Can super-light sterile neutrinos be probed in reactor experiments?

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Abstract

Our work consists of developing an analytical formulation for a superlight sterile neutrino.

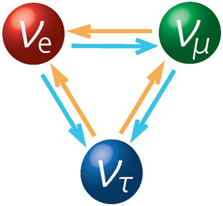
Summary

- Three active flavors
- LSND and MiniBooNE
- Super-light sterile neutrinos
- Conclusions

Three active flavors

Standard 3-Flavor Neutrino Picture

- **Current Understanding:** Three active flavors $(\nu_e, \nu_\mu, \nu_\tau)$.



Flavor neutrinos mix, driving neutrino oscillations.[1]

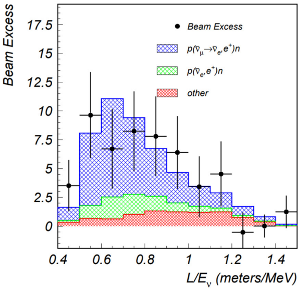
- **High Precision:** Well-established 3ν framework, with most mixing parameters accurately measured.

[1] D. P. Weygand, Sterile Neutrinos?, Quantum Diaries (2014), https://www.quantumdiaries.org/2014/07/27/sterile-neutrinos/ [accessed 11 September 2026].

LSND and MiniBooNE

LSND – Results

In 2001, Los Alamos National Laboratory (LANL) published the LSND results from 1993–1998 data.[1]



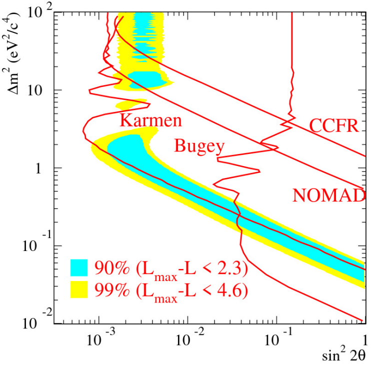
In green/red: beam and background $\bar{\nu}_e$ sources; in blue: potential $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation.[1]

- LSND observed an excess of $\bar{\nu}_e$ events in a pure $\bar{\nu}_\mu$ beam.

[1] AGUILAR, A. et al. (LSND Collaboration). Evidence for neutrino oscillations from the observation of $\overline{\nu}_e$ appearance in a ν_μ beam. Physical Review D, v. 64, n. 11, p. 112007, 13 nov. 2001. DOI: https://doi.org/10.1103/PhysRevD.64.112007.

LSND mass-squared difference

The LSND collaboration data[2] indicate a mass splitting $\Delta m^2 \sim 0.1–10\ \text{eV}^2$.



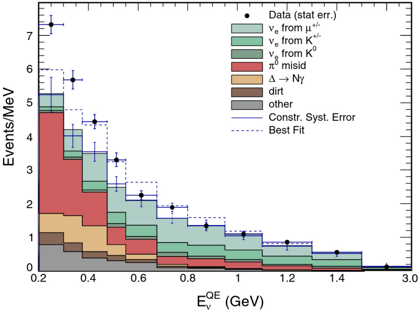
Allowed region in the $(\sin^2 2\theta, \Delta m^2)$ parameter space

from LSND data.

[2] AGUILAR, A. et al. (LSND Collaboration). Evidence for neutrino oscillations from the observation of $\overline{\nu}_e$ appearance in a ν_μ beam. Physical Review D, v. 64, n. 11, p. 112007, 13 nov. 2001. DOI: https://doi.org/10.1103/PhysRevD.64.112007.

MiniBooNE Results

To verify the LSND results, Fermilab built the MiniBooNE experiment. Twenty years after LSND, MiniBooNE published[5] its final dataset (collected 2002–2019).

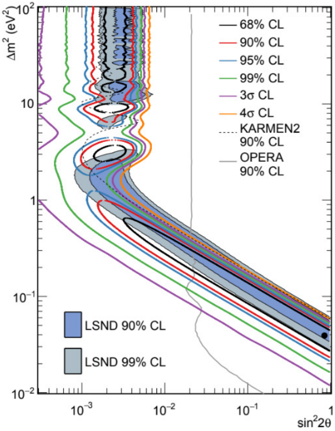


The MiniBooNE anomaly occurs predominantly at low energy (200 MeV $< E_\nu^{QE} <$ 1250 MeV).[5]

- Combined ν and $\bar{\nu}$ data revealed a 638-event excess over Standard Model predictions (4.8σ).

[5] AGUILAR-AREVALO, A. A. et al. (MiniBooNE Collaboration). Significant Excess of Electronlike Events in the MiniBooNE Short-Baseline Neutrino Experiment. Physical Review Letters, v. 121, n. 22, p. 221801, 26 nov. 2018. DOI: https://doi.org/10.1103/PhysRevLett.121.221801.

