Chasing the light sterile neutrino: status of the STEREO experiment

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Abstract. This article describes the status of the STEREO experiment. STEREO is a short-baseline reactor antineutrino experiment, whose primary goal is to study oscillations involving extra sterile neutrino states with $\Delta m^2 \sim 0.1 - 1$ eV, an hypothesis suggested by existing anomalies. Such hypothesis is tested by comparing antineutrino spectra in 6 identical cells located at a increasing distance from the reactor core of the ILL facility. Calibration sources have been used to characterise the detector response, perform energy reconstruction, and study the detection efficiency. Results of these studies, along with preliminary antineutrino and background rates, are reported here. STEREO has started operating in November 2016 and will collect data for 8 reactor cycles. Preliminary results based on 1.5 reactor cycles and ongoing analysis, which are mentioned here, will be released in early 2018.

1. Introduction
Neutrino oscillation is now a well-established phenomenon: all the mixing angles of the PMNS matrix and squared-mass splittings have been measured. However, the absolute scale of neutrino masses, as well as the CP-violating phase in the PMNS matrix, are yet unknown. Moreover, some yet unexplained experimental anomalies challenge the three-family paradigm. One of these anomalies arose in 2011, when novel computations of reactor $\bar{\nu}_e$ spectra pointed out a rate excess of approximatively 3% with respect to previous measurements at close distance ($10 - 100$ m) from various reactor cores (figure 1) [1]. This discrepancy, known as reactor antineutrino anomaly, was later confirmed data collected by Double Chooz, Daya Bay and RENO near detectors, for a global $\sim 2.8 \sigma$ statistical significance [2].

The RAA can be interpreted as an oscillation between the three currently known and an extra sterile neutrino flavour state. If we add a small component of this new flavour state to the existing mass states, as well as a fourth neutrino mass state with $\Delta m^2_{41} \sim 0.1 - 1$ eV mainly consisting of this new flavour state, then the resulting oscillation at very short baseline

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}(L \lesssim 10 \text{ m}) \simeq 1 - \sin^2(2\theta_{\text{new}}) \sin^2(\Delta m^2_{41} L/4E),$$

will explain the experimental deficit of the RAA. Note that other anomalies (Gallium, LSND) can be explained by active-sterile neutrino oscillations. Nonetheless, a global simple solution is disfavoured by disappearance results [2].

2. The STEREO experiment
The STEREO detector is located in the ILL research reactor facility, at a distance of approximatively 9 m from the 58.3 MWth nominal power reactor core. The characteristics of the
Figure 1. Ratios R between observed (N_{exp}) and predicted (N_{cal}) neutrino rates, as functions of the reactor-detector distance L, of the reactor experiments considered in [2].

ILL reactor make it a perfect candidate to study oscillations at a short distance: the compactness of the core (\(r_c = 37\) cm) allows in fact a good resolution of the oscillation, especially at low energies (equation 1), while the high enrichment (93\% 235U) simplifies the issue of accounting for the fuel evolution.

2.1. The detector

The STEREO detector consists of an inner detector, an upper muon veto, calibration systems, and shielding (figure 2). In turn, the inner detector is divided in a target area surrounded sideways by an outer crown. The target is segmented longitudinally in 6 identical cells and filled with Gd-doped liquid scintillator, while the crown is segmented in its 4 sides and filled with a mixture of liquid scintillation similar to that of the target but without Gd doping. The walls that separate the target and gamma catcher, as well as the segmentation walls, consist in a foil of reflecting material sandwiches between acrylic plates. The scintillation light is thus conveyed upwards, where is collected by 48 photomultiplier detector hosted in acrylic buffers (figure 3). The optical coupling is guaranteed by mineral oil, of which these buffers are filled.

The muon veto is a water cherenkov detector, equipped with 20 photomultipliers and positioned above the inner detector. Its purpose is to tag cosmic muons and remove associated background. The inner detector individually, as well as the ensemble of inner detector and veto, are packed in multiple layers of shielding materials in order to suppress different sources of background and noise: \(\mu\)-metal and soft iron to shield photomultipliers from external magnetic fields, lead for high energy \(\gamma\)’s, B and polyethylene for neutrons (figures 4, 5). Moreover, the STEREO area at the ILL facility is bordered by walls of lead, polyethylene, and B, and surmounted by the ILL water channel, which provides a \(\sim 15\) mwe shielding against muons.

