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Advances Toward a Transportable Antineutrino Detector System for Reactor Monitoring and Safeguards

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Above-ground Reactor Monitoring

A collaboration of
Lawrence Livermore
and
Sandia National Laboratories

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SNL: David Reyna (PI), Scot Kiff, Belkis Cabrera-Palmer, Jim Lund, Jim Brennan

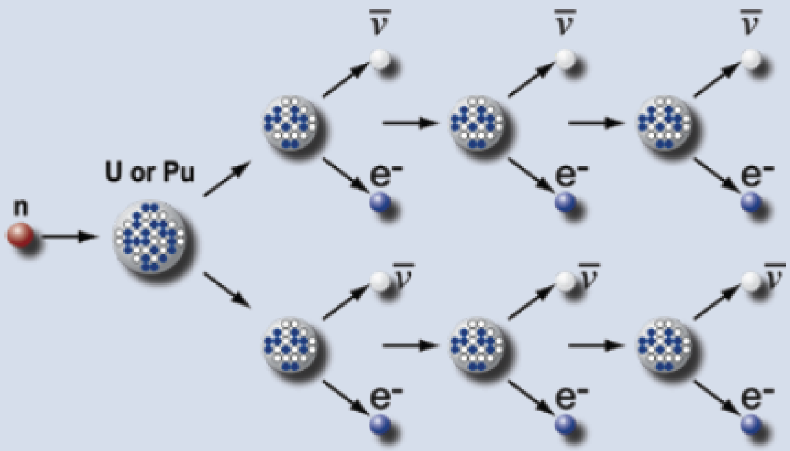
ARM94 (LLNL) — ARM 254 (SNL)

This project addresses requirements 1.1,1.2 and 1.3

Reactors Produce Antineutrinos

Reactors emit huge numbers of antineutrinos

- 6 antineutrinos per fission from beta decay of daughters
- 10^{21} fissions per second in a 3,000-MWt reactor



About 10^{22} antineutrinos are emitted per second from a typical PWR unattenuated and in all directions

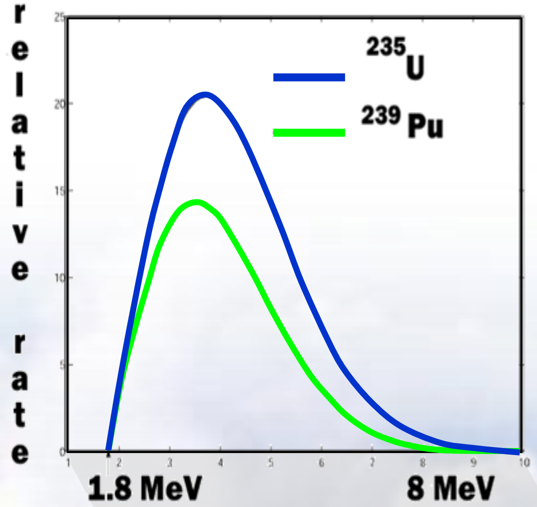
Detected rates are quite reasonable

- 10^{17} antineutrinos per square meter per second at 25-m standoff
- 6,000 events per ton per day with a perfect detector
- 600 events per ton per day with a simple detector (e.g., SONGS1)

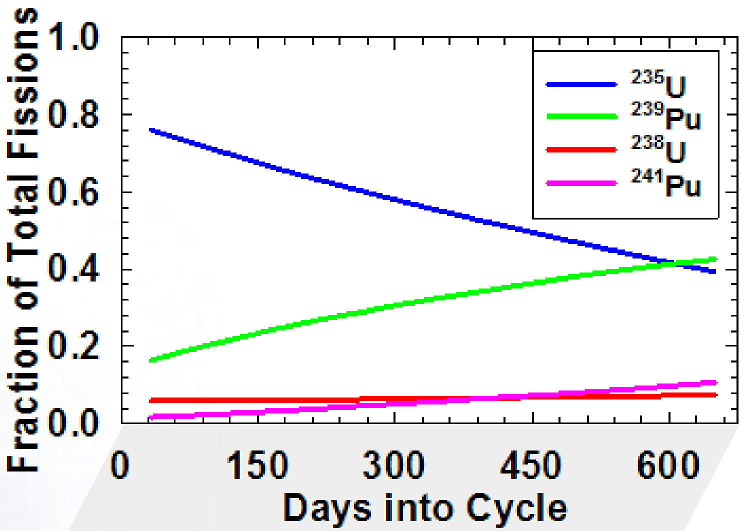
Example: detector total footprint with shielding is 2.5 meter on a side at 25-m standoff from a 3-GWt reactor

