Sterile neutrino exclusion from the STEREO experiment with 66 days of reactor-on data

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The reactor antineutrino anomaly might be explained by the oscillation of reactor antineutrinos towards a sterile neutrino of eV mass. In order to explore this hypothesis, the STEREO experiment measures the antineutrino energy spectrum in six different detector cells covering baselines between 9 and 11 meters from the compact core of the ILL research reactor. In this article, results from 66 days of reactor-on and 138 days of reactor-off are reported. A novel method to extract the antineutrino rates has been developed based on the distribution of the pulse shape discrimination parameter. The test of a new oscillation toward a sterile neutrino is performed by comparing ratios of cells, independent of absolute normalization and of the prediction of the reactor spectrum. The results are found compatible with the null oscillation hypothesis and the best fit of the reactor antineutrino anomaly is excluded at 97.5% C.L.

Neutrino oscillation experiments of the last two decades have measured all mixing angles and mass splittings in a three flavor framework [1]. In the three-neutrino model, no significant disappearance of neutrinos of few MeV energy is expected at baselines of less than 100 m. Nevertheless, many experiments in the vicinity of nuclear reactors have observed a lower electron antineutrino flux than predicted at such distances. There are basically two possible explanations for this observation known as the Reactor Antineutrino Anomaly (RAA) [2]. One is a deficient prediction of the antineutrino flux and spectrum from reactors, due to underestimated systematics of the measurements of beta spectra emitted after fission [3,5] or of the conversion method [6,7], see [8,9] for recent reviews. The other one proposes new physics beyond the Standard Model of particle physics considering an oscillation from active towards a sterile neutrino state [2]. This sterile neutrino option could also explain the deficits observed by the solar neutrino experiments GALLEX and SAGE in their calibrations with intense $^{51}$Cr and $^{37}$Ar neutrino sources [10,12]. The original contours of allowed regions in the $(\sin^2(2\theta_{ee}), \Delta m^2_{12})$ plane given in [2] and their best fit values $(\sin^2(2\theta_{ee}) = 0.14, \Delta m^2_{12}=2.4$ eV$^2$) are used as benchmark in this paper. A recent review of light sterile neutrinos in the context of these anomalies and fits in different scenarios can be found in [13]. In contrast, other experimental results strongly constrain oscillations to sterile neutrinos in different channels, putting tension on global fits [14]. In particular appearance and disappearance data appear incompatible.

Both solutions to the RAA, deficient predictions of reactor antineutrino spectra and intensities as well as new particle physics, can be studied with the data of the STEREO experiment. STEREO is installed at the high flux reactor of the Institut Laue Langevin operating with highly enriched $^{235}$U (93%). Therefore, contributions from fission of other isotopes is negligible and STEREO will provide a pure $^{235}$U antineutrino spectrum measured at 10 m baseline. However, in this paper we concentrate on the sterile neutrino hypothesis as solution of the RAA which has triggered a series of reactor antineutrino experiments at very short baselines [15]. Results of the first two of these experiments, DANSS [16] and NEOS [17], exclude significant parts of allowed regions from Ref. [2]. At the same time, a combined analysis of all reactor antineutrino disappearance experiments still favors oscillations involving a fourth neutrino state at the $3\sigma$ level [14]. The best fit parameters driven by the new DANSS and NEOS results suggest a mass splitting of $\Delta m^2_{14} \approx 1.3$ eV$^2$ and a mixing angle of $\sin^22\theta_{e\nu}\approx 0.05$, which is slightly outside the favored regions of Ref. [2] towards a lower mixing angle. This result is independent from flux predictions, since it is based on the comparison of purely spectral information. The analysis of DANSS compares the antineutrino energy spectrum of the moveable detector for two baselines. However, it awaits calculation of the final systematic uncertainties [16]. NEOS relies on a non-trivial comparison of their data to the measured Daya Bay spectrum [18] obtained at different reactors.
with different detectors where the correction of the spectra requires inputs from predictions.

