Search for the eV-Scale Sterile Neutrino at a Very Short Baseline: Status and Perspectives

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Abstract

From the discovery of the neutrino to the measurement of θ_{13}, the last unknown neutrino mixing angle, nuclear reactors have proved to be a fundamental tool to study these particles, of which much remains to be unveiled. Measurements involving reactor antineutrinos rely on the prediction of their energy spectrum, a nontrivial exercise involving ad hoc methods and carefully selected assumptions. A discrepancy between predicted and measured antineutrino fluxes at a few meters distance from reactors arose in 2011, prompting a series of experimental efforts aimed at studying neutrino oscillation at a baseline that was never tested before. This so-called reactor antineutrino anomaly can, in fact, be accounted for by invoking the existence of new sterile neutrinos at the eV mass scale that participate in the neutrino mixing, an appealing hypothesis tying to other anomalies already observed in the neutrino sector, which opens a door for physics beyond the Standard Model. This article presents an overview of the most recent results of the projects involved in the search for reactor antineutrino oscillations at a very short baseline, and their implication in our current understanding of the reactor antineutrino anomaly and the eV-scale sterile neutrino hypothesis.

Keywords: sterile neutrinos, reactor neutrinos, neutrino oscillation
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1. INTRODUCTION

Ever since the discovery of neutrinos, reactors have played a fundamental role in our quest to understand these elusive particles.

The flavor transition probability of electron antineutrinos (equation (1)) depends, in fact, on two of the angles of the neutrino mixing matrix $U_{PMNS}(\theta_{13}, \theta_{12})$, and both the neutrino squared-mass splittings

$$\begin{aligned} P_{\bar{\nu}_e \to \bar{\nu}_e} \simeq\ & 1 - \sin^2(2\theta_{13}) \sin^2\left(\Delta m^2_{23} L/4E\right) \\ & - \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2\left(\Delta m^2_{12} L/4E\right). \end{aligned} \tag{1}$$

Moreover, electron antineutrinos are produced abundantly in the β decays of reactor fissiles.

In the 2000s, three reactor antineutrino experiments got underway: Double Chooz, Daya Bay, and RENO, the purpose of which was to measure θ_{13}, the at the time last unknown U_{PMNS} mixing angle [1, 2, 3]. The principle on which the measurement was based was that of comparing antineutrino energy spectra in near ($\sim$100 m) and far ($\sim$1 km) detectors, in order to measure a distortion induced by the θ_{13}-driven oscillation. The experimental effort of these three reactor antineutrino experiments was backed by novel calculations of the global $\bar{\nu}_e$ spectra from different fissile isotopes [4, 5], which was aimed at providing a benchmark for near detectors. When comparing the new predicted antineutrino rates with those measured by all existing short baseline experiments (Figure 1), a $\sim$6% discrepancy was observed. This discrepancy, known as reactor antineutrino anomaly (RAA), was subsequently confirmed by the near detectors of Double Chooz, Daya Bay, and RENO themselves [6]

The discovery of the RAA aroused immediate interest from the reactor neutrino community, as it challenges the three-neutrino paradigm and may therefore indicate physics beyond the Standard Model of particle physics. The existence of one (or possibly more) extra neutrino particle, with a mass of about 0.1–1 eV, consisting almost exclusively of a new neutrino flavor, would, in fact, lead to an active-sterile neutrino mixing at 1–10 m baseline and therefore account for the discrepancy. The extra neutrino flavor does not couple with the weak bosons, and these neutrinos are thus called steriles, but mixes with the three standard neutrino flavors by means of an extended U_{PMNS} matrix. This modifies equation (1), for very short baselines, as follows:

$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L \leq 10\,\text{m}) \simeq 1 - \sin^2(2\theta_{ee}) \sin^2\left(\Delta m^2_{14} L/4E\right), \tag{2}$$

where θ_{ee} is the new mixing angle and a diagonal element of the new U_{PMNS}, and Δm^2_{14} the squared-mass splitting between the new neutrino and the standard ones.

