PROSPECT: The Precision Reactor Oscillation and Spectrum Experiment

T.J. Langford
February 4, 2016
Neutrinos in the Standard Model

Pauli: “I have hit upon a desperate remedy to save...the law of conservation of energy.”

**Detection of the Free Neutrino: a Confirmation**

C. L. Cowan, Jr., F. Reines, F. B. Harrison, H. W. Kruse, A. D. McGuire

- Neutrinos were added to the SM to address the beta-decay “anomaly”
- Successfully detected 20 years later at the Savannah River Reactor
Neutrino Anomalies...

solar neutrino anomaly

atmospheric neutrino anomaly


… Lead to Discoveries

Super-Kamiokande 1998: solved atmospheric anomaly

\[ \nu_\mu \rightarrow \nu_\tau \text{ oscillation through the earth} \]

SNO 2001: solved solar anomaly

\[ \text{sum of all } \nu \text{ matched solar prediction} \]

“for the discovery of neutrino oscillations which shows that neutrinos have mass”
Neutrino Oscillations

Neutrinos undergo oscillations between flavor and mass states, implying they are massive (although very light) particles.

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= U
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

where

\[
U =
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\]

\[
= U_e \begin{pmatrix}
1 & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{-i\delta} & 0 & c_{13}
\end{pmatrix} U_{\nu} \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

where \( c_{ij} = \cos(\theta_{ij}) \)
\( s_{ij} = \sin(\theta_{ij}) \)
\( \delta = CP \) phase
Ex: Two Neutrino Oscillation

\[ P_{\alpha \to \beta, \alpha \neq \beta} = \sin^2(2\theta) \sin^2 \left( \frac{\Delta m^2 L}{4E_\nu} \right) \]

where \( \alpha, \beta = \nu_e, \nu_\mu, \nu_\tau \)

Parameters \( \theta \) (mixing angle - amplitude) and \( \Delta m^2 \) (mass splitting - frequency) are defined by nature. We can target specific \( \Delta m^2 \) measurements by designing our experiments to have a certain \( L/E \).
Outline

• Neutrinos in the Standard Model

• Reactor neutrinos and new anomalies

• **PROSPECT**: The Precision Reactor Oscillation and Spectrum Experiment

• Current efforts
Reactors: Tools for discovery

1950s: Reines and Cowan

1980s: Bugey

2000s: KamLAND

2010s: Daya Bay - $\theta_{13}$
Detecting Reactor Neutrinos

**Inverse Beta Decay**

- Loaded Organic scintillator surrounded by photomultiplier tubes
- Neutrinos interact with free protons
- Neutrino energy threshold of 1.8 MeV, producing signal of ~1MeV
- Capture resulting neutron as a tag of IBD interaction (typically Gd)
- Time-correlated signals, separated by ~10s μs

**Figure 6: Antineutrino detector.**

Uncertainty due to backgrounds. A Daya Bay AD has a ratio of GdLS target mass to total liquid mass of 26%, higher than similar experiments, such as Double Chooz or RENO. Radioactive background rates are reduced sufficiently to render systematics in accidental background subtraction negligible in the near/far oscillation analysis.

Reflectors above and below the OA V direct scintillation light towards the PMTs improving the energy resolution and uniformity. Mounted on the SSV lid are three automated calibration units (ACUs) which can position radioactive calibration sources or LED pulsers at different positions in the GdLS and LS volumes. The ACUs and liquid volumes are connected by calibration tubes. The central calibration tubes also connect the GdLS and LS volumes to concentric overflow tanks on the SSV lid. All gas spaces above the overflow tanks were continuously purged with dry nitrogen from a cover gas system. The eight ADs were built above ground in pairs and then moved below ground for filling. GdLS, LS, and MO were pumped simultaneously into an AD as needed while keeping the relative liquid levels within 10 cm of each other. The liquid levels were then topped up to fill the overflow tanks to about 1/3 capacity.

