by the ^{6}Li in the neutron detection sheets. The combination of the prompt positron signal and a delayed series of decay pulses from the ^{6}LiF:ZnS mixture builds up the antineutrino signature. For more details on the SoLid detection principle, one can consult Ref. [5].

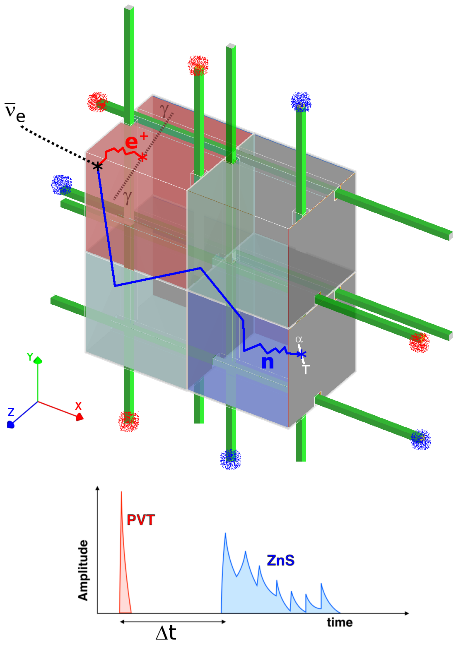

Figure 1: Schematic view of an antineutrino interaction with part of the SoLid detector (top). The resulting IBD signature is also sketched (bottom).

The selection of IBD events is based on the time correlation between positron and neutron capture, their spatial correlation due to high detector segmentation, and on pulse-shape discrimination of the scintillation signals [6].

3. SoLid at the BR2 reactor site

Between the end of 2016 and the spring of 2018 the full scale SoLid Phase 1 detector was built and was then commissioned and installed at the BR2 reactor site in Mol, Belgium. The detector consists of 50 vertical planes, each composed of 16×16 detection cells of $(5\times5\times5)$ cm^3, resulting in a total sensitive mass of 1.6 t. It is housed in a container, that is cooled to about 10°C and is surrounded by additional (50 cm) shielding using slabs of HDPE on the top and bottom and walls of water bricks on the sides.
As illustrated in figure 2, the SoLid set-up is positioned on-axis with the BR2 reactor core and its point of closest approach is about 6 meters. The compact research reactor has a core of $\sim$50 cm diameter and is highly enriched (93.5%) in ^{235}U. BR2 operates in cycles of ca. 24 days with a power between 50 and 80 MW.

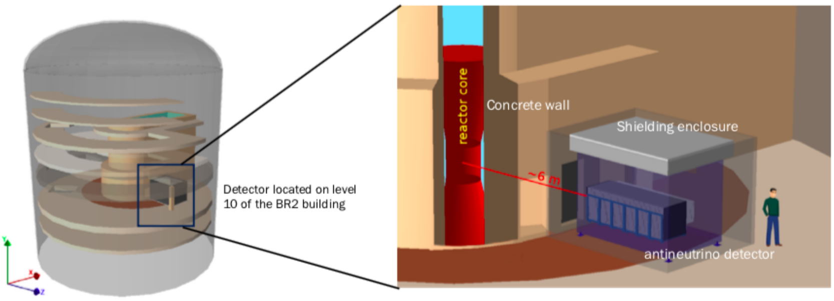

Figure 2: Schematic of the SoLid Phase 1 detector at the BR2 reactor site.

4. Reactor model

The BR2 reactor core is modeled with MCNP [7] and the fuel evolution is calculated using CINDER90 [8]. With these software packages the fission rates and distributions in X, Y, Z and their time-evolution can be extracted, which are used as an input for the models predicting the emitted antineutrino spectrum. There are two methods generally used for this prediction, i.e. the summation method using nuclear databases and the conversion method using ILL β-spectra. Another important input for the calculation of the antineutrino spectrum is the IBD cross-section model. The SoLid collaboration uses predictions from two models corresponding to refs. [9] and [10]. Corrections to the models are taken into account, considering 1st order forbidden transitions, radiative corrections and off-equilibrium effects.

5. IBD Generator

The SoLid collaboration has developed its own Monte Carlo IBD generator, with a detailed implementation of all detector materials (proton content) and geometry. The number of expected

IBDs for every cell (i) and isotope (k) is calculated as

$$N_k^{(i)} = \int_{core} \frac{1}{4\pi L^2}\, n_f\, N_p^{(i)}\, \sigma_{f,k}\, \varepsilon^{(i)}\, d^3r \tag{5.1}$$

where L is the distance between the reactor core and the detection cell, n_f is the number of fissions, $N_p^{(i)}$ is the proton content of cell i, $\sigma_{f,k}$ is the cross-section per fission for isotope k and $\varepsilon^{(i)}$ is the detection efficiency of cell i.

