Nuclear Reactor Antineutrino Directionality via Elastic Electron Scattering in a Gd-doped Water Cherenkov Detector

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Introduction

- Research is being done on using large (kiloton scale) Gd-doped water Cherenkov antineutrino detectors (WCDs) **for long range (> 10 km) remote monitoring of nuclear reactors** [1].
- Detection via inverse beta decay (IBD) ($\bar{\nu}_e + p \rightarrow n + e^+$) **can determine operational status, power level, and fuel burnup** [2].

- **Directional detection of the antineutrino source can reduce backgrounds from nearby reactors and can help search for clandestine reactors.**
- We look to **determine if directionality is possible with antineutrino-electron scattering (ES)** ($\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$) → ES is forward peaked (see Fig. 1), but the reaction rate is ~ 5.4 times smaller than IBD in water.

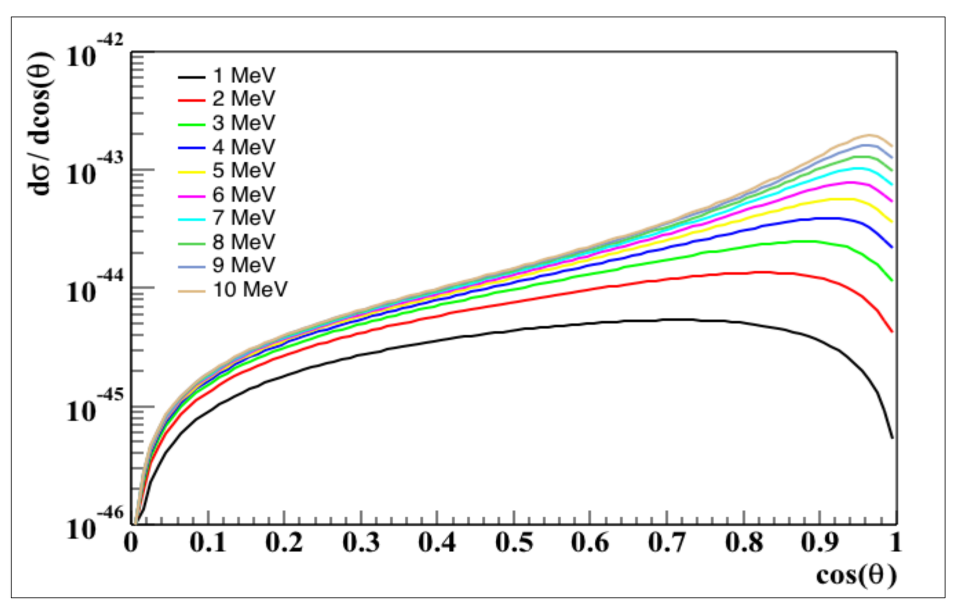
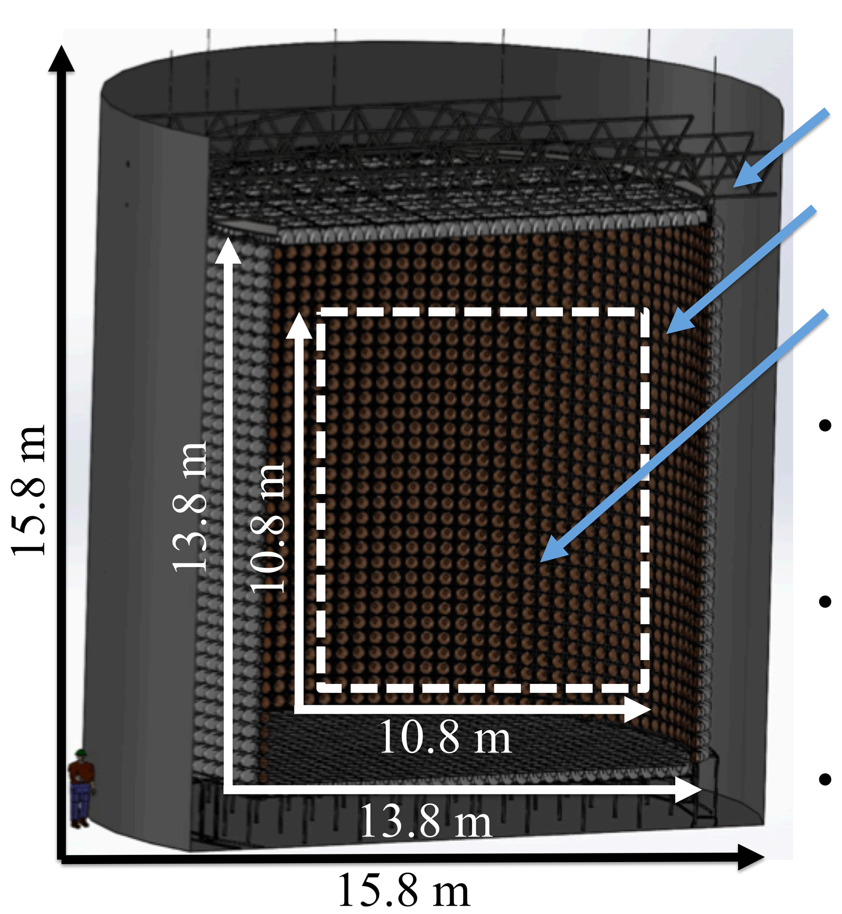