Although the nominal pair-wise production and assembly plan should have resulted in an orderly association of the first SSV with the first IA V and first OA V, this pattern and the orderly placement of ADs into the halls was quickly broken by practical schedule considerations. The first SSV needed extra work to obtain a suitably smooth finish in the O-ring grooves and was used in AD3. The second IA V pair hold-down tabs and calibration ports were mis-aligned, necessitating complimentary changes in the last pair of OA Vs. IA V3 was damaged during an annealing accident and was replaced by IA V9. To obtain the earliest physics data, it was decided to run with only 6 ADs spread over the three experimental halls. The AD naming scheme and major components of each AD are shown in Table 3.

Control of radioactive backgrounds was achieved by strict control of all materials used in the AD and of all procedures used during assembly and construction. Details for individual parts can be found in the related section.

**4.1. Stainless Steel Vessel**

The stainless steel vessels (SSV) are 5000 mm high, 5000 mm diameter cylinders with 12 mm thick low radioactivity stainless steel walls. The external walls are strengthened by 12 mm thick internal ribs. Each SSV (dry) weighs about 24 ton (with an inner volume of $\pi 95 \text{m}^3$). Figure 7 shows the structure of the barrel and lid. When loaded with the acrylic vessels, PMTs, and liquids, an AD weighs $\pi 112 \text{tons}$. Deformations and mechanical strength for the SSV vessel were thoroughly studied using Finite Element Analysis (FEA) code to insure that the design had the required safety factor when a filled SSV was picked up and lowered onto its support stands or when the lid was submerged under 2.5 m of the water. SSVs were constructed in pairs by the Guangdong Shanfeng Chemical Machinery Co. LTD. A SSV barrel was welded together from three subsections: a bottom section including bottom ribs, a top section with a top flange, and a middle barrel section.
Kilometer baseline $\theta_{13}$ precision experiments: Daya Bay, Double Chooz, RENO

Daya Bay antineutrino detectors

Daya Bay site

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

survival probability

detect inverse beta decay:
$$\text{anti-}\nu_e + p \rightarrow e^+ + n$$

Relative measurements reduce dependence on predictions of reactor properties
Reactor neutrino production

- Fission of parent isotopes yield neutron-rich daughters
  - Beta decays produce \( \sim 6\nu / \text{fission} \), <10MeV

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

- Power plants have low-enriched uranium (LEU) cores
  - Mixture of \( ^{235}\text{U}, ^{238}\text{U}, ^{239}\text{Pu}, ^{241}\text{Pu} \)
  - Research Reactors have highly-enriched cores only \( ^{235}\text{U} \)

- Decay Rate
- Spectrum
- Branching Fraction

Fission Daughters

Research Reactors

Power Reactor

1 meter

- ILL
- HFIR
- NBSR
- ATR

T.J. Langford - Yale University

2/4/16 - TUNL Seminar
Predicting Neutrino Flux/Spectra

Two main approaches:

- **Ab-initio**
  - Calculate individual beta-decay spectra for 1000s of isotopes from database info
  - Sum according to cumulative yields
  - **Problem:** databases have huge uncertainties

- **Beta-conversion**
  - Measure cumulative beta spectra from fission parents
  - Use virtual beta-branches to convert into neutrino spectra
  - **Problem:** can virtual branches capture all relevant physics?
Predicting Neutrino Flux/Spectra

- **Early 1980s**: Measurement of $^{235}$U spectrum at Institut Laue–Langevin (ILL)
  - Agrees with ab-initio calculations
  - <5000 neutrinos detected, 20% uncertainties
- **Mid 1980s**: Beta-conversion measurements at ILL, reduce systematics improve uncertainties or predictions
- **1990s**: Bugey PWR spectrum agrees with Beta-conversion spectra
- **1990-2000s**: Measured fluxes agree with predictions
Recent Events: Problems emerge

- **2011**: Two beta-conversion reanalyses increase predicted flux
  - One pure conversion, one hybrid between ab-initio and conversion
  - $3\sigma$ tension with previous experiments
- **Change in Flux/Spectrum**:
  - Conversion: +3%
  - Neutron lifetime: +1%
  - Non-equilibrium isotopes: +1%
- **Could be bias from non-blind analyses?**
Blind analysis of absolute flux agrees with old prediction

*Not a bias effect*
Sterile Neutrinos??

