Status of Searches for Sterile Neutrinos with Reactor and Radioactive Sources

Pranava Teja Surukuchi

July 21, 2022

Snowmass 2021 Community Summer Study
Disclaimers

Focus of this talk:

- eV-scale sterile neutrinos
- Finished or currently running experiments
- A bit US-centric

<table>
<thead>
<tr>
<th>N mass</th>
<th>$\nu$ masses</th>
<th>eV $\nu$ anomalies</th>
<th>BAU</th>
<th>DM</th>
<th>$M_H$ stability</th>
<th>direct search</th>
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<tr>
<td>GUT see-saw</td>
<td>$10^{10-16}$ GeV</td>
<td>YES</td>
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<td>EWSB</td>
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<td>$\nu$ MSM</td>
<td>keV–GeV</td>
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<td>$\nu$ scale</td>
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arXiv: 1301.5516
• Reactor Antineutrino Anomaly (RAA)

• Measured data show ~6% (~3σ) deficit w.r.t updated reactor models
• Solar neutrino experiments GALLEX and SAGE used $^{51}$Cr and $^{37}$Ar as calibration sources

• Measured electron neutrinos 16% (~$3\sigma$) lower than predicted
• Both RAA and GA could be explained by eV-scale sterile neutrinos

• Similar parameter space as suggested by the appearance experiments (see M. Ross-Lonergan’s talk)

• Catalyzed several (particularly reactor neutrino) experiments

Anomalies motivated searches for eV-scale sterile neutrinos
Sterile neutrinos at eV scale:
=> High frequency oscillations at short distances (<10 m)
Relative spectral searches essential to irrefutably test eV-scale sterile neutrinos

• Sterile neutrinos at eV scale:
  => High frequency oscillations at short distances (<10 m)

• Spectrum measured as a function of baseline would be a smoking gun evidence for sterile neutrino oscillations

• Measure spectrum within a single detector, move the detector, or both
## Testing RAA: Recent Reactor Experiments

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* Other reactor neutrino SBL experiments that haven’t performed oscillation search not included
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**PROSPECT is a US-led domestic experiment**
Source: HFIR reactor at ORNL in Tennessee

Detector:

Segmented detector at 7-9 m baselines

PROSPECT detector as installed at Oak Ridge National Laboratory
PROSPECT Experiment: Leveraging Unique Domestic Facility

- **Source:** HFIR reactor at ORNL in Tennessee

- **Detector:**
  - Segmented detector at 7-9 m baselines

- **Excluded best fit point at 2.5σ**

- **Limited by statistics (~50k events)**

- **Improvements in analysis underway (D. Venegas-Vargas on Saturday)**

- **Phase-II detector is at an advanced design stage (F. Sutanto on Saturday)**
PROSPECT Experiment: Leveraging Unique Domestic Facility

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- Excluded best fit point at $2.5\sigma$
- Limited by statistics (~50k events)
- Improvements in analysis underway (D. Venegas-Vargas on Saturday)
- Phase-II detector is at an advanced design stage (F. Sutanto on Saturday)
- Not discussed here: Spectrum measurements by PROSPECT (and others) help understand issues with modeling

Major portion of the suggested sterile neutrino parameter space excluded by PROSPECT and other reactor neutrino experiments (except Neutrino-4)
• Reactor Antineutrino Anomaly: Flux predictions disagree with measurements

• Could the flux predictions be wrong?

\[ R_{a,\text{HM}} = \frac{\sigma_{f,a}^{\text{exp}}}{\sigma_{f,a}^{\text{HM}}} = 0.936^{+0.024}_{-0.023} \]
Individual IBD Yields Disagree with Models

- Neutrino flux at LEU reactors could be measured as a function of fission fractions of $^{235}\text{U}/^{239}\text{Pu}$
- One can extract the contribution (IBD yield) of single isotope to the measured flux
Individual IBD Yields Disagree with Models

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- One can extract the contribution (IBD yield) of single isotope to the measured flux
- $^{239}\text{Pu}$ yield agrees with models
- But $^{235}\text{U}$ yield disagrees
- STEREO’s modern pure $^{235}\text{U}$ IBD yield measurement also agrees with Daya Bay/RENO

Reactor neutrino modeling of $^{235}\text{U}$ disputed by modern IBD yield measurements
Beta Decay Measurements Point Toward $^{235}$U Mismodeling

