A search for sterile neutrinos with PROSPECT

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Motivation: Reactor Antineutrino Anomaly

**Flux deficit**

Daya Bay - CPC 41 (1) (2016)

Anomaly:
- Observed flux shows 6% deficiency with respect to theoretical predictions

Possible explanations:
- Oscillations of $\bar{\nu}_e$ to sterile neutrinos, 1 eV$^2$-scale, **short-baseline**
- Flaws in the models/underlying nuclear data

Global-fit: best-fit point at $\sin^2 2\theta = 0.165, \Delta m^2 = 2.39$ eV$^2$
  (RAA best-fit point)

PROSPECT performs search for short-baseline sterile neutrino oscillations
Experiment

Inverse beta decay (IBD) mechanism of detection of antineutrinos ($^6$Li-doped liquid scintillator EJ-309):

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

- 1-10 MeV prompt signal – ionization and annihilation of positron
- $\sim$0.5 MeV delayed signal – from neutron capture on $^6$Li
- Distinctive tag – 50 µs delay in neutron capture
- Strong background rejection due to coincident signature

Reactor:
- 85 MW High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL)
- Burns highly enriched uranium fuel $^{235}$U

Detector:
- 11 x 14 (154) array of optically separated segments
- Distance from reactor – 7 m
Sterile Neutrino Oscillations Search

\[
P_{ee} = 1 - \sin^2 2\theta_{14} \cdot \sin^2 \left( 1.27 \cdot \Delta m^2_{41} \frac{L}{E} \right)
\]

- Segmented detector design:
  - 154 segments = 154 individual-detectors within one full-volume detector
  - Segments are at different baselines from the reactor

- Relative spectral comparison:
  - Compare measured energy spectrum for each baseline to the scaled full detector energy spectrum

→ Relative and reactor model-independent search for sterile neutrinos
\[ P_{ee} = 1 - \sin^2 2\theta_{14} \cdot \sin^2 \left( 1.27 \cdot \Delta m^2_{41} \frac{L}{E} \right) \]

MC-generated oscillated spectra for different baselines for RAA best-fit point ($\sin^2 2\theta_{14} = 0.165, \Delta m^2_{41} = 2.39 \text{ eV}^2$)

Before spectral shape relativization

After spectral shape relativization
Reactor Neutrino Analysis Dataset

- 33 days of Reactor On
- 28 days of Reactor Off
- 24,461 IBDs detected (0.8-7.2 MeV)
- Average of ~771 IBDs/day
  - Correlated S:B = 1.32
  - Accidental S:B = 2.20
- Best demonstrated S:B for an on-surface reactor experiment

PROSPECT, Phys. Rev. Lett. 121, 251802
IBD Rate vs Baseline

- Events from 108 fiducial segments binned into 14 baseline bins
- Flux follows $1/r^2$ behavior throughout detector volume
- 40% flux decrease from front of detector to back as expected
- The experiment covers range of different baselines
• 33 days of reactor on regime, 28 days of reactor off

• 6 baselines

• Ratio = \frac{\text{Spectrum at Baseline}}{\text{Full detector spectrum}}

• Data are compared to spectrum for modeled oscillations for RAA-best fit value (green dashed line)

• Flat dashed line: null oscillations

• Comparing to RAA best-fit point simulation, data do not follow oscillatory pattern

PROSPECT, Phys. Rev. Lett. 121, 251802
Building $\chi^2$

Compare obtained spectrum ($O$) with predicted spectrum ($E$, expected) for different baselines ($l$) and energies ($e$)

$$\chi^2 = \Delta^T V_{tot}^{-1} \Delta$$

- $\Delta_{l,e} = O_{l,e} - O_e \frac{E_{l,e}}{E_e}$
- $O_e = \sum_{l=1}^{6} O_{l,e}$
- $E_e = \sum_{l=1}^{6} E_{l,e}$

Predicted spectrum:

$E_{l,e} = E_{l,e}^{null} \cdot (1 - \sin^2 2\theta_{14} \cdot \sin^2 \left(1.27 \cdot \Delta m_{41}^2 \frac{L}{E_{\nu}} \right))$

Covariance matrix $V_{tot}$:

- Sum of all covariance matrices $V_x$ produced for each systematic uncertainty and signal and background statistical uncertainties
- Takes into account their correlation between energy and baseline bins
Confidence Interval

• $\chi^2$ is calculated by comparing measured spectra to predicted spectra at each baseline
• Was calculated with Feldman-Cousins approach
• Covariance matrices reflect uncertainties and energy/baseline correlations
• 95% exclusion curve based on 33 days Reactor On operation

Exclude RAA best-fit point at >95% CL (2.2$\sigma$)

Short-baseline reactor experiment Neutrino-4: observation of sterile neutrino oscillations at $\sin^2 2\theta = 0.4, \Delta m^2 = 7.2 \text{ eV}^2$ best-fit point

