near-surface backgrounds for ton-scale IBD detectors

Michael P. Mendenhall for the PROSPECT Collaboration

Lawrence Livermore National Laboratory

Applied Antineutrino Physics, October 11 2018

This work was performed under the auspices of the U.S. Department of Energy
by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Motivation

- Many near-field reactor monitoring applications will require detectors which are portable and able to to operate wherever reactors are.
- This indicates active volumes on the order of a few tons (size scales of 1–2 m), operating in minimal-overburden locations.
- The near-surface background radiation environment and smaller detector size present different challenges from large, underground experiments. "Conventional wisdom" from decades of large detector development is not necessarily applicable.
- The PROSPECT detector provides the first example of surface-level antineutrino detection with > 1 signal to background, providing unique insight into the character of near-surface backgrounds, and effective techniques for background mitigation.

Information sources

Representative detector: Prospect

- Segmented, $\sim 0.07\%$ ^{6}Li-loaded PSD liquid scintillator
- 14×11 segments, each $14.5^2 \times 120\,\text{cm}^3$ ($\sim 25\,\text{l}$)
- Double-ended readout by 5" PMTs (308 total channels)
- $\sim 7\,\text{m}$ from 85 MWth reactor (HFIR at ORNL)
- Minimal overburden (building roof) surface site at 250 m altitude

Corresponding simulation

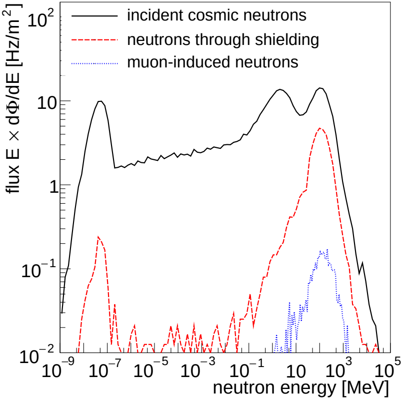
- GEANT4 (version `4.10.04p01`)
- Physics list `QGSP_BERT_HP`, with `G4HadronElasticPhysicsHP` replaced by `HadronElasticWithThermalNeutrons`
- PROSPECT detector response model for analysis of simulation through detector data chain

What causes backgrounds?

Neutrons required for correlated IBD-like backgrounds

10s-of-μs neutron capture timescale is distinctive: longer than electromagnetic interactions (ns), shorter than accidental coincidences ($\gtrsim$ ms). IBD-mimic correlated events are highly unlikely without neutrons involved.

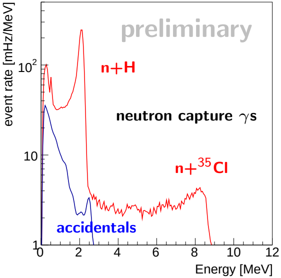
Near surface, primarily cosmic fast neutron background



Ambient surface neutron spectrum, and toy model processed through 1 mwe shielding. Cosmic fast neutrons dominate flux in detector at surface; several meters down, these will be sufficiently attenuated that local muon spallation becomes the dominant background source.

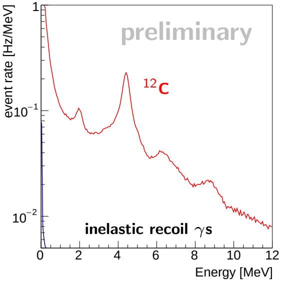
primary IBD-mimic mechanisms

Most false-IBD events come from one of two interaction mechanisms:



capture, capture

Subsequent capture of two thermal neutrons, where the first captures on an unintended nucleus (primarily H) producing a gamma misidentified as a positron.



recoil, capture

Fast neutron interactions followed by capture (of the same or two different neutrons), where the “neutron-like” character of the initial interaction is obscured.