In StereO, the antineutrino spectrum with energies up to about 10 MeV is measured in a segmented detector using six identical target cells, each having a slightly different baseline. The detector center is located at about 10 m distance from the ILL core. The sterile neutrino hypothesis can be tested by comparing the measured antineutrino energy spectra of the different cells. A neutrino oscillation with a mass splitting in the eV region would manifest in a clear spectral pattern of a distance-dependent distortion of the energy spectrum along the detector axis. In this first sterile neutrino analysis, spectra ratios using one cell as a reference are used. In this way, no reactor spectrum prediction is needed and the analysis is independent from the absolute flux normalization, minimizing systematic uncertainties.

The StereO detector system (see Figure 1) consists of an antineutrino detector, a muon veto on top and several calibration devices. The antineutrinos are detected via the inverse beta decay reaction (IBD) on hydrogen nuclei in an organic liquid scintillator: \( \bar{\nu}_e + p \rightarrow e^+ + n \). The six optically separated cells of the Target (TG) volume are filled with a gadolinium (Gd) loaded liquid scintillator for a total of almost 2 m\(^3\). They are read out from the top by 4 photomultiplier tubes (PMT) per cell. The IBD signature is a delayed coincidence of a prompt positron and a delayed neutron capture event. The antineutrino energy is directly inferred from the prompt event. The neutron from the IBD reaction is moderated and then mainly captured by Gd isotopes. This capture creates a characteristic delayed signal of a gamma cascade with about 8 MeV total energy. These gammas can interact in the TG and in an outer volume, called Gamma-Catcher (GC), which surrounds the TG. It is filled with liquid scintillator without Gd and equipped with a total of 24 PMTs. In some cases, the GC serves also for the total positron energy, detecting annihilation gammas escaping the TG. The mean capture time of the coincidence signal is about 16 \( \mu s \) allowing for efficient discrimination of accidental background. Moreover, background events are strongly reduced by a thorough passive shielding design of various materials with a total mass of about 65 tons. On the ILL site, StereO is installed underneath a water channel providing, together the reactor building, an overburden of 15 m w.e. against cosmic radiation. Remaining background can be measured during phases with the reactor turned off. A method has been developed to convert the PMT signals into a reconstructed energy, taking into account light cross-talk between cells. The reconstructed energy resolution \((\sigma/E)\) for \(^{54}\text{Mn}\) \(\gamma\)-rays (0.835 MeV) is about 9\%. Energy nonlinearity, due to the quenching effects, is measured precisely and reproduced in the Monte Carlo (MC) at the percent level. More information on the detector and its performances can be found in ref. [19]. The analysis presented in this article concerns the phase-I of the experiment with about 66 days of reactor-on and 138 days of reactor-off [20].

Table I lists the set of IBD selection cuts corresponding to the best compromise between detection efficiency and background rejection, although the results remain quite stable around the chosen values. Beyond the basic cuts on energy and capture time (cuts 1-3 in table I), advantage is taken of the segmentation of the detector to better tag the topology of energy deposits of IBD events: a compact prompt event with the only potentially escaping particles being the 511 keV annihilation \(\gamma\)-rays (cuts 4 and 5), the expanded energy deposition pattern of the \(n\)-Gd capture ensuring a minimal deposit in the TG (cut 6) and a maximum distance between the reconstructed vertices of prompt and delayed signals (cut 7). Large part of the cosmic-rays induced background is rejected by applying a 100 \( \mu s \) muon veto (cut 8) and an isolation cut to get rid of multi-neutron cascades (cut 9). Non-tagged muons that stop and decay in the very top layer of the detector, without depositing more than 7.1 MeV energy, may be mistaken as IBD candidates. For these events, the light distribution between PMTs of the vertex cell is more asymmetric than for events in the detector bulk. Therefore, the asymmetry, defined as the maximum of single PMT charge in the cell divided by the total PMT charge, allows to remove the majority of them (cut 10). The main contributions to the dead time are from the muon veto and isolation cuts. The total correction ranges from 10 to 15\% depending on the single rates induced by the activities of the neighboring experiments. It is accurately computed using two independent methods and leads to a relative uncertainty of 0.3\% over the data taking time.
Inside the above selection cuts, an average of 396.3 ± 4.77νe/ day is detected with a signal to background ratio of about 0.9, averaged over the prompt energy window. This signal has been separated from the remaining background using a Pulse Shape Discrimination (PSD) parameter, defined as the ratio of the pulse tail charge and the pulse total charge. The PSD distribution of the prompt event of all pair candidates is shown in figure 2 for one of the 11 reconstructed energy bins defined in the analysis. Two classes of events clearly appear, the proton recoils induced by fast neutrons, showing up at high PSD, and the electron recoils at low PSD, where the IBD positrons are expected.