The RAA ties to other anomalies observed in the neutrino sector: the gallium anomaly, i.e., a deficit in the neutrino counts from radioactive sources observed in the 1980s by gallium-based solar neutrino experiments, and recently confirmed by the BEST collaboration [8]; and the appearance of ν_e in a ν_μ beam at a short baseline observed by LSND and MiniBooNE (in tension with $\nu_\mu \to \nu_\mu$ disappearance results) [9]. Although both these anomalies point to extra sterile neutrino flavors, a simple global solution combining them and the RAA is currently disfavored in the neutrino oscillation experimental framework.

2. REACTOR ANTINEUTRINO OSCILLATION AT A VERY SHORT BASELINE

In order to test the eV-scale sterile neutrino hypothesis, the oscillation signature must be disentangled from the absolute rate and its associated errors. This is achieved by measuring the antineutrino spectrum at a very short baseline ($\leq$10 m), in a similar way as for θ_{13}-aimed experiments (Figure 2). Then, the new oscillation parameters, Δm^2_{14}, θ_{ee}, are tested against data with two different hypotheses: the oscillation hypothesis, which re-

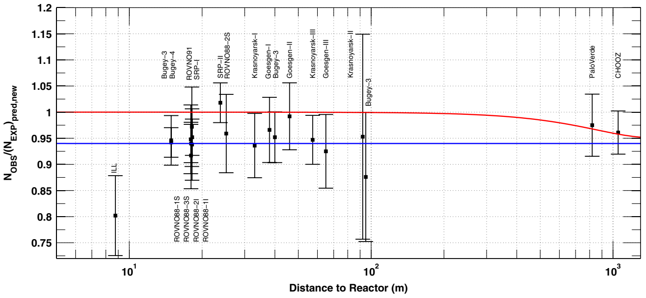

FIGURE 1: Illustration of the reactor antineutrino anomaly: the experimental results are compared with a prediction with three active neutrino families (red) and a solution including a new neutrino mass state (blue) [7].

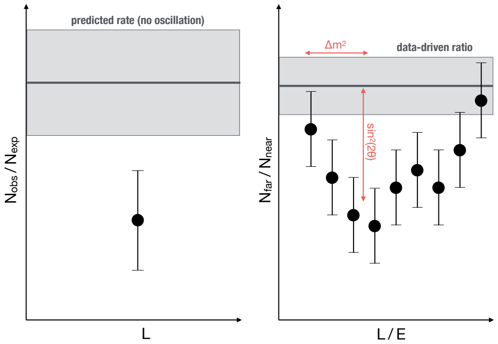

FIGURE 2: RAA tested with rate-only measurements vs prediction (left), or with a model-independent near-far detector spectra comparison (right).

sults in a best fit, i.e., the best values of Δm^2_{14}, θ_{ee} for which an oscillation fits the data, and a confidence level contour; the null hypothesis, which produces an exclusion plot (Figure 3), i.e., a curve representing the region of the Δm^2_{14}-θ_{ee} phase space that is excluded by data with a given confidence level.

The capability of an experiment to exclude part of the RAA allowed region depends on several factors: a high statistic, which in turns depends on the reactor power and detection efficiency, and signal-over-background ratio, both result in a higher sensitivity to small values of the oscillation amplitude θ_{ee}; the size of the reactor core and the distance from the detector, on the other hand, affect the sensitivity in terms of accessible frequencies, or Δm^2_{14} (Figure 3).

The different experiments that were built to test the eV-scale sterile neutrino hypothesis using reactor antineutrinos, which will be listed in the next section, are based on similar detection principles with different technological approaches. For all of them, reactor antineutrinos are detected via inverse beta decay (IBD) interactions in a scintillating material (liquid or plastic). The delayed coincidence of the positron scintillation and sudden annihilation, and neutron capture, provides the strong signature that is crucial to disentangling IBD interactions in the sea of single events.