capture, capture mechanism

- Likely when multiple correlated low-energy neutrons (produced by spallation in the local shielding) enter the detector.
- Heavy-nucleus shielding (lead) is a potential source; should be separated from active volume by, *e.g.*, borated poly.
- Tends towards outer layers of detector (limited range of thermalized neutrons).
- Ability to correctly identify neutron captures suppresses backgrounds.
- Increased availability of distinctive capture target nuclei (*e.g.* ^{6}Li) reduces unwanted (*e.g.* n+H) captures.

recoil, capture mechanism

- Produced by fast neutron (10s of MeV) interactions in detector.
- Can be more deeply penetrating than capture,capture events.
- ^{12}C resonance is distinctive signature feature; other contributions at all energies.
- Otherwise-identifiable recoil components “hidden” under gammas.
- Suppress by overburden shielding, PSD, segmentation.

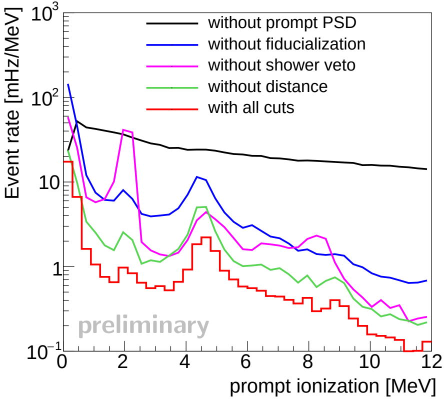
Background rejection detector capabilities

PROSPECT's multiple capabilities work together to reject backgrounds:

- Passive shielding
- Neutron capture identification (^{6}Li loading + PSD)
- Prompt event classification (PSD, segmentation) — without PSD, potentially possible with detailed topology information.
- Shower veto (high energy, recoil, or capture)
- Prompt-delay distance (position reconstruction)
- Fiducialization (detector as active shielding)

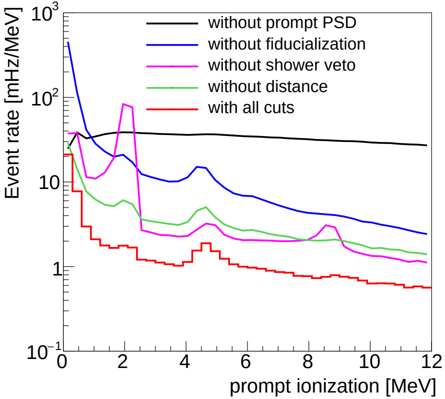
The relative impact of different detector capabilities is demonstrated by disabling different components in analysis.

Background capability impacts (Prospect data)



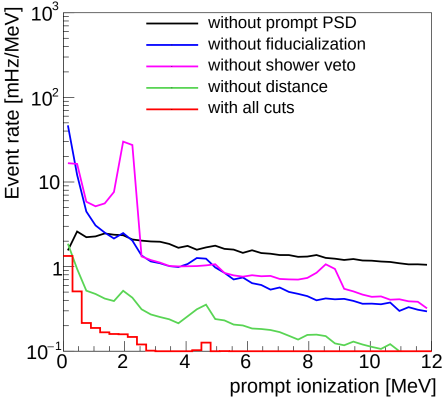
- Rejecting prompt event neutron recoils (PSD) is most critical.
- Sufficient detector size to fiducialize comes next — a large enough detector could do without PSD.
- Shower veto especially effective on capture, capture mechanism.
- Prompt/delay distance is easy and helpful.

Background capability impacts (simulation)



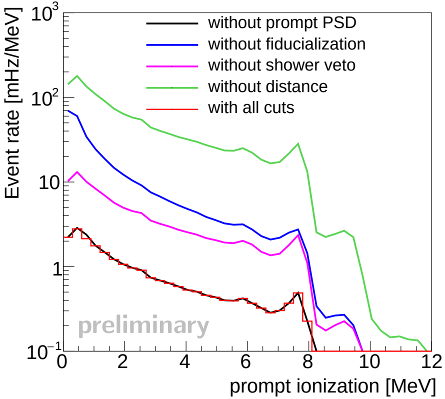
- Simulation does a good job of predicting these response patterns, making it a valuable tool for assessing detector design choices.
- This plot shows the contributions from simulated cosmic neutrons alone, which explain most correlated backgrounds in the data.

