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The reactor antineutrino anomaly and sterile neutrinos

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Summary. — From the discovery of the neutrino to the measurement of the last of the neutrino mixing parameters, nuclear reactors have proved indispensable in the study of these particles, of which much remains to be unveiled. Recent and past measurements using reactor neutrinos rely on the prediction of their spectrum, a non-trivial exercise involving *ad hoc* methods and carefully selected assumptions. A discrepancy between predicted and measured fluxes at a short distance from reactors, known as reactor antineutrino anomaly, arose in 2011, prompting the birth of new experiments aiming to study neutrino oscillation at a very short baseline. Such anomaly can be in fact explained invoking the existence of a new sterile neutrino at the eV mass scale that participate in the neutrino mixing, an enticing hypothesis that ties to other anomalies already observed in the neutrino sector and opens a door for physics beyond the Standard Model. This article presents an overview of the most recent experimental results on the search for reactor neutrino oscillation at very short baseline, and their implication in our current understanding of the reactor antineutrino anomaly and the sterile neutrino hypothesis.

1. – Introduction

Since the discovery of neutrinos, reactors have played a crucial role in the study of these elusive particles. The flavor transition probability of electron antineutrinos (eq. (1)) that are produced in β decays of reactor fissile elements is in fact sensitive to two of the so-called mixing angles of the PMNS matrix (θ_{13}, θ_{12}), and to both the squared-mass splittings

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

θ_{13} was the last of the mixing angles to be determined; nowadays, it is the most precisely measured parameter of the $\mathrm{U_{PMNS}}$ matrix. This was achieved thanks to the reactor neutrino experiments Double Chooz, Daya Bay, and RENO, which were built in the 2000's with this aim [1-3], and the long-baseline T2K experiment [4]. The basic idea of θ_{13}-aimed reactor neutrino experiments was to compare spectra in near and far ($\sim 1\,\mathrm{km}$) detectors to measure a spectral distortion due to the θ_{13}-driven oscillation.

In 2011, a novel calculation of the global $\bar{\nu}_e$ spectrum [5, 6], aimed at providing a benchmark for near detectors, showed a rate excess of $\sim 6\%$ in the model compared to previous short baseline measures (fig. 1). This discrepancy, known as reactor antineutrino

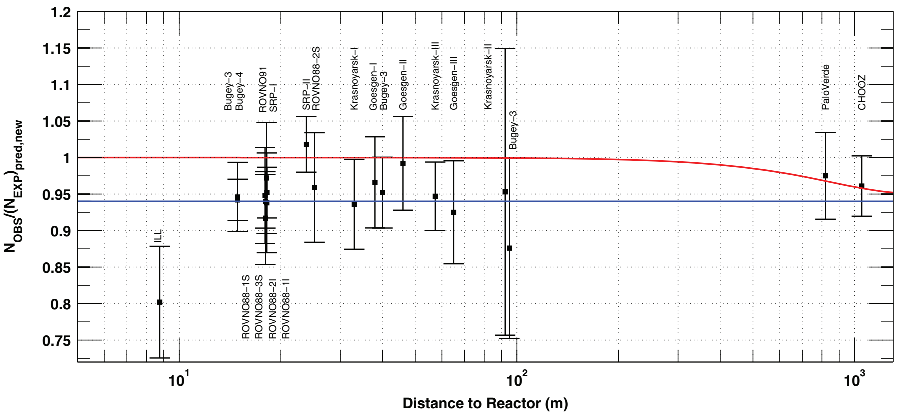

Fig. 1. – Illustration of the reactor antineutrino anomaly: the experimental results are compared with a prediction with three active neutrino families (red) and a solution including a new neutrino mass state (blu) [7]. Reprinted with permission from MENTION G. *et al.*, *Phys. Rev. D*, **83** (2011) 073006, `https://doi.org/10.1103/PhysRevD.83.073006`. Copyright (2011) by the American Physical Society.

anomaly (RAA) [7], was later confirmed by neutrino rate measurements performed with the Double Chooz, Daya Bay and RENO near detectors [8].