Neutrino-4 best fit also disfavored at >95% CL
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Short-baseline reactor experiment Neutrino-4: *observation of sterile neutrino oscillations at $\sin^2 2\theta = 0.4, \Delta m^2 = 7.2 \text{ eV}^2$ best-fit point*

*Neutrino-4 best fit also disfavored at >95% CL*
Feldman-Cousins Approach

- Standard (incorrect) method does not handle boundary features such as bounded nature of $\sin^2 2\theta$ (0,1) or cases when oscillation frequency approaches energy bin size. Feldman-Cousins method solves those problems

- Comparing p-values for Feldman-Cousins and standard (incorrect) methods:

<table>
<thead>
<tr>
<th>P-values</th>
<th>3v-oscillation hypothesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feldman-Cousins</td>
<td>0.58</td>
</tr>
<tr>
<td>Standard (incorrect) confidence intervals assignment</td>
<td>0.14</td>
</tr>
</tbody>
</table>

- If standard (incorrect) confidence levels used instead of Feldman-Cousins:
  - We say 3ν is less compatible with data than it actually is

- Illustrates an importance of using Feldman-Cousins
The construction of the test statistic probability distribution through Monte Carlo techniques is hence mandatory in order to ensure accurate results. The Monte Carlo construction is computationally demanding, but it is feasible as proved by the experiments that are already performing it. Indeed, the proposed analysis procedure is very similar to the what is used by e.g. MiniBooNE and PROSPECT.

“Statistical Methods for the Search of Sterile Neutrinos”, Matteo Agostini, Birgit Neumair

arXiv: 1906.11854
Conclusion

• PROSPECT performs search for short-baseline sterile neutrino oscillations from highly-enriched $^{235}\text{U}$ reactor

• Segmented detector design and relative spectral comparison used in the analysis allow relative and reactor model-independent study

• With 33 days of data, PROSPECT disfavored RAA sterile neutrino best fit point at 95% C.L. (2.2σ)

• Feldman-Cousins method is necessary to assign correct confidence intervals
Thank you!
Backup Slides
Comparison to Neutrino-4 Results

Neutrino-4, arXiv:1809.10561 “The first observation of effect of oscillation in Neutrino-4 experiment on search for sterile neutrino”

Short-baseline reactor experiment Neutrino-4: observation of sterile neutrino oscillations at $\sin^2 2\theta = 0.4, \Delta m^2 = 7.2$ eV$^2$ best-fit point

PROSPECT already covers Neutrino-4 best-fit point and 1σ at 95% CL
Comparison to Neutrino-4 Results

Neutrino-4:

- Use “standard” method of constructing confidence intervals

\[ \Delta \chi^2 (\sin^2 2\theta_{14}, \Delta m^2_{14}) = \chi^2 - \chi^2_{\text{min}} < A, \]
\[ (A = 2.30(1\sigma), A = 6.18(2\sigma), A = 11.83(3\sigma)) \]

- Poor agreement between measured and predicted spectrum

- Non-linear effects of detector response are not taken into account

Prompt signal spectrum (blue) vs MC-simulated spectrum for U-s sera35 (red)
$\Delta \chi^2$ and critical $\chi^2$ maps

Confidence Intervals

• For each set \((\Delta m_{14}^2, \sin^2 2\theta_{14})\) 1000 oscillated MC toy datasets are generated
• Fluctuations in the toys are determined by statistical and systematic uncertainties
• For each toy dataset and every point in \((\Delta m^2, \theta)\)-grid, \(\chi^2_{\text{min}}\) is calculated \(\Delta \chi^2\):
  \[
  \Delta \chi^2 = \chi^2_{\text{min,true}} - \chi^2_{\text{min,best-fit}}
  \]

  \(\chi^2_{\text{min,true}}\) is \(\chi^2_{\text{min}}\) for true oscillation parameters used in generation of the particular toy; \(\chi^2_{\text{min,best-fit}}\) is \(\chi^2_{\text{min}}\) for best-fit oscillation parameters for this particular toy
• \(\chi^2_C(\alpha)\) is defined for each point in \((\Delta m^2, \theta)\)-grid such that
  \[
  \frac{\sum_0^{\Delta \chi^2} P(\Delta \chi^2)}{\sum_0^{\infty} P(\Delta \chi^2)} = \alpha
  \]
  where \(P(\Delta \chi^2)\) – probability density distribution (PDF) of \(\Delta \chi^2\)
• Point in oscillation parameter grid is excluded at \(\alpha\) confidence interval, if
  \[
  \Delta \chi^2_{\text{data}} > \Delta \chi^2_C
  \]

Toy datasets are compared with predicted oscillated spectrum

Example of a toy L-E distribution