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Alessandro Minotti

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Chasing the light sterile neutrino with the STEREO detector

A Minotti

IRFU - CEA Saclay, 91191 Gif-Sur-Yvette, France

E-mail: alessandro.minotti@cea.fr

Abstract. The standard three-family neutrino oscillation model is challenged by a number of observations, such as the reactor antineutrino anomaly (RAA), that can be explained by the existence of sterile neutrinos at the eV mass scale. The STEREO experiment detects $\bar{\nu}_e$ produced in the 58.3 MW_{th} compact core of the ILL research reactor via inverse beta decay (IBD) interactions in a liquid scintillator. Using 6 identical target cells, STEREO compares $\bar{\nu}_e$ energy spectra at different baselines in order to observe possible distortions due to short-baseline oscillations toward eV sterile neutrinos. IBD events are effectively singled out from μ radiation by selecting events with a two-fold coincidence that is typical of an IBD interaction. External background is reduced by means of layers of shielding material. A Cherenkov veto allows to partially remove background produced by cosmic muons, and the remaining component is measured in reactor-off periods and subtracted statistically. If no evidence of sterile neutrinos after the full statistics of 6 reactor cycles is gathered, STEREO is expected to fully exclude the RAA allowed region.

1. Introduction

Neutrino oscillation — in its standard three-family formulation — is now a well characterised phenomenon; all mixing angles (θ_{12} , θ_{23} , and θ_{13}) and absolute squared-mass splittings (Δm_{12}^2 and Δm_{23}^2) have been measured. Nonetheless, the sign of Δm_{23}^2 (mass hierarchy), as well as the CP-odd phase δ_{CP} and the octant of θ_{23} , are still unknown. Furthermore, neutrino masses call for physics beyond the Standard Model, but their absolute scale is yet to be determined.

The three-family paradigm is challenged by experimental anomalies, some of which can be explained by the existence of at least one extra sterile neutrino and an additional Δm_{14}^2 at the eV scale. Such anomalies include the observed deficit, at very short baseline, of reactor antineutrinos, and of neutrinos from gallium sources. The former, named *reactor antineutrino anomaly* (RAA), arises from results of various past reactor antineutrino experiments re-evaluated after a novel calculation of antineutrino spectra [1]. With an extra $\Delta m_{14}^2 \sim 1\text{eV}$, the disappearance of $\bar{\nu}_e$ at very short baseline can be expressed by Eq. 1, where L is the distance from the source of neutrinos and E their energy

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} \sim 1 - \sin^2 2\theta_{ee} \sin^2 \Delta m_{14}^2 L/E. \quad (1)$$

The main goal of the STEREO experiment is to probe the possible existence of sterile neutrinos at the eV mass scale by observing a L -dependent distortion in the E spectra of reactor $\bar{\nu}_e$.



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2. The STEREO experiment

The detector of STEREO is located at the ILL¹ research reactor, in Grenoble, at a distance of ≈ 10 m from the reactor core (Fig. 1). $\bar{\nu}_e$ are produced in the 58.3 MW_{Th} compact reactor core (40 cm diameter), and detected via inverse beta decay (IBD) interactions in a segmented volume with liquid scintillator. The signature of an IBD (Eq. 2) is a two-fold coincidence between the signal that arises from the positron scintillation and sudden annihilation, and that from the delayed neutron capture; such signature strongly singles out IBD interactions from single-interaction radioactive background



The amount of light produced in the liquid scintillator by the positron is proportional to its energy, and allows to infer the energy of the interacting $\bar{\nu}_e$ (Eq. 3)

$$E_{\bar{\nu}_e} \approx E_{e^+} + 0.8 \text{ MeV}. \quad (3)$$

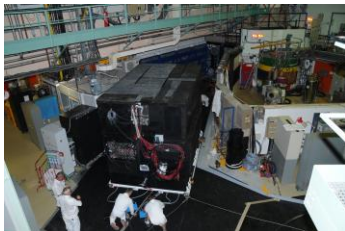


Figure 1. The STEREO detector as it moved towards its final position, below the ILL water channel, in May 2016.

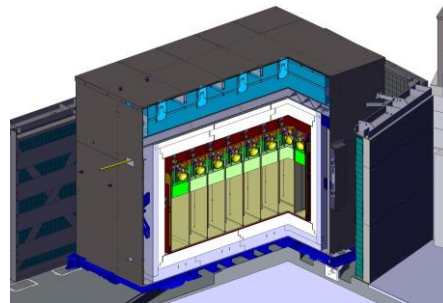


Figure 2. The STEREO inner detector consists of 6 target cells and an outer crown (dark yellow) with upper buffers on top of cells (green), is packed in shielding layers, and topped by a H₂O Cherenkov veto (blue).