The interest that immediately arose around the RAA comes from the fact that it may be an indication of physics beyond the Standard Model. By adding a new neutrino with a mass of 0.1–1 eV, consisting almost exclusively of an extra sterile flavor, in fact, the discrepancy can be accounted for by the oscillation of active into sterile neutrinos at a very short baseline. This because sterile neutrinos do not interact weakly but mix with standard neutrino flavors via an extended U_{PMNS} matrix. The presence of extra 0.1–1 eV neutrinos modifies eq. (1), for very short baselines, as follows:

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

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

2. – Detection techniques and challenges

Difficulties in predicting the neutrino rate limits the sensitivity of past rate-only measurements: we therefore needed to disentangle the oscillating signature from the absolute rate by measuring the antineutrino spectrum at very short baseline ($\leq 10\,\mathrm{m}$), as shown in fig. 2. The new oscillation parameters (Δm^2_{14}, θ_{ee}) are tested against data: the oscillation hypothesis results in a best fit and confidence level contours; the null hypothesis in an exclusion plot (fig. 3). The oscillation hypothesis, tested against the neutrino rate discrepancy of the RAA, provides us with a region of the parameters' space that needs to be investigated in order to test the existence of sterile neutrinos. The better the statistics (reactor power, detection efficiency), the more sensitive we are to the disappearance (θ_{ee}). The reactor core size and distance from the detector, on the other hand, affect the sensitivity in terms of accessible frequencies (Δm^2_{14}).

Reactor antineutrinos are detected via inverse beta decay (IBD) interactions in a scintillating material. The delayed coincidence of the positron scintillation and sudden

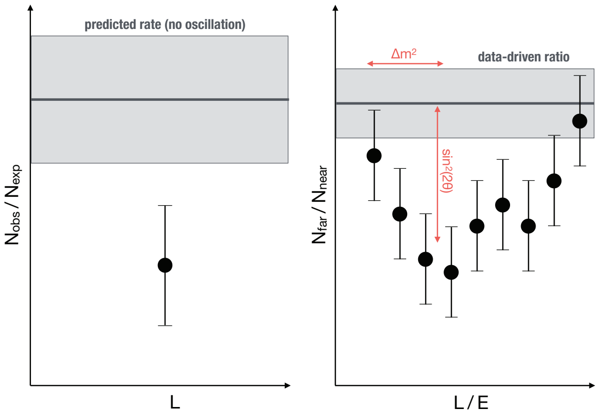

Fig. 2. – RAA tested with rate-only measurements *vs.* prediction (left), or with a model-independent near-far detector spectra comparison (right).

annihilation, and neutron capture, provides the strong signature that is needed to identify the IBDs in the sea of single events. Nonetheless, accidental coincidences, or two-fold physical coincidence (*e.g.*, fast neutrons producing proton recoil before being captured) can mimic the signature of an IBD event. Background is a key challenge for surface detectors aimed at short baseline reactor neutrino oscillation measurements. 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.

Short baseline reactor neutrino experiments can be located at highly-enriched uranium (HEU) research reactor facilities, profiting from the short baseline and compact cores, and the absence of fuel evolution, or at low enriched uranium (LEU) power reactors, for higher statistics (see fig. 3). The used detector can be segmented, allowing for a model-free comparison of $\bar{\nu}_e$ spectra in difference cells, or not segmented, with a single $\bar{\nu}_e$ spectrum compared with predictions. A fine segmentation allows also for a better background rejection using the event topology, but introduces dead material and a more

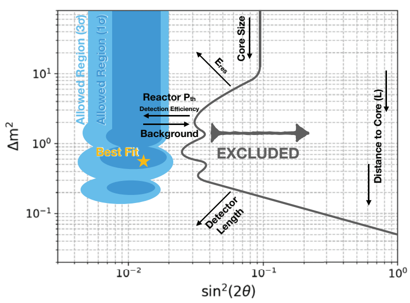

Fig. 3. – Example of allowed region for sterile neutrino oscillation and exclusion plot, with the experimental factors that affect the sensitivity.

complex inter-calibration of cells. Finally, the neutron capturing isotope of choice can be gadolinium, well-established and with a high energy deposit ($\simeq 8\,\mathrm{MeV}$) and cross-section, or ^{6}Li, where the localised quenched energy deposit can be selected via PSD.

3. – A worldwide hunt

There are, worldwide, 6 experiments that were designed to test the RAA and the sterile neutrino hypothesis: NEOS [9] in Korea, DANSS [10] and Neutrino-4 [11] in Russia, SoLiD [12] in Belgium, STEREO [13] in France, and PROSPECT [14] in the US. 5 of these experiments have collected data and published results on their oscillation analysis, while SoLiD is currently under commissioning.