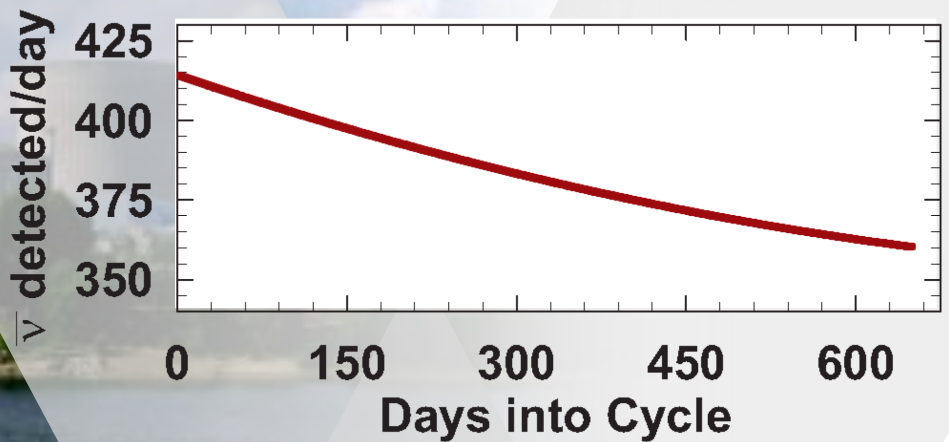
The Antineutrino Rate varies with Isotope

The energy spectrum and integral rate produced by each isotope is different



The fuel of a PLWR evolves under irradiation: ^{235}U is consumed and ^{239}Pu is produced



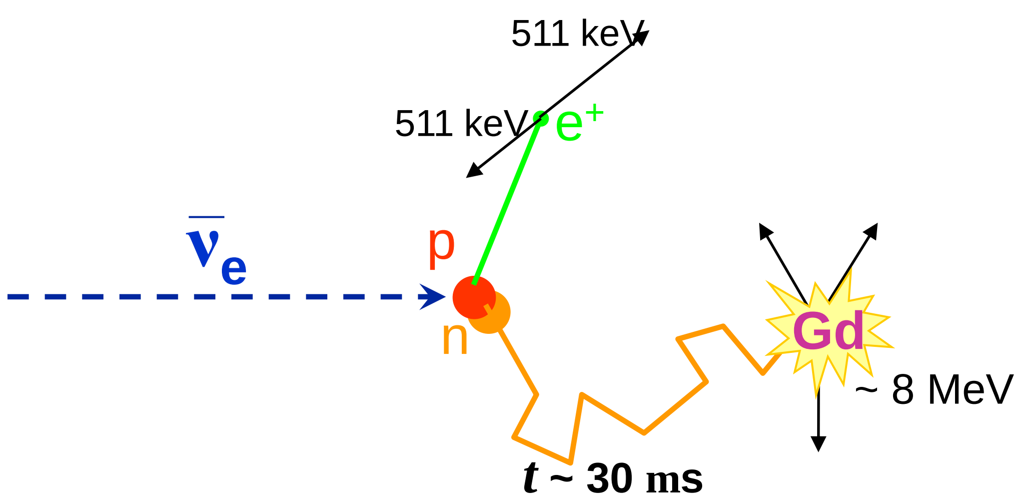


Antineutrino Detection: Standard Detector Technology

- **We use the same antineutrino detection technique used to first detect (anti)neutrinos:**

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- **Standard detectors of gammas and neutrons are sufficient to find this correlated signature**



prompt signal + n capture on Gd

- **Positron**
  - **Immediate**
  - **1- 8 MeV (incl 511 keV gs)**
- **Neutron**
  - **Delayed (t = 28 ms)**
  - **~ 8 MeV gamma shower**

Project Goals

<u>Simulation/Analysis</u>:

Study the sensitivity of antineutrino monitoring techniques and help generate future detector requirements

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<u>Experiment</u>:

"… demonstrate the practical utility of above-ground antineutrino detectors as a new tool for reactor safeguards and cooperative monitoring."

