PROSPECT
Precision Oscillation and Spectrum Experiment

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For the PROSPECT Collaboration
Short Baseline (anti)Neutrino Anomalies

The distance travelled by the neutrino in meters and agrees well with the expectation from neutrino background including the ILL shape-only information in the analysis of the reactor antineutrino anomaly. The best limit. As already noted in Ref. [481], the data from ILL showed a spectral deformation that corresponds to the 3 active neutrino mixing solution fitting the data, with $\sin^2 2\theta = 0.927$.

The fourth neutrino hypothesis (3+2 model) has two additional parameters compared to the 3+1 case. Considering that the confidence level at which the no oscillation hypothesis is $\chi^2$-forbidden transition amplitude $|\Delta m^2| \cdot \sin^2 2\theta < 0.5\%$ [27]. A evidence for $\Delta m^2 < 10^{-6}$ eV$^2$. All $\nu_e$ disappear in SBL reactors. The $\nu_e$ disappear in LBL reactors. 95% CL for $|U_{e4}|^2$. $\theta$ is translated into a confidence level by taking into account the number of parameters relevant in each model.

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The experiments have found agreement with the expected cross section $\sigma_{\nu e}^{\alpha} \approx 10^{-4}$ nb/MeV for the reaction $\nu e \rightarrow e^+\nu$. Global data on solar neutrinos, see appendix for details.

Because other experiments have given us great confidence in the range of 2.0–2.5 MCi could be made if the Ca-containing source experiments with Ga and interpreted as a measurement of the Ca-containing source. The prototype for the production of a much more intense source.

Based on the experience gained in making this source, the elaborate several techniques for source intensity measurement. To prove that a very intense source could be made, and to here were to develop the technology of source fabrication. Source engineers for BN-600 conclude that sources in the range of 2.0–2.5 MCi could be made if the Ca-containing source experiments with Ga and interpreted as a measurement of the Ca-containing source.

Acknowledgments

The Acknowledgments section includes a list of contributors and their affiliations. The acknowledgments note the support received from various institutions and organizations, as well as the importance of collaboration and networking.
Short Baseline (anti)Neutrino Anomalies

Abazajian et al. arxiv:1204.5379

Abdurashitov et al. PRC 73, 045805

T2K Caravaca et al. NUFACT2014

Accidental

T.J. Langford - Yale University
Reactor $\bar{\nu}_e$ for short baseline oscillation searches

- Multi-MeV span of energies combined with multiple detectors provide broad L/E coverage
- Compact core research reactors ideal for search:
  - Small cores allow access to faster oscillations $\sim \Delta m^2 \sim O(1\text{eV}^2)$
  - *HEU provides near static spectrum throughout cycle*
  - True reactor-off periods to measure ambient backgrounds

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**Very-Short-Baseline Reactor Signal**

- Detect reactor neutrinos via inverse beta decay interaction in liquid scintillator detector
- Look for spectral distortions in position, energy
- Characteristic L/E oscillation pattern

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**Oscillated:**

\[
\Delta m^2 = 1.8 \text{ eV}^2, \quad \sin^2 2\theta = 0.5
\]

**Unoscillated**

- 30% Efficiency
- 15cm position resolution
- 10%/sqrt(E) Energy Resolution

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Heeger, Mumm, Tobin, BRL

*PRD D 87 (2013)*

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One 3x1x1 m$^3$ detector, 1m$^3$ 20 MW HEU core, 4m closest distance

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Heeger et al.

*PRD 87 073008*
PROSPECT Short Baseline Reactor Experiment

**Physics Goals:**
- Search for short baseline $\nu_e$ oscillations (L/E ~ .5 - 7 m/MeV)
- Use segmentation to directly search for spectral distortions from sterile $\nu$
- Precision measurement of the $^{235}$U neutrino spectrum for physics and safeguards
- Develop technology to detect reactor neutrinos at minimal overburden

**Detector Design:**
- Two-phase detector deployment:
  - Phase 1: Near Detector
  - Phase 2: Near+Far Detectors
- Segmented detectors with pulse-shape discriminating $^6$Li scintillator

**Challenges:**
- Minimal overburden, cosmogenic backgrounds
- Reactor-related backgrounds
  - High energy ($\leq$10MeV) gammas
- Relative segment variations and calibration and position-related systematics

