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Latest results of the STEREO search for a sterile neutrino at a research reactor

Loïc Labit[a,*]

[a] *Universite Grenoble Alpes, Universite Savoie Mont Blanc, CNRS/IN2P3, LAPP Chemin de Bellevue 74000 Annecy, France*

E-mail: labit@lapp.in2p3.fr

In the last years, reactor neutrino experiments have played a prominent role in understanding neutrino oscillations, in particular with the precise measurement of the mixing angle θ_{13}. However, following a reevaluation in 2011 of reactor antineutrino fluxes, a discrepancy between measured and expected fluxes, known as the Reactor Antineutrino Anomaly (RAA), was observed and has yet to be fully understood. This anomaly could result from the existence of an additional (thus sterile) light neutrino state participating in the oscillation. The parameter values that best match this conjecture are: $\sin^2(2\theta_{ee})$=0.17 and Δm^2_{41}=2.3 eV^2.
The STEREO experiment was designed to test this oscillation hypothesis independently of predicted antineutrino spectra and fluxes, using the antineutrinos emitted by the compact core of the research reactor at the Laue-Langevin Institute (ILL) in Grenoble, France. The target, located at about 10 m from the core, is segmented in six cells, allowing for a measurement of the antineutrino energy spectrum at various baselines, so that the experiment is sensitive to the oscillation toward a sterile neutrino that would distort each cell's spectrum differently.

In 2018 the STEREO collaboration published its first results excluding the RAA best fit with a confidence level of more than 99% and excluding a large part of the parameter space. This paper presents the latest results of STEREO with significantly improved sensitivity to the oscillation of a sterile neutrino, including measurements of antineutrino flux normalization and spectrum shape emitted by a ^{235}U-dominated nuclear fuel.

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*Speaker

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1. Introduction

In 2011, a reevaluation of the predicted flux of antineutrinos produced by nuclear reactors led to a 6.5% deficit at 2.7σ significance between observed and predicted flux for baselines under 100 m [1]. This deficit, named Reactor Antineutrino Anomaly (RAA), could be explained by underestimated or missing systematics in the computation of the predicted antineutrino flux; or else by Beyond-Standard-Model physics, in the form of a non-weakly interacting additional neutrino known as sterile neutrino.
Assuming the existence of a sterile neutrino, the survival probability of antineutrinos at distances below 100 m can be written as:

$$\mathcal{P}_{\nu_e \to \nu_e} = 1 - \sin^2(2\theta_{ee}) \sin^2(\Delta m^2_{41} \frac{L}{4E}) \quad (1)$$

where L is the distance traveled by the antineutrino and E is the antineutrino energy, θ_{ee} is the mixing angle and $\Delta m^2_{41} = m^2_4 - m^2_1$ is the difference between the squared new mass eigenvalue m_4 and the first mass eigenvalue m_1. The RAA is best explained by an oscillation toward a sterile neutrino state with parameters: $\sin^2(2\theta_{ee}) = 0.17$ and $\Delta m^2_{41} = 2.3$ eV^2 [2]. The baseline and energy dependence in the survival probability implies that by searching for distortions in the antineutrino's energy spectra at several baselines, a prediction independent test of the sterile neutrino hypothesis and its oscillation parameters can be made. This is the approach adopted by the STEREO experiment.

2. Detector design

The STEREO experiment [3] is located at the ILL neutron facility in Grenoble, FRANCE. It is placed at a distance of about 10m from the 93%-enriched ^{235}U reactor of 58.3 MW thermal power. Additional shielding is provided by the reactor water channel for an overburden of 15 m.w.e. The STEREO detector is based on a Gd-loaded organic liquid scintillator technology [4]. Antineutrinos are detected through their inverse beta decay (IBD): $\bar{\nu}_e + p \to e^+ + n$. A coincidence search is performed between the prompt signal, given by the positron energy deposition and the delayed neutron capture on Gd.
The segmentation of the 2.4 m^3 target volume in six identical and optically isolated cells allows for the measurement of the antineutrino spectra at six baselines ranging from 9.4 to 11.1 m. The detector is calibrated and its stability is monitored over time through the deployment of radioactive gamma and neutron sources with energy ranging from 0.5 to 4.4 MeV. Sources can be inserted inside each cell as well as underneath and around the detector.
A special attention was given to the cascade of gammas following a neutron capture on Gd in the simulation. A novel description of the energy levels of the Gd isotopes was implemented in the simulation using the FIFRELIN package, which resulted in an improvement of the agreement between data and simulation [5, 6].