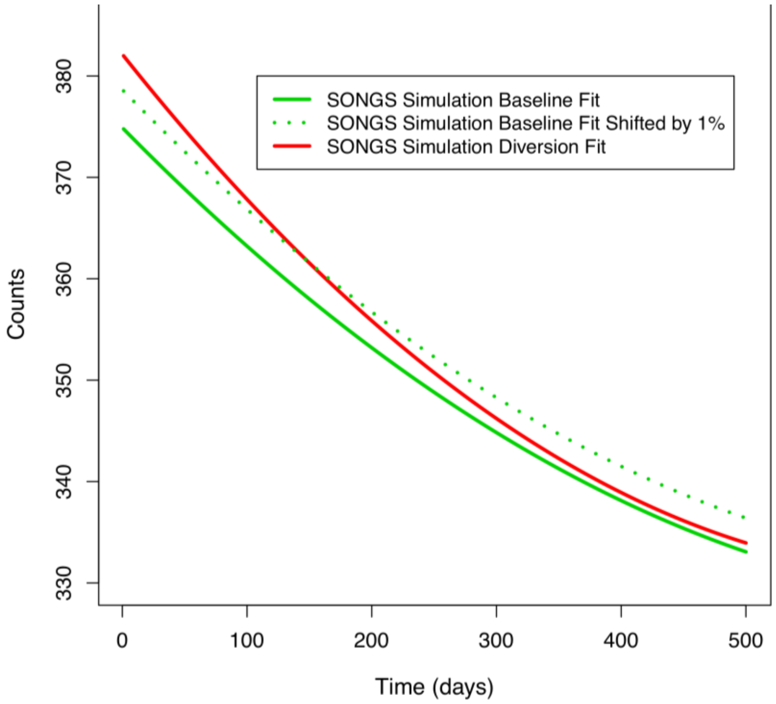
Our demonstration standard: Deploy a detector that can observe a reactor ON/OFF transition with:

3s statistical uncertainty within 7 days
5s statistical uncertainty within 30 days

<u>Relevant Requirement for Pu Production Detection:</u>

.."Quantify how much weapon-useable plutonium can be, is being, or has been produced in a reactor of interest over a given period of time.."

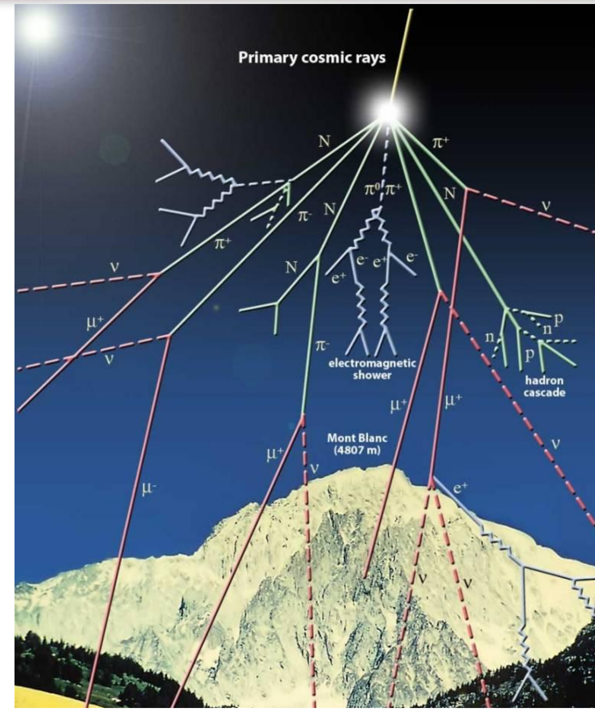
Summary of Sensitivity Studies



- Removal of 70 kg of Pu can be discovered with 0.95 probability/0.05 FP, in 90 days with the same footprint detector as SONGS1, but 3x better intrinsic efficiency
  - Similar detectors have already operated (Rovno) and we are designing a detector with the required features.
- A 1% upward shift in the reported or actual power would reduce the probability of detection from 0.95 to 0.23 (FP = 0.05)
  - Continued analysis of the entire 500 day cycle would still detect diversion with probability 0.99 - even with the thermal power shift (FP = 0.05)
  - A reported 1% shift in the thermal power is itself suspicious
- Neutrino spectrum analysis can in principle remove the ability to mask diversion using a power shift – study is underway

