A Precision Oscillation and Spectrum Experiment

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on behalf of the PROSPECT collaboration
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A Short-Baseline Reactor Neutrino Experiment

Search for sterile neutrinos through neutrino oscillations
Test reactor anomaly

Measurement of the Relative Reactor Flux and Spectrum at Different Baselines independent of reactor models/predictions
Segmented detector
Relative measurement within detector

Test allowed oscillation parameter space

oscillated spectrum
unoscillated spectrum

each segmented measures L/E
High Flux Isotope Reactor, Oak Ridge National Lab

US Research Reactor

- **power**: 85 MW (research)
- **fuel**: highly enriched uranium ($^{235}$U)
- **core shape**: cylindrical
- **size**: $h=0.5m$ $r=0.2m$ (compact)
- **duty-cycle**: 41%


Research Reactor Spectrum

- HEU core provides static spectrum of mainly $^{235}$U.

Compact reactor core

Compact core (< 1m) avoids oscillation washout
PROSPECT Experimental Location

- established on-site operation
- easy access 24/7, user facility
- door to outside
- internet access, utilities
Physics Objectives

1. Search for short-baseline oscillation at distances <10m
2. Precision measurement of $^{235}\text{U}$ reactor $\bar{\nu}_e$ spectrum

One Experiment, 2 Detectors

Phase I
one movable detector AD-I, ~7-12 m baseline

Phase II
two detectors, movable AD-I, ~7-12m baseline stationary AD-II, ~15-19m baseline
- movable detector enables systematic control, background checks, and increased physics reach
- phased approach mitigates risks

whitepaper, arXiv:1309.7647
PROSPECT collaboration

physics program, on arXiv this week
PROSPECT collaboration
Physics Objectives

1. Search for short-baseline oscillation at distances <10m
2. Precision measurement of $^{235}$U reactor $\bar{\nu}_e$ spectrum

One Experiment, 2 Detectors

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Power</td>
<td>85 MW</td>
</tr>
<tr>
<td>Shape</td>
<td>Cylinder</td>
</tr>
<tr>
<td>Size</td>
<td>$0.2\ m \times 0.5\ m\ h$</td>
</tr>
<tr>
<td>Fuel</td>
<td>HEU</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>41% reactor-on</td>
</tr>
</tbody>
</table>

**Antineutrino Detector 1 (AD-I)**
- Cross-section: $1.2 \times 1.45\ m^2$
- Proton density: $5.5 \times 10^{28}\ p/m^3$
- Total Target Mass: 2940 kg
- Fiducialized Target Mass: 1480 kg
- Baseline range: 4.4 m
- Efficiency in Fiducial Volume: 42%
- Position resolution: 15 cm
- Energy resolution: $4.5%/\sqrt{E}$
- S:B Ratio: 3.1, 2.6, 1.8
- Closest distance: 6.9 m, 8.1 m, 9.4 m

**Antineutrino Detector 2 (AD-II)**
- Total Target Mass: $\sim$10 ton
- Fiducialized Target Mass: $\sim$70%
- Baseline range: $\sim$4 m
- Efficiency in Fiducial Volume: 42%
- Position resolution: 15 cm
- Energy resolution: $4.5%/\sqrt{E}$
- S:B ratio: 3.0
- Closest distance: 15 m

**Operational Exposure**
- Phase I: 1, 3 years
- Phase II: 3 years

whitepaper, arXiv:1309.7647
PROSPECT collaboration

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PROSPECT collaboration
PROSPECT Physics

A Precision Oscillation Experiment

An experimental approach to test for oscillation of eV-scale neutrinos

Phase I = AD-I, 3 years
Phase II = AD-I + AD-II, 3+3 years

Objectives
4σ test of best fit after 1 year
>3σ test of favored region after 3 years
5σ test of allowed region after 3+3 years
PROSPECT Physics

