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Status of the search for light sterile neutrinos at short baseline

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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 reports 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.

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1. Introduction

Since the discovery of neutrinos, reactors have played a crucial role in the study of these elusive particles. Not least, the hunt for θ_{13} [1–3], the last of the neutrino mixing angles to be determined, which prompted an effort to better estimate reactor antineutrino spectra [4, 5]. This also marked the birth of the so-called reactor antineutrino anomaly (RAA) [6], a discrepancy between estimated and observed reactor antineutrino rates at short baseline, which could be solved by introducing light ($\sim$ 1 eV) sterile neutrinos. Since then, a number of experiments, namely DANSS [7] and Neutrino-4 [8] in Russia, STEREO [9] in France, SoLid [10] in Belgium, NEOS [11] in Korea, and PROSPECT [12] in the US, were built to search for the signature of an oscillation at very short baseline ($\lesssim$ 10 m), that would imply the existence of extra sterile neutrino families.

2. The hunt for light sterile neutrinos

The experiments designed to investigate the RAA at reactors detect reactor $\bar{\nu}_e$ via inverse beta decay (IBD) with a well-established technique. The delayed coincidence of the positron scintillation and sudden annihilation, and neutron capture, of the IBD, provides the signature of the antineutrino interaction. Strategies to deal with residual background, a major challenge for very short baseline experiments that operate at surface level, include: passive shielding (polyethylene, boron, iron, water) and active vetoes; pulse shape discrimination (PSD); and statistical subtraction of accidental coincidences and cosmogenic background using data collected during reactor off periods.

The sterile neutrino hypothesis is tested by comparing spectra at different baselines. This can be done by comparing a measured with a 0-baseline predicted spectrum (NEOS), or, with a less model-dependent approach, IBD spectra in different detector segments (STEREO, Neutrino-4). The number of segments can be increased and their size reduced (DANSS, PROSPECT, SoLid), to allow background rejection via event topology, at the expenses of a more complex inter-calibration of detector segments.

Different reactor types are used as antineutrino source. Some experiment (DANSS, NEOS) take advantage of the high statistics granted by the high $\bar{\nu}_e$ flux of low-enriched uranium (LEU) commercial nuclear reactors. Others (Neutrino-4, STEREO, SLOID, PROSPECT) exploit compact highly-enriched uranium (HEU) research reactors, which ensure single-isotope production and a higher sensitivity in the oscillation region. Reactor antineutrinos are detected in a scintillator, liquid (LS) or plastic (PS), that is doped with gadolinium or lithium to enhance the detection efficiency of the neutrons produced in inverse beta decay (IBD) interactions. Table 1 summarises the different characteristic of the above-mentioned experiments.

3. Results and implications

The DANSS [13, 14], NEOS [11, 15], STEREO [16, 17], and PROSPECT [18] experiments published oscillation results that exclude large portions of the RAA region and its best fit ($\sin(2\theta_{ee})$ = 0.14, Δm^2_{41} = 2.4 eV^2) at > 90 % CL, while Neutrino-4 alone claims the observation of a $\Delta m^2_{41} \sim$ 10 eV^2 oscillation [19]. Figure 1 shows allowed contours from the RAA and Neutrino-4, as well as exclusion contours from the short baseline reactor neutrino experiments described in this work, together with the contribution from tritium neutrino experiments such as KATRIN [20].

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

Table 1: Sumary of the main features of the experiments investigating the RAA with reactors at short baseline. Commercial low-enriched uranium (LEU) have higher thermal power (P_{th}) and therefore provide an increased statistics, at the expense of bigger core sizes. Different segmentations are used to compare spectra for the oscillation analysis as well as to reduce background, while the $\bar{\nu}_e$ detection via IBD relies on liquid (LS) or plastic (PS) scintillator doped with a n-capturing element. A range in the baseline indicates a movable detector.

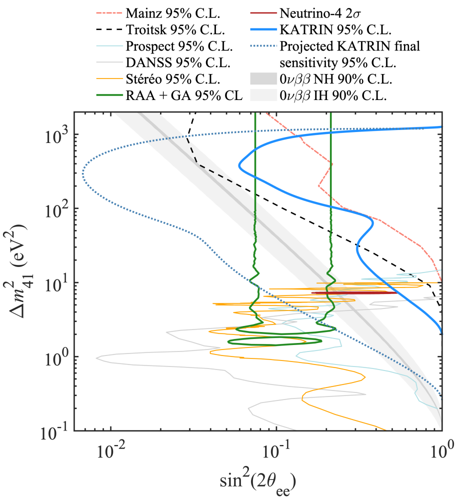

Figure 1: Allowed and exclusion contours for the RAA, short baseline reactor antineutrino experiments, and tritium neutrino experiments. From [20].

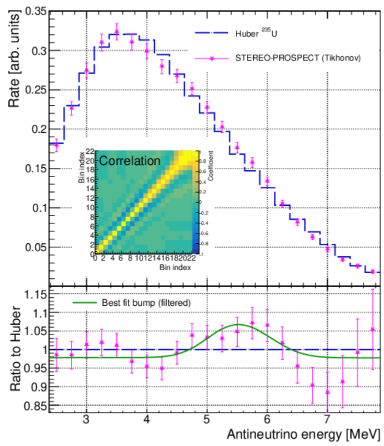

Figure 2: Combined ^{235}U spectrum from the STEREO and PROSPECT collaborations. From [22].

A spectral distortion at $E_\nu \simeq 6\,\mathrm{MeV}$ was also observed in θ_{13}-aimed neutrino experiments, that could be due to unknown branches (isotope related) [21]. Figure 2 shows a combine spectral analysis released by the STEREO and PROSPECT collaborations, that confirms the distortion with $2.4\,\sigma$ significance and $A = 9.9 \pm 3.3\,\%$ for pure ^{235}U, suggesting that the effect is independent on other isotopes [22]. The Daya Bay experiment separated ^{235}U and ^{239}Pu contribution to $\bar{\nu}_e$ flux, claimeing that the RAA rate deficit comes mainly from ^{235}U, which challenges the sterile neutrino hypothesis [23]. Meanwhile, limits of current spectrum models are emerging, and the treatment of forbidden decays could change both normalisation and spectral shape [24].

4. Conclusions

The quest for θ_{13} prompted new models for reactor $\bar{\nu}_e$ spectra, which marked the emergence of the so-called reactor antineutrino anomaly. Several projects worldwide were designed to study the anomaly and investigate the possible existence of extra sterile neutrino families by looking for active-sterile antineutrino oscillation at short baseline from reactors. These projects faced new and existing experimental challenges and produced compelling results in term of oscillation analyses, as well as new spectral and rate analyses for reactor antineutrinos. Meanwhile, the limits of existing models are also being pushed by theoretical advancements. Overall, the combination of the rapidly-advancing analysis of data from reactor short-baseline experiments, and the improvement of models, is putting the sterile neutrino hypothesis as a solution for the RAA under increasing pressure.

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