Fig. 1. Differential ES cross-section with respect to the cosine of the scattering angle, θ, for various antineutrino energies [3].

- This work serves as an introductory investigation into reactor directionality via ES in large WCDs → **we aim to estimate the expected ES signal and background, and propose several strategies to reduce background.**

Detector Design



Outer (veto) region

Inner (target) region

Fiducial volume

- 3.1 kilotons of 0.1% Gd-doped water in total.
- 4300 10-inch photomultiplier tubes (PMTs).
- **1 kiloton fiducial volume.**

- **1500 meters of water equivalent (m.w.e.)** underground.
- **13 km** from a **3.8 GWt** light water reactor.
- Roughly consistent with the **WATCHMAN** project [1].

Detection and Reconstruction

- Following an ES event, the scattered electron will produce a **Cherenkov light cone** (see Fig. 2).

- The direction and interaction vertex of the scattered electron **is reconstructed via the light pattern detected by the PMTs.**

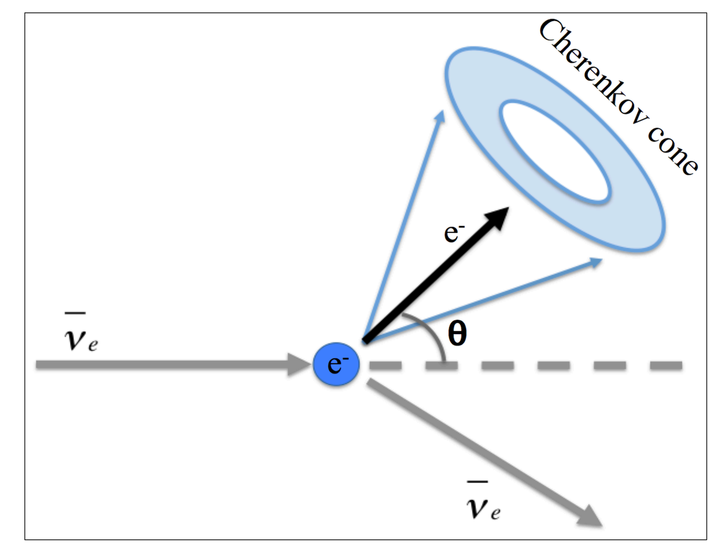


Fig. 2. Diagram of the ES interaction.

Signal and Background

- Signal: estimate using the number of antineutrinos produced per fission [4-5], the reactor power level, the detector distance and size, and the cross-section.
  → **~1850 ES events per year**.

- Background: **gamma rays from steel, rock, and PMTs, solar neutrinos, misidentified IBD events, cosmogenic radionuclides, and radon** → estimate by independent simulations and scaling from other experiments (Super-K, KamLAND, and SNO) [6-11].

GEANT4 Simulation

- Simulate one year of signal and background using **GEANT4**, sampling position, energy, and direction (see Fig. 3 for a visualization).