Best-fit 3+1

If not a bias effect, what is it?

- Problem with prediction?
- Detector effect that isn’t understood?
- New physics?

Sterile Neutrino:

- High frequency oscillation
- Mass splitting ~1eV^2
- Baseline ~few meters
Other Sterile Neutrino Hints

- **LSND**
  - decay at rest

- **MiniBooNE**
  - short baseline accelerator

- **GALLEX/SAGE**
  - Ga source calibration

- anti-$\nu_e$ appearance
- low energy $\nu_e$ appearance
- $\nu_e$ disappearance
Impact on Future Experiments

eV-scale neutrinos would impact:

- Expected neutrino spectrum for Long-baseline oscillation searches
- Mass ordering for Double Beta Decay searches

Needs to be addressed soon

Gandhi, Kayser, Masud, Prakash
arXiv:1508.06275
New Anomaly: Spectral Feature

- All three $\theta_{13}$ experiments have observed a spectral deviation between 4-6MeV prompt energy (5-7MeV neutrino energy)
- Predictions based on beta-conversion (Huber, Mueller, Haag)
- Tracks with reactor power, observed in both Near and Far detectors
- Cannot be explained by known detector effects
New Anomaly: Spectral Feature

- Beta-converted spectra could be wrong:
  - Use Allowed shapes for all decays, known to be incorrect
  - Error in the measurements?
  - Ab-initio calculation for one database seems to reproduce the feature
  - **Problem**: Large uncertainties and missing data
  - **Problem**: More complete database doesn’t reproduce the shape
  - **Feature seems to track with** $^{238}U$ content, could point to one fission parent as the problem?
Anomalies lead to Discoveries

- Flux deficit remains after blinded analysis
- No existing experiment is able to probe these questions
- We need new data
- Spectral anomaly could point were to look
  - All $\theta_{13}$ measurements at LEU power reactors
  - HEU measurement powerful crosscheck
The Precision Reactor Oscillation and Spectrum Experiment
Phased Experimental Plan

**Physics Goals:**
- Search for short baseline $\nu_e$ oscillations using detector segmentation
  - Distortions in energy spectrum that vary with baseline
  - Measure $^{235}$U antineutrino spectrum to illuminate the spectral anomaly

**Experimental Strategy:**
- **Phase 1:**
  - Sterile neutrino search, cover best fit region at $4\sigma$ in 1 year
  - World-leading $^{235}$U spectrum with 100k events/year
- **Phase 2:** World-leading short baseline sensitivity

**Challenges:**
- Minimal overburden, cosmogenic backgrounds
- Reactor-related backgrounds
  - High energy ($\approx 10$MeV) gammas
oscillations. For energies above the IBD threshold and baselines below 100 m, the approximated
that 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
and sin \( \theta_{12} \) as well as sin \( \theta_{13} \) value.

The reactor antineutrino anomaly could be explained through the existence of a fourth non-
oscillation, taking into account the new antineutrino spectra, the corrections of the neutron
oscillations. For simplicity the analysis presented here is restricted to the 3
standard neutrino mass states. The other possible explanation of the anomaly is based on a real physical e
contamination without oscillation, fitting the data, with sin \( \theta_{23} \) and sin \( \theta_{13} \). A reanalysis of the data of Ref. [481] was carried out in order
new value. It should be noted that the observed event rate is compatible with an oscillation pattern in their ratio of measured over predicted events.

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\[ \frac{N_{\text{obs}}}{N_{\text{pred}}} = \frac{1 + \varepsilon_{\text{systematic}}}{\sum_{\nu\text{-neutrino}} (1 + \varepsilon_{\text{systematic}})} \]

where \( \varepsilon_{\text{systematic}} \) represents the systematic uncertainty in the measurement, and \( \sum_{\nu\text{-neutrino}} \) is the sum over all neutrino types.

