Search for sterile neutrinos at very short baseline reactor experiments

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Many plots are taken from recent neutrino conferences. Many thanks to authors.
ν oscillations in 3 generations are well measured

\[ U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix} \]

\[ \theta_{23} \sim 45^\circ \]

- Atmospheric
- Reactor
- Accelerator

\[ \theta_{13} \sim 8^\circ \]

- Reactor
- Accelerator

\[ \theta_{12} \sim 34^\circ \]

- Solar
- Reactor

\[ |\Delta m^2_{31}| \sim 2.4 \times 10^{-3} \text{ eV}^2 \]

\[ \Delta m^2_{12} \sim 8 \times 10^{-5} \text{ eV}^2 \]

**Z boson width gives** \( N_{\nu} \text{(active)} = 2.9840 \pm 0.0082 \)**
There are several indications of 4th neutrino

LSND, MiniBoone: $\bar{\nu}_e$ appearance
SAGE and GALEX $\nu_e$ deficit (GA)
Reactor $\bar{\nu}_e$ deficit (RAA)

Indication of a sterile neutrino
$\Delta m^2 \sim 1 \text{ eV}^2$
$\sin^2 2\theta_{14} \sim 0.1$
=> Short range neutrino oscillations

Inverse Beta Decay (IBD) process

Reactor models are based on ILL measurements of 235U, 239Pu, 241Pu electron spectra.
Recently Kurchatov Inst. Group observed 5.4% smaller ratio of e- yields for 235U/239Pu (arXiv:2103.01684v1). This can explain the RAA!
Recent (2018) indications of sterile neutrinos

**NEUTRINO-4**: $\Delta m^2 \sim 7 eV^2$ $sin^2 2\theta \sim 0.35$! JETP Lett. 109 (2019) no.4, 213; Arxiv:2005.05301 Phys.Rev.D 104, 032003 (2021)

**MiniBooNE** $\nu_e$ excess of 4.8$\sigma$ (6$\sigma$ with LSND) Phys.Rev.Lett. 121 (2018) no.22, 221801

**NEUTRINO-4** claimed observation of sterile neutrinos although significance is only 2.7$\sigma$ and there are concerns about validity of the analysis: M.D., N.Skrobova JETP Lett.112,199(2020) C.Giunti et al. Phys.Lett.B 816(2021)136214
Very weak indication of $\nu_\mu$ disappearance in ICE Cube (but with large $\Delta m^2$ as in Neutrino -4)

- 8 years of atmospheric $\nu_\mu$

$\nu_\mu$ disappearancne channel

- Best fit (frequentist):
  - $\Delta m_{41}^2 = 4.5 \text{ eV}^2$
  - $\sin^2(2\theta_{24}) = 0.10$

$\rightarrow$ Consistent with Null hypothesis (p-value: 8 %)

Searches for sterile neutrinos are very exciting
Many experiments are searching for sterile neutrinos with $m \sim \text{eV}$ including 9 reactor experiments
Antineutrino detection

Inverse Beta-Decay (IBD) \( \bar{\nu}_e + p \rightarrow e^+ + n \)

\( E_e \approx E_\nu - 1806 \text{ MeV} \)

Reactor models do not describe well antineutrino spectrum

Measurements at one L not sufficient to observe oscillations
All recent experiments observe a bump at 4-6MeV.

Or a dip? (more pronounced in Neutrino-4)
Is Reactor Antineutrino Anomaly Real?

Reactor models are based on ILL measurements of $\beta$ spectra from $^{235}\text{U}$, $^{239}\text{Pu}$, $^{241}\text{Pu}$ n-induced fission isotopes

Recently Kurchatov Inst. Group observed 5.4% smaller ratio of $\beta$ yields for $^{235}\text{U}/^{239}\text{Pu}$ (arXiv:2103.01684v1). This can explain the RAA!

**FIG. 1.** Ratios $R = \frac{e^\text{S}_5}{e^\text{S}_9}$ between cumulative $\beta$ spectra from $^{235}\text{U}$ and $^{239}\text{Pu}$ from ILL data [11] (blue) and KI data [10] (red). Total electron energies are given. Only statistical errors are shown. 

$\left(\frac{5\sigma_f}{9\sigma_f}\right)_\text{KI} = 1.45 \pm 0.03$ - 5.4% smaller than ILL

DayaBay and RENO observed smaller $^{235}\text{U}$ flux than in Huber-Mueler model (based on ILL results) 

$\left(\frac{5\sigma_f}{9\sigma_f}\right) = 1.44 \pm 0.10$ - 5.4% smaller than ILL


$^{238}\text{U}$ contribution should be also reduced since it is normalized on $^{235}\text{U}$

With new values for $^{235}\text{U}$ and $^{238}\text{U}$ contribution measured $\nu$ fluxes agree with predictions

→ No Reactor Antineutrino Anomaly? - Wait till confirmation of KI results

In any case modern searches for sterile $\nu$ do not use predictions for absolute $\nu$ fluxes and predicted shape of the reactor $\nu$ spectra.