3. Oscillation analysis

The dataset analysed here is composed of 565 days of alternating reactor-on and reactor-off periods, from which are removed the first 24 h following a large transition of the reactor power. The first background reduction work is done by applying cuts.

A first pair of cuts selects the characteristic energy of the two sub-events, the positron and neutron capture signals. Another set of cuts checks the time-distance correlation of the two sub-events. Additional cuts ensure that the event can be attributed to a specific cell. Finally a set of cuts on the elapsed time before and after the closest muon-veto trigger rejects muon and muon-induced background.
After the cuts have been applied, the residual background is discriminated further by exploiting the time profile ("pulse shape") of light emission of the prompt event. The parameter chosen for the pulse shape discrimination (PSD) is the ratio between the integrated charge in the tail of the distribution and the integrated charge in the whole distribution: Q_{tail}/Q_{tot}. The PSD can distinguish between two populations: electron recoils and proton recoils, the former one being composed of IBD events, correlated electron background induced by cosmics and accidentals (dominated by gammas). Proton recoils are due to muon-induced fast neutrons. To extract the number of IBD candidates, the backgroung PSD distribution must be known, it is extracted from the reactor-off phases after correction for temperature effects. The signal over background ratio S/B averaged over the studied energy range amounts to ~0.8 peaking to ~1.8 between 2.5 and 4.5 MeV. The oscillation analysis is performed in 11 energy bins of 500 keV width between 1.625 MeV and 7.125 MeV. In each of the six cells the relative number of IBD candidates is compared to a common expectation minimising the following χ^2:

$$\chi^2 = \sum_{l=1}^{N_{\text{cells}}} \sum_{i=1}^{N_{\text{Ebins}}} \left(\frac{A_{l,i} - \phi_i M_{l,i}(\vec{\alpha})}{\sigma_{l,i}} \right)^2 + \sum_{l=1}^{N_{\text{cells}}} \left(\frac{\alpha_l^{\text{EscaleU}}}{\sigma_l^{\text{EscaleU}}} \right)^2 + \left(\frac{\alpha^{\text{EscaleC}}}{\sigma^{\text{EscaleC}}} \right)^2 + \sum_{l=1}^{N_{\text{cells}}} \left(\frac{\alpha_l^{\text{NormU}}}{\sigma_l^{\text{NormU}}} \right)^2$$

where l and i are indices running over all cells and energy bins respectively, $A_{l,i}$ and $\sigma_{l,i}$ are the number of measured candidates from the IBD extraction and its statistical uncertainty. $M_{l,i}$ is the expected number of neutrinos given by MC simulation with the Huber-Muller energy spectrum. The $M_{l,i}$ dependence on the oscillation parameters is given by Eq. 1, the nuisance parameters α^{EscaleC}, $\alpha_l^{\text{EscaleU}}$ and α_l^{NormU} account respectively for cell-to-cell corelated energy scale, uncorrelated energy scale and cell-to-cell uncorelated normalisation uncertainties, all nuisance parameters are constrained by their respective uncertainties $\sigma_l^{\text{EscaleC, EscaleU, NormU}}$ via pull terms. To prevent the dependence on an absolute rate or shape prediction in this analysis, the ϕ_i are added as free normalisation parameters that differ for each energy bin but are common to all cells.
A $\Delta\chi^2$ formalism is then used to test a specific hypothesis; where $\Delta\chi^2$ is the difference between the minimised χ^2 with parameters of interest fixed to the tested hypothesis and the minimised χ^2 with all parameters allowed to vary. To test the no-oscillation hypothesis a comparison between the $\Delta\chi^2$ of the data and the distribution obtained from 10 000 pseudo-experiments is done. This comparison gives a p-value of 9% hence the no-oscillation hypothesis can not be rejected at 95% C.L. To obtain the exclusion contour of the oscillation parameters space (see Figure 1) a two-dimensional scan of the parameter space is performed generating 10 000 pseudo-experiments for each oscillation hypothesis. The generation of numerous pseudo-experiments is mandatory as the conditions to use Wilk's theorem are not met in a neutrino oscillation search. In particular the best fit point of the RAA is rejected at more than 99.9% C.L. [7]