3·1. *The NEOS experiment.* – Located at the Yeonggwang nuclear power plant, South Korea, NEOS profits from a simple design: with a 1008 l Gd-loaded (0.48%) liquid scintillator tank, the measured $\bar{\nu}_e$ spectrum is compared with a prediction extracted from Data Bay data to test the oscillation hypothesis [9]. NEOS has accumulated a very high statistics (~ 2000 IBD/day) thanks to the 2.8 GW Yeonggwang commercial reactor. They also experimented a degradation of the light yield in time.

The data from phase-I (180 days reactor-on and 46 days rector-off) allowed NEOS to exclude the RAA best fit with 90% CL, while a phase-II oscillation analysis is ongoing. The phase-II data is expected to increase NEOS sensitivity by a factor of 2. A $\bar{\nu}_e$ spectrum with phase-I and -II data was also recently released [15].

3·2. *The STEREO experiment.* – Located at the Institut Laue Langevin (ILL) research reactor facility, STEREO employs a segmented design, where 6 cells filled with gadolinium-loaded liquid scintillator are used for a cell-to-cell relative oscillation analysis [13]. Around the target cells, 4 gamma-catcher cells allow to increase the neutron detection efficiency. The compact HEU (58 MW) reactor core and short baseline (9–11 m from core) grants a little damping of the oscillation, but the little overburden and the reactor facility are sources of noise.

The combined data from phase-I and -II (65000 IBDs from 179 days of reactor-on and 235 days reactor-off), with a signal-over-background ratio (S/B) of ~ 1, allowed STEREO to publish an oscillation analysis where the RAA best fit is excluded with $> 99\%$ CL. The full data set will result in a factor 2 increase in the sensitivity [16, 17]. In addition to the oscillation analysis, STEREO released an absolute ^{235}U rate measurement, as well as an pure ^{235}U antineutrino spectral shape, using phase-II data [18].

3·3. *The PROSPECT experiment.* – PROSPECT employs a highly-segmented design, with a 4 ton ^{6}Li-loaded liquid scintillator divided into 11×14 optically separated segments [14]. This results in a good E_{res}, and a 2D reconstruction of events. Located at the High Flux Isotope Reactor (HFIR) at the Oak Ridge National Laboratory (85 MW), PROSPECT profits from a relatively high statistics (530 IBD/day) and S/B (> 1) for a HEU experiment.

The collaboration published results of the oscillation analysis with 50000 IBDs (105 days reactor-on and 78 days reactor-off), excluding the RAA best-fit at 98.5% CL [19]. They also released a data-driven pure ^{235}U spectrum, as well as combined analyses with Data Bay and STEREO [20, 21]. All these results are based on the dataset from 2018; an improved analysis exploiting dead cells, which should result in a 50% increase in statistics) is ongoing.

3·4. *The DANSS experiment.* – Located at the 3.1 GW Kalinin Nuclear Power Plant, DANSS is also a highly-segmented detector: 2500 gadolinium-coated plastic scintillator

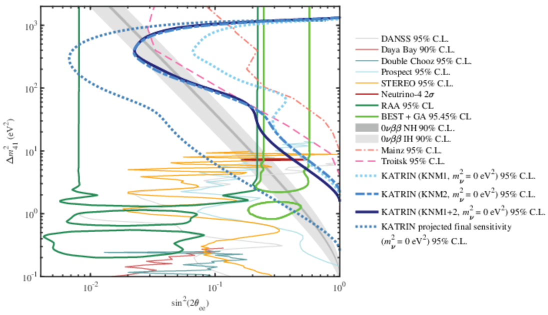

Fig. 4. – The 95% CL KATRIN exclusion contours (blue) from the first two measurement campaigns (from [25]), together with other tritium and short baseline reactor neutrino experiments. An estimation of KATRIN final sensitivity is also present (blue dotted line).

strips, divided into 50 modules with single and combined readout, enable a quasi-3D reconstruction of events [10]. DANSS profits from a movable detector that shifts up and down below the reactor, which provides some overburden (50 mwe) and an excellent statistics (~ 5000 IBD/day, $S/B \sim 60$).

Their oscillation analysis is obtained by comparing spectra measured at 3 different heights, *i.e.* distances from the reactor, allowing them to reject a large portion of the RAA allowed region [22, 23] DANS collected an impressive amount of IBDs (5.5 million in 5 years). A detector upgrade is ongoing, the goal of which is to halve energy resolution and increase detector volume.