Residual background consists of accidental coincidences or two fold physical coincidence (e.g., fast neutrons producing proton recoil before being captured, spallation muons followed by Michel's electrons) that can mimic the signature of an IBD event. Background is a key challenge for detectors aimed at short baseline reactor neutrino oscillation measurements, which cannot take advantage of being underground. The reactor itself is a source of background, producing high rates of neutrons, while cosmic rays contribute with spallation neutrons and γ-emitting cosmogenic isotopes. Strategies to deal with background include passive shielding (neutron moderators such as polyethylene and boron, gamma absorbers such as iron and water) and active vetoes, pulse shape discrimination (PSD), and statistical subtraction of accidental coincidences and cosmogenic background using reactor-off data.

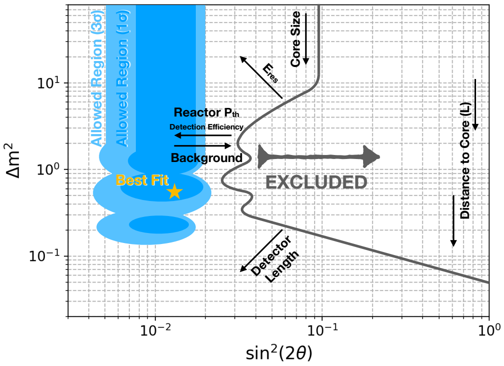

FIGURE 3: Example of allowed region for sterile neutrino oscillation and exclusion plot, with the experimental factors that affect the sensitivity.

A significant difference between the short baseline reactor neutrino experiments lies in the choice of the type of reactor: research reactor facilities have compact cores, allowing for a shorter baseline and a better Δm^2 resolution, and use highly enriched uranium (HEU), with ^{235}U being the main responsible of the $\bar{\nu}_e$ yield; commercial reactors, on the other hand, have a higher thermal power and therefore antineutrino yield, but with the time-dependent isotope contribution of the low-enriched uranium (LEU) fuel. The detector that is placed near the reactor core can be segmented, which allows for a model-independent comparison of $\bar{\nu}_e$ spectra in difference detector segments, or not segmented, with a single measured $\bar{\nu}_e$ spectrum being compared with predictions. On top of that, a fine segmentation allows to reconstruct the event topology, a useful tool for the rejection of residual background, with the caveat of introducing dead material and requiring a more complex inter-calibration of detector cells. Finally, the detection efficiency for IBD neutrons can be enhanced by means of dopants. The element of choice is typically gadolinium, thanks to its high neutron capture cross-section and the associated released energy ($\simeq$8 MeV), or, in some cases, ^{6}Li, where the localized quenched energy deposit from the neutron capture can be selected via PSD.

3. THE WORLDWIDE HUNT FOR THE eV-SCALE STERILE NEUTRINO

After the emergence of the RAA, several projects have been proposed to test the sterile neutrino hypothesis with reactors. Of these, six were eventually built and put into operation: NEOS [10], in South Korea; DANSS [11] and Neutrino-4 [12], both in Russia; SoLiD [13], in Belgium; STEREO [14], in France; and PROSPECT [15], in the USA. Of these, five have collected data and published results on an oscillation analysis, while the SoLiD detector is currently under commissioning. In this section, a brief description of each experiment and its latest results will be given.

3.1. *The NEOS Experiment*

The NEOS experiment is located at the Yeonggwang nuclear power plant, South Korea. The detector takes advantage of a simple and well-established design, consisting of a 1008 l gadolinium-loaded (0.48%) liquid scintillator tank surrounded by photomultiplier tubes and enveloped in passive shielding and a plastic scintillator active muon veto. The measured $\bar{\nu}_e$ spectrum is compared with a prediction extracted from Data Bay data and tested against an oscillation hypothesis [10].

NEOS has accumulated high statistics, thanks to the 2.8 GW Yeonggwang commercial reactor that generates ~2000 IBD/day in the detector. A degradation of the light yield and attenuation length of the scintillator in time, on the other hand, resulted in a total 40% loss of light during the whole data taking.