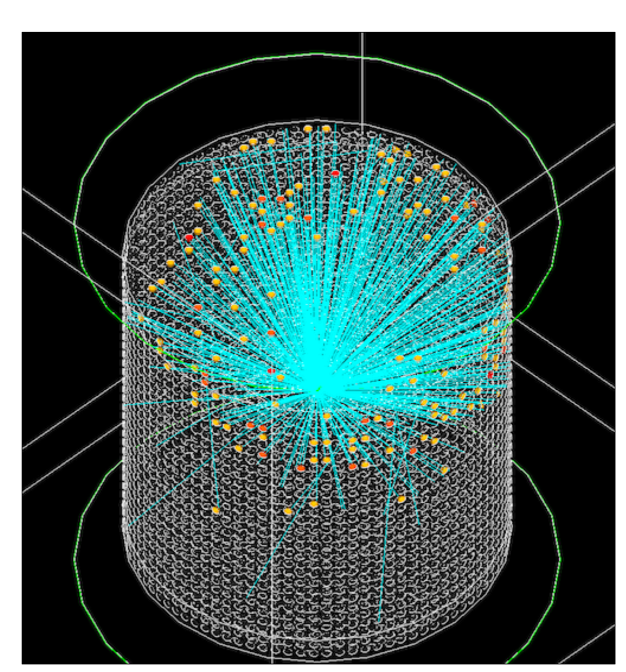


Fig. 3. Visualization of an ES event simulated in GEANT4.

- Analyze the photoelectron (PE) distributions for each source individually (see Fig. 4).

Results

- **Backgrounds are dominated by the PMTs, radon, and cosmogenic radionuclides.**

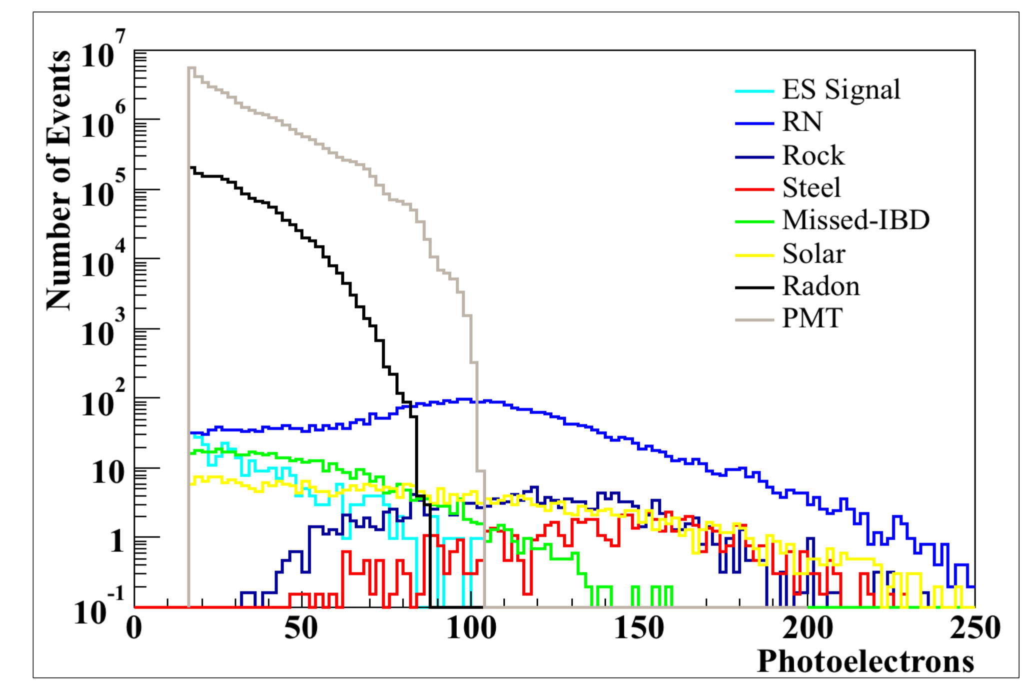


Fig. 4. One year PE spectra of signal and backgrounds in the kiloton fiducial volume.

- If we increase the buffer thickness (the region between the fiducial volume and PMTs), **we can essentially reduce the PMT background to zero** (see Fig. 5).

