PROSPECT: Precision Reactor Oscillation and Spectrum Experiment

Xiangpan Ji
for the PROSPECT collaboration

Brookhaven Forum 2019
Neutrino Oscillation

Neutrino oscillation indicates:
- Neutrinos have mass
- Neutrino flavor eigenstates are mixture of mass eigenstates

\[ P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 2\text{Re} \sum_{j>i} U_{\alpha i} U_{\alpha j}^* U_{\beta i} U_{\beta j} \left( 1 - e^{i\Delta m_{ij}^2 L/2E} \right) \]

Neutrino mixing matrix \((U)\)

\[
\begin{pmatrix}
    \nu_e \\
    \nu_\mu \\
    \nu_\tau
\end{pmatrix} =
\begin{pmatrix}
    1 & 0 & 0 \\
    0 & \cos\theta_{23} & \sin\theta_{23} \\
    0 & -\sin\theta_{23} & \cos\theta_{23}
\end{pmatrix} \begin{pmatrix}
    \cos\theta_{12} & \sin\theta_{12} & 0 \\
    -\sin\theta_{12} & \cos\theta_{12} & 0 \\
    0 & 0 & 1
\end{pmatrix} \begin{pmatrix}
    \nu_1 \\
    \nu_2 \\
    \nu_3
\end{pmatrix}
\]

Flavor eigenstates \(\nu_e, \nu_\mu, \nu_\tau\)

Mass eigenstates \(\nu_1, \nu_2, \nu_3\)

- Atmospheric/Long baseline accelerator
- Short baseline reactor/Long baseline accelerator
- Solar/Long baseline reactor

Nature Commun. 6 (2015) 6935

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Nuclear Reactor As Antineutrino Source

- Commercial reactors in Nuclear Power Plants have low-enriched uranium (LEU) cores
  - Mixture of fissions: $^{235}\text{U}$ (~55%), $^{239}\text{Pu}$ (~30%), $^{238}\text{U}$ (~10%), $^{241}\text{Pu}$ (~5%)
  - Large power: ~3 GW$_{\text{th}}$
- Research reactors have highly-enriched uranium (HEU) cores
  - $^{235}\text{U}$ fission fraction ~99%
  - Lower power, few tens of MW$_{\text{th}}$
  - Compact size

- Nuclear reactors produce pure $\bar{\nu}_e$ from beta decays of fission daughters
  - Low energy: < 10 MeV
  - ~6 $\bar{\nu}_e$/fission
  - $2 \times 10^{17} \bar{\nu}_e$/MW$_{\text{th}}$ per second

Credit:nobelprize.org
Reactor Antineutrino Anomaly (RAA): Flux Deficit

What’s the origin of the $\bar{\nu}_e$ flux deficit?
- Problems from reactor model predictions?
- New physics?

<table>
<thead>
<tr>
<th>Sterile neutrino: doesn’t interact in the SM</th>
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<tbody>
<tr>
<td>• High frequency oscillation</td>
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<td>• Mass splitting ~1 eV$^2$</td>
</tr>
<tr>
<td>• Baseline ~few meters</td>
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$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{14} \sin^2 \left(1.267 \frac{\Delta m^2_{41} L}{E} \right) - \sin^2 2\theta_{13} \sin^2 \left(1.267 \frac{\Delta m^2_{31} L}{E} \right)$
Physics Objectives:

- **Reactor model independent search for neutrino oscillations into eV-scale sterile states**
- **Precision measurement of the $^{235}\text{U}$ antineutrino spectrum**

Segmented detector design using the pulse shape discrimination (PSD) capable $^6\text{Li}$-doped liquid scintillator (LiLS) provides powerful near-surface background rejection.
**Experiment Site: HFIR**

**Power:** 85 MW  
**Core shape:** cylindrical  
**Size:** $h=0.5m$, $\phi=0.44m$  
**Duty-cycle:**  
46%, 7 cycles/yr, 24 days  
**Fuel:** highly-enriched uranium reactor, >99% $^{235}U$ fissions

**Site Challenges:**  
detector near surface, little overburden  
(<1m water equivalent)

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Reactor Neutrino Detection through IBD Reaction

Inverse beta decay (IBD):
\[
\bar{\nu}_e + p \rightarrow e^+ + n
\]
\[
E_{\bar{\nu}} \approx T_{e^+} + 1.8 \text{ MeV}
\]
The positron carries most of the $\bar{\nu}_e$ energy

\[
S(E_{\bar{\nu}}) = c \cdot f \cdot s(E_{\bar{\nu}}) \cdot \sigma(E_{\bar{\nu}})
\]

isotope fission fraction

isotope neutrino spectrum

IBD cross section

reactor thermal power, energy released per fission, baseline, target protons, detection efficiency, oscillation, etc.

*Credit: Nature Commun. 6 (2015) 6935*
IBD Detection with LiLS

6Li-loaded LS manufactured at BNL

ν̄e + p → e+ + n
n + 6Li → α + t
Event Topology

PSD = Q_{tail}/Q_{full}

Event Signature:
- Prompt signal: positron from IBD
- Delayed signal: n capture on 6Li
The two are time- and space- correlated

The Pulse Shape Discrimination (PSD) of scintillator distinguishes the β⁺-like event (IBD signal) and n-like event (most significant background at HFIR).