The reactor-off data collected by STEREO are used to parameterize accurately the PSD distribution of the correlated background induced by cosmic rays. Data are split into time bins of 1 week and energy bins of 500 keV width. For each bin, the PSD distribution is modeled with a multi-Gaussian function: one Gaussian for electronic recoils, one for proton recoils and one for accidental coincidences. The accidental coincidences component is determined by fitting, in a combined way, its PSD distribution obtained very accurately by opening many (typically 100) delayed windows for each prompt candidate and rescaling the obtained distributions by the number of windows. The PSD distribution of the random coincidences is almost purely electronic since gammas dominate the single rates. In the fitting procedure, the position and the width of the electronic recoil Gaussian are constrained using their very accurate determination on the PSD distribution of single events. The positions of the Gaussians drift with time due to temperature changes and to the evolution of the light collection efficiency and cross-talk of the cells during phase-I. However, the ratio of the areas, $R_{\text{cosmic}} = A_{\text{off}} / A_{\text{p}}$, was found to be compatible with a constant and in particular, independent on the atmospheric pressure. The average over time of this ratio for each energy bin is the only parameter of the reactor-off data transposed to the analysis of the reactor-on data. The reactor-on PSD distribution for each cell and time-energy bin is then fit using this background model with an additional Gaussian to reproduce the antineutrino signal. The area of the additional Gaussian gives the number of neutrino for the time-energy bin. The mean and sigma values of the antineutrino Gaussian are set free to vary by about 15% (σ value of a pull term) around these values. This range was set to include all observed fluctuations between the electronic recoil peak and the neutrino peak. In contrast to a fixed cut on the PSD value, this novel method permits a full separation of electronic and proton recoils in spite of the overlapping distributions and accounts for slow drifts in the PSD distribution. The method is insensitive to dead time differences between reactor-on and reactor-off runs since rates entering in the ratios are measured simultaneously and only ratios are transferred between reactor-on and reactor-off measurements. The remaining systematics due to the deviation of the PSD shape model from the true shape is controlled by the high goodness of fit for all energy bins of reactor-off PSD distributions. Moreover, since this model is applied to all cells, potential deviation from the model will be further suppressed in the ratio of spectra used in the oscillation search.

To search for a possible oscillation toward a sterile neutrino in the data, a ratio method is used. It consists in dividing bin by bin the spectrum of cells 2 to 6 by the spectrum of cell 1, which serves as a reference, and comparing these ratios between data and MC. This formalism is insensitive to the model of the reactor spectrum and relies only on the relative difference between cells. However, the variance of the ratio cannot be properly computed when the denominator approaches zero within few sigma units. Therefore, this analysis has been limited to $E_{\text{prompt}} < 7.125 \text{ MeV}$. A profile $\Delta \chi^2$ method is used with:

| Applied cut |
|---|
| Energy | (1) $1.625 \text{ MeV} < E_{\text{prompt}} < 7.125 \text{ MeV}$ |
|        | (2) $4.5 \text{ MeV} < E_{\text{delayed}} < 10 \text{ MeV}$ |
| Time   | (3) $0.25 \mu s < \Delta T_{\text{prompt-delayed}} < 70 \mu s$ |
| Topology | (4) $E_{\text{GC, prompt}} < 1.1 \text{ MeV}$ |
|        | (5) $\forall i \neq i_{\text{vertex, } E_{i, \text{prompt}}} < 0.8 \text{ MeV}$ |
|        | (6) $E_{\text{Target, delayed}} > 1 \text{ MeV}$ |
|        | (7) $D_{\text{prompt-delayed}} < 600 \text{ mm}$ |
| Rejection of μ induced background | (8) $100 \mu s$ after a muon tag |
|        | (9) Coinc. with event $> 1.5 \text{ MeV}$ |
|        | (±100 μs window) |
|        | (10) $Q_{\text{max}} / Q_{\text{cell, prompt}} > 0.5$ |