Instead relative measurements at different L are studied
Comparison of Very Short Base Line reactor experiments
DANSS is installed on a movable platform under 3.1 GW WWER-1000 reactor (Core: $h=3.7m$, $\varnothing=3.1m$) at Kalinin NPP. 

~50 mwe shielding => $\mu$ flux reduction ~6!

No cosmic neutrons!

Detector distance from reactor core 10.9-12.9m (center to center) changed 2-3 times a week!

5000 IBD events/day at top detector position

Trigger: $\Sigma E(\text{PMT})>0.5-0.7\text{MeV}$ => Read 2600 wave forms (125MHz), look for correlated pairs offline.

Fuel fission fractions: average, start and end of campaign [%]

- $235\text{U}$: 54.1 63.7 44.7
- $239\text{Pu}$: 33.2 26.6 38.9
- $238\text{U}$: 7.3 6.8 7.5
- $241\text{Pu}$: 5.5 2.8 8.5
Fit in 1.5-6 MeV range (to be conservative)

Using current statistics 2016-2020 (~5 million IBD events)
we see no statistically significant indication of 4ν signal:
\[ \Delta X^2 = -3.2 \ (\text{< 1.3} \sigma) \] for 4ν hypothesis best point \[ \Delta m^2 = 1.3 \text{ eV}^2, \sin^2 2\theta = 0.014 \]

RAA has been excluded with \[ \Delta X^2 = 107. \]

RAA was excluded by DANSS with more than 5σ already in 2018
(arXive:1804.04046v1)
The DANSS results

- Exclusion region was calculated using Gaussian CLs method (for $e^+$ in 1.5-6 MeV to be conservative),
- New data make limits more smooth in reasonable agreement with sensitivity
- The most stringent limit reaches $\sin^2 2\theta < 8 \times 10^{-3}$ level (best in the world).
- A very interesting part of 4ν parameters is excluded.
- The most probable point of RAA+GA is excluded at 5σ confidence level (already in 2018)
The DANSS upgrade

**Main goal:** to reach resolution $13\%/\sqrt{E}$ w.r.t. current very modest $34\%/\sqrt{E}$.

**New geometry:**
- **Strips:** $2\times5\times120$ cm, 2-side 4SiPM readout
- **Structure:** 60 layers x 24 strips: $1.7$ m$^3$
- Setup uses the same shielding and moving platform.
- Gd is in foils between layers.
- Upgrade will be finished in 2022

**Strip tests at $\pi$-beam**
- Transverse and longitudinal responses are very uniform
- Longitudinal nonuniformity can be further corrected
- More work on SiPM-WLS fiber connection is needed

**New scintillator strips**
- WLS fiber positions were optimized for better uniformity of response

**Neutrino-4 claim can be tested**
- 1.5 years of data taking
- Sensitivity 2018
- Neutrino-4 positive result
- Sensitivity of Upgraded DANSS
v spectrum normalized to another reactor
Collected new data but problems with Gd
Recently RENO used NEOS data and measured v flux to improve NEOS limits

1m³ LS
No segmentation

$\sigma_{E}/E=5\%$ at 1 MeV

PSD removes 70% of background

Depth 20mwe

S/B = 23

Only one L=24m

Large core size
d=3.1m h=3.8m

Power 2815 MWt;
Recently RENO used NEOS data and measured \( \nu \) flux to improve NEOS limits. Best point (\( \Delta M^2 = 2.37 \text{ eV}^2 \)) agrees with best point of GA+RAA, but p-value is 13% only because of systematic uncertainties.

This point was excluded by DANSS.

**Best fit**: \( \Delta m^2_{41} = 2.37 \pm 0.03 \text{ eV}^2 \), \( \sin^2 2\theta_{14} = 0.09 \pm 0.03 \)

\[ \chi^2_{4\nu,\text{min}} / \text{NDF} = 23.2 / 57 \quad \chi^2_{3\nu} / \text{NDF} = 34.9 / 59 \]

- P-value (assuming 3\( \nu \) with MC) \( \sim 13\% \)
- Weak hint for the sterile neutrino oscillation
- The best fit is compatible with the RAA allowed region

NEOS-II (2018 -- 2020)

- Refurbished detector from NEOS-I.
- Took full fuel cycle (500 days) + 2 OFF periods
- Time evolution of reactor ν flux/shape
- Spectral decomposition ($^{235}$U, $^{239}$Pu)
- Rate+Shape analysis

➤ Analysis is on-going!