- **Best-Fit Point (0.039 $\mathbf{eV^2}$):** Solid black dot in the lower-right area, just below 10^{-1} (0.1).
- **Main Region (0.03 to 1.0 $\mathbf{eV^2}$):** Preferred parameter space allowed by the data.



The MiniBooNE anomaly is predominantly at a low-energy scale (200 MeV $< E_\nu^{QE} <$ 1250 MeV).[5]

[5] AGUILAR-AREVALO, A. A. et al. (MiniBooNE Collaboration). Significant Excess of Electronlike Events in the MiniBooNE Short-Baseline Neutrino Experiment. Physical Review Letters, v. 121, n. 22, p. 221801, 26 nov. 2018. DOI: https://doi.org/10.1103/PhysRevLett.121.221801.

LSND and MiniBooNE: Signal of New Physics?

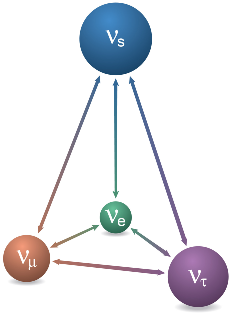
Both LSND and MiniBooNE results contradict the 3-active-neutrino framework, which allows only two independent mass squared differences:

$$\Delta m_{31}^2 = \Delta m_{32}^2 + \Delta m_{21}^2$$

A 4th non-weakly interacting (sterile) neutrino explains these anomalies without violating CERN LEP limits.

The Sterile Neutrino Hypothesis

- **Fourth State:** LSND and MiniBooNE anomalies suggest additional neutrino flavor(s).
- **Sterile Nature:** SM gauge singlet with zero weak interactions.
- **Oscillation Effect:** Active-sterile mixing ($\nu_{\text{active}} \to \nu_s$) modifies standard oscillation patterns.



Active-to-sterile mixing modifies standard oscillation probabilities.[1]

[1] Brookhaven National Laboratory. Sterile Neutrinos? MicroBooNE Finds No Evidence for Preferred Scenario (2021). Available at: `https://www.bnl.gov/newsroom/news.php?a=26547`.

Current Context & Motivation

- **MicroBooNE:** Disfavors the simplest sterile neutrino scenario for the MiniBooNE excess; new models are required.
- **Alternative Models:** Heavy sterile neutrinos (seesaw mechanism).
- **Our Work:** Investigating a light sterile neutrino model at the sub-eV^2 scale. ($|\Delta m^2| \ll 1$ eV^2).

Super-light sterile neutrinos

Motivation & The Sub-meV Scale

- **Super-Light Scenario:** We consider a super-light sterile neutrino in the regime $\Delta m^2_{14} \sim 10^{-7}$–$10^{-3}$ eV^2
  - focusing on $\Delta m^2_{14} \sim 10^{-7}$ eV^2.

Mixing Parametrization for JUNO

Left-Multiplied Matrix (4×4)

$$U = U_S \begin{pmatrix} U_{\mathrm{PMNS}} & 0 \\ 0 & 1 \end{pmatrix}, \quad U_S = \tilde{R}_{34} R_{24} \tilde{R}_{14}$$

Key Simplification for $\bar{\nu}_e$ Disappearance:

- JUNO is sensitive strictly to U_{ei} matrix entries.

Theoretical Framework & Oscillation Probabilities

- **Oscillation Model ($3+1$):**

$$P_{ee} = 1 - 4\sum_{i<j} U_{ei}^2 U_{ej}^2 \sin^2\left(\frac{\Delta m_{ji}^2 L}{4E}\right)$$

- **Super-Light Regime Modifications:**
  - New mass splitting $\Delta m_{14}^2 \ll \Delta m_{31}^2, \Delta m_{21}^2$.
  - Introduces an additional slow-oscillation phase over reactor baselines ($L \sim 50\,\mathrm{km}$).
  - Parameter space of interest: $(\sin^2 2\theta_{14}, \Delta m_{14}^2)$.

Juno and Reactors experiments

- **Key Objectives:**
  - Update bounds using existing data (KamLAND, Daya Bay).
  - Assess **JUNO**'s sensitivity and parameter constraints.

Conclusions

- **Superlight Frontier:** The mass splitting limit proposed in our project has not yet been explored in the literature.
- **JUNO Sensitivity:** Leverage JUNO's high energy resolution and the short baseline to detect subtle, slow-oscillation distortions in reactor $\bar{\nu}_e$ survival probability..
- **Global Synergy:** Combining KamLAND and Daya Bay data breaks active-sterile degeneracies, setting robust baseline limits for future experiments.

Acknowledgments

Questions ?

May the force be with you !