The data collected during phase-I (180 days of reactor-on and 46 days of rector-off) allowed NEOS to exclude the RAA best fit with 90% CL. The oscillation analysis on phase-II data (388 days of reactor-on and 112 days of rector-off) is ongoing and will enhance the sensitivity by a factor of 2. More recently, a $\bar{\nu}_e$ spectrum with phase-I and -II combined data was released by the collaboration [16].

3.2. *The STEREO Experiment*

The STEREO detector is located at the at the Institut Laue Langevin (ILL), a research reactor facility in Grenoble, France. It employs a segmented design, where 6 optically separated cells, filled with gadolinium-loaded liquid scintillator, act as antineutrino targets. This allows for an oscillation analysis where the antineutrino spectrum is compared cell by cell to suppress systematic uncertainties [14]. 4 gamma-catcher cells are placed around the target cells, in order to increase the neutron detection efficiency. On top of the cells are the photomultiplier tubes, and the scintillation light is conveyed upstream by means of reflective walls. The detector is topped by a water Cherenkov muon veto and wrapped with several layers of shielding materials.

The compact HEU (58 MW) reactor core and short baseline (9–11 m from core) pf ILL grant little damping of the oscillation, but the small overburden and the reactor facility are sources of noise. Overall, the signal-over-background ratio (S/B) is around 1.

The combined data from phase-I and phase-II (65000 IBDs from 179 days of reactor-on and 235 days of reactor-off) allowed STEREO to publish oscillation analyses where the RAA best fit is excluded with >99% CL [17, 18]. In addition to the oscillation analysis, STEREO released the most precise measurement of the antineutrino flux from ^{235}U, as well as a pure ^{235}U antineutrino spectral shape, using phase-II data [19].

3.3. *The PROSPECT Experiment*

The design of the PROSPECT detector is a highly segmented one. The target consists of a 4-tonne ^{6}Li-loaded liquid scintillator, divided into 11×14 119 cm long optically separated segments. The segments are equipped with readouts on both sides, resulting in a good energy resolution, and the capability to perform a 2D reconstruction of events [15]. The inner detector is, in a similar fashion to other detectors mentioned here, packed in shielding layers and topped with a muon veto.

PROSPECT is located at the High Flux Isotope Reactor (HFIR) in the Oak Ridge National Laboratory (85 MW), USA. For a HEU research reactor, HFIR grants to PROSPECT a relatively high statistic (530 IBD/day) and S/B (> 1).

The PROSPECT collaboration published an oscillation analysis with 50000 IBDs (105 days of reactor-on and 78 days of reactor-off), excluding the RAA best fit with a 98.5% CL [20]. They also measured a data-driven pure-^{235}U spectrum, which they released together with combined analyses with both the Data Bay and STEREO collaborations [21, 22]. These results are based on the dataset from 2018, collected using 97 out of 154 segments. This is due to the fact that several of the PROSPECT phototubes failed because of the liquid scintillator inlet. An improved analysis using a single readout, which will allow the collaboration to exploit dead cells and result in a 50% increase in statistics, is ongoing.

3.4. *The DANSS Experiment*

The DANSS experiment is located at the 3.1 GW Kalinin Nuclear Power Plant. The detector employs an even finer segmentation with respect to PROSPECT, with 2500 gadolinium-coated plastic scintillator strips. The strips are divided into 50 modules with single and combined readouts, which allows DANSS to perform a quasi-3D reconstruction of events [11]. DANSS is a movable detector that shifts up and down below the reactor. This provides a double advantage: firstly, the reactor itself provides some overburden from cosmic rays (of about 50 mwe) as well as an excellent statistic (~5000 IBD/day, S/B $\sim$ 60); secondly, the comparison of antineutrino spectra measured at 3 different heights allows DANSS to suppress systematic uncertainties in their oscillation analysis.