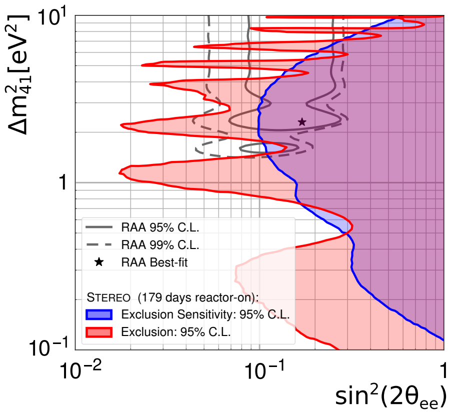

Figure 1: Exclusion contour (red) and exclusion sensitivity contour (blue) at 95 C.L. of phase-I+II. Overlaid are the allowed regions of the RAA (grey) and its best-fit point (star) [2].

Quantity	Symbol	Value	Uncertainty (%)
Number of ν/fission	$N_\nu^{[2,8]MeV}$	1.846	2.40
Huber prediction		1.722	2.40
Correction factors		1.072	0.10
Number of fissions/day		1.30×10^{23}	1.44
Thermal power	$< P_{th} >$	49.2 MW	1.44
Energy per fission	$< E_f >$	20.4 MeV	0.13
Fraction of interacting ν	τ_{int}	8.10×10^{-21}	0.56
Solid angle			0.50
IBD cross section	σ_{IBD}		0.22
MC statistics			0.12

Quantity	Symbol	Value	Uncertainty (%)
Correction of p number	$c_p^{Data/MC}$	0.983	1.00
Detection efficiency	ϵ_d	0.2049	0.54
Correction of delayed efficiency	$c_n^{Data/MC}$	0.9774	0.86
Predicted IBD yield		383.7 d^{-1}	2.10 ⊕ 2.40
Observed IBD yield		363.8 d^{-1}	0.88 ⊕ 1.06
Statistics			0.88
ν extraction method			0.65
Reactor induced bkg			0.83
Off-time method			0.14

Table 1: Summary of relevant quantities for the absolute rate measurement and their relative uncertainties.

4. Absolute rate measurement

The STEREO experiment is able to provide a precise measurement of the antineutrino yield using highly enriched ^{235}U [8]. The dataset considered here amount to 119 days of reactor-on data and 211 days of reactor-off. In a nuclear reactor, antineutrinos are produced from β^- decays of the fission products and the total number of emitted antineutrinos is given by:

$$N_\nu^{\text{emi}} = \frac{< P_{th} >}{< E_f >} \iint \sum_i [f_i(t) S_i(E_\nu)] dE_\nu dt \times (1 + c_{SNF}) \tag{2}$$

where $< P_{th} >$ is the mean reactor thermal nuclear power, $< E_f >$ is the mean energy released per fission, $f_i(t)$ is the activity of the i^{th} β emitter, $S_i(E_\nu)$ is its antineutrino energy spectrum and c_{SNF} is a correction due to the contribution of the spent nuclear fuel. From the number of emitted antineutrinos, the prediction on the number of detected antineutrinos is given by:

$$N_\nu^{pred} = N_\nu^{emi} \times \tau_{int} \times S_{SNF}^{\text{on-off}} \times c_p^{\text{Data/MC}} \times \epsilon_d \times c_n^{\text{Data/MC}} \tag{3}$$

with τ_{int} the fraction of interacting antineutrinos, $c_p^{Data/MC}$ the proton number correction, ϵ_d the total detection efficiency, $c_n^{Data/MC}$ the detection efficiency correction of the delayed signal and $S_{SNF}^{\text{on-off}}$ the suppresion factor of the spent fuel contribution due to the substraction of reactor-on and off data. These quantities and their uncertainty are presented in Table 1. Finally the predicted antineutrino rate is 383.7 ± 8.1[sys]±9.2[model] $\bar{\nu}_e$/day, whereas the observed rate is 363.8±5.0 $\bar{\nu}_e$/day which leads to an observed to predicted ratio of 0.948±0.008[stat] ± 0.023[sys] ± 0.023[model]. The result is in very good agreement with the world average of pure ^{235}U measurements [9].