2.2. Signal and background

Antineutrinos produced in the reactor are detected via their inverse beta decay (IBD) interactions with the free protons of the STEREO detector

\[ \bar{\nu}_e \ p \rightarrow e^+ \ n. \]  \hfill (2)

The two-fold coincidence between the positron ionising the liquid scintillator and suddenly annihilating with an electron of the medium, and the delayed neutron capture, provides a clear signature of the IBD, allowing for a strong suppression of sigle-event noise. Residual background
Figure 2. Outline of STEREO. The inner detector consists of six target cells and an outer crown (ochre yellow) surmounted by buffer cells (green), it is packed in multiple shielding layers, and surmounted by the muon veto (blue).

Figure 3. Top view of the STEREO inner detector, before the last two target buffers where installed. Note the 40 photomultipliers with their red bases, and the reflecting walls inside.

Figure 4. The STEREO inner detector inserted in shielding layers; from the inside out: μ-metal, borated polyethylene, lead, soft iron.

Figure 5. The B₄C-coated STEREO detector, as it moves on air cushions to its final position below the ILL water channel.

include all events that can mimic such coincidence, mostly γ’s and neutrons generated in muon spallations or from the reactor, either from the same source or in accidental coincidence. The presence in the target liquid compound of Gd, a n-capturer with high cross-section and released energy (∼ 8 MeV), enhances the neutron detection efficiency, while the un-doped crown allows to fully contain γ energy deposits and to additionally suppress background thanks to event topology.

2.3. Oscillation analysis
STEREO aims to test the hypothesis of oscillation between active and sterile neutrinos at short distance by comparing spectra of neutrino detected in its 6 identical target cells. Such phenomenon, in fact, would result in a distortion of the spectra at different distances from the neutrino sources (figures 6, 7). The energy of an antineutrino interacting via IBD can be inferred directly from that of the positron (equation 2).
Figure 6. Ratio between neutrino observed with \(N_{\text{obs}}\) and without \(N_{\text{exp}}\) active-sterile neutrino oscillation, for the RAA best fit parameters and as a function of the positron energy \(E_{\text{vis}}\), for the reactor closest (blue) and furthest (red) target cell.

Figure 7. Expected renormalised positron spectra, for the RAA best fit parameter, in case of active-sterile oscillation for the reactor closest (blue) and furthest (red) target cell, and in case of no oscillation (black).

3. Status of the analysis of the data

The STEREO detector was fully assembled by April 2016; it was then moved to the operating position (figure 5) and started to take data in November of the same year. A first data set was collected, consisting of 70 days with the reactor operating, and 25 days of reactor off. Subsequently, a long shutdown and component replacement of the reactor compelled a disassembling of the experiment. This period was used for maintenance and improvement of the detector performance. The detector is now again operational and is collecting reactor-off data since October 2017. The ILL reactor is due to start its operation in early 2018, allowing for STEREO to collect data from additional 7 cycles in 2018-2019. What follows refers to the analysis of data collected in the first phase.

3.1. Detector calibration

The detector response of STEREO is monitored using regular calibration runs with \(\gamma\) and neutron sources, using three independent systems: an internal system consisting of tubes entering the target cells where the source is deployed; an external automated system allowing for a deployment of the source around the detector, and an underneath rail that can be used to deploy sources below the detector floor (figure 8).

\(\gamma\) sources of various energy spanning from approximatively 0.5 to 4.5 MeV are used for the energy calibration. From each source, cell-by-cell calibration coefficients, i.e. conversion factors between collected light and deposited energy, are obtained (figure 9). The variation of collected light peaks with the source position along the vertical axis is estimated to be below 6% and is well reproduce by our Monte Carlo simulation. Calibrations with the \(^{54}\text{Mn}\) source \((E_\gamma = 0.38\ \text{MeV})\) are used to calculate the cross-talk between cells arising from optical photons that occasionally cross the reflecting walls. In order to obtain the deposited energy in each cell for a given event, we perform a matrix inversion process on the values of light collected by photomultipliers, taking into account calibration coefficients obtained with \(^{54}\text{Mn}\) and cross-talk values. Then a correction for the non-linearity of the energy response, or quenching (figure 9), is applied.

