PROCEEDINGS OF SCIENCE

Searching for the eV-Scale Sterile Neutrino at Very Short Baselines

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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 non-trivial 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, that opens a door for physics beyond the Standard Model. With this article, the author intends to give an overview of the most recent results of the projects involved in the search for reactor antineutrino oscillation at a very short baseline, as well as their implication in our current understanding of the reactor antineutrino anomaly and the eV-scale sterile neutrino hypothesis.

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1. Introduction

In recent years, the field of neutrino physics has observed a series of anomalies that suggest beyond the Standard Model scenarios, including the possible existence of a new neutrino state with a mass in the range of 0.01 to 1 eV consisting of a new sterile flavor. These anomalies have puzzled the neutrino community, and triggered experimental and theoretical endeavours to investigate their nature. The reactor antineutrino anomaly, emerged in 2011 when novel calculations of neutrino yields from Uranium (U) and Plutonium (Pu) isotopes indicated a 6.3% mismatch between predicted and observed antineutrino rates at very short distances from nuclear reactors [1], prompted a number of experiments worldwide that investigated very short baseline (<100m) oscillations at reactors. The gallium anomaly, a deviation in observed and measured neutrino flux in gallium-based solar neutrino experiments irradiated by a beta-decaying source, has seen its significance strengthened ($> 5\sigma$) by the recent results of the BEST collaboration [2]. Finally, the LSND/MiniBooNE anomaly, i.e. the appearance of electron neutrinos in a muon neutrino beam at low energies, with a 6.1σ significance, already challenged by disappearance results and the MicroBooNE dataset [3], is set to be directly tested by the Short-Baseline Neutrino (SBN) program at Fermilab [4].

2. Sterile Neutrino Searches at Reactors

Reactor very short baseline experiments aim to disentangle oscillation signatures from absolute rate measurements, addressing the limitations of predictions (Figure 1 left). This involves testing oscillation parameters (Δm^2, θ) against experimental data under both oscillation and null hypotheses (Figure 1 right). The main challenge to this endeavor consists in detecting antineutrinos in near-surface locations. Background mitigation strategies involve passive shielding, active vetoes, pulse shape discrimination (PSD), and statistical subtraction. Experimental differences arise from the type of reactor used: research reactors with compact cores offer shorter baselines and improved Δm^2 resolution, while commercial reactors provide higher antineutrino yields. Detectors may be segmented or not: segmentation allows to compare measured antineutrino spectra to reduce systematic uncertainties; a fine segmentation allows for event topology reconstruction and background rejection, albeit with increased complexity. Doping scintillating compounds with gadolinium enhances neutron detection efficiency, offering a high neutron capture cross-section and associated energy release, while ^{6}Li allows for detecting neutron captures via PSD.

Experiments such as DANSS, NEOS, STEREO, and PROSPECT have effectively ruled out significant portions of the Reactor Antineutrino Anomaly (RAA) mid-low Δm^2 region and its best-fit parameters [5–8]. Investigations into high Δm^2 values, although posing tensions with cosmological constraints, are being explored through experiments like KATRIN and utilizing solar neutrino data [9] (Figure 2 left). Interestingly, despite the stringent exclusions, individual spectra from experiments such as the DANSS/RENO ratio or the somewhat criticized Neutrino-4 result (2.8σ, $\Delta m^2 \simeq 7.3\,\text{eV}^2$) can still accommodate oscillatory behavior [10]. It's noteworthy that the resolution of the rate discrepancy varies depending on the adopted model, and that more recent models see the significance of the discrepancy drastically reduced [10]. Additional experimental evidence challenging the hypothesis of sterile neutrinos as an explanation for the RAA come from Daya Bay [11], RENO [12], and NEOS [6], which deconvoluted the antineutrino yields of ^{235}U and

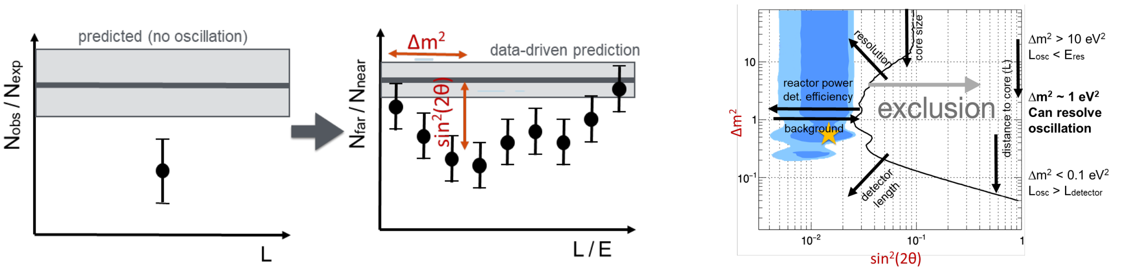

Figure 1: RAA tested with rate-only measurements vs prediction and with a model-independent near-far detector spectra comparison (left); example of allowed region for sterile neutrino oscillation and exclusion plot, with the experimental factors affecting the sensitivity (right).