3˙5. *The Neutrino-4 experiment.* – The Neutrino-4 detector, a $3\,\mathrm{m}^3$ liquid scintillator divided into 5×10 vertical sections of $0.235 \times 0.235 \times 0.85\,\mathrm{m}^3$ each, is located at the compact core SM-3 research reactor (100 MW thermal power) [11].

The oscillation analysis is performed by comparing spectra at 6 distances (similarly to STEREO), 6–12 m from the reactor core. Neutrino-4 analysis excludes a portion of the RAA allowed region. Nonetheless, the data are also compatible with a $\Delta m^2 \simeq 7.3\,\mathrm{eV}^2$ neutrino oscillation, the evidence of which has a 2.8σ CL [24].

3˙6. *The SoLiδ experiment.* – SoLiδ [12] has a highly-segmented 3D detector design, with 12800 $5\times5\times5\,\mathrm{cm}^3$ optically separated PVT cubes, each layered with ^{6}LiF:ZnS(Ag) for neutron identification. The detector, under commissioning at the BR2 research reactor of SCK-CEN (Mol, Belgium), profit from the design to reject background via event topology, and from a very close distance from the reactor core (5.5 to 12 m).

4. – Global results and perspectives of short baseline reactor neutrino experiments

Each of the four experiments: DANSS, NEOS, STEREO, PROSPECT, excluded large portions of the RAA region and its the best fit value at $> 90\%$ CL [9, 15-17, 19, 22, 23], while Neutrino-4 claims the observation of a $\Delta m^2 \simeq 7.3\,\mathrm{eV}^2$ neutrino oscillation with 2.8σ CL [24]. Despite the challenges of a combination of these results (different statistical methods, "wiggly" nature of the spectra), growing statistics is helping us progressing towards a combined exclusion of the RAA parameter phase space (*e.g.*, in fig. 5). Furthermore, STEREO, PROSPECT, DANSS are releasing their χ^2 tables and data to help combined fits. Lastly, KATRIN, a 200 t spectrometer for the measurement of the ν_e mass, has also published results on light sterile neutrinos, with an exclusion plot (fig. 4) that has a strong synergy with reactor short-baseline searches [25].

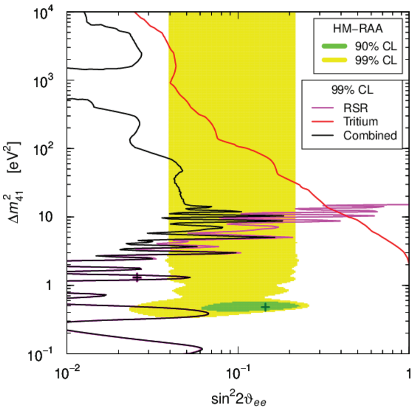

Fig. 5. – Exclusion curve from short baseline reactor neutrino experiments (RSR), and KATRIN and other tritium experiments, combined analysis (from [26]).

5. – Other experimental evidences

In 2014, a spectral distortion at $E_\nu \sim 6\,\mathrm{MeV}$ was observed in θ_{13}-aimed reactor neutrino experiments [27]. While the origin of the distortion is unknown, it was postulated that it could be due to non-linearities in the energy reconstruction [28], various source of physics beyond the Standard Model (*e.g.* [29]), or unknown branches (isotope related) [30, 31]. Recently, STEREO and PROSPECT released a combine spectral analysis confirming the distortion with $2.4\,\sigma$ significance and an amplitude $A = 9.9 \pm 3.3\%$ for pure ^{235}U (fig. 6), claiming that the distortion is independent of other isotopes [21]. While limits of current spectrum models are emerging, it has been pointed out that the treatment of forbidden decays could change both normalisation and spectral shape (fig.7), accounting for both observed anomalies [32].

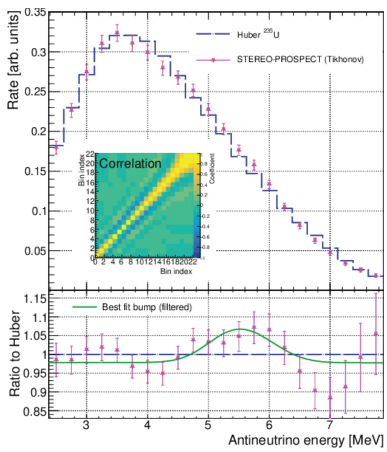

Fig. 6. – STEREO and PROSPECT jointly unfolded ^{235}U spectrum with diagonal errors and prediction normalized to unit area (top) and as ratio to model (from [21]). Reprinted with permission from Almázan H. *et al.*, *Phys. Rev. Lett.*, **128** (2022) 081802, `https://doi.org/10.1103/PhysRevLett.128.081802`.