According to this value $N_k^{(i)}$, a number of IBD events are randomly generated in each cell, using a reactor position from the fission map, a value E_ν from the isotope's spectrum and a position inside the detector cell. This results in a set of predicted IBD events with antineutrino parameters like E_ν and L_ν.

6. Detector response

To map the relation of the antineutrino spectrum and the resulting prompt energy spectrum, a detector response model is built. Generated IBD events are interfaced with the SoLid Geant4 detector model, the SoLid read-out simulation and the reconstruction software (Saffron), accounting for the IBD energy shift, the experiment's energy resolution, detection efficiency, etc.. Finally all IBD selection criteria are also applied to these events, to account for the selection efficiency. This MC chain leads to a prediction of E_{vis} and L_{vis}, given the "true" neutrino values E_ν and L_ν. A map of these values, also called the detector response matrix, is shown in figure 3.

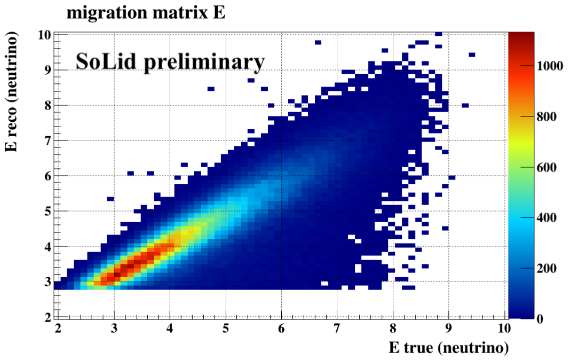

Figure 3: The SoLid detector response matrix, mapping the antineutrino energy spectrum to the resulting prompt energy spectrum.

The high detector resolution allows to determine the position of the IBD interaction with a few cm accuracy. Therefore a similar response matrix is built for the distance parameter L.

To be precise, both matrices are combined into one large response matrix linking bins in (E_ν, L_ν) space to bins in (E_{vis}, L_{vis}).

7. Sensitivity studies

The SoLid oscillation analysis is performed in 2D, namely in reconstructed length L_{vis} (bins i of size ~10 cm) and reconstructed energy E_{vis} (bins j of size ~500 keV). The χ^2 can be expressed in a simple form as

$$\chi^2 = \sum_{ij} \frac{\left(N_{ij}^{\text{data}} - N_{ij}^{\text{MC}}(\sin^2(2\theta_{ee}), \Delta m_{41}^2)\right)^2}{\sigma_{ij}} \tag{7.1}$$

For a full analysis, including all (un)correlated uncertainties, the χ^2 is determined using either pull terms or covariance matrices. The segmentation of the SoLid detector along the reactor-detector axis also allows to perform a near/far analysis, resulting in the cancellation of a number of correlated uncertainties, such as flux, cross-section and detector uncertainties.

Figure 4 shows the SoLid exclusion regions for the existence of a sterile neutrino in the oscillation parameter space (Δm_{41}^2, $\sin 2\theta_{ee}$) assuming 150 and 450 days of reactor on data, assuming an IBD detection efficiency of 30%, a signal-to-background ratio of 3:1 and an energy resolution of $14\%/\sqrt{E_{vis}}$. The contours cover the global best fit point and a large area of the reactor antineutrino anomaly and Gallium anomaly regions.

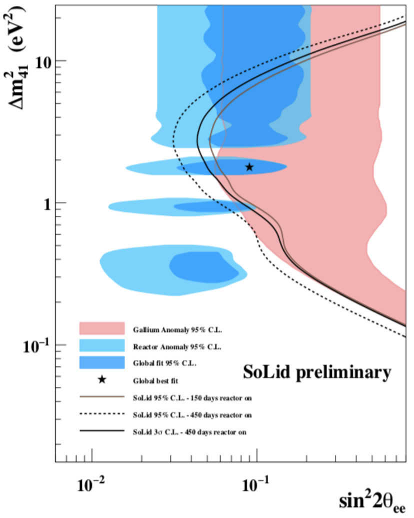

Figure 4: Exclusion regions for 150 and 450 days of reactor on.

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