Correlation + PSD:
- Identify IBD signal
- Reject backgrounds

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JINST 13 (2018) P06023
PROSPECT Detector Design

- 154 segments (14 x 11)
  - ~25 liters of LiLS per segment, total mass: 4 ton
  - Segment: 119cm x 15cm x 15cm

- Thin (1.5mm) reflector panels held in place by 3D-printed support rods

- **Segmentation enables:**
  1. Relative measurements
  2. Calibration access throughout volume
  3. Position reconstruction
  4. Event topology ID
  5. Fiducialization
Background Rejection

Passive Shielding
- detector near surface,
- little overburden (<1m water equivalent)

Active Suppression
- Optimized detector design for background ID and suppression
- Combine PSD, shower veto, event topology, and fiducialization
- Active suppression of background $> 10^4$

*HDPE: high density polyethylene
*BPE: borated polyethylene
Construction and Installation

Arrival at Oak Ridge  
At HFIR  
Filling LiLS from mixing tank  
March 5, 2018  
Began operation

Oct 2017 – Jan 2018 at Yale Wright Lab

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Energy Reconstruction

- High performance of energy reconstruction: a key part for the precision measurement of neutrino oscillation and spectrum
- Gammas sources: $^{137}$Cs, $^{60}$Co deployed throughout detector, measure single segment response
- High-energy beta spectrum: Fast-neutron tagged $^{12}$B
- Full-detector $E_{\text{rec}}$ within 1% of $E_{\text{true}}$
- High light collection: $795\pm15$ PE/MeV

Calibration spectra

Resolution vs. energy
4.5%@1MeV

Measurement of $^{235}$U Spectrum

- 40.3 days of reactor-on exposure
- 37.8 days of reactor-off exposure
- $\sim 31000$ IBD candidate events (reactor-off candidate events scaled to match exposure) $\sim 6 \times$ greater statistics than ILL (1981)
- Measured spectrum with good S/B at surface 1.7/1 (0.8-7.2 MeV)

![Prompt Energy Spectrum](image-url)
Is PROSPECT consistent with Huber $^{235}$U model?

$\chi^2/\text{ndf} = 51.4/31$, p-value = 0.01

Huber model broadly agrees with spectrum but exhibits large $\chi^2/\text{ndf}$ with respect to measured spectrum, not a good fit

Shape of measured $^{235}$U spectrum is consistent with deviation relative to prediction observed at LEU reactors (e.g. Daya Bay)

PROSPECT current measurement is statistics limited. Expect improvement as more data are collected.
First Oscillation Analysis Data Set

33 days of reactor-on exposure
28 days of reactor-off exposure

\[25461 \pm 283\] IBDs detected
Average of 771 IBDs/day

S/correlated background = 1.32
S/accidental background = 2.2

IBD event selection defined and frozen on 3 days of data

Reactor on Reactor off Reactor on

Neutrino Rate vs. Baseline

- Observation of $1/r^2$ behavior throughout detector volume
- Cover a wide relative baseline range
- 40% flux decrease from front of detector to back as expected

Neutrino Spectrum vs. Baseline

Illustration of Spectral Distortion vs. Baseline

\[ P_{\nu_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{14} \sin^2 \left( 1.267 \frac{\Delta m^2_{41} L}{E} \right) \]

- Compare spectra from 6 baselines to measured full-detector spectrum
- Good agreement between the data and the no-oscillation hypothesis
- Direct ratio search for oscillations, reactor model independent


Dashed flat line: no oscillation, \( \chi^2/\text{ndf}=61.9/80 \)
Dashed curve: RAA
Oscillation Search Results

- Feldman-Cousins based confidence intervals for oscillation search

- Covariance matrices captures all uncertainties and energy/baseline correlations

- Critical $\chi^2$ map generated from toy MC using full covariance matrix

- 95% C.L. exclusion curve based on 33 days of reactor on operation

- Cross checked with an independent analysis using Gaussian CLs method (NIMA 827 (2016) 63-78)

Direct test of the Reactor Antineutrino Anomaly Disfavors RAA best-fit point at >95% (2.2$\sigma$)
• PROSPECT started taking data in March, 2018
• Background rejection and energy resolution meet expectation and match Monte Carlo
• World-leading signal-to-background for a surface-based detector (< 1mwe overburden). Observed antineutrinos from HFIR with good signal/background.
• First oscillation analysis on 33 days of reactor-on data disfavors the RAA best-fit at 2.2σ.
• Performed a modern high-statistics $^{235}$U spectrum measurement using a surface-based detector; currently statistics limited
• More data has been collected and analysis is ongoing
PROSPECT Collaboration

Funded by:

14 institutions, 70 collaborators

Lawrence Livermore National Laboratory
NIST
Brookhaven National Laboratory
Oak Ridge National Laboratory
Yale
Drexel University
Backup
eV-scale Sterile Neutrino Hints

**LSND**
- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance
- $L/E \sim 30\text{m}/30\text{MeV}$

**MiniBooNE**
- $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance
- $L/E \sim 500\text{m}/500\text{MeV}$

**GALLEX/SAGE: Solar $\nu$ expts, Calibrated $\nu_e$ source:** $^{51}\text{Cr}$ and $^{37}\text{Ar}$
- $\nu_e$ disappearance

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**Phys. Rev. D64:112007, 2001**

**Phys. Rev. Lett. 121, 221801**


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R = 0.84 ± 0.05
Reactor Antineutrino Spectral Anomaly: the “Bump”

- Bump in 4-6 MeV prompt energy (5-7 MeV neutrino energy) observed in 2014 by three $\theta_{13}$ experiments
- Cannot be explained by detector effects such as energy response
- Problems from reactor model predictions?