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Surface Neutrino Detection

Must be very close to research reactor
- Reactor-related backgrounds (gammas and thermal n)
- Detector will have to operate at the surface (or close to it)
- *Cosmic-rays are problematic*
Reactor Backgrounds

Targeted shielding effectively reduced gamma backgrounds
Cosmogenic Backgrounds

- `<10 MeV` neutrons are effectively shielded
- `>100 MeV` neutrons create showers of particles and many secondary neutrons
- IBD-like backgrounds stem mainly from fast neutron interactions
Three-pronged effort to address these backgrounds:

1. New detector design
2. New liquid scintillator
3. New shielding design
Segmented Antineutrino Detector

- 3ton lithium-loaded liquid scintillator ($^6$LiLS) detector
- 120 optical segments
  - 15x15x119cm$^3$, ~25 liters each
- Identify multiple particle interactions, reject showers
- Double-ended PMT readout
- Access for calibration sources between every cell

PROSPECT Antineutrino Detector Design

(a) The RAMF and AD in place at HFIR. (b) a cutaway diagram of the AD. (c) The unit cell

PROSPECT: A Precision Reactor Oscillation and Spectrum Experiment

PROSPECT Phase I detector

HFIR

Core

Shielding

Containment

Segments

LiLS

PMTs

$^6$LiLS

PROSPECT Unit Segment

PROSPECT Cells and Containment

PROSPECT Unit Segment

PROSPECT Antineutrino Detector (AD) and a Reactor Antineutrino Measurement Facility (RAMF). The RAMF plays an absolute comparison between data and simulation predictions that combine the effects of cosmic ray showers (muons and neutrons) with accidental neutron capture signature and targeted shielding applied to background "hot-spots" at HFIR.

To realize the aforementioned physics program, PROSPECT will construct and deploy an Anti-Neutrino Detector (AD) and a Reactor Antineutrino Measurement Facility (RAMF). The RAMF will provide general-purpose low-background space, movement capability, data acquisition, local computing and utilities required to perform scientific measurements and R&D at HFIR. When deployed in the RAMF, the AD will meet the performance requirements necessary to search for short baseline oscillations and complete the precision spectrum measurement and discussed above.

Both components can support a wide variety of activities at the conclusion of PROSPECT Phase I.

Figure 13

1. Access for calibration sources
2. Movable radioactive sources to calibrate cell energy response and timing. Cables, fibers, and array. A carefully selected subset of the support rods house either optical fibers or tubes contained in the full AD will suppress backgrounds substantially, achieving signal to background of ~15x15x119cm$^3$, ~25 liters each

3. Identifying multiple particle interactions, reject showers
4. Double-ended PMT readout
5. Access for calibration sources between every cell

These data have been used to validate the PROSPECT AD simulation. For example, Fig. 12b displays an absolute comparison between data and simulation predictions that combine the effects of cosmic ray showers (muons and neutrons) with accidental neutron capture signature and targeted shielding applied to background "hot-spots" at HFIR.

Comparison of IBD-like event energy spectra with the reactor on and off (Fig. 12a right) indicates that IBD-like rate in PROSPECT-20. Although the IBD-like time distribution of IBD-like events are in good agreement, with the results being consistent with fully explaining the observed IBD-like rate in PROSPECT-20.
IBD Detection with $^6\text{LiLS}$

Prompt signal: 1-10 MeV positron from inverse beta decay (IBD)

Delay signal: ~0.6 MeV signal from neutron capture on $^6\text{Li}$ with PSD signature

Pulse-shape Discrimination 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

Coincidence Signature of event:
e-like prompt signal, followed by a ~50$\mu$s delayed neutron capture

Coincidence + PSD allows rejection of vast majority of backgrounds
LiLS Requirements:

- High light yield (>6000ph/MeV) for energy resolution
- Excellent pulse-shape discrimination (PSD)
- Non-toxic, high flashpoint
- Stable and affordable

LiLS based on EJ-309 meets all requirements

- 8200ph/MeV, excellent PSD
- Safe to operate at a reactor

developed novel LiLS with excellent light yield, PSD, and neutron capture capabilities
Optimize space, weight, and total background suppression

- Main problem are ~100MeV neutrons
  - create majority of IBD-like backgrounds (gamma-like prompt, neutron capture)
- Neutron spallation on high-Z shielding increases backgrounds
  - Need neutron shielding inside lead shielding
Optimize space, weight, and total background suppression

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BG Rejection via Detector Design

Neutron coincident events

Event rate [mHz/MeV]

- n+H
- Neutrinos!
- 12C inelastic
- Shower veto
- Topology
- Fiducialization

Background reduction steps:
- Efficient PSD and neutron tagging
- Identification of multiple particle interactions
- Fiducialization

Active suppression of >3 orders of magnitude
PROSPECT Signal and Background

- Signal (dashed) and background (solid) prompt spectra are shown through selection cuts.
- $S/B$ better than 1:1 is predicted.
- Rate and shape of the residual IBD-like background can be measured with high precision during reactor off periods.