Muon background component (simulation)



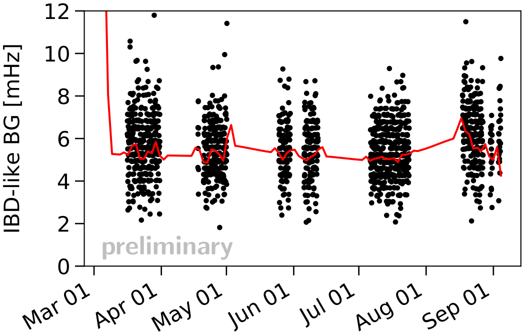
- Same analysis as preceding slide for simulated non-neutron cosmic backgrounds (mainly muons).
- In the near-surface environment, muons produce much less background than cosmic neutrons.
- Predominantly contribute to capture, capture mechanism channel by multi-neutron spallation showers.

Accidental background component (Prospect data)



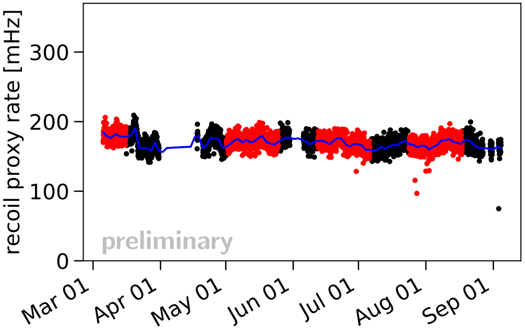
- PROSPECT reactor-on accidental backgrounds, measured with off-time coincidence window.
- Dominated by high-energy neutron capture gammas (especially on iron).
- Reactor-off is much lower.
- Prompt-delayed distance provides strongest suppression, followed by fiducialization.
- Anti-shower veto removes many neutron captures that might pair with accidentals.

Background time variation



- The IBD-like correlated background distribution is measured during reactor-off periods to subtract from reactor-on.
- Changes in the fast neutron background (correlated with atmospheric pressure) cause O(10%)-level variations.
- How to correct for fluctuations in background subtraction?

Background normalization proxies

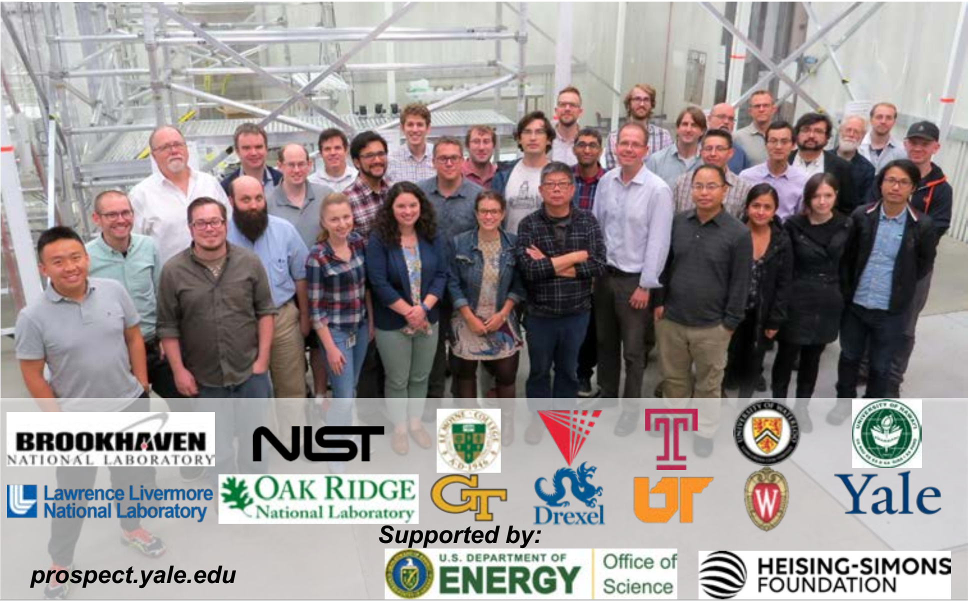


- “Almost-IBD-like” proxy event rates continuously track variations.
- Shown: rate of recoil, capture coincidences passing IBD cuts, except replacing “positron-like” with “recoil like” prompt requirement.
- On/off subtraction normalization determined from proxy variables.