S. Seo 20th Lomonosov Conference
Fig. 1. General scheme of an experimental setup. 1 – detector of reactor antineutrino, 2 – internal active shielding, 3 – external active shielding (umbrella), 4 – steel and lead passive shielding, 5 – borated polyethylene passive shielding, 6 – moveable platform, 7 – feed screw, 8 – step motor, 9 – shielding against fast neutrons from iron shot.

85MW 235U Reactor (42x42x35cm3)

1.8m3 LS detector (5x10 sections)

L=6-12m, $\sigma_E/E$~16% at 1MeV $\sim$200ev./day

No PSD; 3.5mwe => S/B~0.54

720 days ON 860 days OFF
Indication of oscillations with large $\Delta m^2 \sim 7.3 \pm 1.17 \text{eV}^2$ and $\sin^2 2\theta = 0.36 \pm 0.12$

Major Advantages

- Compact reactor core with large power
- Segmented and movable detector
- Very short distances to core (6-12) m
- No background from other experiments
- Model independent analysis

Major Disadvantages

- No PSD
- Small overburden (3.5 mwe)
- Small S/B=0.54
- Modest $\sigma_{E/E} = 16\%$ at 1 MeV

Significance 2.7 $\sigma$
There are concerns about validity of Neutrino-4 analysis


1. Concerns about treatment of detector energy resolution:
Neutrino-4 argues that with a big width of the energy bin (500 keV) one should not take into account actual energy resolution (~16% /√E).
But for the most important region E>5MeV more that 50% of signal goes to neighbor E bins - This is huge effect which can not be neglected! (MD’19,MD&Skrobova’20)
Detailed simulations show that inclusion of E resolution decreases the significance to 2.2σ and moves the best point to sin²(2θee)=1, excluded by other measurements (Giunti’21)
Recently (Phys.Rev.D 104, 032003 (2021)) Neutrino-4 studied effects of E resolution but didn’t include them properly

2. Background in outermost detector sections is not known (MD’19,MD&Skrobova’20)
Neutrino-4 shows that without these sections significance drops to ~2σ but does not take it into account in calculations of the significance

3. Wilks theorem used in analysis is not valid (Andriamirado’20 ,MD&Skrobova’20, Coloma’20)
Neutrino-4 shows that without this assumption significance drops to 2.7σ

4. Averaging the same data with different bins in E has no statistical meaning (MD&Skrobova’20)

The best way to address these concerns is to do experiment sensitive to claimed νs parameters
Neutrino-4 future plans

Collaboration creates a new much better detector with 2 PMT per section, with pulse shape discrimination of background, with more Gd

Sensitivity of the new detector will be 3 time better

It will start data taking in 2022, initially at the same SM-3 reactor and then will move to the PIK reactor in St. Petersburg

This will be an excellent experiment sensitive to large $\Delta m^2$!
PROSPECT DETECTOR DESIGN

- 154 segments, 119cm x 15cm x 15cm
  - ~25 liters per segment, total mass: 4 ton
- Thin (1.5mm) reflector panels held in place by 3D-printed support rods
- Segmentation enables:
  1. Calibration access throughout volume
  2. Position reconstruction (X, Y)
  3. Event topology ID
  4. Fiducialization
- Double ended PMT readout for full (X, Y, Z) position reconstruction
- Optimized shielding to reduce cosmogenic backgrounds
Excellent PSD allows to achieve $S/B=1.36$ on earth surface
Excellent energy resolution of 4.5% at 1 MeV
Localized detection of neutrons
Elaborate calibration system

Unfortunately 42% of 154 modules do not work properly due to PMT
PROSPECT results and prospects

Upgrade plans arXiv:2107.03934

- PMT outside LS
- Section Length 1.17m → 1.45m
- 6Li fraction 20% higher
- S/B 1.4 → 4.3
- $N_{IBD}(\text{effective})$ 15k → 200k

Data taking at HIFR before 2024

arXiv:2006.11210
The STEREO detector

Data taking is finished

arXiv:1804.09052

Invert Beta Decay

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]

Prompt signal

\[ \bar{\nu}_e \] energy

> 1.8 MeV

1.5m

Delayed signal

Mean neutron capture time 16 \( \mu \)s

Stainless steel vessel

Acrylic buffers

Calib. tubes

Gamma catcher

Target

6 cells filled with Gd-loaded liquid scintillator

4 top PMTs per cell

Gamma-catcher

Outer-crown to detect \( \gamma \)'s escaping from the Target + active shielding

24 PMTs

Neutrino 2018 - Heidelberg

Jacob Lamblin, LPSC Grenoble
DANSS limits are much stronger at 1-2 eV\(^2\) but Prospect and Stereo are better for large masses