- Reactor (conversion) models reliant on the $\beta$-decay measurements done in 1980s
- Recent claim: Issue with calibration in the original $\beta$-decay measurements
- New measurement of $^{235}$U/$^{239}$Pu $\beta$-decay spectra performed at Kurchatov Institute
- Shows that $^{235}$U normalization was overestimated (assuming $^{239}$Pu normalization is correct)

$R \equiv \frac{eS_5}{eS_9} = \frac{\sigma_9}{\sigma_5} \cdot \frac{N_9}{N_5} \cdot \frac{n_5}{n_9}$

$^{235}$U mismodeling seem to be the source of RAA
• Updated models don’t agree with canonical Huber-Mueller (HM) model
• Updated models agree with Daya Bay + RENO evolution + STEREO
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Updated models agree with Daya Bay + RENO evolution + STEREO.

Reactor mismodeling and sterile neutrinos not (yet) mutually exclusive.
Current Reactor Neutrino Status

- Updated models don’t agree with canonical Huber-Mueller (HM) conversion model
- Updated models agree with Daya Bay + RENO evolution + STEREO
- Reactor mismodeling and sterile neutrinos not (yet) mutually exclusive
- Rely on baseline-dependent spectral measurements to mitigate model-dependence

![Graph showing current reactor neutrino status](image)
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• Reactor mismodeling and sterile neutrinos not (yet) mutually exclusive
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• Significant portion of the suggested parameter space excluded
• $\sim \Delta m^2 > 5 \text{ eV}^2$ yet to be excluded
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Baseline-dependent reactor spectra are essential to probe flavor transformation scenarios
• BEST: Gallium source experiment similar to GALLEX and SAGE

• Source: 3 MCi of $^{51}$Cr source

$e^- + ^{51}$Cr $\rightarrow ^{51}$V + $\nu_e$

$^{71}$Ge production at each distance measured separately

PRL:128.232501

• Two zones:

1. Inner sphere (L ~ 0.660 m)

2. Outer cylinder (L ~ 1.096 m)
BEST Results

- Data taking July - Nov 2019
- Measured rate lower than expected in **both volumes**
  - $R_{\text{in}} = 0.79 \pm 0.05, R_{\text{out}} = 0.77 \pm 0.05$
- BEST reinforces Gallium Anomaly at > 5 $\sigma$
- Conventional nuclear physics can’t resolve the large discrepancy
• Data taking July - Nov 2019

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BEST reinforces Gallium Anomaly and is consistent with eV-scale sterile neutrino hypothesis
The deficit from GA is too high to be compatible with updated reactor rates.
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• Also major portions of 3+1 suggested parameter space by GA excluded by relative reactor spectral data
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• Complex situation: Vanilla 3+1 model seems increasingly less likely to explain combinations of datasets (see M. Hostert’s talk)
More Data to Clarify the Complex Situation

- The deficit from GA is too high to be compatible with updated reactor rates
- Also major portions of 3+1 suggested parameter space by GA excluded by relative reactor spectral data
- KATRIN is starting to exclude parameter space from high $\Delta m^2$
- Complex situation: Vanilla 3+1 model seems increasingly less likely to explain combinations of datasets (see M. Hostert’s talk)
- Upcoming and planned experiments will clear up the controversial Neutrino-4 hints and help deambiguate future LBL data

Improved reactor and radioactive source experiments are essential to probe flavor transformations scenarios
Summary and Outlook

- Past decade experimental program successfully followed through the recommendations from Snowmass 2011
- New data and updated models increasingly suggest reactor $\bar{\nu}_e$ mismodeling as the cause for RAA
- The significance of gallium anomaly is strengthened by the BEST experiment
- Complicates the situation and highlights the need for more data
- Models beyond 3+1 sterile neutrinos increasingly need to be invoked to reconcile all data
- Complementary data from upcoming and planned reactor and radioactive source experiments essential to address the anomalies
Back up
Reactor Neutrino Predictions

\[ S(E_{\nu}) = \sum_{i=0}^{n} R_i \sum_{j=0}^{m} f_{ij} S_{ij}(E_{\nu}) \]

Summation approach
- Use existing databases and sum the spectra from all the beta decay branches
- 1000s of branches; Databases are incomplete/wrong

Conversion method
- Measure beta spectrum and fit it to virtual branches to convert to neutrino spectrum
- Is all relevant physics captured by virtual beta branches

Reactor antineutrino predictions are very complicated

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Pranava Teja Surukuchi, Snowmass 2021 CSS, July 2022
• Experimental progress in the past decade successfully followed through recommendations from Snowmass 2011