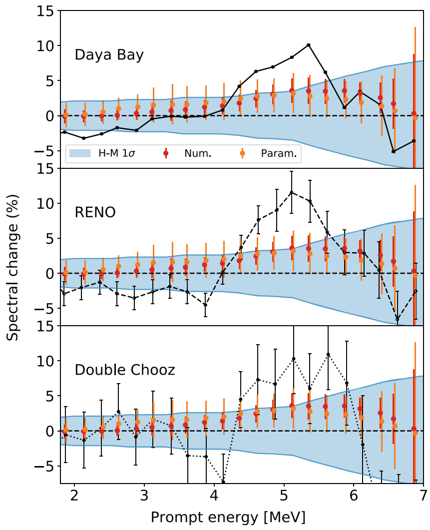

Fig. 7. – Normalized spectral ratios for three modern experiments relative to predictions, and normalized forbidden spectrum correction (described in [32]).

Thanks to their very high statistics, Daya Bay and RENO can separate ^{235}U and ^{239}Pu contribution to the $\bar{\nu}_e$ flux, by measuring it as a function of fuel evolution within reactor cores. The results (fig 8) show that the rate deficit responsible for the RAA comes mainly from ^{235}U [33], disfavouring the sterile neutrino hypothesis. The estimation of antineutrino spectra is based on global β spectra measured at ILL [34]. A recent re-evaluation of these spectra, obtained in Kurchatov Institute, suggests a $\sim 5\%$ excess in the ^{235}U to ^{239}Pu ratio for ILL data (fig. 9) [35]. This is compatible with the RAA excess and also with the indications from Daya Bay.

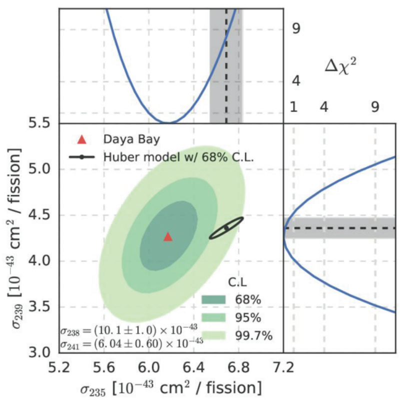

Fig. 8. – Daya Bay combined measurement of ^{235}U and ^{239}Pu IBD yields per fission (red triangle) and CL contours (green), compared with models (black). From [33]. Reprinted with permission from An F. *et al.*, *Phys. Rev. Lett.*, **118** (2017) 251801, `https://doi.org/10.1103/PhysRevLett.118.251801`.

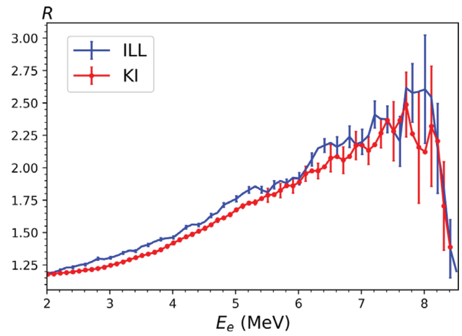

Fig. 9. – Ratios R between cumulative β spectra from ^{235}U and ^{239}Pu from ILL data (blue) and Kurchatov Institute data (red). From [35]. Reprinted with permission from Kopeikin V. *et al.*, *Phys. Rev. D*, **104** (2021) L071301, `https://doi.org/10.1103/PhysRevD.104.L071301`. Copyright (2021) by the American Physical Society.

6. – Conclusions

The quest for θ_{13} in the 2010's prompted new models for reactor $\bar{\nu}_e$ spectra, which showed a $\sim$ 6% discrepancy with measured rates. Several projects worldwide were launched to study this anomaly and test the sterile neutrino hypothesis by looking for neutrino oscillations at very short baseline, and produced compelling results in the last decade. Overall, the sterile neutrino hypothesis as a solution of the RAA is under increasing pressure by experimental results and advancements in theoretical models. Thanks to the these different contributions, we are starting to better understand our antineutrino rates and spectra, as well as our detectors; an important effort in view of the future of reactor neutrino physics.

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