Development of PROSPECT detectors for precision antineutrino studies

On behalf of the PROSPECT collaboration,

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PROSPECT collaboration at DPF 2015:
K.Gilje - Neutrino - Aug 5 @7:00 - Sensitivity and discovery potential of PROSPECT
Physics objectives:
1. Precision measurement of $^{235}$U reactor anti-$\nu_e$ spectrum
2. Search for short-baseline oscillation at distances <10m

Phased approach:
- addresses experimental situation in a timely manner
- mitigates risks
- systematic control and increased physics reach
- allows collaboration to stay nimble and respond to results from phase 1, expand only as needed
PROSPECT Phase 1 Detector

Physics goals:
- probe sterile $\nu$ parameter space at 3$\sigma$ in 1 calendar year
- precision measurement of $^{235}\text{U}$ neutrino spectrum

Phase 1 near detector:
- 2.5 tons $^6\text{Li}$-loaded liquid scintillator
- $\sim 10\times 14$ segmented array with low-mass optical separators
- double-ended PMT readout
- movable, baseline coverage 7-11m

Near-surface detection challenges:
- cosmogenic + reactor backgrounds
- reduction techniques
  1. multi-layer shield to suppress n,$\gamma$
  2. time correlated $\beta$+n signal from IBD
  3. particle ID from Pulse Shape Discrimination
  4. segmentation allows for identification of spatially coincident signals and fiducilization
Phased detector development approach

**PROSPECT-0.1**
- **Y,H**
- Aug 2014
- Spring 2015
- Characterize LS

**PROSPECT-2**
- **Y,H**
- Winter 2014-15
- Aug 2015
- Background studies

**PROSPECT-20**
- **Y,H**
- Spring -Summer 2015
- Characterize segment

**PROSPECT-Nx20**
- **H**
- Late 2015*
- Mechanical prototype

**PROSPECT-2k**
- **H**
- Late 2016*
- Physics measurement

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*technically driven schedule

HFIR = H, Yale = Y

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What are we looking for?

inverse beta decay (IBD)

\[ \nu_e \rightarrow p + \beta^+ + e^- \]

\[ n + {^6}\text{Li} \rightarrow \alpha + t \]

\[ \Delta d \approx 100\mu m \]

prompt (\( t_0 = 0 \)): 1-10MeV annihilation

delay (\( t_c = 40\mu s \)): 0.6MeVee (n, \(^6\text{Li}\)) capture

coincidence of these two signals indicates an IBD event
Major backgrounds at near-surface site

**Correlated Backgrounds:**
- cosmogenic fast neutrons (neutrons and muon-induced spallation)
- multiple neutron captures (cosmic showers)

**Uncorrelated Backgrounds (accidental):**
- reactor-related gammas or gammas from internal backgrounds ($^{232}$Th, $^{40}$K)

| Signal                  | inverse beta decay
<table>
<thead>
<tr>
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<th></th>
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<tbody>
<tr>
<td></td>
<td>$\gamma$-like prompt, n-like delay</td>
</tr>
<tr>
<td>Background</td>
<td>fast neutron</td>
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<tr>
<td></td>
<td>n-like prompt, n-like delay</td>
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<tr>
<td></td>
<td>accidental gamma</td>
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Phase 1 cosmic neutron event

Representative 500 MeV primary
Site background characterization at HFIR

- conducted detailed evaluation at 3 high power HEU reactors (ATR, HFIR, NIST)
- characterized sources and distribution of reactor and cosmogenic background
- all sites viable for PROSPECT
- HFIR selected for operation schedule and logistics


**established feasibility by completing exhaustive assessment and selected HFIR**
Tackling backgrounds with detector design

- the neutron capture on $^6$Li allows for event localization, and combined with the localized $e^+$ gives a spatial correlation in addition to the IBD temporal correlation
- easy fiducialization to control gamma backgrounds
- designed localized shielding to suppress cosmogenic and reactor correlated backgrounds

**IBD in $^6$Li**

- effect of increasing lead wall on gammas

**Detector structure and passive shielding designed for near-surface backgrounds**
Tackling backgrounds with PSD

Pulse Shape Discrimination (PSD) will provide important particle identification information.

- **Prompt signal**: 1-10 MeV positron from inverse beta decay
- **Delay signal**: 0.6 MeV signal from neutron capture on $^6$Li

<table>
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<tr>
<th>PSD signatures</th>
<th>Signal</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signal</strong></td>
<td>inverse beta decay</td>
<td>fast neutron</td>
</tr>
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<td></td>
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</table>

**Accidental gammas**

**Particle ID strongly suppresses cosmogenic correlated and reactor-induced uncorrelated backgrounds**

PROSPECT-2 (LiLS)

- **Cf-252**
- **(n,Li)**
- **n**
- **$\gamma$**

Prompt: 1-10 MeV positron from inverse beta decay
Delay: 0.6 MeV signal from neutron capture on $^6$Li

**arXiv1309.7647**
Liquid scintillator (LS) development

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 ($\sigma/E$) of 5.2% at 0.6MeV$_{ee}$

