Safeguards - a Passive Standoff Capability
Provides a remote, non-intrusive reactor to observe the sterile neutrinos. To investigate this tantalizing possibility, there exists an additional neutrino anomaly from the theoretical side.

Spectral Shape as a Function of Energy and Baseline
Possibility of sterile neutrino oscillation as an explanation of observed electron antineutrino deficits

Precision Measurement of Reactor Spectrum
Anomalies in spectral shape at ~ 5-6 MeV
Provide complementary measurement of $^{235}$U (fuel evolution)

Flux Deficit

Spectral Anomaly

Isotopic Evolution

Reactor Monitoring

Detected candidates per day

Predicted rate
Reported power
Observed rate, 30 day average

Fuel Cycle $n$
Refueling Outage
Fuel Cycle $n+1$

Detector Response

Local discrepancy:

Previous data
Daya Bay
World Average

Error is experimental only.

Daya Reactor Flux Evolution

National Institute of Standards and Technology

Daya Bay, PRL 118 251801 (2017)

P. Mumm for the PROSPECT Collaboration

AAP, LLNL, 2018
Experimental Strategy

1. Search for short-baseline sterile-neutrino oscillations independent of reactor models
2. Measure antineutrino spectrum due to $^{235}$U
3. Demonstrate near-field surface operation

Experimental Strategy:
- Compact HEU research reactor
- $^6$Li-doped liquid scintillator provides unique compact tag and light yield
- Segmented detector localizes events and supports background rejection
- Measure high-resolution spectrum at a range of baselines (7-9m in current position)
- Search for characteristic relative spectral distortions within detector volume
High Flux Isotope Reactor (HFIR) and ORNL

- 85MW highly enriched uranium reactor
  - >99\% \(^{235}\)U fissions, effectively no isotopic evolution
- Compact core (44cm diameter, 51cm tall)
- Short baselines of order meters
- 24 day cycles, 46\% reactor up time
  - Allows equal stats for detailed study of cosmogenic backgrounds
- User facility 24/7 access

![PROSPECT-20 shield](image)

**Detailed model of power density**
Ambient Backgrounds

Electron-like event rate in detector

- Shortest baselines at HFIR imply in-building operation
  - high time-dependent gamma rates (in some locations approaching 5 mrem/hr)
  - time and spatially varying thermal neutron fields
  - only facility overburden concrete roof (<1 mwe), atmospheric neutron interactions highly significant
- Design for background rejection
Design Overview

- Single 4,000 L $^6$Li-loaded liquid scintillator (3,000 L fiducial volume)

- 11 x 14 (154) array of optically separated segments

- Very low mass separators (1.5 mm thick)
  - Corner support rods allow for full in situ calibration access

- Double ended PMT readout, with light concentrators
  - good light collection and energy response ~4.5-5% $\sqrt{E}$ energy resolution
  - full X,Y,Z event reconstruction

- Optimized shielding to reduce cosmogenic and local backgrounds
6Li Loaded Liquid Scintillator

- Compact, segmented detector needs a capture signal that is highly localized
  - Minimize position dependent efficiency variation
  - Distance between prompt/delay to reject accidental backgrounds

- R&D program led to 0.07% 6LiLS loaded liquid scintillator based on EJ-309, meets all requirements.
  - Capture time long compared to scattering physics, short compared to accidental rate.
  - High light yield (8200ph/MeV) for energy resolution
  - Particle ID through pulse-shape discrimination (PSD)
  - Long term stability, material compatibility, nonflammable

6Li loading via Reverse micelles:
- Surfactants added to base liquid scintillator
- Dynamically stable
- Relatively high loading possible > 0.1%
- Minimal reduction in light yield
- Minimal reduction of PSD performance

Event topology:
\[ \beta^+ + \nu_e + p \rightarrow \beta^+ + n \]
Unique IBD Signature

Event Coincidence Signature: e-like prompt signal, followed by a \( \sim 40-50\mu s \) delayed neutron capture

- Coincidence + PSD to reject backgrounds

Pulse-shape Discrimination (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
Background Rejection

- Detector design further optimized for background rejection
- A sequence of cuts leveraging spatial and timing characteristics of an IBD yields $> 10^4$ background suppression and signal to background of $> 1:1$.
- Rate and shape of residual IBD-like background can be measured during multiple interlaced reactor-off periods.

See M. Mendenhall’s talk later this workshop
Correlation between cosmogenic backgrounds and atmospheric pressure:
- Fast Neutron
- Fast Neutron + nLi,
- Inelastic recoil + nLi,
- Correlated captures
- IBD-like (passes all cuts)

Measure correlation during reactor off time, use it to correct average background subtraction during reactor on (typical scaling < 0.5%)

Opportunity to study surface background in detail
PROSPECT: a Precision Oscillation and Spectrum Experiment

November 1st, 2017
November 17th, 2017

PROSPECT: a Precision Oscillation and Spectrum Experiment
December 2017 - January 2018, Dry commissioning at Yale
PROSPECT: a Precision Oscillation and Spectrum Experiment

February 2018, arrival at ORNL

Liquid scintillator was stored at BNL in 28 (55-gallon) drums. A temperature controlled truck was used to transport the scintillator to Oak Ridge Nat. Lab.