Aboveground Challenge: Increased backgrounds

- **Without overburden, an aboveground detector is exposed to:**
  - **An increased muon rate**
  - **Hadronic showers**
  - **Electromagnetic showers**
  - **Secondary particles produced by all of the above in the detector and its surroundings**
- **Belowground (only a few meters) many of these cosmic backgrounds are significantly reduced**
  - **SONGS1 design would not have survived aboveground backgrounds**
- **A shield can control backgrounds more simply than detector design**
  - **Need to reduce neutron impact is severe**
  - **Constructed a high-quality shield within a transportable 20’ shipping container**



2 Detector Technologies:
Different Methods of Background Rejection

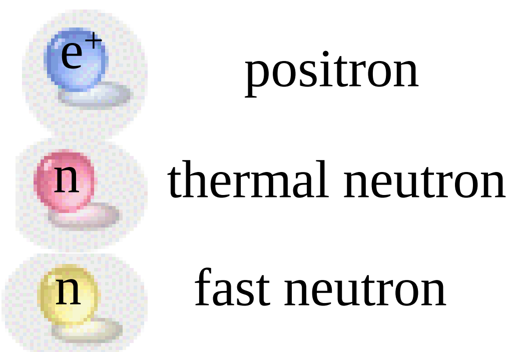
The "Smart" (complex) Detector: Segmented Scintillator with Particle Identification (PID)

Identify and reject:

- **Fast neutrons**
- **Gamma-rays**

Explicitly tag final state products:

- **Positron**
- **Thermal neutron (capture)**



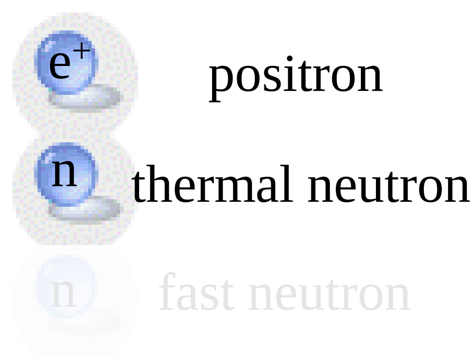
The "Dumb" (simple) Detector: Gd-Doped Water Cerenkov

Indifferently sensitive to:

- **Positron**
- **Neutron (captures)**
- **Gamma**

Insensitive to an important class of background:

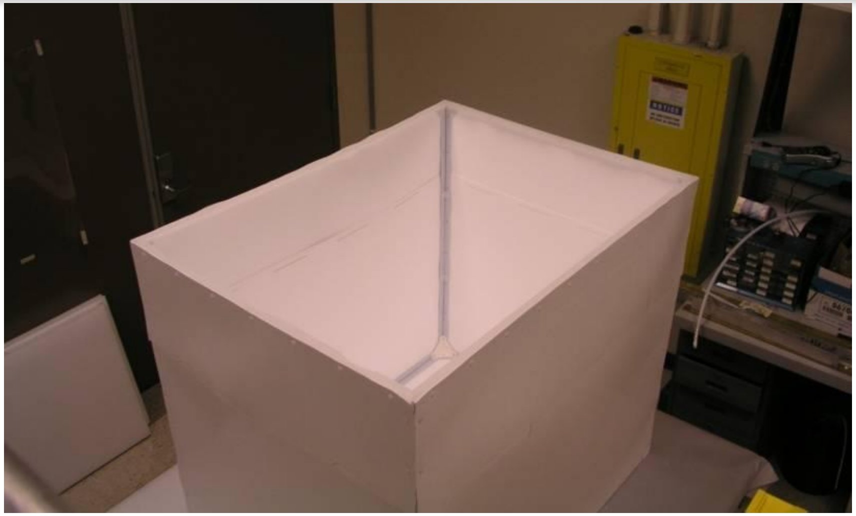
- **Fast neutron recoils**



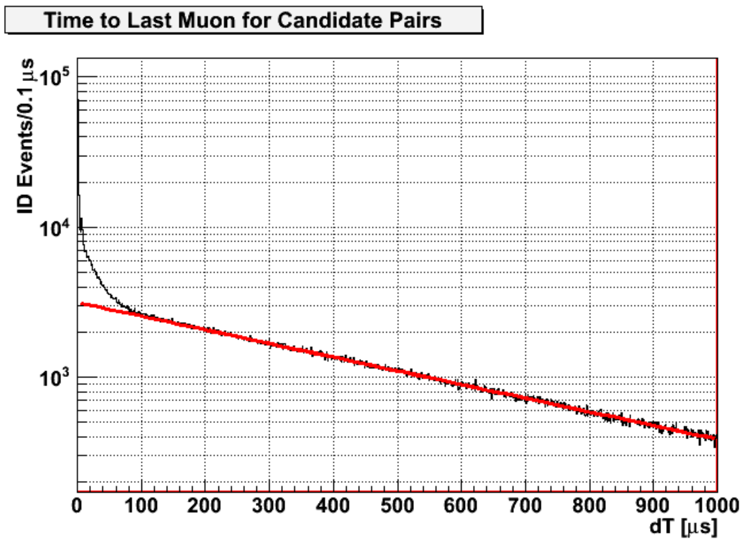
First Try: No Particle Identification, Just Physics

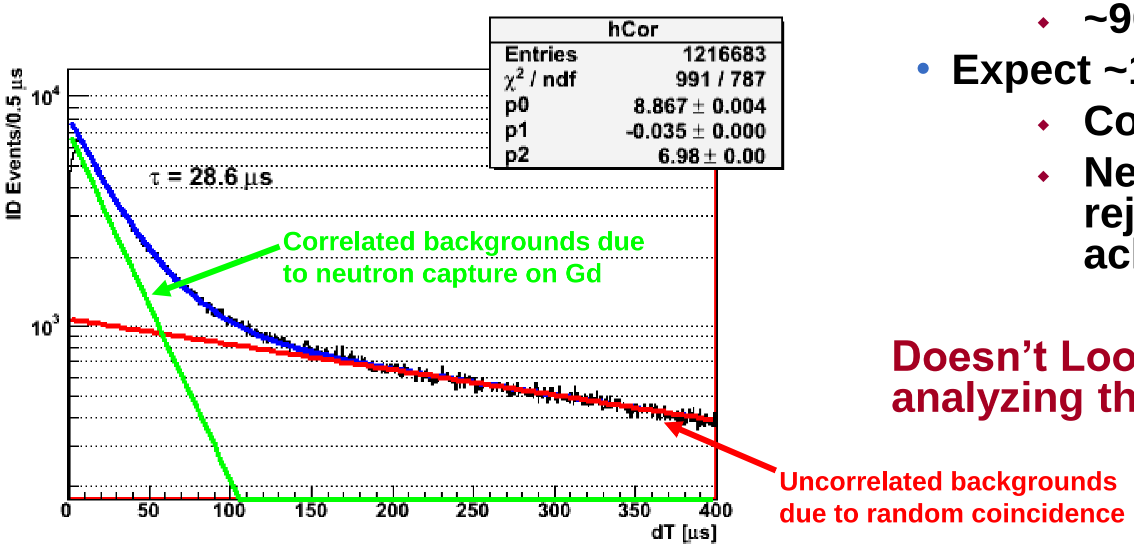
A Water Based Antineutrino Detector

- Water Cerenkov used for *neutrino* detection
  - Deployability – Environmentally safe
  - Reduced sensitivity to fast neutron backgrounds
  - Poor energy resolution, due to:
    - Directionality of photons
    - Low number of photons
    - Minimum electron/positron energy required to produce any photons
- Addition of a neutron capture agent (~0.2% $GdCl_3$) allows for antineutrino detection via inverse beta decay
- Previous small-scale test showed promise so we have improved it
  - 4 x larger volume to ~1 ton effective
  - Better light collection efficiency