<table>
<thead>
<tr>
<th>Cuts</th>
<th>IBD signal</th>
<th>Cosmic BG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure</td>
<td>Daily</td>
<td>Phase I</td>
</tr>
<tr>
<td>PSD</td>
<td>1630</td>
<td>7.3e5</td>
</tr>
<tr>
<td>Time (1, 2, 3)</td>
<td>1570</td>
<td>7.1e5</td>
</tr>
<tr>
<td>Spatial (4, 5)</td>
<td>1440</td>
<td>6.5e5</td>
</tr>
<tr>
<td>Fiducial (6)</td>
<td>660</td>
<td>3.0e5</td>
</tr>
</tbody>
</table>

Simulated event rates $(0.8 \leq E \leq 7.2$ MeV) after applying background rejection cuts.
Short Baseline Oscillation Search

**Sensitivity:**
- Phase I (1 yr) at 3σ
- Phase I (3 yr) at 3σ
- Phase I + II (3+3 yr) at 3σ
- Phase I + II (3+3 yr) at 5σ
- SBL Anomaly (Kopp), 95% CL
- All νe Disappearance Experiments (Kopp), 95% CL
- SBL + Gallium Anomaly (LSN), 95% CL
- Daya Bay Exclusion, 95% CL

**Best Fit Oscillation**

- Mass Splitting: 1.78 eV²; Osc. Amplitude: 0.09

**Figure 8.**
- (Left) PROSPECT Phase I and Phase II sensitivities to a single sterile neutrino flavor. Phase I probes the best-fit point at 4σ after 1 year of data taking and has >3σ reach of the favored parameter space after 3 years. The combined reach of Phase I+II after 3+3 years of data taking yields a 5σ coverage over the majority of the parameter space below $Dm_{14}^{2} \approx 10 \text{ eV}^2$.
- Daya Bay exclusion curve is from [68].
- (Right) Increase in oscillation sensitivity to sterile neutrinos during Phase I by operating AD-I at two positions instead of at the front or middle position only.

**PROSPECT oscillation sensitivity** is determined using a $c^2_{min}$ minimization [70]. Systematic uncertainties are included by minimizing over nuisance parameters in addition to the new oscillation parameters ($Dm_{14}^{2}$, $sin^2 2\theta_{14}$). We take a conservative approach by allowing uncertainties for these parameters to vary broadly with little near and far detector relative normalization does in the recent $q_{13}$ experiments. Furthermore, as AD-I is moved, the relative contribution of each segment to a particular $L/E$ bin varies, reducing the effect of both correlated and uncorrelated systematic biases more efficiently than a single extended detector.

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- Segmented detector designed for oscillation search
  - Each cell is a separate “detector”
  - Oscillatory $L/E$ between segments limits uncertainties from reactor
  - **True oscillometry needed for confirmation of sterile neutrinos**
  - Probe best-fit region at >3σ in 1 year
A Movable Detector

Sensitivity: Phase I for 1 year at 3σ
- Front Position
- Movable Position
- Middle Position
- SBL Anomaly (Kopp), 95% CL
- All νe Disappearance Experiments (Kopp), 95% CL
- SBL + Gallium Anomaly (LSN), 95% CL

• AD-1 is designed to translate by 1m, almost half the detector length
• Improves the sensitivity from <3σ to greater than 4σ
• Provides powerful systematics check
• ~700 inverse beta decays detected per day, 100k/year (30x ILL rate)
• Best energy resolution of any reactor neutrino experiment (4.5%@1MeV)

