Energy Scale Calibration in PROSPECT

June 1, 2018

Bryce Littlejohn
Illinois Institute of Technology
on behalf of the PROSPECT collaboration
PROSPECT Overview

• Short-baseline reactor antineutrino experiment
• Recently installed at High Flux Isotope Reactor (HFIR) at Oak Ridge National Lab (ORNL) in Tennessee, USA
• On-surface: minimal overburden
• Aims:
  • Search for eV-scale sterile oscillations
  • Measure the $^{235}$U antineutrino spectrum
Why HFIR?

- 85 MW HEU reactor: >99% $^{235}\text{U}$ fissions
- Compact core: 50cm tall, 42cm wide
- Position available near the core (7 - 12 m)
- Short reactor cycles (~25d)
- >50% reactor off-time for background measurements
- As a user facility, detailed core model is available
Experimental Design

- Segmented design
  - Single 4-ton scintillator volume
  - Optical subdivided into 154 (11x14) isolated segments
  - Segment read out by PMTs on each end
- Target spans ~2m of baseline
- Pulse-shape discriminating (PSD) scintillator, 0.1% $^6$Li by weight
  - non-flammable, non-toxic
  - doped with trace $^{227}$Ac for calibration
- Full PMT waveform readout
- Entire assembly built on moveable air caster platform
AD Tour: Li-Doped Scintillator

- Li-doped LS provides unique signature for antineutrino detection
  - Inverse beta decay (IBD) on p in scintillator
  - IBD neutrons capture on \(^6\)Li
  - Specific PSD signature from correlated prompt/delayed signals
- LiLS developed by PROSPECT
  - Based on Eljen EJ-309
  - \(^6\)Li dissolved in water, surfactant enables stable water/LS mix
  - QA/QC, compatibility tests performed at many PROSPECT institutions

\[
\begin{align*}
Q(n, ^6\text{Li}) &= 4.78 \text{ MeV} \\
E_{\nu e} &\propto E_{\nu} \\
t_{\text{cap}} &\approx 40 \mu\text{s} \\
n_H &\approx 80\% \text{ of captures}
\end{align*}
\]
**AD Tour: Target Segmentation System**

- Optical panels direct light to PMTs at either cell end
  - Total internal reflection from teflon casing
  - Specular reflection from 3M DF2000M foils
  - Fabrication completed at IIT in mid-2017
  - QA/QC done in parallel

*Production QA: Panel thickness*

<table>
<thead>
<tr>
<th>hDimension</th>
<th>Entries</th>
<th>Mean</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4213</td>
<td>46.19</td>
<td>1.2</td>
</tr>
</tbody>
</table>

*Optical Separator Fabrication*

*Production segmentation system reflector panel*
AD Tour: Support Rod Components

- Pinwheel rods support optical separators, PMT housings while defining dry calibration axes

- Mass-produced via 3D-printing of ABS plastic extensive QA

Production QA: pinwheel arm thickness

3D-Printing precision: +/- ~0.003”
AD Tour: PMT Housings

- Housings separate LiLS-incompatible PMTs from scintillator, provide standard building blocks for assembly of AD target

- Intensive QA procedures
  - Leak checking, PMT testing, and dimensional checks
AD Tour: Detector Shielding

• Considerations
  • At surface: cosmic backgrounds. cosmic neutrons in particular.
  • At reactor: gamma backgrounds!

• Shielding design
  • Outside: hydrogenous shielding for cosmic, reactor neutron flux
  • Middle: lead for shielding gammas
  • Inner: hydrogenous borated material to shield neutron interactions in lead
  • Can also use outer layer of cells to fiducialize
AD Tour: Detector Shielding

- Borated PE shielding under target
- Outer PE layer (in purple)
- Target package with partial lead shielding
- Same, with fully outer shielding package
AD Tour: Readout

- CAEN 14-bit, 250 MHz fast waveform digitizers
- Zero-suppressed triggering: read out ALL channels above X ADC when ANY segment's channels are above Y ADC.
- 148 total samples per channel readout: ~0.6 us window

Imagine reading out the first 148 samples of these waveforms...

Clearly well-suited for PSD scintillator!