Some tension with Neutrino-4 result
5 × 5 × 5 cm³ PVT cubes
- Non-flammable scintillator
Cubes are optically separated using Tyvek wraps
$^{6}$LiF:ZnS(Ag) screens for neutron identification
Light collected through optical fibers and silicon photomultipliers (SiPMs require low-voltage)
Good pulse shape discrimination of background (# peaks over thresh) 
In-situ measurements of neutron detection efficiency

Major Advantages

Compact reactor core with large power
Highly segmented detector -> 3D recons.
Very short distances to core (6-9) m
Good PSD of background -> S/B~3
Localized detection of neutrons
Elaborate calibration system

Major problems

Modest $\sigma_E/E=14\%$ at 1 MeV
Calibration challenge - 12800 cubes
Large background!

BiPo background
Internal radioactivity from ZnS layers contamination
External Radon decay.

With a complicated ML signal separation SoLid finally managed to observe IBD events.

No physics results so far
## Comparison of experiments

<table>
<thead>
<tr>
<th></th>
<th>DANSS</th>
<th>NEOS</th>
<th>v - 4</th>
<th>PROSPECT</th>
<th>SoLid</th>
<th>STEREO</th>
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<tbody>
<tr>
<td>Power [MWt]</td>
<td>3100</td>
<td>2815</td>
<td>90</td>
<td>85</td>
<td>50-80</td>
<td>58</td>
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<tr>
<td>Core size [cm]</td>
<td>ø=3200h=3700</td>
<td>ø=3100h=3800</td>
<td>42x42h=35</td>
<td>ø=51h=44</td>
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<td>ø=40h=80</td>
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<td>Overburden [mwe]</td>
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<td>20</td>
<td>3.5</td>
<td>&lt;1</td>
<td>10</td>
<td>15</td>
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<tr>
<td>Distance [m]</td>
<td>10.9-12.9 Movable</td>
<td>24</td>
<td>6-12 Movable</td>
<td>7-9</td>
<td>6-9</td>
<td>9-11</td>
</tr>
<tr>
<td>IBD events/day</td>
<td>5000</td>
<td>1965</td>
<td>200</td>
<td>750</td>
<td>~450</td>
<td>400</td>
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<td>PSD/ Readout</td>
<td>- / 3D</td>
<td>+ / 1D</td>
<td>- / 2D</td>
<td>+ / 3D</td>
<td>+ / 3D</td>
<td>+ / 2D</td>
</tr>
<tr>
<td>S/B</td>
<td>58</td>
<td>23</td>
<td>0.54</td>
<td>1.36</td>
<td>?</td>
<td>0.9</td>
</tr>
<tr>
<td>σ_E/E [%] at 1 MeV</td>
<td>33</td>
<td>5</td>
<td>16</td>
<td>4.5</td>
<td>14</td>
<td>9</td>
</tr>
</tbody>
</table>

Red - good    Black - bad
MC estimates give smaller significance than $X^2$ with 2dof


DANSS, NEOS, PROSPECT, Bugey-3 data

Significance of the best point
($\Delta m^2 = 1.3$ eV$^2$, $\sin^2 2\theta = 0.026$) is $1.8 \sigma$ only

FIG. 3. Contours of the $1\sigma$ (blue), $2\sigma$ (red), and $3\sigma$ (green) allowed regions in the ($\sin^2 2\theta_{ee}, \Delta m_{31}^2$) plane obtained with the combined analysis of the data of the four reactor spectral-ratio experiments NEOS [12], DANSS [14], Bugey-3 [26], and PROSPECT [27]. The solid lines represent the contours obtained with our Monte Carlo evaluation of the distribution of $\Delta \chi^2$, and the dashed lines depict the contours obtained assuming the $\chi^2$ distribution. Also shown are the marginal $\Delta \chi^2$'s (black) for $\sin^2 2\theta_{ee}$ and $\Delta m_{31}^2$, together with the $\Delta \chi^2$ values corresponding to $1\sigma$ (blue), $2\sigma$ (red), and $3\sigma$ (green) obtained with the $\chi^2$ distribution (dashed) and our Monte Carlo (solid). The blue cross indicates the best-fit point.
Very strong limits on $\nu_\mu$ disappearance

\[ P_{\nu_\alpha \rightarrow \nu_\beta}^{SBL} \approx \sin^2 2\vartheta_{\alpha\beta} \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E} \right) \]

\[ \sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2 \]

\[ P_{\nu_\alpha \rightarrow \nu_\alpha}^{SBL} \approx 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E} \right) \]

\[ \sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2) \]