Proposed near and far detectors shown at HFIR.
oscillations. For energies above the IBD threshold and baselines below 100 m, the approximated
there is a group of three active neutrino masses separated from an isolated neutrino mass, such
therein) with a large
standard neutrino, corresponding in the flavor basis to a sterile neutrino
hypothesis at 2
only analysis discussed above, that of Ref. [481] was reproduced, excluding the no-oscillation
contour in Fig. 14 of Ref. [448] was reproduced for the shape-only analysis (while for the rate-
to include the ILL shape-only information in the analysis of the reactor antineutrino anomaly. The
be mentioned that the parameters best fitting the data reported by the authors of Ref. [481] were
the best limit. As already noted in Ref. [481], the data from ILL showed a spectral deformation
distances [391, 449], the Goesgen and Bugey-3 measurements exclude oscillations with 0
448] is used. From the analysis of the shape of their energy spectra at di
the next section. In that analysis, shape information from the Bugey-3 and ILL published data [391,
sensitive of them, involving experts, would certainly improve the quantification of the anomaly.
The blue line displays a solution including a new neutrino mass state, such as
illustration, the red line shows a 3 active neutrino mixing solution fitting the data, with sin
are added in quadrature. The mean averaged ratio including possible correlations is 0.927
mean lifetime, and the o
1 eV
2
0.12, as well as sin
2
m
0.85.
2
1.15
0.85
0.95
1.05
1.15
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Relative Power (arb.)

Abazajian et al.
arxiv:1204.5379
HFIR Baselines

HFIR Research Reactor

• High Flux Isotope Reactor at Oak Ridge National Lab
• 85MW HEU reactor, 42% uptime
• 42cm x 50cm cylindrical core
  • Detailed modeling available
• Active research program with many experiments currently running
Background Characterization

- Extensive background characterization performed at three reactor sites (NIST, HFIR, ATR)
  - Thermal and fast neutrons
  - $\gamma$-ray spectroscopy (NaI and HPGe)
  - Muon flux
- Important findings:
  - Significant temporal and spacial variations
  - High energy $\gamma$ background from thermal neutron capture
  - Cosmogenic rates scale with altitude and overburden as expected

![FaNS Fast Neutron Detector at HFIR](image1)
![HPGe detector at HFIR](image2)
![Energy Spectrum](image3)

Table V: The run details for measurements of the cosmogenic neutron backgrounds with FaNS-1. NIST A113 is a room in the reactor building with minimal shielding ($\ll 10$ cm), while HFIR 0, 1, 3 cover the near locations within the confinement area, and HFIR 2 is outside the reactor building where the far detector would be located. Flux uncertainties shown here are only from statistics.

<table>
<thead>
<tr>
<th>Location</th>
<th>Exposure (hr)</th>
<th>Flux ($E_{n}&gt;1$ MeV) (n/cm$^2$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIST A113</td>
<td>156</td>
<td>$(5.6 \pm 0.1) \times 10^3$</td>
</tr>
<tr>
<td>HFIR 0</td>
<td>23</td>
<td>$(2.8 \pm 0.3) \times 10^3$</td>
</tr>
<tr>
<td>HFIR 1</td>
<td>12</td>
<td>$(4.1 \pm 0.3) \times 10^3$</td>
</tr>
<tr>
<td>HFIR 2</td>
<td>8</td>
<td>$(4.4 \pm 0.3) \times 10^3$</td>
</tr>
<tr>
<td>HFIR 3</td>
<td>14</td>
<td>$(3.6 \pm 0.3) \times 10^3$</td>
</tr>
</tbody>
</table>

Comparing the NIST measurement with the HFIR outside location (HFIR 2) we see a slight deficit in the HFIR flux. However, this can possibly be explained by the presence of a large (30-40') concrete wall that shadows the location.
PROSPECT Detector Design

- Double Ended Readout
- Very thin wall Segmentation
- LiLS for n-tagging

- ~2.5ton active volume of LiLS
- O(100) optical reflecting segments with very thin walls
- Can use the segmentation to create a fiducial volume

Optimized passive shield design
Li-loaded Liquid Scintillator

- Two types under development:
  - **LAB** and **DIPN**
- Both shown to be viable options for PROSPECT
- Optimization of light yield, pulse shape discrimination (PSD), and capture time is underway