**Phase-1 precision will surpass spectral model uncertainties**

• Directly test reactor neutrino models
• Produce a benchmark spectrum for future reactor experiments
**Phased Detector Development**

**PROSPECT-0.1**  
Aug 2014  
Spring 2015  
- 5cm  
- 0.1 liter LS cell

**PROSPECT-2**  
Dec 2014  
Feb 2015  
- 12.5cm  
- 1.7 liter LS cell

**PROSPECT-20**  
March 2015  
- 1m  
- 23 liter LS cell

**PROSPECT-50**  
February 2016  
- 1.2m  
- 2x25 liter LS segments

**PROSPECT-625**  
Early 2016*  
- 1.19m long  
- 25x25 liter LS segments

*technically driven schedule

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**PROSPECT**  
Phase I  
Late 2016*

**PROSPECT Phase I**  
- 120x30 liter LS segments  
- 15x15x119cm

*technically driven schedule

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**PROSPECT: A Precision Reactor Oscillation and Spectrum Experiment**

DE-FOA-0001381 to reactor-produced $^6\text{Li}$-rays following this selection are minimal due to the selectivity of the $^6\text{Li}$ neutron capture signature and targeted shielding applied to background “hot-spots” at HFIR.

Comparison of IBD-like event energy spectra with the reactor on and off (Fig. 12a right) indicates that IBD-like backgrounds are cosmogenic and that reactor generated backgrounds are negligible.

These data have been used to validate the PROSPECT AD simulation. For example, Fig. 12b displays an absolute comparison between data and simulation predictions that combine the effects of cosmic ray showers (muons and neutrons) with accidental $^8\text{Be}$-ray coincidences. Both the energy and time distributions of IBD-like events are in good agreement, with the results being consistent with fully explaining the observed IBD-like rate in PROSPECT-20. Although the IBD-like background rate is higher than the expected $\nu_e$ interaction rate, improved shielding and cuts possible in the full AD will suppress backgrounds substantially, achieving signal to background of 1.

**Experimental Realization**

To realize the aforementioned physics program, PROSPECT will construct and deploy an Antineutrino Detector (AD) and a Reactor Antineutrino Measurement Facility (RAMF). The RAMF will provide general-purpose low-background space, movement capability, data acquisition, local computing and utilities required to perform scientific measurements and R&D at HFIR. When deployed in the RAMF, the AD will meet the performance requirements necessary to search for short baseline oscillations and complete the precision spectrum measurement and discussed above. Both components can support a wide variety of activities at the conclusion of PROSPECT Phase I.

2.4.1 PROSPECT Antineutrino Detector Design

![Antineutrino Detector Diagram](image)

**Figure 13**: (a) The RAMF and AD in place at HFIR. (b) A cutaway diagram of the AD. (c) The unit cell structure. (d) Inner and outer dimensions of the AD.

The PROSPECT antineutrino detector (AD) will consist of a segmented array of $^6\text{Li}$-loaded liquid scintillator (LiLS) filled cells. Low-mass high-reflectivity optical separators divide the total active volume ($\ll 3000$ l) into 120 individual cells (Fig. 13) providing baseline and event topology information independent of light transport and timing. Each cell shares optical separators and hollow support rods with its nearest neighbors and is readout at both ends by PMTs. Constraints on light-collection uniformity determine cell length and cell cross-section is constrained by the physical dimensions of the PMT assembly. To maintain LiLS compatibility, the PMT and divider are housed inside a polycarbonate module with a light guide for optical coupling. Modules are bolted together (10 high by 12 long) to form a support structure for the optical separator array. A carefully selected subset of the support rods house either optical fibers or tubes containing movable radioactive sources to calibrate cell energy response and timing. Cables, fibers, and...
Full-scale Test Detector

- **PROSPECT-20**
  - 23L test cell of 6Li-loaded Liquid Scintillator
  - 15x15x100 cm$^3$ detector
  - Measured Light collection: 530PE/MeV
  - 4.5%@1 MeV energy resolution
  - Measured PSD Figure of Merit: 1.4 at (n,Li) capture
  - >99.9% background rejection
  - Double-ended readout
    - uniform light collection and position reconstruction