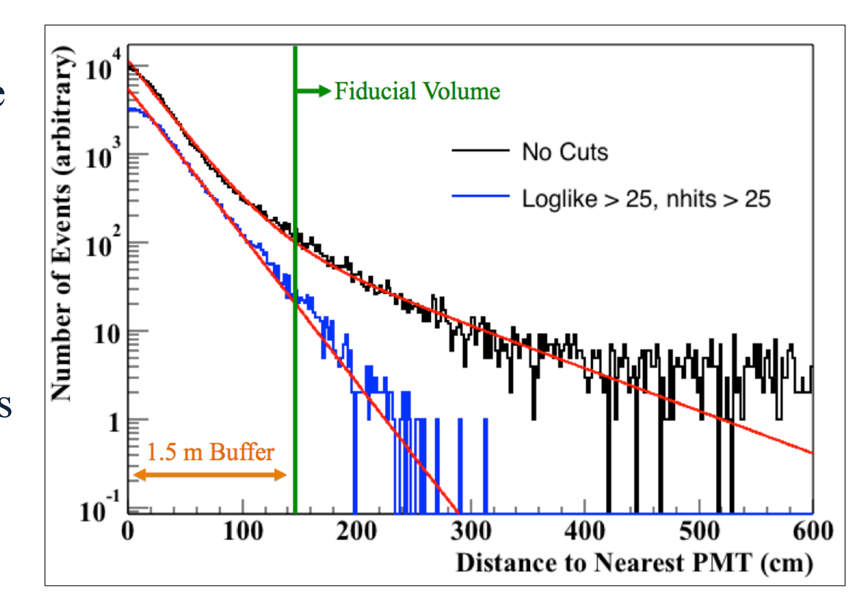


Fig. 5. Distance from the reconstructed vertex to the closest PMT (black). After poorly fit events are removed (blue).

- We compare the PE spectra of ES, radon, and cosmogenic radionuclides (see Fig. 6).
- **Radon can be removed while retaining <u>some</u> signal if a high PE cut (80 PE) is used.**
- However, the radionuclide background begins to dominate at these energies → **Will need to place detector deeper underground.**

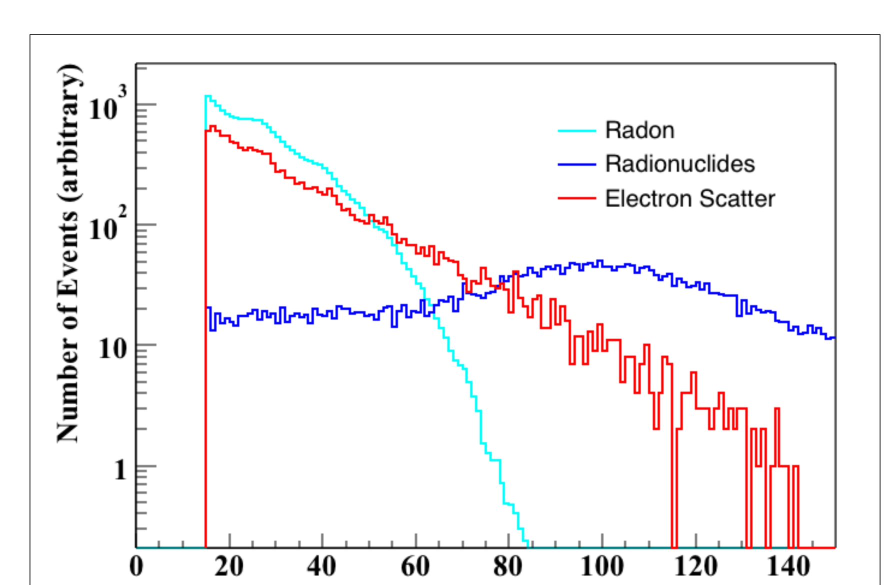


Fig. 6. PE spectra for ES, radon, and cosmogenic radionuclides (unnormalized).

Conclusions

- PMT backgrounds can be suppressed with a sufficiently large buffer thickness, leaving radon and cosmogenic radionuclides to dominate background.
- Radionuclide background can be reduced with more overburden and radon background can be removed using a high PE threshold.
- A larger detector will be needed to accommodate both the larger buffer and to increase the ES signal detection rate.

Future Work

- Determine pointing ability by analyzing the directional reconstructions of the signal and background.
- Investigate directional significance as a function of radon contamination, detector depth, and detector size.
- The results will outline a list of conditions that will enable a WCD to determine the direction of nuclear reactor antineutrinos.

References

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