Prompt signal: 1-10 MeV positron from inverse beta decay (IBD)
Delay signal: ~0.5 MeV signal from neutron capture on \(^6\)Li

\[ \begin{align*}
\nu & \rightarrow \alpha \\
N & \rightarrow e \_Li \\
\gamma & \rightarrow \beta \_N \\
\tau & \rightarrow \nu
\end{align*} \]

Yale Test Cell

5” Cylinder, 2Liters of LiLS, double ended readout
Li-loaded Liquid Scintillator

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  - LAB and DIPN
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5" Cylinder, 2Liters of LiLS, double ended readout
2D PSD for IBD Identification

- Two dominant backgrounds at the low-overburden:
  - Reactor-related gammas (accidental coincidences)
  - Cosmogenic fast neutrons (real coincidences)

- *PSD on prompt and delayed signals rejects both types of backgrounds*

**PSD Signatures**

- Inverse Beta Decay
  - $\gamma$-like prompt, n-like delay
- Fast Neutron
  - n-like prompt, n-like delay
- Accidental Gammas
  - $\gamma$-like prompt, $\gamma$-like delay
2D PSD for IBD Identification

- Two dominant backgrounds at the low-overburden:
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  - Cosmogenic fast neutrons (real coincidences)
- \textit{PSD on prompt and delayed signals rejects both types of backgrounds}

\begin{itemize}
\item 5” cell in ambient background field
\item Applying cuts in energy and PSD
\end{itemize}
Projected PROSPECT Sensitivity

- **Phase 1**: Large near detector accumulates statistics rapidly, >1000 IBD/day
- **Phase 2**: Combined detectors cover significantly larger range of L/E
- "Prediction-free" analysis covers best fit in 1yr at 3σ

**Physics Goals**
- Search for sterile ν\text{e} oscillations at short-baseline
- Probe and resolve "reactor anomaly"
- Precision measurement of 235\text{U} ν\text{e} spectrum for physics and safeguards

**Deploy two segmented liquid scintillator detectors close to compact research reactor core**
- Near detector target: \(\approx 1\) ton
- Far detector target: \(\approx 10\) ton

**Challenges**
- Reactor background and limited overburden.
- Event-by-event background discrimination
- Relative segment normalization and calibration

**Mass Splitting**: 1.00 eV²
- Phase I @ HFIR, 1 year live-time, 3σ CL
- Phase II @ HFIR, 3 years live-time, 5σ CL
- Reactor Anomaly, 95% CL
- Disappearance Exps, 95% CL

**Baseline/Energy (m/MeV)**

**Projected PROSPECT Sensitivity**

- Heeger, et. al, arXiv:1307.2859
Summary

• The PROSPECT experiment is a two-phase antineutrino experiment designed to make precision measurements

  • *Search for short baseline oscillations as a sign of sterile neutrinos*

  • *Direct measurement of the $^{235}$U antineutrino spectrum*

• Backgrounds have been characterized and targeted shielding is being designed to minimize their impact

• *Novel Li-loaded scintillator is ready for large scale testing and is feasible for the full experiment*

• *Within one year of Phase 1 operation test the best fit value of the reactor/source anomaly*
PROSPECT Collaboration

58 collaborators
11 universities
5 national laboratories

reactor sites

Brookhaven National Laboratory
University of Chicago
Drexel University
Idaho National Laboratory
Illinois Institute of Technology
Lawrence Livermore National Laboratory
Le Moyne College
National Institute of Standards and Technology
Oak Ridge National Laboratory
Temple University
University of Tennessee
Virginia Tech University
University of Waterloo
University of Wisconsin
College of William and Mary
Yale University
Backup
PROSPECT Shielding Design

- **Layer 1:** Borated poly to reduce thermal neutron captures on high-Z material
- **Layer 2:** Lead to shield gamma rays
- **Layer 3:** Lithiated poly to shield muon-induced neutrons from Pb.
  - Limits neutron-capture gammas from $^{10}$B
- **Simulated reduction:** Gammas: $4\times10^{-3}$, Fission-neutrons: $2\times10^{-5}$
  - Currently being tested at NIST for the miniTimeCube* detector, where PROSPECT test cells will be operated and shielding models verified

* A Portable Directional Anti-Neutrino Detector being developed by U. Hawaii, U. Maryland, and the National Geospatial Intelligence Agency