Strong limits on disappearance $\rightarrow$ strong limits on appearance

\[ \sin^2 2\vartheta_{e\mu} = 4|U_{e 4}|^2 |U_{\mu 4}|^2 \approx \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu} \]
Appearance and disappearance experiments are not compatible

Addition of 2-nd sterile neutrino does not help

M. Dentler et al
JHEP v8, p.010, 2018

Appearance

Disappearance

99.73% CL
2 dof

\Delta m^2 [eV^2]

\sin^2 2\theta_{\mu e}

Addition of 2-nd sterile neutrino does not help
Cosmological data strongly disfavor a sterile neutrino on ~ 1 eV mass-scale

However there are models that can accommodate such ν

For example in a model with additional pseudoscalar a neutrino on ~ 1 eV mass-scale is allowed (M. Archidiacono et al., arXiv: 2006.12885).

Moreover, this model alleviates tension between different $H_0$ measurements.

Combined fit with SBL reactor experiments gives $m_s = 1.14$ eV
Summary

Two new indications of sterile neutrinos in 2018: MiniBooNE and NEUTRINO-4

However sterile neutrinos can not explain simultaneously appearance and disappearance results

Strong limits on sterile neutrino parameters were obtained by DANSS and NEOS. PROSPECT and STEREO extended limits to higher $\Delta m^2$

Significance of sterile neutrinos in VSBL reactor experiments (w/o Neutrino 4) is ~2σ only

Reactor neutrino spectrum predictions are still quite uncertain
8 MeV bump not understood.

Measured X-section for 235U is 5% smaller than in H-M model

New measurement of beta spectra from 235U and 239Pu at KI give 5% smaller ratio than ILL results -> smaller X-section for 235U --> RAA becomes weaker

New results with increased sensitivity are expected in near future from DANSS, NEOS-II, NEUTRINO-4, PROSPECT, SOLID and STEREO
Backup slides
Sensitivity to fuel evolution

Top – Middle – Bottom data with and without fuel evolution correction

Raw data w/o fuel correction

Fuel-corrected data
Comparison with experiments based on spectra ratio at different distances measured with identical detectors

90% CL limits

Daya Bay

Bugey

DANSS’18

$\Delta m^2, \text{eV}^2$

$\sin^2 2\theta$

$10^{-2}$  $10^{-1}$  $10^{0}$  $10^{1}$
Polystyrene based scintillator

Y11 1.2mm Ø WLS fibers
PMT R7600U-300

Gd containing coating 1.6 mg/cm²
0.35%wt

10 layers = 20 cm

X-Module

Y-Module

SiPMs

• 2500 scintillator strips with Gd containing coating for neutron capture
• Light collection with 3 WLS fibers
• Central fiber read out with individual SiPM
• Side fibers from 50 strips make a bunch of 100 on a PMT cathode = Module

• Two-coordinate detector with fine segmentation – spatial information
• Multilayer closed passive shielding: electrolytic copper frame ~5 cm, borated polyethylene 8 cm, lead 5 cm, borated polyethylene 8 cm
• 2-layer active µ-veto on 5 sides
~5000 events/day in detector fiducial volume (78% of full volume) at ‘Top’ position.

Cosmic background ~1.7% (Top position, E: 1.5-6MeV). Signal/Background >50!

- Continuous detector calibration with cosmic muons
- Very modest energy resolution of ~33% at 1 MeV
- Very large size of the reactor core (⌀ 3.1m, h=3.7m)
- → Smearing of the oscillation pattern
Daya Bay observed smaller 235U X-section than Huber model

STEREO also observed smaller X-section for pure 235U fuel

Kopeikin et al. remeasured recently ratio of cumulative beta spectra for 235U/239Pu and obtained 1.054 times smaller value than ILL (arXiv:2103.01684)

This leads to a smaller value of 235U antineutrino X-section (6.27$^{+0.13}_{-0.13}$) in agreement with Daya Bay and STEREO

RAA becomes weaker

Modern experiments do not use absolute flux predictions
Global fit of disappearance data without Neutrino-4
(M. Dentler et al JHEP v8, p.010, 2018)

Electron neutrino disappearance

Assumes $\chi^2$ distribution with 2 dof and old DANSS data (1 year).
With 5 years of DANSS data significance of best point
$(\Delta m^2 = 1.3 \text{ eV}^2, \sin^2 2\theta = 0.014)$ is only $\sim 1.3 \sigma$