Preliminary Water Detector Analysis



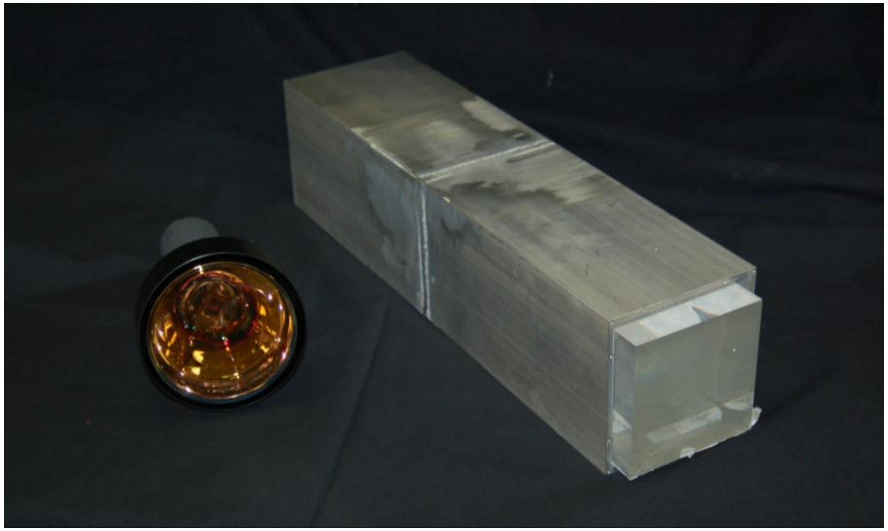


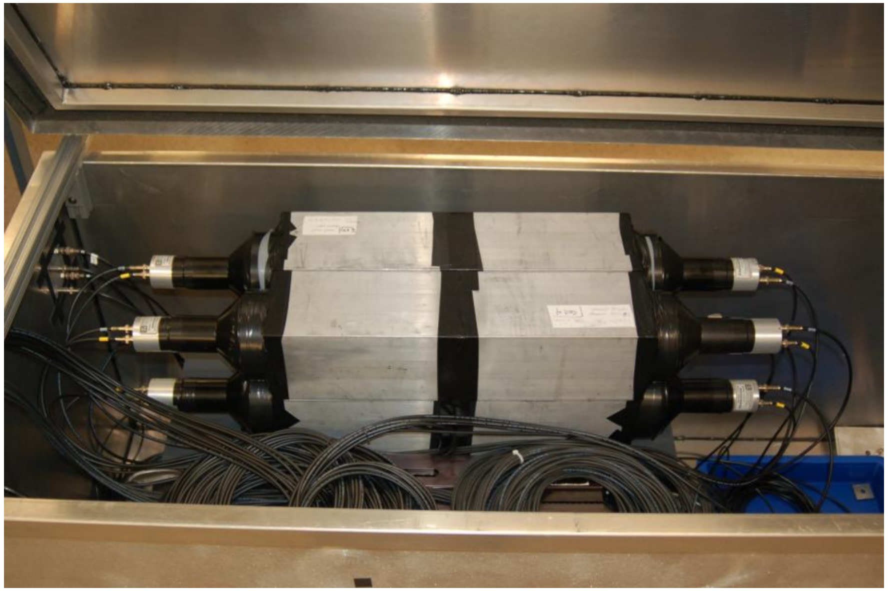
- Initial operation of muon system looks good
  - >98% efficiency to detect muons
  - 100 μs veto around muon detection eliminates most cosmic induced showers
    - Gives 21% deadtime
- Clean separation of correlated events from uncorrelated backgrounds through timing
  - Time constant of ~28 μs for neutron capture on Gd
- Preliminary Analysis
  - Correlated background: ~40,000 ev/day
    - ~90,000 without muon veto
  - Expect ~100 $\overline{\nu}_e$ events/day
    - Could get 2 sigma in 14 days
    - Need at least a factor 4 further rejection of backgrounds to achieve our original goal