TABLE I. Selection cuts for IBD-pair candidates.
\[ \chi^2 = \sum_{i=1}^{N_{\text{bin}}} \left( \frac{R_{\text{Data}}^{i ightarrow} - R_{\text{MC}}^{i ightarrow} (\alpha)}{V_i} \right)^2 + \sum_{l=1}^{N_{\text{Cells}}} \left( \frac{\sigma_l^{\text{Norm}}}{\sigma_l} \right)^2 + \sum_{l=0}^{N_{\text{Cells}}} \left( \frac{\sigma_l^{\text{Escale}}}{\sigma_l} \right)^2 \]  

(1)

where \( T_{l,i} \) are the predicted spectra including oscillation and detector response.

First, the null oscillation hypothesis has been tested. Figure 3 compares the measured ratios and the simulated ratios without oscillation after minimization letting free the nuisance parameters. The simulated ratios are not perfectly flat because the energy response can slightly vary from one cell to another. The \( \chi^2 \) value is 87.8 to be compared with 78.7, the value obtained with free nuisance parameters and oscillation parameters. From the probability density function (PDF) obtained by MC, the \( \Delta \chi^2 \) of 9.1 corresponds to a p-value of 0.34. Hence, the null oscillation hypothesis cannot be rejected.

To infer an exclusion contour in the oscillation parameter space, a raster scan method [21] has been used. It consists in dividing the 2D parameter space into slices with one slice per \( \Delta m^2_{14} \) bin and computing for each slice the \( \chi^2 \) as a function of \( \sin^2(2\theta) \) with free nuisance parameters. Then, the \( \Delta \chi^2 \) values are computed using the minimum value of each slice and not the global minimum. The 90\% C.L. exclusion contour corresponds to the parameter space where the \( \Delta \chi^2 \) is higher than the value giving a one sided p-value of 0.1 in the PDF obtained by MC for each bin of the parameter space. The result is shown in Figure 3. The obtained exclusion contour is centered around the sensitivity contour with oscillations due to the statistical fluctuations. The original RAA best fit is excluded at 97.5\% C.L. For the first time, an experiment has been able to measure, at the same time, the energy spectrum at different distances from a compact core of a research reactor and to exclude the RAA best fit values without any assumption on the emitted spectrum.

These first results demonstrate the ability of the Stereo experiment to detect antineutrinos above the residual background, dominated by cosmic-ray induced events. With the novel method presented in this paper, the proton recoil component of this background is measured in the temperature and pressure conditions of the reactor-on data taking while the associated relative contamination of electronic recoils is well-constrained from the reactor-off data. The accuracy of the background subtraction is thus driven by the statistics, which naturally improves as more reactor-off data are acquired between the reactor-on periods. The Stereo data taking is still in progress and should reach the nominal statistics, 300 days at nominal reactor power, before the end of 2019.

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[1] M. C. Gonzalez-Garcia, M. Maltoni and T. Schwetz, JHEP 1411 (2014) 052.
[2] G. Mention, M. Fechner, T. Lasserre, T. A. Mueller, D. Lhuillier, M. Cribier and A. Letourneau, Phys. Rev. D 83 (2011) 073006.
[3] F. von Feilitzsch, A. A. Hahn, K. Schreckenbach, Phys.
FIG. 3. Measured ratios for the cells from 2 to 6 (blue points) compared to the null oscillation hypothesis model (red lines). Energy is the reconstructed energy of the prompt event.

FIG. 4. Exclusion contour of the oscillation parameter space. The RAA values and contours are from [2].