Along with \(\gamma\) sources, an alpha reaction neutron source of Am-Be is used to study the detector response to neutrons. More specifically, we calculated the capture time of neutrons from the source, which is consistent with that measured for IBD candidates. Moreover, the fraction of captures on Gd and its dependency on the neutron position was measured, allowing for a correction of the Monte Carlo simulation. Such results will be used in the calculation of a global
neutron detection efficiency for the oscillation analysis.

3.2. Neutrino selection

An IBD selection is defined basing on the following steps: first, we select pairs of events that are separated by a time interval of less than 70 μs; then we apply separate energy conditions on the prompt and delayed event

\[
\begin{align*}
2 \text{ MeV} &< E_{\text{dep}}^{\text{det}} < 8 \text{ MeV} \quad \land \quad E_{\text{dep}}^{\text{GC}} < 1.1 \text{ MeV} \quad \text{(prompt)} \quad (3) \\
5 \text{ MeV} &< E_{\text{dep}}^{\text{det}} < 10 \text{ MeV} \quad \land \quad E_{\text{dep}}^{T_g} > 1 \text{ MeV} \quad \text{(delayed)} \; ; \quad (4)
\end{align*}
\]

finally, additional cuts are applied to reject residual background (table 1). Accidental coincidences of neutrons/γ’s interacting in the detector are estimated online using multiple off-time windows, and the amount is subtracted statistically from IBD candidates. Our analysis is based on a estimation of neutrino spectra for reactor-on and -off periods and statistical subtraction of the latter from the former to obtain a “pure” antineutrino spectrum for each target cell. In order to achieve that, IBD rates (figure 10) are corrected for the atmospheric pressure, which influences the rate of cosmic muons and therefore some background components.

3.3. Expected sensitivity

At the present state, the STEREO collaboration is working on refining the IBD selection and cuts, the systematics for the -off subtraction, and finalise the energy reconstruction for the final oscillation analysis. The signal-over-background ratio and the predicted statistics are close...
Figure 10. IBD rates for data collected during the STEREO first phase, with a correction for atmospheric pressure applied. The refined set of cuts described in table 1 allowed to reduce the background (red points) with respect to a simple IBD selection (black points).

Figure 11. Predicted sensitivity of STEREO, assuming 400 $\bar{\nu}_e$/day in 300 days, a signal-over-background ratio of 1.5, a detection efficiency of 60%, energy scale and flux systematics of 4 and 2% respectively.

to expected requirements that will allow us to cover a broad spectrum of the active-sterile neutrino oscillation phase-space allowed by the RAA (figure 11). The works done during the long shutdown have seen a sizeable improvement of the detector performance, while meanwhile the IBD selection and energy reconstruction were refined.

4. Conclusions
The RAA points to physics beyond the Standard Model in the hypothesis of oscillations involving extra light sterile neutrinos. The STEREO experiment aims to test such hypothesis by searching oscillations of antineutrinos at very short distance from the ILL reactor core source. In its first phase, STEREO has collected data from 1.5 reactor cycles, plus 25 days of reactor off, that we are currently analysing. Furthermore, a second phase is currently ongoing, foreseeing the collection of data from 7 additional cycles by 2019. Although the mitigation of reactor-induced and cosmic background represents a challenge for surface-level reactor antineutrino experiments, we achieved an remarkable control of accidental coincidences, while signal-over-background ratio is close to our intended goal. Our collaboration is working on the refinement of topological cuts, while systematics uncertainties are being defined. A technical paper describing the detector and analysis performances, as well as preliminary oscillation results, will be published in early 2018.

Acknowledgments
STEREO is an international collaboration of CEA-Saclay, ILL, LAPP, LPSC and MPIK, supported by ENIGMASS and ANR. The author wishes to thank P2IO and ANR for co-financing his fellowship, as well as all the STEREO collaborator, with a special mention for his former colleagues of CEA-Saclay.

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