ISO tank Filling

Mix all 6LiLS drums into one tank

Antineutrino Detector filling

February 2018, arrival at ORNL

Moving into position at HFIR

Batches mixes and sparged

FIRST MUON TRACK
Liquid scintillator was stored at BNL in 28 (55-gallon) drums. A temperature-controlled truck was used to transport the scintillator to Oak Ridge Nat. Lab. ISO tank Filling: mix all 6LiLS drums into one tank. Antineutrino Detector filling: February 2018, arrival at ORNL. Moving into position at HFIR: Batches mixes and sparged: 6/5/18, 9:57 PM.
Liquid scintillator was stored at BNL in 28 (55-gallon) drums. A temperature controlled truck was used to transport the scintillator to Oak Ridge Nat. Lab.

ISO tank filling
mix all 6LiLS
 drums into one
tank

February 2018, arrival at ORNL

Batches mixed and sparged

Moving into position at HFIR

IBD CANDIDATE

February 2018, arrival at ORNL

Batches mixed and sparged

Moving into position at HFIR
Performance: Pulse Shape Discrimination

- Excellent discrimination of gamma interactions, and nuclear recoils
- Well separated $^6$Li-n capture peak
- As dominant backgrounds are cosmogenic fast neutrons, reactor-related gamma rays, and reactor thermal neutrons:
  - Vast majority identified and rejected by PSD for Prompt and Delayed signals
Detector Uniformity and Stability

• **Calibration Source Deployment:**
  - 35 calibration source tubes throughout detector to map energy response
  - Segment to segment uniformity ~1%
  - $^{252}$Cf source to study neutron capture efficiency

• **Intrinsic radioactive sources**
  - Track uniformity over time with distributed internal single-segment sources:
  - Alpha lines from $^{212}$Bi→$^{212}$Po→$^{208}$Pb decays, nLi capture peak
  - Reconstructed energy stability over time < 1%
Energy Reconstruction

- Sources deployed throughout detector, measure single segment response
- Full-detector $E_{\text{rec}}$ within 1% of $E_{\text{true}}$

Resolution vs Energy

- Fast-neutron tagged $^{12}\text{B}$
  - High-energy beta spectrum calibration
- High light collection: $795\pm15$ PE/MeV

![Calibration Spectra](image1.png)

![Resolution vs Energy](image2.png)
Relative target mass needed for oscillation search

- \( ^{227}Ac \) added to LS prior to filling
- Double alpha decay \((^{219}Rn \rightarrow ^{215}Po \rightarrow ^{211}Pb)\), highly localized, easy to ID, 1.78ms lifetime
- Measured absolute z-position resolution of < 5cm
- Direct measurement of relative target mass in each segment
Began operations March 5, 2018

First 24 hours of operation:

- Reactor On: $1254 \pm 30$ correlated events between $[0.8, 7.2 \text{MeV}]$
- Reactor Off: $614 \pm 20$ correlated events (first off day March 16)
- Time to $5\sigma$ detection at earth’s surface: $< 2 \text{hrs}$

Working on analysis of $^{235}\text{U}$ antineutrino spectrum with current dataset, significant increase in statistics
Results From First Data Set

- 33 days of Reactor On
- 28 days of Reactor Off
- IBD event selection defined and frozen on 3 days of data
- 24,608 IBDs detected
- Average of ~750 IBDs/day
- Correlated S/B = 1.36
- Accidental S/B = 2.25

Excellent signal-to-background for a surface detector (< 1mwe overburden)
Results From First Data Set

- 108 fiducial segments binned into 14 baselines
  - Wide range of baselines accessible within detector
- Observed change in flux follows $1/r^2$

![Graph showing IBD counts vs baseline](image)
Results From First Data Set

- Compare measured energy spectrum for 6 baselines to the scaled full-detector no-oscillation energy spectrum
- Null oscillation yields a flat spectrum

![Illustrative Oscillation](image)

![Prompt Energy Distribution](image)
Results From First Data Set

Reactor model independent test of reactor antineutrino anomaly

- 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% exclusion curve based on 33 days Reactor On operation

RAA best-fit disfavored at >95% (2.2$\sigma$)
Comparison to Neutrino-4

![Graph showing comparison to Neutrino-4](image)
Conclusions and Outlook

- PROSPECT running since March 2018 and is performing well
- Demonstrates technical approach
  - scalable/modular (to a degree)

- Very good signal-to-background at the surface (< 1 mwe), consistent with MC/R&D-based expectations
  - Observed HEU reactor spectrum with ~1 day of data

- First 33 days of data:
  - Address RAA at >2.2 sigma (arXiv: 1806.02784)

- Currently working on:
  - high-statistics spectral analysis (47/40 days On/Off), results soon.
  - Updated oscillation analysis underway
  - By 2019 6 reactor cycles w/ approximately equal off time.

- Expect valuable data on surface near-field operation (safeguards) and related cosmogenic backgrounds going forward
  - Much more to do in exploring full event topology
PROSPECT: a Precision Oscillation and Spectrum Experiment

A D
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C

SECTION A-A
SCALE 1 : 8
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