DANS recorded an impressive amount of IBD events (6 million in 5 years). The collaboration published results rejecting a large portion of the RAA-allowed region [23, 24]. The DANSS collaboration is planning a detector upgrade in 2023, the goal of which is to increase the active volume of the detector while halving the energy resolution.

3.5. *The Neutrino-4 Experiment*

The Neutrino-4 detector consists of a 3 m^3 liquid scintillator divided into 5×10 vertical sections of $0.235 \times 0.235 \times 0.85\,\mathrm{m}^3$ each. It is located near the 100 MW thermal power compact core of the SM-3 research reactor [12].

The Neutrino-4 oscillation analysis is performed by measuring and comparing antineutrino spectra at 6 distances from the reactor core, for a baseline range of 6–12 m. Their data, when tested against the null hypothesis, allow excluding a significant portion of the RAA-allowed region. The oscillation hypothesis is also tested, and the Neutrino-4 collaboration claims observation of a ν_e disappearance compatible with a new $\Delta m^2 \simeq 7.3\,\mathrm{eV}^2$ and $\sin^2(2\theta_{ee}) \simeq 0.26$, with $2.8\,\sigma$ CL [25]. Such claim was criticized by others on the basis of poor handling of systematic uncertainties and assessment of the energy resolution [26, 27].

3.6. The SoLiδ Experiment

The SoLiδ experiment also employs a highly segmented 3D detector design, with 12800 $5 \times 5 \times 5\,\mathrm{cm}^3$ optically separated PVT cubes, each layered with ^{6}LiF:ZnS(Ag) for neutron identification [13]. The detector, which is under commissioning at the BR2 research reactor of SCK-CEN (Mol, Belgium), takes advantage of the quasi-3D reconstruction to reject background via event topology and of a very close distance from the reactor core (5.5 to 12 m).

A summary of the main features of the reactor facilities, as well as the detectors, for the abovementioned experiments, is given in the following table.

	Core P_{th}	Core size	Baseline
DANSS	3 GW (LEU)	$1.5^2\pi \times 3.6\,\mathrm{m}^3$	10.7–12.7 m
Neutrino-4	90 MW (HEU)	$35 \times 42 \times 42\,\mathrm{m}^3$	6–12 m
STEREO	58 MW (HEU)	$0.37^2\pi \times h\,\mathrm{m}^3$	8.8–11.2 m
SoLiδ	72 MW (HEU)	$0.5^2\pi \times h\,\mathrm{m}^3$	5.5 m
NEOS	2.8 GW (LEU)	$3.1^2\pi \times 3.7\,\mathrm{m}^3$	23.7 m
PROSPECT	85 MW (HEU)	$0.2^2\pi \times 0.5\,\mathrm{m}^3$	7 m
	Overburden	Segments	Material
DANSS	~50 mwe	5 cm (2D)	Gd-doped PS
Neutrino-4	few mwe	22.5 cm (2D)	Gd-doped LS
STEREO	~15 mwe	25 cm (1D)	Gd-doped LS
SoLiδ	~10 mwe	5 cm (3D)	Li-layered PS
NEOS	~20 mwe	—	Gd-doped LS
PROSPECT	few mwe	15 cm (2D)	Li-doped LS

4. THE STERILE NEUTRINO HYPOTHESIS IN THE LIGHT OF RECENT RESULTS

Each of the four experiments: DANSS, NEOS, STEREO, PROSPECT, published oscillation analyses that exclude a portion of the RAA region, as well as the best-fit value with a sensitivity of >90% CL [23, 24, 10, 16, 17, 18, 20]. While individual spectra are still compatible with an oscillation (e.g., Neutrino-4 measured $\Delta m^2 \simeq 7.3\,\mathrm{eV}^2$ with $2.8\,\sigma$ CL), the combination of these results is in contrast with the oscillation hypothesis, especially in the mid-low region of Δm^2 (Figure 4).