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PROSPECT Unit Segment

PROSPECT-20 Paper arXiv:1508.06575
PROSPECT-20 at HFIR

- Operated for four months at HFIR
  - Two HFIR cycles
- Shielding package roughly 25% mass of full shield
- Reactor-related backgrounds mitigated
  - Targeted local shielding
  - Active background rejection with LiLS
- Validation of background simulations for full PROSPECT detector

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**IBD-like Events**

- Reactor On
- Reactor Off

**Energy (MeV)**

**Counts/MeV/s**

**Data Simulation**

**Rate (mHz/µs)**

**Time Separation (µs)**

- $2 \times 10^{-1}$
- $10^{-2}$
- $10^{-3}$
PROSPECT-50 Demonstrator

PROSPECT-50:
- 50 liters of $^6\text{LiLS}$
- Two PROSPECT segments

Test platform of each subsystem
- Thin-walled reflector panels
- PMT enclosures
- Filling system and procedure
- Calibration system
  - LED optical
  - Source capsules
- Cell-to-cell variation

Calibration Tube

83”
PROSPECT-50 Demonstrator

Acrylic tank arrived at Yale

Calibration Tube

PROSPECT-50:
• 50 liters of 6LiLS
• Two optical segments
• Test platform of each subsystem
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Ongoing: PROSPECT-50
• Mechanical prototype to validate detector components and test operation of subsystems.
  – PMT housing with light guide
  – Reflectors
  – Calibration
  – LS filling

12/16/15
Ke Han, Yale University

Acrylic tank arrived at Yale
Low-mass optical separators

Compatibility:
• extensive material compatibility testing required to ensure long-term LS performance
• focus on materials proven in recent experiments - PTFE, acrylic, polypropylene, …
• long-term mechanical stability verified

Separators:
• physics goals demand low inactive mass, high reflectivity, and long-term compatibility
• developed multi-layer system meeting all requirements
• fabrication procedures for full-scale system under validation

produced robust low-mass separators from LS-compatible materials
Calibration Techniques

**pulsed laser sources**
- LiLS light transmission
- PMT gain and timing

**encapsulated γ sources**
- energy scale
- scintillator non-linearity

**neutron sources**
- PSD calibration
- neutron detection efficiency

**radioactive and cosmogenic backgrounds** will be used to monitor and calibrate detector response between source deployments

*Example: PROSPECT-20*
- through going muons
  - $^{40}$K
- $n$ capture on $^6$Li

**R&D on scintillator spiking** with $^{227}$Ac
- segment uniformity, relative LiLS mass measurements
Summary and Outlook

• Neutrino anomalies have lead to discoveries

• The reactor flux and shape anomalies offer a window to new physics

• PROSPECT will cover the sterile neutrino best fit region at $3\sigma$ within its first calendar year

• PROSPECT will measure the $^{235}\text{U}$ spectrum with the highest precision to-date

• Key design goals have been demonstrated and technical implementation is underway
Pulse Shape Discrimination


\[ PSD = \frac{Q_{\text{tail}}}{Q_{\text{full}}} \]

energy+PSD cuts for prompt and delay signals

PROSPECT-2 (LiLS)

particle classification: light particles = “gamma-like”, heavy charged = “neutron-like”
Baselines Probe Different Parameters

- Rich reactor Neutrino program at different baselines

From: Vogel, Wen, Zhang

[Graph showing flavor fraction versus distance]
Predicting Neutrino Flux/Spectra

Two main approaches:

- **Ab-initio**
  - Calculate individual beta-decay spectra for 1000s of isotopes from database info
  - Sum according to cumulative yields
  - Problem: databases have huge uncertainties

- **Beta-conversion**
  - Measure cumulative beta spectra from fission parents
  - Use virtual beta-branches to convert into neutrino spectra
  - Problem: can virtual branches capture all relevant physics?

• Devised in 50's, each method has lost and gained favor over the years

Example: 144Ce Decay

• Very complicated!
ILL $^{235}$U Spectrum Measurement

- **1981**: Only published measurement of $^{235}$U spectrum at ILL reactor in France
- ±20% uncertainties, unable to constrain reactor models
- Fewer than 5000 neutrino events detected