Latest Results of the STEREO Experiment: a Search for a Sterile Neutrino at Very Short Baseline

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Abstract. The increasingly precise study of antineutrinos spectra from reactors has revealed a deviation between the prediction and the measurements, which could indicate the existence of a new neutrino. This new neutrino state would not couple with the weak interaction (a sterile neutrino) and its mass would be around 1 eV/c^2. The STEREO experiment aims at testing this hypothesis using a gadolinium-loaded liquid scintillator in a segmented neutrino target at 10 meters distance from the compact core of the ILL research reactor, in Grenoble (France). The hypothesis of an oscillation towards a light sterile neutrino is tested by performing a relative comparison of measured $\nu_e$ spectra between cells. The data recorded during 119 (211) days of reactor turned on (off) are compatible with the null oscillation hypothesis and reject the original best-fit of the RAA at 99.8 % C.L. The analysis efforts are now pointing towards measurements involving absolute predictions in flux and shape of the antineutrino spectrum.

1. Introduction

The Reactor Antineutrino Anomaly (RAA) was established in 2011, when a new spectral prediction of reactor antineutrinos showed a 6% deficit in the rates observed by previous reactor experiments [1]. A possible explanation for this discrepancy consists in introducing a fourth sterile neutrino at the eV mass-scale into which electronic antineutrinos would oscillate. In the simplest model with one sterile neutrino, the probability of disappearance of $\nu_e$ at very short baseline writes in good approximation:

$$P_{\bar{\nu}_e \to \bar{\nu}_e} (L,E) \simeq 1 - \sin^2 (2\theta_{\text{new}}) \sin^2 \left( \Delta m^2_{\text{new}} L / 4E \right)$$

where $E$ is the $\nu_e$ energy, $L$ is the distance between the core and the detector, and $\theta_{\text{new}}$ and $\Delta m^2_{\text{new}}$ the mixing angle and the square of mass splitting introduced by the additional sterile neutrino. The original RAA best-fit parameters are $(\sin^2 (2\theta_{\text{new}}); \Delta m^2_{\text{new}})_{\text{RAA}} = (0.14; 2.4 \text{ eV}^2)$.

Alternatively, an erroneous prediction of the corresponding $\nu_e$ flux – due to underestimated systematics, biases in the conversion method or normalization errors – could also explain this deficit. Besides the search for sterile neutrinos, a deep understanding of reactor $\nu_e$ spectrum is thus crucial. Moreover, in addition to the RAA, discrepancies in shape with respect to prediction are observed by Double Chooz, Daya Bay, RENO and NEOS. These experiments all measure $\nu_e$ from commercial reactors. Measurements close to $^{235}$U-enriched reactor cores will bring valuable complementary information and enable to test the hypothesis of anomalies driven by one single isotope.
In this context, STEREO is designed to be sensitive to the favored RAA region and aims at providing a new high-precision reference measurement of the reactor $\nu_e$ spectrum for pure $^{235}$U.

2. Experimental Setup

The STEREO active volume for $\nu_e$ detection consists of six identical cells (the Target) which cover different distances of propagation from 9.4 to 11.2 meters from the ILL compact reactor core in Grenoble [2]. The neutrino oscillation hypothesis associated to sterile neutrino can be tested by looking for a relative distortion of the $\nu_e$ energy spectrum with distance. Antineutrinos are dominantly produced by fission products of the $^{235}$U isotope in the 93% enriched uranium fuel and are detected via the inverse beta decay (IBD) process in the liquid scintillator filling out the detector: $\nu_e + p \rightarrow e^+ + n$. The signature of this reaction is a coincidence in time and space between a prompt energy deposit provided by the positron and its annihilation, and a delayed $\gamma$ cascade coming from the neutron capture after its thermalization and diffusion in the medium. Neutron detection efficiency is enhanced by loading the 2 $m^3$ of the Target liquid with gadolinium, thanks to the high neutron capture cross-section and energy release (8 MeV) of this element. The mean capture time of a neutron is about 18 $\mu$s in the Target. The optical separation of the cells is provided by reflective walls consisting of acrylic plates and reflective foils (3M™ Enhanced Specular Reflector). Light from scintillation produced in the liquid is collected by four 8-inches photomultiplier tubes (PMT) on the top of each cell, placed inside an acrylic buffer and immersed into mineral oil for optical contact. The possible energy leaks out of the Target are handled by a surrounding crown – filled with unloaded liquid scintillator – retrieving escaping $\gamma$s from positron annihilation or the $\gamma$ cascade from neutron capture. A cross-sectional view of the STEREO detector is presented in Fig. 1.

![Figure 1. Cross-sectional drawing of the STEREO detector.](image-url)

The radioactive environment in the reactor building and the detector location at ground level make the measurement challenging. First, the background is mitigated thanks to several layers of passive shieldings: magnetic shielding, polyethylene, lead walls and neutron absorbers, with a total mass of about 65 tons. The detector also benefits from the coverage of a 15 m water equivalent overburden provided by the water channel and the pool of the ILL reactor, reducing...
the cosmic background. In addition, a Cherenkov muon-veto detector on the top of the STEREO setup acts as an active shielding against this background by tagging muons.