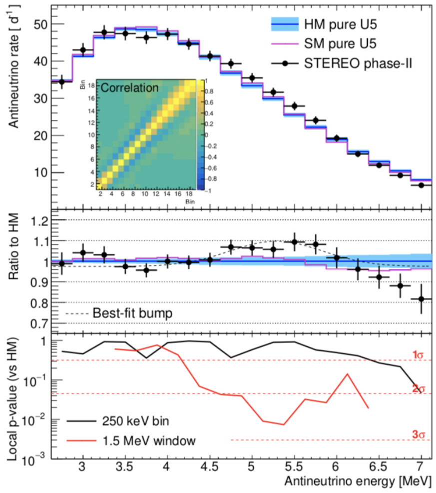

Figure 2: (top) Measured IBD yield spectrum along with area-normalized Huber-Mueller (HM) and Summation model (SM) predictions, including reactor-related corrections. Data error bars include statistical and systematic uncertainties. The almost diagonal correlation matrix is displayed. The blue error band on the HM prediction include theoretical uncertainties from [12] without the normalization component. (middle) Ratios to HM prediction. (bottom) Local p-value quantifying the significance of deviations from HM for each individual 250 keV bin and for a 1.5 MeV sliding window (6 consecutive bins).

5. Spectrum shape unfolding

In addition to the RAA, a shape anomaly is present in the antineutrino energy spectrum [10]. This anomaly takes the form of an excess of events for antineutrinos with energy around 6 MeV. The origin of this anomaly and whether it is related to the RAA or caused by independent effects remains unclear. The STEREO experiment is able to provide a model-independent ^{235}U-induced antineutrino energy spectrum [11]. The ^{235}U-induced spectrum denoted as ϕ is modelled by re-weighting each energy bin i of a reference (or prior) spectrum ϕ^0 with weights λ_i: $\phi_i(\vec{\lambda}) = \lambda_i \phi_i^0$. In this analysis the Huber model for ^{235}U is taken as a prior spectrum [12]. We take into account reactor-related flux corrections $\phi_i^{\text{corr}}(\vec{\alpha})$ where $\vec{\alpha}$ is a set of nuisance parameters. Hence the total antineutrino energy spectrum is given by: $\phi_i^{tot} = \phi_i(\vec{\lambda}) + \phi_i^{\text{corr}}(\vec{\alpha})$ that yields to the following reconstructed energy spectrum prediction for each bin j:

$$N_j(\vec{\lambda}, \vec{\alpha}) = \sum_i R_{ij}(\vec{\alpha}) \phi_i^{tot}(\vec{\lambda}, \vec{\alpha}) \tag{4}$$

with $R_{ij}(\vec{\alpha})$ being the detector response matrix. Finally the spectrum in the antineutrino energy space is evaluated by finding the values of the λ_i that best minimise the following χ^2:

$$\chi^2(\vec{\lambda}, \vec{\alpha}) = \sum_j \left(\frac{N_j(\vec{\lambda}, \vec{\alpha}) - D_j}{\sigma_j} \right)^2 + |\vec{\alpha}|^2 + \mathcal{R}_1(\vec{\lambda}) \tag{5}$$

with D_j the data spectrum in reconstructed energy space and σ_j the associated statistical uncertainty, $|\vec{\alpha}|^2$ controls the variations of the nuisance parameters and $\mathcal{R}_1(\vec{\lambda})$ is a regularisation term that prevents large unphysical bin-to-bin variations in the unfolded spectrum. The regularisation term is given by : $\mathcal{R}_1(\vec{\lambda}) = r \sum_i (\lambda_{i+1} - \lambda_i)^2$ where r is a tunable strength parameter chosen to minimise the dependence to the prior spectrum.

The analysed data shows the presence of a local excess of events at ~4.5 MeV with a ~ 2.4σ significance with respect to the Huber model prediction, see Figure 2.

6. Conclusion

More than 150 000 neutrinos have been detected by the STEREO experiment of which only half have been analysed as of today, yet a major portion of the RAA allowed parameters space is significantly excluded, in particular the best fit point of the RAA is rejected at more than 99.9%. Additionally, the absolute antineutrino rate from a 93%-enriched ^{235}U reactor has been measured, leading to an observed to predicted ratio of 0.948±0.008[stat] ± 0.023[sys] ± 0.023[model] taking the Huber-Muller model as prediction. Finally, we provide an unfolded antineutrino reactor spectrum. Its study showed the presence of a local excess of events at ~4.5 MeV with a ~2.4σ significance with respect to the Huber-Muller prediction. Further analyses with the rest of the acquired data of the STEREO experiment should provide more stringent constraints on the RAA parameters space, as well as on the antineutrino absolute rate and spectrum shape.

7. Acknowledgment

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