PROSPECT, arXiv:1805.09245
Development Timeline

PROSPECT-0.1
Characterize LS
Aug 2014-Spring 2015

NIM A 806 401 (2016)

PROSPECT-2
Background studies
Dec 2014 - Aug 2015

NIM A 806 401 (2016)

PROSPECT-20
Segment characterization
Scintillator studies
Background studies
Spring/Summer 2015

JINST 10 P11004 (2015)

PROSPECT-50
Baseline design prototype
Spring 2016

arXiv:1805.09245

PROSPECT AD
2017

5cm length 0.1 liters LS, $^6$LiLS

multi-layer shielding

12.5 length 1.7 liters $^6$LiLS

local reactor shielding

1m length 23 liters LS, $^6$LiLS

1x2 segments 1.2m length 50 liters $^6$LiLS

11x14 segments 1.2m length ~4 tons $^6$LiLS
Recent Development Example: P50

- Demonstrated detector performance in full 2-cell prototype
- >800 PE/MeV: ~4%/√E photo-statistics resolution
- 85cm cell attenuation length
- Excellent PSD (FOM=1.5)
- Can reconstruct positions along a cell length using time and charge information
First assembled layer complete!
Detector Assembly

https://prospect.yale.edu/media
Lifting, Transport, Filling

- Lifting inner detector into aluminum tank
- Loading detector on truck for trip to HFIR
- Mixing tank and scintillator barrels at Oak Ridge
Installation at HFIR

 Fully installed AD

 Fully installed AD Racks
PROSPECT Is Now Operational

- Detector installed and filled with scintillator in mid-February
- Followed by period of commissioning
- Background data and partial commissioning during March-April
- We are now in neutrino data-taking mode.

https://news.yale.edu/2018/05/18/prospecting-antineutrinos
SBL Reactor Experiment Requirements

- Primary requirements to meet PROSPECT physics goals:
  - Spectrum measurement:
    - HEU reactor: enables comparison to existing LEU measurements
    - Energy resolution: enables elucidation of features in specific energy ranges
    - Well-understood absolute response: ultimate limiter of measurement precision
  - Sterile neutrino search:
    - Multiple baselines: required for a sterile search independent of the exact underlying spectrum shape.
    - Well-understood relative response: enables relation of any baseline-to-baseline signal variations directly to short-baseline oscillations
- Meet requirements while also rejecting copious backgrounds
SBL Reactor Experiment Requirements

• Primary requirements to meet PROSPECT physics goals:

• Spectrum measurement:
  • HEU reactor: enables comparison to existing LEU measurements
  • Energy resolution: enables elucidation of features in specific energy ranges
  • Well-understood absolute response: ultimate limiter of measurement precision

• Sterile neutrino search:
  • Multiple baselines: required for a sterile search independent of the exact underlying spectrum shape.
  • Well-understood relative response: enables relation of any baseline-to-baseline signal variations directly to short-baseline oscillations

• Meet requirements while also rejecting copious backgrounds
Calibration Principles

• Strategy to achieve well-understood energy response:

\[ E_{\text{rec}}(z_{\text{rec}}, t, s) = A_{\text{ADC-MeV}} \times B(s, z_{\text{rec}}) \times C(t) \times D(E_t) \]

• A: ADC-MeV conversion constant
• B: Equalize energy for point-like depositions in all detector positions
• C: Stabilize energies over time
• D: Properly characterize non-linearity and energy loss

• Other calibration needs:
  • Calibrate out global timing offsets between PMT channels
  • Establish time/segment-stable PSD cuts and \( z_{\text{rec}} \)
  • Ensure stability in signal rate normalization between all segments

• Calibration menu options:
  • User-controlled optical and radioactive calibration sources throughout detector
  • Ambient cosmogenic and radioactive backgrounds
Menu Options: Calibration System

- Pitch in optical lattice allows access for calibration system
- Utilize these axes for optical and radioactive calibration
- Both deployed through teflon tubes in support rods
  - Stationary optical sources
  - Retractable radioactive sources
    - Deploy in many z-positions
    - Swap sources between axes
    - Deploy different gamma sources for extensive energy scale calibration

Optical Lattice with Calibration Channels

PROSPECT Unit Segment

½” ID Calibration Channel
Menu Options: Calibration System

- Radioactive Calibration Boxes
- In-axis optical calibration components
- Exchangeable radioactive source
- Optical system pulser and splitter
- Source drive motor inside box
• A wide variety of intrinsic background peaks also available for calibration purposes

• Intrinsic radioactivity:
  • $^{219}$Rn - $^{215}$Po ($\alpha,\alpha$) chain from $^{227}$Ac doping
  • Bi - Po ($\beta,\alpha$) chain from detector U-Th
  • Radioactive singles: $^{40}$K, $^{208}$Tl, reactor n-captures on nearby materials

• Cosmic-induced sources:
  • Cosmogenic n-produced isotopes, like $^{12}$B
  • Cosmogenic n captures
  • Muons
Calibration Principles

- **Strategy to achieve well-understood energy response:**

  \[ E_{\text{rec}}(z_{\text{rec}}, t, s) = A_{\text{ADC-MeV}} \times B(s, z_{\text{rec}}) \times C(t) \times D(E_t) \]

- **A**: ADC-MeV conversion constant
- **B**: Equalize energy for point-like depositions in all detector positions
- **C**: Stabilize energies over time
- **D**: Properly characterize non-linearity and energy loss