3. Detector Response
The response of the liquid and the electronics are monitored automatically using LEDs with dedicated acquisitions. The energy response of the detector is monitored on a weekly basis using mainly $\gamma$ radioactive sources, while the neutron capture response is studied with a dedicated AmBe neutron source. The Monte-Carlo simulation (MC) of the detector is tuned to calibration data and reproduces energy non-linearities at the percent level. Energy deposition for each event is reconstructed thanks to an algorithm that corrects light-cross talks between cells at first order. This method is applied in both data and MC. The total energy resolution is of 9% at 0.8 MeV. Cell-to-cell residual discrepancies between the simulation and the data are taken into account through the uncorrelated energy scale uncertainties. The reconstructed energy is monitored along time using the 2.2 MeV $\gamma$ peak from cosmic-induced neutron capture on hydrogen in the liquid. This study has finally shown that a sub-percent stability is achieved.

Recently, a special attention has been given to the modelization of the $\gamma$ emission after the neutron capture on gadolinium, whose signal is the signature of an IBD interaction. A significant improvement in the description of the deexcitation cascades was obtained thanks to the FIFRELIN code, taking advantage of the latest experimental data and recommended nuclear models and data evaluations. Further details can be found in [3].

4. Antineutrino Signal Extraction
The IBD selection for the analysis of Phase-II$^1$ presented here was performed on 119 (211) effective days of reactor turned on (off) data, by looking for coincidences between prompt [1.625-7.125 MeV] and delayed [4.5-10 MeV] signals within a 70 $\mu$s time windows. In addition, 100 $\mu$s clean gates are imposed before and after each pair candidates as well as a muon-veto. An extra constrain on asymmetry of charge deposition in the PMTs of the vertex cell is applied in order to reject non-tagged muons that stop and decay in the top layer of the detector. The detector segmentation is also used to further reduce the IBD background, details are presented in [4].

The remaining background is handled by the Pulse Shape Discrimination (PSD) which provides an extra information on the nature of the energy deposit: electron-recoil, as in $\overline{\nu}_e$ interaction, or proton-recoil, induced by fast neutrons. This capability is made possible by the different scintillation decay time constants of the liquid depending on the nature of the energy deposit. For STEREO, the relevant observable is provided by the ratio of the tail charge over the total charge collected from each PMT signal, $Q_{\text{tail}}/Q_{\text{tot}}$. Once this quantity is corrected from the liquid temperature correlation, the stability of the correlated background is tested while the reactor is turned off. Induced by cosmic events, the correlated background rate shows a correlation with the atmospheric pressure and the filling level of the water pool above the detector. Despite these environmental variations, the shape of the correlated background distributions was shown to be very stable under all the different conditions encountered during data taking. With this reference background shape, the $\overline{\nu}_e$ candidates are extracted separately for each cell and each energy bin from a fit of the PSD distributions obtained with the reactor-on data with a model utilizing reactor-off periods, with only a scaling parameter for the background model. The accidental pair component – dominated by electronic recoils – is measured online with very high accuracy by looking for random coincidences in 100 delayed windows for each prompt candidate. Finally, the neutrino component is modeled with a gaussian PSD shape and the rate in each energy bin is obtained from the integral estimate of the fitted PSD model.

$^1$ Phase-II stands for data taken between Oct. 2017 and Jan. 2019.
5. Results and Outlooks

The oscillation analysis is performed by looking for the relative distortions of the $\nu_e$-spectra between the six cells. The measured spectra $D_{cb}$ are compared to the simulated spectra $M_{cb}$ using:

$$\chi^2 = \sum_{c} \sum_{b} \sum_{c'} \sum_{b'} (D_{cb} - \phi_b M_{cb}) \left[ V_{\text{cov}}^{-1} \right]_{cb,c'b'} (D_{c'b'} - \phi_{b'} M_{c'b'}) ,$$

where $\phi_b$ terms are free parameters for each energy bin $b$, common to all cells, allowing an oscillation inference independent of any reactor-based predictions. $V_{\text{cov}}^{-1}$ represent the inverse covariance matrix which take care of the statistical uncertainties as well as the relevant systematic errors.

The $\chi^2$ test has shown that the data are compatible with the null-hypothesis (no sterile neutrino) with a p-value of 40%. Thus, a Raster-Scan method is utilized to generate exclusion contours at 90% C.L. as shown in Fig. 2. In particular, the original RAA best-fit point [1] is excluded at 99.8% C.L. STEREO is continuing data taking under very stable conditions, and will cover its full sensitivity to the RAA region with twice more statistics by mid-2020.

The analysis efforts are now pointing toward measurements involving absolute predictions in flux and shape of the antineutrino spectrum. In order to carry out such studies, a high precision in the treatment of the energy scale is required. Complementary to the calibration sources, the cosmic induced $^{12}\text{B}$ beta decay is being used to provide new stringent constrains up to 14 MeV. The spectrum has been extracted in the data by looking for a coincidence signal of a stopping muon followed by a beta event coming from a $^{12}\text{B}$ decay. The MC spectrum on the other hand has been built up by taking into account the three main branches of the $^{12}\text{B}$ decay, the $^{12}\text{N}$ background and the vertices distributions of the stopping muons. The comparison between the measured and simulated spectra – shown on Fig. 3 – will be used to identify potential energy scale biases and will refine the estimation of the systematic uncertainties.

![Figure 2](image1.png)  
**Figure 2.** Exclusion contour at 90% C.L. (red). The original RAA contours and best-fit points are indicated with gray lines, and black star, respectively. The expected sensitivity is shown in blue.

![Figure 3](image2.png)  
**Figure 3.** Comparison between the measured beta decay spectrum of the $^{12}\text{B}$ (black) with the simulation (red).

References
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