SAND2011-7352C

Neutron Detection and Identification using ZnS:Ag/^{6}Li in Segmented Antineutrino Detectors

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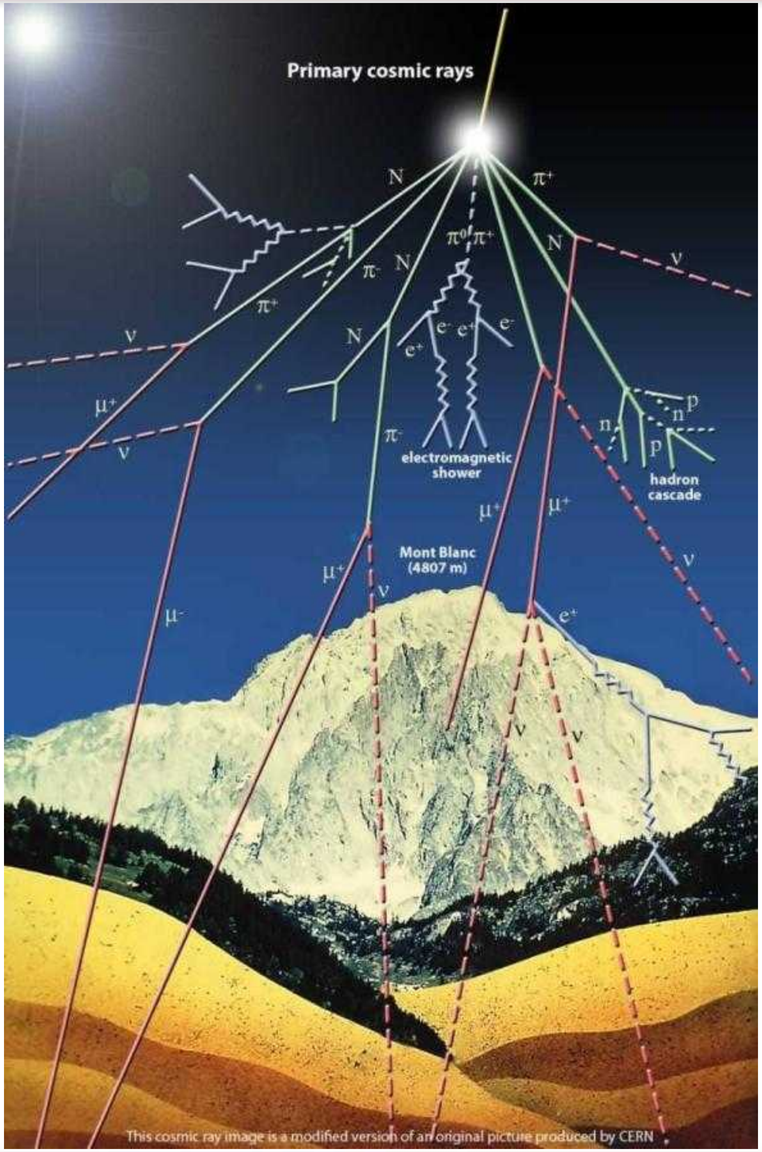
A Novel Technology for Reactor Safeguards

- Antineutrino Monitoring of Reactors provides independent measurements of Thermal Power and Fissile Inventory
  - Non-intrusive with NO connection to plant systems
  - Continuous Remote Monitoring
  - Highly tamper resistant
- Potential Applications to Present and Future Safeguards
  - Independent Confirmation of Operator Declarations
  - Reduction in needed Inspector visits
  - Provide fissile content information for Next-Generation fuel cycles (MOX, Th, bulk process)

Primary Focus: Aboveground

- 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
- Fast neutron calculation is sobering
  - Proton recoils of >10 MeV will look like positron signal
  - Calculation based on Hess Spectrum and differential n-p cross-section
    - Expect $5x10^5$ events per day (~6Hz) per ton of LS (unshielded)
- A shield can control backgrounds more simply than detector design
  - Neutron shielding and muon vetos have been improved from SONGS1
- Particle Identification can be a powerful tool
  - Identify and reject fast neutrons and multi-neutron events
  - Explicitly tag final state Positron and thermal neutron (capture)