A Precision Spectrum Experiment

A precision measurement to address spectral unknowns

Phase I = AD-I only

Objectives

Measurement of $^{235}$U spectrum

Compare different reactor models

Compare different reactor cores

Measurement of HEU ($^{235}$U) spectrum

IBD signal backgrounds after analysis cuts

between 2-6 MeV:

average stat. precision < 1.5%, systematics < 2%
PROSPECT Physics

A Precision Spectrum Experiment

A precision measurement to address spectral unknowns

Testing models of the $^{235}$U $\bar{\nu}_e$ energy spectrum

Objectives

Measurement of $^{235}$U spectrum

Compare different reactor models

Compare different reactor cores

Phase I = AD-I only

Different reactor cores
Antineutrino Detector

Antineutrino Detector Segments
PMT
Light Guide
Optical Separator
$^6$LiLS
Antineutrino Detector

- 3000L of $^6\text{Li}$ liquid scintillator
- 120 scintillator loaded cells, ~15x15x120cm
- double ended PMT readout, light guides, <4-5%/√E resolutions
- thin optical separators, minimal dead material
- containment vessel, filled in place
PROSPECT Event Detection

Event Identification

- **Prompt signal**: 1-10 MeV positron from inverse beta decay (IBD)
- **Delay signal**: ~0.5 MeV signal from neutron capture on $^6$Li
- **40μs delayed n capture**

**Signal**
- inverse beta decay (IBD)
- γ-like prompt, n-like delay

**Backgrounds**
- fast neutron
- n-like prompt, n-like delay
- accidental gamma
- γ-like prompt, γ-like delay

Background reduction is key challenge
PROSPECT Event Detection

Event Identification

- inverse beta decay (IBD)
  - γ-like prompt, n-like delay

backgrounds

- fast neutron
  - n-like prompt, n-like delay

- accidental gamma
  - γ-like prompt, γ-like delay

Background reduction is key challenge

Background Reduction through detector design & fiducialization

IBD event in segmented $^6$LiLS detector

Pulse Shape Discrimination

5” cell with Cf252 source

signal

40μs delayed n capture

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

Delay signal: ~0.5 MeV signal from neutron capture on $^6$Li
Lithium-loaded Liquid Scintillator

Development

Novel scintillator cocktail:
- PSD LiLS that is non-toxic, non-flammable
- extensive studies with LAB, Ultima Gold
- EJ-309 gave best light yield, PSD

Scintillator specs (PROSPECT-0.1):
- Light Yield\textsubscript{EJ-309} = 11500 ph/MeV
- Light Yield\textsubscript{LiLS, measured} = 8200 ph/MeV
- prominent neutron capture peak in LiLS
- PSD FOM at (n, Li) is 1.79
- energy resolution (σ/E) of 5.2% at 0.6MeVee

developed novel LiLS with excellent light yield, PSD, and neutron capture capabilities
PSD critical for background reduction
Prototype Detectors
PROSPECT-20 w/ LiLS and Unloaded LS

**Light Yield/ PE Spectra**

- Compton edge of $^{60}$Co and $^{217}$Bi γ-rays and the quenched (n, Li) capture peak from $^{252}$Cf neutrons
- light collection: 522±16 PE/MeV

**Pulse Shape Discrimination**

- n,Li
- γ-like events
- n-like events

PSD performance for Cf-252.

unloaded LS studies described in
2015 JINST 10 P11004, arXiv:1508.06575,
PROSPECT collaboration
Antineutrino Detector Segmentation

Low-mass, optical separators

Minimum dead material

Low-mass reflector prototypes

Fiducialization

Phase 1 cosmic neutron event

Representative 500 MeV primary

Phase I AD-1, IBD-like neutron segment

![Graph showing photoelectrons and events per IBID/15 p.e.]

- No inactive mass
- PROSPECT AD
- Bugey 3

*e+ wall study*
Reactor Antineutrino Measurement Facility (RAMF) at HFIR

- local shielding next to reactor wall
- multi-layer passive shield around detector (water bricks, HDPE, borated HDPE, lead)
- general purpose digitizing electronics and DAQ
- general utilities
- easy access
Background Measurements at HFIR

IBD-like events for reactor-on and off
reactor generated backgrounds are minimal
IBD-like backgrounds are cosmogenic

Simulated Signal and Background Spectra

Signal (dashed) and background (solid) prompt spectra are shown through selection cuts.