Summary: understanding IBD backgrounds

- Cosmic fast neutrons produce most near-surface correlated backgrounds.
- Simulations can provide good predictions of detector response to backgrounds.
- A combination of detector capabilities work together to mitigate backgrounds.
- Characterization of the prompt positron-candidate event is especially important. Segmentation plus recoil PSD provides a powerful handle on this.

PROSPECT Collaboration



Supported by:

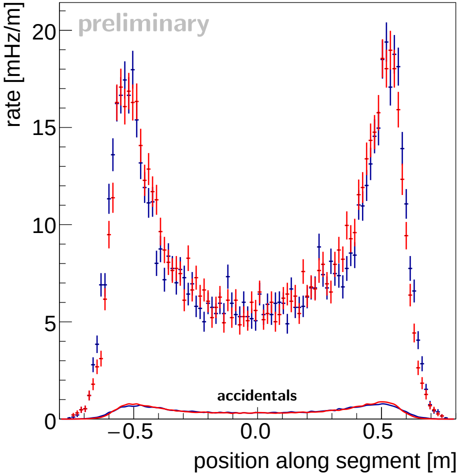
prospect.yale.edu

U.S. DEPARTMENT OF ENERGY | Office of Science

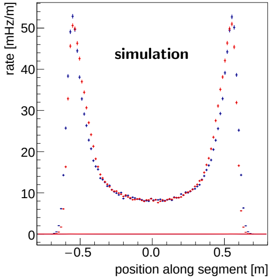
HEISING-SIMONS FOUNDATION

Bonus Slides

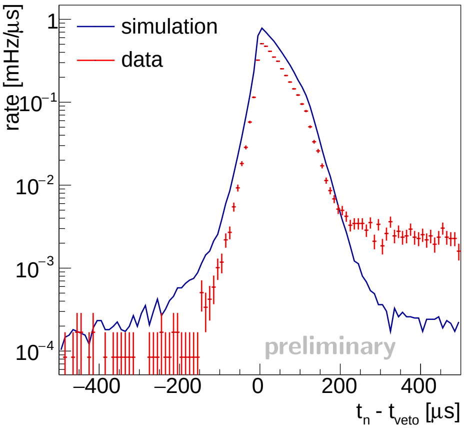
Fiducialization: IBD background positions (data)



- IBD-like background event prompt (red) and capture (blue) event positions along length of cell.
- Outermost segments excluded.
- Fiducializing on both prompt and delayed position helps more than either alone.



Shower veto timing



- Time between delayed neutron capture and nearest veto-inducing event (high energy or neutron interaction).
- Data compared with cosmic neutron background simulation.
- Shorter time component, driven by neutron interactions in immediate vicinity.
- Long tail of neutrons arriving after showers, from interactions far outside detector (not included in MC); vetoing all these would result in large deadtimes.

Passive shielding guidelines

- Priority is to knock down fast neutron flux.
- Highest energy neutrons (tens to hundreds of MeV) stopped by total overburden mass — some benefit per mass from hydrogenous material; engineering/space constraints may indicate lead.
- Inner shielding should moderate, capture secondary neutrons from outer shielding layers (borated poly inside lead).
- Fast neutrons come from above — prioritize shielding on top.
- Individual thermal/epithermal neutrons are not a large concern.
- High-energy accidental gamma backgrounds (*e.g.* neutron capture on iron) may have intense "hot spots" requiring extra local shielding.