The core of the STEREO detector consists of 6 identical cells filled with gadolinium-loaded liquid scintillator (Fig. 2). To verify whether the oscillation towards a sterile neutrino occurs, the energy spectra from different cells, which are placed at different baselines, are compared; in this way systematic uncertainties associated to the evaluation of such spectra are drastically reduced. Gadolinium, with its large n-capture cross-section and released energy (8 MeV, shared between multiple γ 's), enhances the IBD detection efficiency. γ 's from n-capture or positron annihilation that escape the target cells interact in most cases in an outer crown filled with unloaded liquid scintillator, allowing for a full energy reconstruction of the event. The light produced in the prompt and delayed event of an IBD interaction is collected by 48 8-inch photomultiplier tubes (PMTs) located in buffers placed on top of each target and gamma catcher cell. The buffers are filled with mineral oil to improve light collection by the PMTs. All internal surfaces of the cells and the crown are covered with VM2000 reflective foils layered with acrylic plates that convey optical photons to the upper PMTs. Moreover, an external water Cherenkov veto equipped with 20 PMTs detects cosmic muons crossing its volume.

The mitigation and estimation of residual background is a crucial aspect in STEREO. A considerable component of the background comes from the reactor activity, both directly and through extraction of neutrons in neighbouring experiments, consisting in accidental coincidences of γ 's and neutrons produced in fissions and decays of products. Neighbouring experiments make also use of magnetic fields, which can interfere with PMT signals. The detector of STEREO is

¹ Institut Laue-Langevin

surrounded by layers of different shielding materials: μ -metal and soft iron (to mitigate magnetic fields); polyethylene and B_4C (to absorb reactor-induced neutrons); lead (to absorb reactor-induced μ 's). Cosmic-induced events can mimic the delayed coincidence of an IBD interaction. Such background is mostly rejected with the muon veto and the use of a combination of PSD and topological cuts; the remaining component is measured and subtracted statistically using reactor-off periods. Estimated rate of IBD is ~ 400 per day in the whole detector, while background should not exceed such number after cuts are applied.

STEREO is calibrated regularly to monitor the detector response and stability. Light produced by LEDs is injected into the detector through optical fibres on an hourly basis to calibrate PMTs, study the linearity of the electronics, survey the properties of the liquids, and monitor geometrical effects. Radioactive sources are deployed inside the cells at different heights using internal tubes, as well as underneath and along the detector via dedicated systems. μ sources, along with muon-induced events such as spallation neutron captures and ^{12}B decays, provide benchmarks to calibrate the energy response of the detector. Furthermore, spallation neutrons and neutron sources are used to determine the IBD detection efficiency and to characterise and reject background, as well as to tune the PSD.

3. Status of STEREO and discovery potential

STEREO started recording data at ILL in November 2016. IBD interactions from a full 50-day reactor cycle were collected, as well as data from a 20-day period of reactor off.² Preliminary results of collected photoelectrons (pe) for a ^{54}Mn μ source are shown in Fig. 3. In case of no evidence of oscillation toward sterile neutrinos, STEREO expects to fully exclude the $\sin^2 2\theta_{14}$ Δm_{ee}^2 phase-space allowed by the RAA in 300 days of data taking with full reactor power, i.e. 6 cycles (Fig. 4). Moreover, the experiment will provide a new reference measurement of pure ^{235}U $\bar{\nu}_e$ spectrum and shed light on spectral distortions observed by other experiments [2].

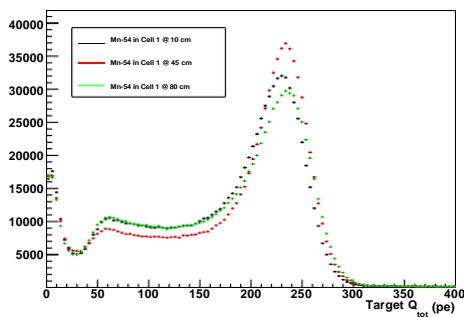


Figure 3. Number of pe collected in STEREO for ^{54}Mn deployed at different heights in a target cell. The energy response of 270 pe/MeV at the 0.83 MeV of the emitted μ has a up-down discrepancy of less than 2%.

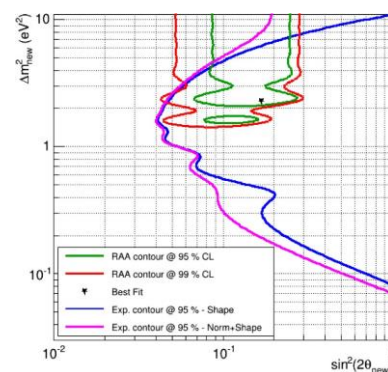


Figure 4. Simulated exclusion plot of STEREO, assuming a 300 days exposure, 1.5 signal over background, 60% detection efficiency, and a 2% error on the energy scale.

- [1] G Mention et al. "Reactor antineutrino anomaly". *Physical Review D* 83.7 (2011), p. 073006.
 [2] C Buck et al. "Investigating the spectral anomaly with different reactor antineutrino experiments". *Physics Letters B* 765 (2017), pp. 159–162.

² Note added after the conference.