Doesn't Look so good….but we are still analyzing the full data set

Second Try: PID with Segmented Scintillator Detector

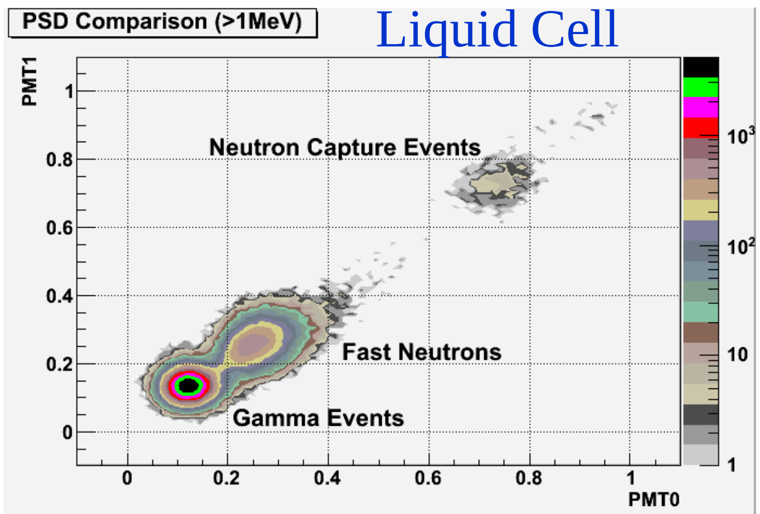
- **Individual Segments contain organic scintillator with ZnS:Ag/^{6}LiF) screens on outer surface**
  - **3 cells with Plastic scintillator**
  - **1 cell with Liquid scintillator**
- **Use of ZnS:Ag with ^{6}LiF allows identification of neutron capture**
  - **ZnS:Ag is sensitive to alpha from n-capture on Li**
  - **Very slow scintillator time constant (~100ns) allows pulse shape discrimination to separate n-capture from γ events**
- **With Liquid Scintillator, proton recoils are also easily identified**
  - **Allows a comparison to test need for additional rejection**
- **Ultimate design would be for 16 cells but this 4-cell prototype was sufficient for first testing**

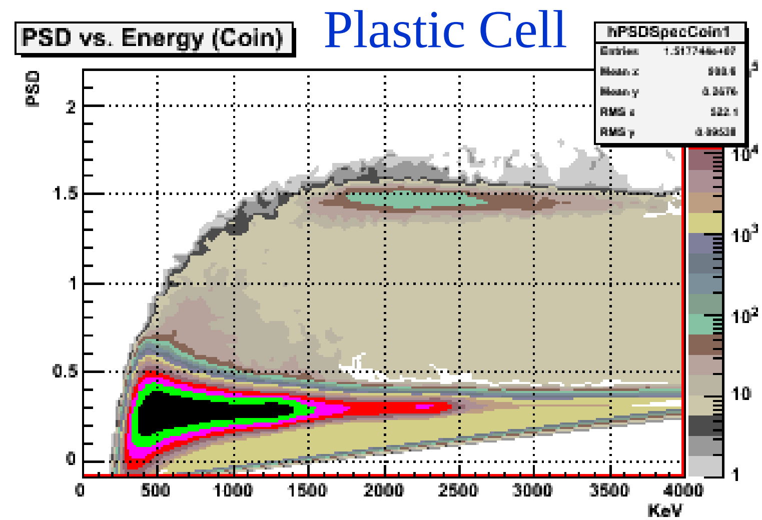




Particle Identification (PID)

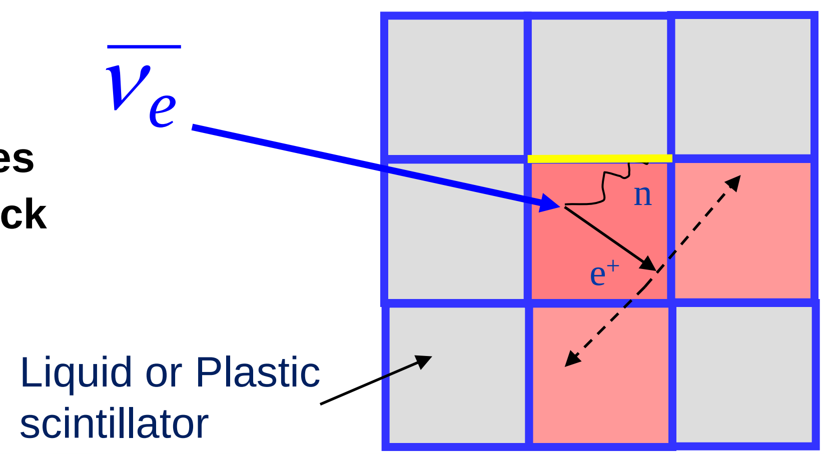
Neutron identification through Pulse Shape Discrimination (PSD)