• New data and updated models increasingly suggest reactor $\bar{\nu}_e$ mismodeling as the cause of RAA

• Meanwhile, the significance of gallium anomaly is strengthened by BEST experiment, making situation complex, highlighting need for more data

• Models beyond 3+1 sterile neutrinos increasingly need to be invoked to reconcile all data

• **Complementary data from upcoming and planned reactor and radioactive source experiments will be needed to identify the sources of the anomalies**

• Addressing the anomalies will clear up the N4 and LBL situation
• Spectra shapes measured by $\theta_{13}$ experiments at LEU reactors disagree with state-of-the-art models
• Sterile neutrinos cannot explain this anomaly
• Points towards reactor models being wrong
### STEREO Experiment

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- 334 (543) rx-on (rx-off) days
- Segmentation provides baselines
- Excluded RAA best-fit at >4σ
- Data taking ended
NEOS Experiment

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- 180 (46) days reactor-on/off
- Single volume stationary detector
- Excluded RAA best-fit at $>4\sigma$
- NEOS-II: Refurbished NEOS detector
- Data taking finished: Sep 2018 - Oct 2020
- Results expected this year

PRL 118, 121802 (2017)
DANSS Experiment

- 5 years of data: 5.5 million events
- Oscillation search using movable detector
- Excluded RAA best-fit at $>5\sigma$
- Detector upgrade underway

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Neutrino-4 Experiment: Claim

- 5 years of data
- Oscillation search using movable detector
- Claim oscillation:
  - $(\Delta m^2 = 7.3, \sin^22\theta = 0.36) \ @ \ 2.9\sigma$
- Detector upgrade underway

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PRD:104.032003
Neutrino-4 Experiment: Questions

- 5 years of data
- Oscillation search using movable detector
- Claim oscillation:
  \( (\Delta m^2 = 7.3, \sin^2 2\theta = 0.36) @ 2.9\sigma \)
- Detector upgrade underway

Several questions raised:

* Statistical approach to oscillation search (arXiv:2006.13147; EPJC.81,2; PLB.136,214)
* Impact of backgrounds on the results (JETP Lett 112, 452–454)

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95% CL
PROSPECT and STEREO already disfavor Neutrino-4 BF @ > 95% CL
Why Do We Care?

- Events per 0.25 GeV
- $E_V$ (GeV)
- $\Delta m^2_{41} [eV^2]$
- $\sin^2 \theta_{14}$
Reactor Neutrino Flux: Modeling

- Questions on the validity of conversion method
- Inclusion of forbidden decays, doesn’t change the picture much
- For summation method: corrections in databases (Sonzogni et.al., PRL 116, 132502)
- Pandemonium effect also plays a systematics effect
- TAGS measurements of the individual β spectra of various high yield and high Q isotopes (Estienne et.al. and Rasco et.al.)
- Summation data:
  - Agrees with DYB for $^{239}$Pu
  - For $^{235}$U agreement gets better by day
- Caveat: No uncertainties assigned, expected to be at ~5% level
Initially the spectral deviation were thought to be with the conversion approach

Databases updated

Included new data TAGS data

Shows a better agreement b/w conversion and summation

=> Disagreement between LEU data and conversion method

Treatment of forbidden decays called into question

Proper understanding of the shape factors important in modeling the spectra
• PROSPECT and STEREO experiments highest statistics HEU experiment
• PROSPECT
  • 50k events
  • S:B = 1.4:1
• Spectrum not in disagreement with Huber
• $^{235}$U solely (not at all) responsible disfavored at 2.4$\sigma$ (2.2$\sigma$)
PROSPECT

![Graph showing relative spectrum at baseline over prompt energy in MeV for different baselines: 6.7 - 7.4 m, 7.4 - 7.5 m, 7.5 - 7.7 m, 7.7 - 7.8 m, and 7.8 - 8.0 m. The graph compares data, RAA, and best fit lines.]
Conversion method is reliant on the $\beta$-decay measurements done at ILL, France in 1980s

Recent claim: Issue with calibration for the original ILL $\beta$-decay measurements

Kopeikin et.al., (arXiv 2103.01684) performed a measurement of $^{235}$U/$^{239}$Pu $\beta$-decay spectra

Shows that $^{235}$U normalization was overestimated (assuming $^{239}$Pu normalization is correct)

No systematic uncertainties presented and peer-reviewed results not yet published

If confirmed, it would effectively resolve the original motive for RAA