^{239}Pu and observed a substantial rate deficit (∼ 8 %), with ^{235}U identified as the primary contributor (Figure 3 left). STEREO's detailed estimation of the pure ^{235}U antineutrino rate further supports this, indicating an overall deficit of 5.0 ± 1.3 % for Highly Enriched Uranium (HEU) [13] (Figure 3 right). Additionally, a recent re-evaluation of global β spectra reveals an approximately 5 % excess in the ^{235}U to ^{239}Pu ratio [14], providing further evidence that challenges the sterile neutrino hypothesis and is consistent with the observed deficit in the RAA.

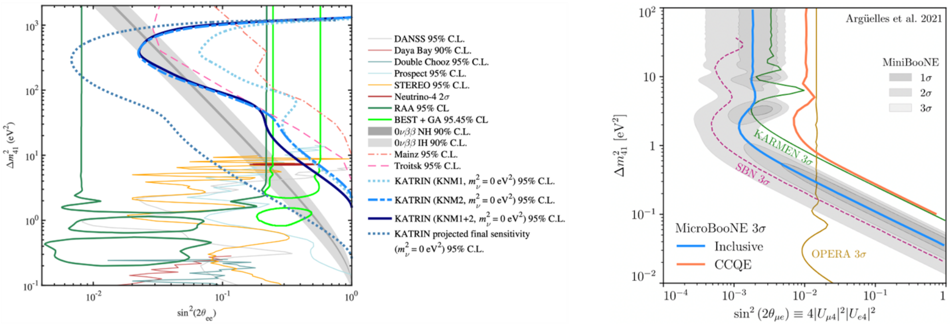

Figure 2: Exclusion plots obtained by KTARIN and other short baseline oscillation searches in the sin(θ_{ee}-Δm^2_{41} phase-space (left) [9], and by accelerator neutrino experiments in the sin($\theta_{\mu e}$-Δm^2_{41} phase-space (right) [15].

Another aspect of reactor neutrino experiments is the observed spectral distortion at an energy of approximately 6 MeV in experiments focused on the θ_{13} in 2014. Notably, collaborative efforts between STEREO and PROSPECT, focusing solely on ^{235}U [16], and NEOS [6], considering both U and Pu, have collectively confirmed that the presence of ^{235}U alone can sufficiently account for this intriguing spectral distortion. Moreover, modelled biases have been successfully employed to replicate this effect by benchmarking against the latest reactor neutrino data, offering valuable insights into the underlying physics of reactor neutrino oscillations [17].

3. The Other Anomalies

The Gallium anomaly presents a notable discrepancy with constraints from reactor, solar, and KATRIN data, creating a strong tension [18]. This anomaly involves various potential culprits, in-

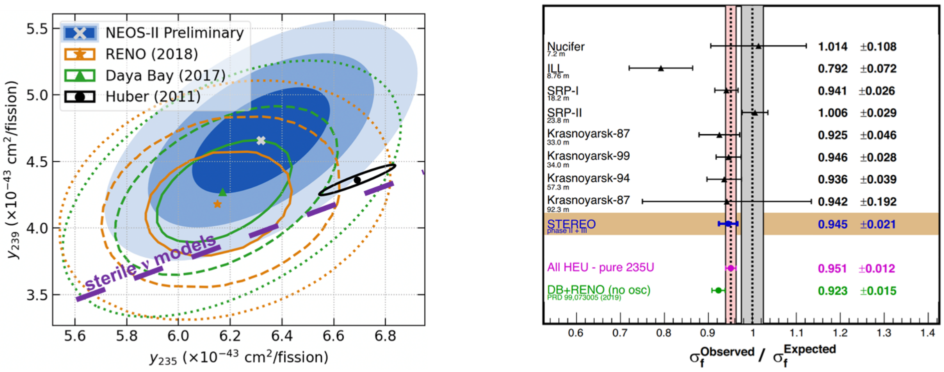

Figure 3: Antineutrino yields from different isotopes as deconvoluted by Daya Bay, RENO, and NEOS (left) [6]; antineutrino flux estimation from STEREO compared with previous results (right) [13].

cluding cross-section variations (subject to multiple calculations), the half-life ($\tau_{1/2}$) of germanium, which has seen new measurements aligning with older data, and considerations regarding source calibration and the efficiency of germanium extraction. While fine-tuned Beyond Standard Model explanations are plausible, the LSND/MiniBooNE anomaly also contributes to this intriguing landscape (Figure 2 right). Here, tensions with disappearance results are noted, and potential sources of uncertainty, such as unknown background contributors, are highlighted. MicroBooNE's constraints on photon interpretation further underscore the complexity [15]. Amidst these challenges, the Fermilab Short Baseline Program is poised to explore these phenomena further [4].

4. Conclusions

The search for eV-scale sterile neutrinos has led to significant advancements in our understanding of neutrino physics and potential extensions to the Standard Model. While the RAA anomaly may have faded, the Gallium and LSND/MiniBooNE anomalies remain active areas of research. The tension between these anomalies and other experimental data adds complexity to the search for sterile neutrinos. With intense experimental and theoretical efforts ongoing, the quest for sterile neutrinos continues to shape the forefront of particle physics.

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