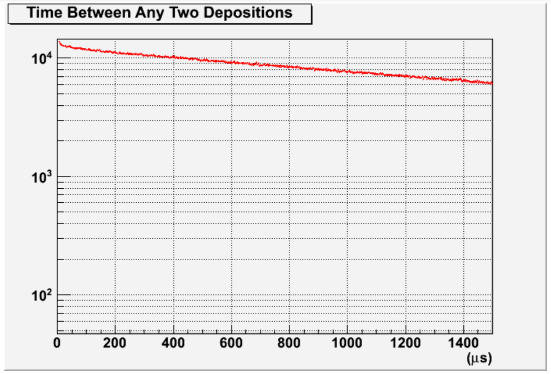


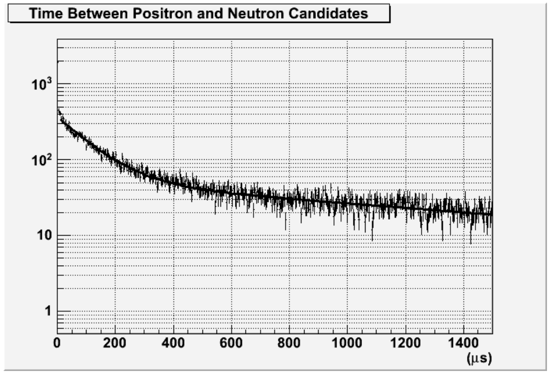
Positron Identification through Topology

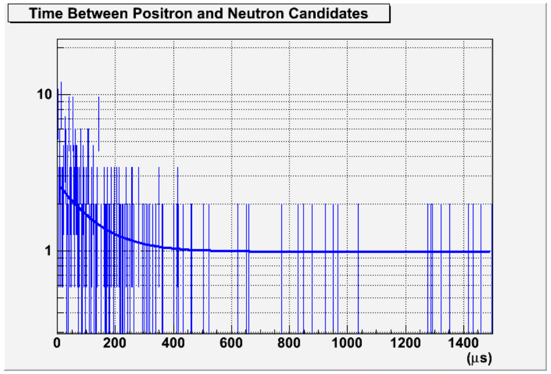
- Positrons are rare in nature
  - Deposit most of their kinetic energy very quickly through standard ionization losses
- Positrons will annihilate into two back-to-back 511 keV gammas
  - Very distinctive signature
  - Gammas will travel ~2-5” through most scintillators



First Analysis of Reactor Off Data







No PID
225,200 ev/day

Only Neutron PID
1,830 ev/day

Max PID info
23 ev/day

- **Detector efficiencies look reasonable**
  - **Overall efficiency 0.5 – 15%**
    - **Compare to 10% for SONGS1**
  - **N-capture efficiency of 18%**
  - **Positron efficiency 2—87%**
- **Detector Performance looks stable**
- **Background rates are reasonable for a possible observation of reactor transition**
  - **2 – 4 orders of magnitude rejection**
  - **2 methods of analysis agree**
- **Based on expected ν_e signal, expect 3 sigma detection in 4 – 6 weeks**
  - **Expect 1 – 37 ev/day**
  - **Scaled to 16-cell array, this would satisfy the original goal**
- **Very encouraged by technology performance**

Conclusion

- **Previously demonstrated short and long term relative monitoring of power operational status, and fissile content in reactors**
- **This project aims to expand the range of utility by enabling above ground deployment**
- **We have examined several powerful tools to achieve the required ~3-5 orders of magnitude suppression of background**
- **The hoped for demonstration of both water and scintillator paths will permit design trade-offs for end users**
- **Sensitivity studies have shown that a reasonable facsimile of the SONGS1 detector is sensitive to at least 70 kg Pu diversion in 90 days**