<table>
<thead>
<tr>
<th>Cuts</th>
<th>IBD signal</th>
<th>Cosmic BG</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSD</td>
<td>1630</td>
<td>2.1e6</td>
</tr>
<tr>
<td>Time (1, 2, 3)</td>
<td>1570</td>
<td>3.4e4</td>
</tr>
<tr>
<td>Spatial (4, 5)</td>
<td>1440</td>
<td>9900</td>
</tr>
<tr>
<td>Fiducial (6)</td>
<td>660</td>
<td>250</td>
</tr>
</tbody>
</table>

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.

Simulated event rates, 0.8 ≤ E ≤ 7.2 MeV after applying background rejection cuts.
PROSPECT Calibration

- **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
PROSPECT Detector and Shielding at HFIR Development

**PROSPECT-0.1**  
*Characterize LS*  
Aug 2014 - Spring 2015  
- 5cm length  
- 0.1 liters  
- LS, $^6$LiLS

**PROSPECT-2**  
*Background studies*  
Dec 2014 - Aug 2015  
- 12.5 length  
- 1.7 liters  
- $^6$LiLS

**PROSPECT-20**  
*Segment characterization*  
*Scintillator studies*  
*Background studies*  
Spring/Summer 2015  
- 1m length  
- 23 liters  
- LS, $^6$LiLS

**PROSPECT-50**  
*Baseline design prototype*  
Winter 2015  
- 1x2 segments  
- 1.2m length  
- 50 liters  
- $^6$LiLS

**PROSPECT-400**  
*Fiducialization and background studies*  
Mid 2016  
- 4x4 segments  
- 1.2m length  
- 400 liters  
- $^6$LiLS

**PROSPECT AD-I**  
*Physics measurement*  
Late 2016  
- 10x12 segments  
- 1.2m length  
- ~3 tons  
- $^6$LiLS

*Technically ready to proceed directly to near detector with available funding*  

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**PROSPECT Phase I AD-I**  
- Reactor core
- Local reactor shielding
- Multi-layer shielding
Validation of Monte Carlo from HFIR Data

Monte Carlo Validation from operating multiple prototypes at HFIR site

PROSPECT-2

operation and combined exposure

PROSPECT-20
Validation of Monte Carlo from HFIR Data

• PROSPECT-20 measured cosmic backgrounds during reactor-off
• PROSPECT-20 ‘simple’ Monte Carlo agrees well with data

• confident in extrapolating MC to Phase I detector
• after series of effective cuts, can reach S:B > 3:1
• surpasses physics goals target
• will measure these backgrounds during reactor-off time in Phase I

PROSPECT-20 prototype deployment validated background Monte Carlo
Validation of Monte Carlo from HFIR Data

PROSPECT-20 measured cosmic backgrounds during reactor-off
PROSPECT-20 ‘simple’ Monte Carlo agrees well with data

Confident in extrapolating MC to Phase I detector
After series of effective cuts, can reach S:B > 3:1
Surpasses physics goals target
Will measure these backgrounds during reactor-off time in Phase I

Allows prediction of S:B for PROSPECT Phase I

Phase I simulated signal + cosmics after cuts
PROSPECT R&D and Technical Activities

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PROSPECT Collaboration

High Flux Isotope Reactor, Oak Ridge National Laboratory

site of experiment
High Flux Isotope Reactor, Oak Ridge National Laboratory

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Brookhaven National Laboratory
Drexel University
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
University of Waterloo
University of Wisconsin
College of William and Mary
Yale University

63 collaborators
13 institutions
3 national laboratories
Summary

• New data are needed to address the existing reactor anomalies.

• PROSPECT Phase I will
  – Probe favored region of eV-scale sterile neutrinos at $>3\sigma$ with 3 years of data.
  – Measure $^{235}$U $\bar{\nu}_e$ spectrum, address spectral deviation, and provide new constraints on reactor antineutrino models complementary to current and future LEU measurements.

• PROSPECT R&D
  – Have developed LiLS detectors that can mitigate reactor- and cosmogenic related backgrounds.
  – Multiple detectors have been deployed at HFIR in preparation for full-size detector.
  – Completed R&D for technical verification and to mitigate technical, cost, and schedule risks.

• Ready to proceed with construction of Phase I.

• Data taking in 2017 with first physics results in 2018 possible.

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