The Δm^2 region, on the other hand, already in tension with cosmological models, is being probed by the KATRIN experiment, a 200-tonne spectrometer for the measurement of the ν_e mass that has also published results on the eV-scale sterile neutrino [28].

There are other experimental evidences, besides the results mentioned so far, that challenges the eV-scale sterile neutrino hypothesis. The Daya Bay, RENO, and more recently, NEOS experiments, accumulated significant statistics of IBD events from LEU reactors. This enabled the measurement of the $\bar{\nu}_e$ flux as a function of fuel evolution within reactor cores, which in turn allowed deconvoluting the ^{235}U and ^{239}Pu relative antineutrino yields. Although the results were slightly different, all three experiments observed a significant antineutrino rate deficit from ^{235}U (6–8%), while the ^{235}U yield was compatible with models [30]. Recently, the STEREO collaboration measured the absolute antieutrino rate from ^{235}U using the ILL HEU reactor. Their result (overall 5 % deficit) is partly in tension with fuel deconvolution analyses, and overall compatible with the RAA.

In all models that estimate antineutrino spectra from different fissile isotopes, single branches are obtained from global β spectra [32]. These spectra were recently remeasured at the Kurchatov Institute, where a ~5% excess in the ^{235}U to ^{239}Pu ratio was observed with respect to existing ILL data (Figure 5) [31]. This excess is not only compatible with the abovementioned fuel deconvolution results but also matches the overall excess that is responsible for the RAA.

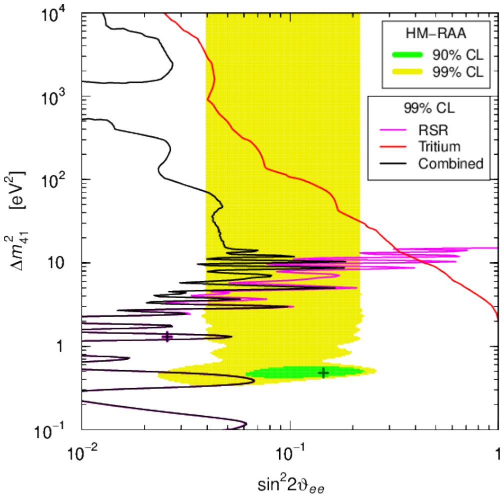

FIGURE 4: Exclusion curve from short baseline reactor neutrino experiments (RSR), and KATRIN and other tritium experiments, combined analysis (from [29]).

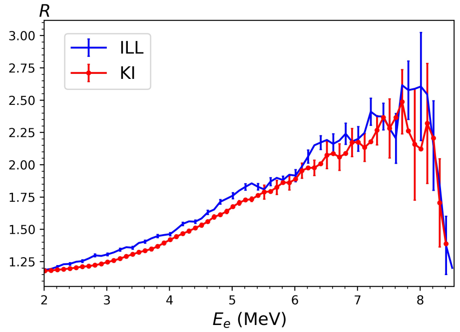

FIGURE 5: Ratios R between cumulative β spectra from ^{235}U and ^{239}Pu from ILL data (blue) and Kurchatov Institute data (red) (from [31]).

Last but not least, a spectral distortion at $E_\nu \sim 6\,\mathrm{MeV}$ was observed in 2014 by θ_{13}-aimed reactor neutrino experiments [33]. While the origin of the distortion is unknown, it was postulated that it could be due to nonlinearities in the energy reconstruction [34], various sources of physics beyond the Standard Model (e.g., [35]), or unknown branches (isotope related) [36, 37]. The distortion was confirmed both by STEREO and PROSPECT (HEU experiments) for ^{235}U-only and by NEOS (LEU experiment) for U+Pu. Nevertheless, a combined spectral analysis released by the STEREO and PROSPECT collaborations indicates that the ^{235}U alone can account for the distortion with a $2.4\,\sigma$ CL significance (Figure 6) [22].