**Co-60**

![Graph showing Co-60 and EJ-309 comparison]

**Cf-252**

![Graph showing PSD for Cf in LiEJ-309]

**(n, Li)-like delay in LiEJ-309**

![Graph showing (n, Li)-like delay]

developed novel LiLS with excellent light yield, PSD, and neutron capture capabilities
Compatibility and design of low-mass 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 separators with good reflectivity from LS-compatible materials
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Segment response: light collection and PSD studies

**PROSPECT-20atYale (EJ-309):**
- optimize collection, PSD with air-coupled specular separators (external)
- average light collection: 527±10 photoelectrons/MeV
- low energy PSD (0.5-0.7MeV) allows for 99.99% rejection of γ, 99% acceptance n events
- detailed technical paper forthcoming

**excellent PSD is obtained in realistic geometry at target light collection of 500pe/MeV**
Segment response: double-ended readout

Collection from sum of 2 PMTs

double-ended readout allows for uniform optical collection, enhanced PSD, and axial position resolution
Simulation to benchmark prototype data

Simulations have been developed to meet distinct needs:

1. **Background mitigation**
   develop single flexible Monte Carlo, benchmark against prototypes, enable extrapolation to full detector

2. **Detector response**
   detailed model of detector response ensures PROSPECT has precision spectral measurement capability

3. **Design**
   simulations further used to optimize shielding, light transport, etc in context of science goals

prototyping program has enabled validation of mechanics, detector response, and simulation models
Validation of MC from prototypes at HFIR site

PROSPECT-2 at HFIR

PROSPECT-20 at HFIR

combined exposure

PROSPECT-2

PROSPECT-20

15

reactor on

on-site prototype deployment verified operational interfaces and provided validation of background MC

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PROSPECT: Hands-on science
Next steps for PROSPECT

PROSPECT is ready to proceed with building the Phase 1 near detector at HFIR.
1. PROSPECT Phase 1 is ready to proceed with precision $^{235}$U spectrum measurement and short baseline oscillation search.

2. The PROSPECT R&D program has:
   - successfully **deployed multiple prototype detectors** to validate detector performance and simulation models, as well as establish on-site operational procedures
   - developed a **detailed understanding of near-surface backgrounds** at research reactor facilities, including HFIR, as well as background mitigation techniques
   - **developed technology required for the Phase 1** detector: Li-doped liquid scintillator, low-mass separators, and segment design that optimize light collection, PSD, and uniformity
   - **produced simulation models** validated against prototype data that allow reliable predictions of Phase 1 detector performance
The PROSPECT Collaboration

3 reactor sites | 5 national laboratories | 9 universities | 63 collaborators

prospect.yale.edu
Current PROSPECT work

PROSPECT is actively continuing R&D to prepare for the building of Phase 1
Back-up: PROSPECT-2 at HFIR

Detector geometry: 1.7L cylinder
Scintillator: Li-loaded EJ-309
PMTs: 5” flat ET9823
Shielding: poly, Pb, Bpoly
Reflectors: diffuse Gore
DAQ: CAEN 1720 (12bit)
Purpose: background reduction method
Back-up: PROSPECT-20 at HFIR

Detector geometry: 23L 1-meter rectangle
Scintillator: Li-loaded EJ-309
PMTs: 5” flat ET9823
Shielding: poly, Pb, Bpoly, water bricks
Reflectors: 3M SolarMirror
DAQ: CAEN 1720 (12bit)
Purpose: Operate full PROSPECT segment
Back-up: PROSPECT-20 at Yale

Optics optimization studies:
- Reflector type
- Reflector coupling
- PMT read-out
- Compare to simulation

Soon to come:
- Optical coupler geometries
- Li-loaded EJ-309

Detector geometry: 23L 1-meter rectangle
Scintillator: EJ-309
PMT(s): 5” spherical Hamamatsu R6594
Shielding: Pb
Reflectors: variable
DAQ: CAEN 1730 (14bit)
Purpose: optimize optics of full segment
Back-up: PSD parameter

\[ PSD = \frac{Q_{\text{tail}}}{Q_{\text{full}}} \]
Lithium dopant in liquid scintillator

1. Small detectors that do not have full calorimetry information. But, neutron capture on $^6\text{Li}$ allows for single-site topology.

2. PROSPECT will be in a high gamma environment, with energies ranging from 1-10MeV. This background will not interfere with neutron captures since $(n, \text{Li})$ events fall in the “n-like” pulse shape discriminate (PSD) band.

Can contain $(n, \text{Li})$ events in segments and extract from backgrounds.
Coincidence analysis:
- cosmogenic fast neutrons (real)
- cosmogenic showers (multiple captures)
- reactor-related gammas (accidental)

PSD cuts on prompt and delayed signals rejects many of these backgrounds.
Accidentals reduced significantly with energy and PSD cuts.
PROSPECT-20 at Yale

- total internal reflection and specular reflectors give best collection and PSD
- double-ended PMT readout essential for uniformity