- **Now let’s take a look through each of these steps**
Timing Calibration

- First step: equalize timing among all PMTs: sub-ns precision
  - Required for absolute z-positions, z-dependent energy scale corrections
  - Within a cell: optical flasher
  - Within+between cells: cosmic muons

![Relative Timing Offsets](image)

**Preliminary AD data**
A: PE-MeV Conversion

- Convert from ADC to MeV using cosmic n-\(^6\)Li capture
  - High sample rates and purity, ubiquitous throughout detector
- Note: currently not implementing single-PE calibration
  - Have checked single-PE scale with occasional high-gain runs

PROSPECT-50 Data

PROSPECT, arXiv:1805.09245
**B: Uniformity Versus Position**

- Reconstruct z-positions using relative timing/charge information from a segment’s PMTs: sub-10cm resolution.
- Done using internal calibration source z-scans and internal geometric features.
- Clean nLi peak used for equalizing energy scale at all positions.
- Example: Bi-Po decays from detector-intrinsic $^{238}$U, $^{232}$Th.

![Graph showing Po energy mean vs cell number](image)

**Preliminary AD data**

![Radioactive decay chain diagram](image)
C: Uniformity in Time

- Clean nLi peak used for stabilizing reconstruction over time
- Need checks from other peaks: many available in ambient bkgds.
- Example: Bi-Po decay chain

\[ (^{214}\text{Bi} \rightarrow ^{214}\text{Po} \rightarrow ^{208}\text{Pb}) \alpha \text{ Mean Energy vs Time} \]
D: Energy Scale Calibration

- **Non-linearity determination:** fit of MC to data while varying MC non-linearity parameters
  - Gamma calibration sources in center
  - Cosmogenic n-produced $^{12}$B
  - Can fit spectra for single segments or all combined.

- **Energy loss validation:** data-MC comparison of energy loss vs segment, z
  - $^{22}$Na is ideal: contains annihilation gammas, like IBD prompt signal

---

**Source** | **Decay [keV]**
--- | ---
$^{22}$Na | $e^+ \rightarrow 511\gamma, 1274\gamma$
$^{60}$Co | $1173\gamma, 1332\gamma$
$^{137}$Cs | $662\gamma$
$^{252}$Cf | Spontaneous fission $\rightarrow n$

---

**Preliminary AD data**

$E_{rec}$ from center-deployed Cs-137 gamma source
Summary

• PROSPECT is now installed at HFIR and is in data-taking mode
• Many sources are available to produce an energy scale that is well-defined and stable in position and energy
• Have demonstrated excellent position- and time-stability in $E_{\text{rec}}$
• Stay tuned for more data!

http://prospect.yale.edu/

Funding:
Thanks!
More LS Characterization

- Light Yield ~25% below EJ309
- LiLS shows 15% drop in light yield; consistent with O$_2$ quench; 10% increase after N$_2$-bubbling a sample
- Attn. length comparatively stable
- Produced LiLS in 28 batches; QA done on all batches; nearly all passed all QA checks.
Actinium Doping

- Relative cell volumes determined by coincident alpha decays in Ac-227 decay chain (Po-215: $T_{1/2} \sim 1.8$ ms)
- Dissolved 0.5 Bq of Ac-227 in detector active volume
- Well separated from background with PSD, energy, and timing cuts
- Efficiency corrected “RnPo” rates proportional to volume
Backgrounds and Expected Rates

- MC benchmarked by detector prototype data from HFIR site
- cosmogenic backgrounds (solid) and signal (dashed) per cut selection
**Physics Motivations**

**Reactor anti-neutrino anomaly**

- New flux predictions (2011) leads to 6% flux deficit for reactor neutrino experiments
- Possible explanations:
  - \(\sim\)eV scale sterile neutrino
  - flux calculations and/or inputs deficient

**The 5-7 MeV “bump”**

- \(\theta_{13}\) experiments (Daya Bay, Reno, Double Chooz) all see excess events in 5-7 MeV neutrino energy
- Precise U-235 spectrum helpful for determining source(s) of discrepancy
Example: Only $^{239}$Pu, or Only $^{235}$U?

- HEU reactors burn only $^{235}$U
  - What will the data:model comparison from 4-6 MeV look like from HEU?
    - No bump = bump mainly from U235
    - Larger bump = bump mainly from Pu239
    - Same bump = something else is responsible…
  - Upcoming SBL reactor experiments are crucial
    - PROSPECT: HFIR reactor
    - STEREO: ILL reactor
    - Solid: BR2 reactor
  - Good reason to believe these experiments, combined with $\theta_{13}$ experiments, can produce meaningful new constraints.

Future: New HEU Measurements

- Would be great to probe a wider range of fission fractions

- How about 100% U235, instead of ~50-60%?
  - If $^{235}$U is to blame, antineutrino flux deficit should be even larger here

- Enter PROSPECT: at highly-enriched $^{235}$U HFIR reactor in Oak Ridge, Tennessee