The results from STEREO and PROSPECT represent a new frontier in reactor neutrino physics. The modeled bias can, in fact, reproduce the spectral distortion, by benchmarking to the most recent reactor neutrino data [38]. Antineutrinos can, therefore, inform nuclear data for the first time.

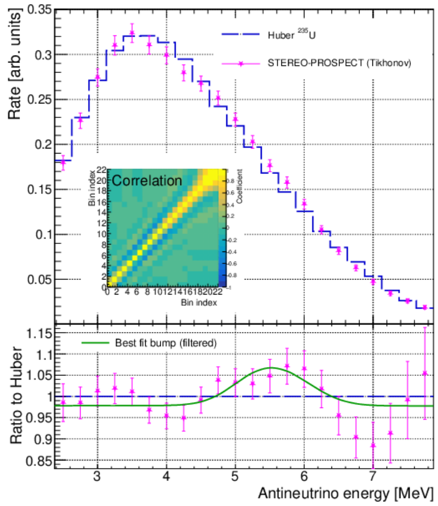

FIGURE 6: STEREO and PROSPECT jointly unfolded the ^{235}U spectrum with diagonal errors and prediction normalized to unit area (top) and as a ratio to model (from [22]).

Current reactor antineutrino models are limited by several factors, such as a large uncertainty for the weak magnetism term [39], the selection of average Z distributions for the fit of the ILL spectra, incomplete or biased nuclear data schemes, and the treatment of forbidden decays. For the latter, it has been pointed out that it could account for both the normalization and spectral shape (Figure 7), and therefore explain both the RAA and the spectral anomaly [40]. It therefore appears that, to completely solve the RAA, the problem must be tackled from both the experimental (increase in statistic, detector upgrades) and theoretical point of view (new models, better corrections) [41].

5. CONCLUSIONS

The experimental effort to measure θ_{13}, in the 2010s, prompted the development of a novel modelisation of the energy spectra of reactor $\bar{\nu}_e$. This marked the emergency of a discrepancy in the predicted versus measured $\bar{\nu}_e$ rates, known as reactor antineutrino anomaly. A number of projects were launched around the world to test the exciting hypothesis of new sterile neutrinos being responsible for such anomaly, the goal of which was to measure neutrino oscillation at a baseline never tested before with reactors. These experiments ran for several years, facing new challenges in terms of background rejection, technology, and handling of systematic uncertainties. Thanks to their results, in combination with other experimental evidence, the eV-scale sterile neutrino hypothesis is under increasing pressure, and other hypotheses such as a renormalization of the ^{235}U beta spectrum, or taking into account forbidden branches, have taken hold as valid solutions to the RAA.

The contribution from short-baseline reactor antineutrino oscillation searches is not limited to the study of the RAA. Thanks to the results from the different projects mentioned here, we now possess a better understanding of reactor antineutrino rates and spectra, and can inform nuclear physics using neutrinos. Last but not least, the development and characterization of novel reactor antineutrino detectors represents an important effort for the future of this field.

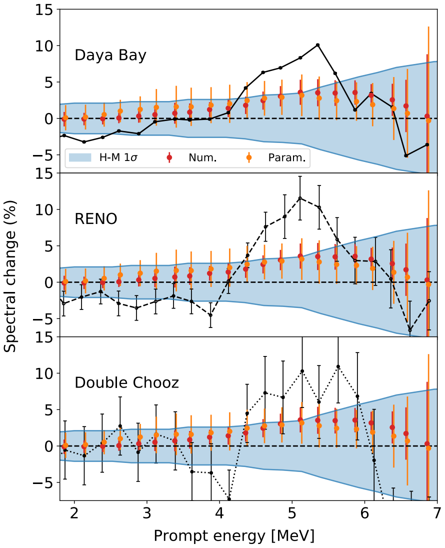

FIGURE 7: Normalized spectral ratios for three modern experiments relative to predictions and normalized forbidden spectrum correction (described in [40]).

CONFLICTS OF INTEREST

The author declares that there are no conflicts of interest regarding the publication of this paper.

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