Improved Inverse Beta Decay event selection and its impact on the PROSPECT oscillation analysis

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The University of Tennessee Knoxville
On behalf of the PROSPECT collaboration
October 13th – DNP2021 Meeting
PROSPECT Detector at HFIR

- 93% 235U Fuel
- 85 MW thermal power
- Compact core
- Huge flux in the few MeV range
- ~50% duty cycle for BG measurements

14 x 11 array of 6Li doped liquid scintillator for detecting reactor antineutrinos (6.7-9.2 m from compact highly enriched uranium reactor core)

Antineutrino Detection

Use of the IBD process

\[ \bar{\nu}_e + p \rightarrow \beta^+ + n \]

- **PROSPECT** detects antineutrinos via the Inverse Beta Decay (IBD) process
- Prompt signal \((e^+)\) provides a good energy estimate of incoming \(\nu\)
- Localized delayed \((n - ^6Li)\) signal

- Differences in ionization density between electronic/nuclear recoil type events result in distinct pulse shapes for each event
- Prompt and delayed signal possesses unique pulse shapes (different from background events)

IBD Event Selection

- **IBD Topology-based cuts**
  - Neutron Capture Region
  - Prompt PSD
  - Prompt-Delayed signal distance
  - Prompt-Delayed Timing
  - Fiducial z cut

- **Veto cuts**
  - Muon Veto Time
  - Neutron Veto Time
  - Recoil Veto time

- Sequential application of selection cuts results in a significant reduction of background events

- These selection criteria was used for most recent results

Motivation for a final PROSPECT-I Analysis

• Previous results were impacted by the periodic loss of photo-multiplier tube bases throughout data collection.

Detector configuration used for PRD analysis

154 segments with two PMTs

• In order to improve upon previous results, two new data recovery approaches have been proposed:

Data Splitting & Single Ended Event Reconstruction (SEER)

First Approach: Data Splitting

- Split PROSPECT-I data into distinct periods in order to recover statistics.
- Maximize number of live segments in each period

Time evolution of dead channels in the PROSPECT detector

- 20% of total number of PMTs
- 10% of total number of PMTs
Criteria for Calibration-Based Splitting

- Each period should start immediately after a new calibration campaign.
- Each period must contain one full RxOn cycle.
- All periods should have RxOff data before and after each corresponding RxOn cycle:
  - Period 1 is an exception since there is no prior RxOff data available.
- Keep ratio of RxOff/RxOn files between 50%-70%.
  - Since there is no calibration campaign between periods 3 and 4, we used the ratio of RxOff/RxOn files to define these two (70%).
Criteria for Calibration-Based Splitting

<table>
<thead>
<tr>
<th>Period</th>
<th>Double Ended Segment</th>
<th>Single Ended Segment</th>
<th>Blind Segments</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROSPECT Latest Results</td>
<td>97</td>
<td>47 (not-used)</td>
<td>10</td>
</tr>
<tr>
<td>Period 1</td>
<td>127</td>
<td>24</td>
<td>3</td>
</tr>
<tr>
<td>Period 2</td>
<td>131</td>
<td>21</td>
<td>2</td>
</tr>
<tr>
<td>Period 3</td>
<td>123</td>
<td>28</td>
<td>3</td>
</tr>
<tr>
<td>Period 4</td>
<td>110</td>
<td>39</td>
<td>5</td>
</tr>
<tr>
<td>Period 5</td>
<td>97</td>
<td>47</td>
<td>10</td>
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</table>
Second Approach: SEER

- The implementation of SEER into the existing analysis presents a great opportunity to improve our current results (statistics and S:B).

- Lacks energy and position reconstruction capabilities

- Provides a good handle on particle identification (great background suppression)
The implementation of SEER into the existing analysis presents a great opportunity to improve our current results.

**Existing cuts:**
- n-Li capture
- Prompt PSD cut
- IBD prompt-delay distance
- Prompt-delay timing difference
- Fiducial volumes

**Existing Vetoes**
- Muon veto
- n-Li capture veto
- n-p recoil veto
- Pileup veto

**New:**
- SEER cut:
  - Prompt SEER PSD cut
- SEER veto:
  - Neutron (capture/recoil) veto
IBD Event Selection + SEER - New Cuts Needed

- The implementation of SEER into the existing analysis presents a great opportunity to improve our current results.

Existing cuts:
- n-Li capture
- Prompt PSD cut
- IBD prompt-delay distance
- Prompt-delay timing
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Existing veto:
- Muon veto
- n-Li capture veto
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Need to optimize IBD selection including new cuts:
- Neutron (capture/recoil) veto
- SEER PSD cut
Cut optimization including new SEER cuts - metrics

- In order to optimize the IBD selection cuts with the new SEER analysis the following data and metrics were considered:
  - 20% of the data used for the PRD
  - Effective IBD counts

\[
\text{IBD}^{\text{Effective}} = \sum_{0.8\text{MeV}}^{7.2\text{MeV}} \frac{1}{(\sigma_{\text{IBD}}/\text{IBD})^2}
\]

- Signal to cosmogenic background ratio (S:CB)
- Signal to accidental background ratio (S:AB)
- \(nH\) peak signal to background ratio
- \(nC\) peak signal to background ratio
Cut optimization including new SEER cuts - example

Neutron Veto Time [$\mu s$]:
- IBD candidates are rejected if their delayed capture times are within $\mu s$ of another n-6Li candidate
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Neutron Veto Time [$\mu$s]:
- IBD candidates are rejected if their delayed capture times are within $\mu$s of another n-6Li candidate

- Introduction of new SEER cuts into our optimization results in a ~30% increase in effective statistics
- Other metrics exhibit similar improvement
## Summary of Results with DS and SEER

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<tr>
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<th>Improved</th>
<th>Unchanged</th>
<th>New</th>
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<td>IBD Neutron Capture: PSD</td>
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- An increase of ~50% in effective statistics is expected when including SEER cuts into our IBD selection re-optimization

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- Increase of ~27% in total IBD counts using DS
- Increase of ~50% in effective statistics sing DS
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Stay tuned for DS+SEER Analysis!
June 2021 Collaboration Meeting, 43 Collaborators