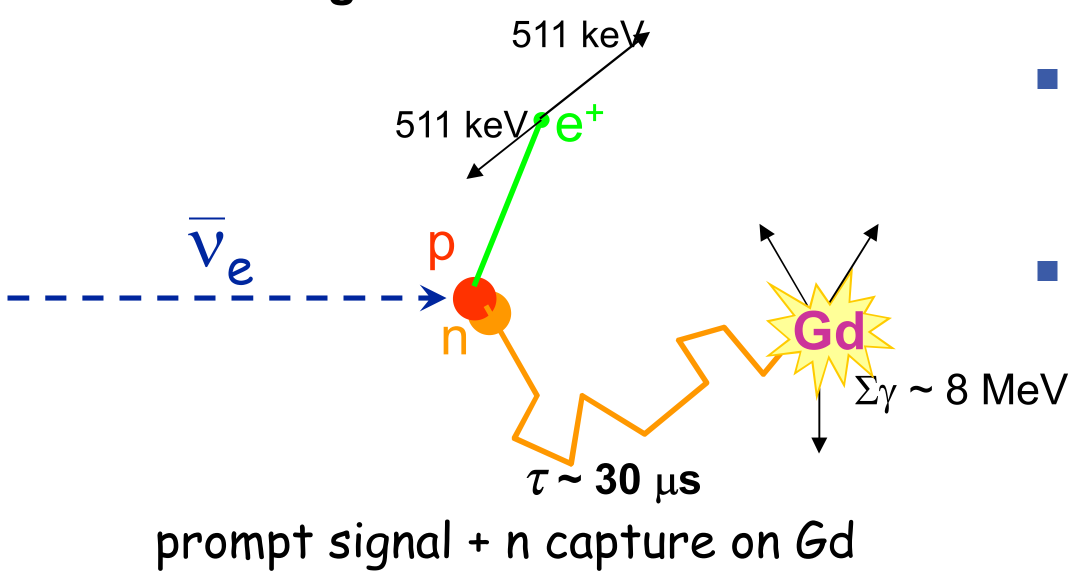


Standard Detection of Inverse Beta-decay

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

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

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

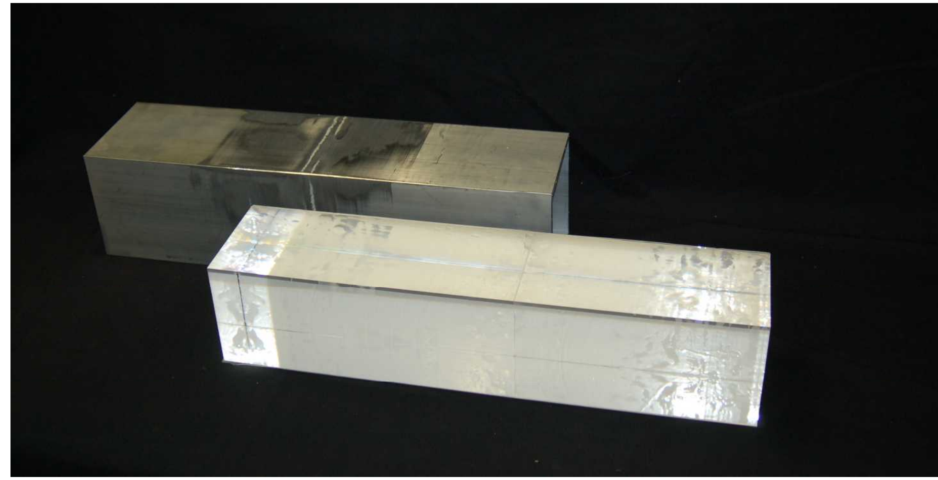


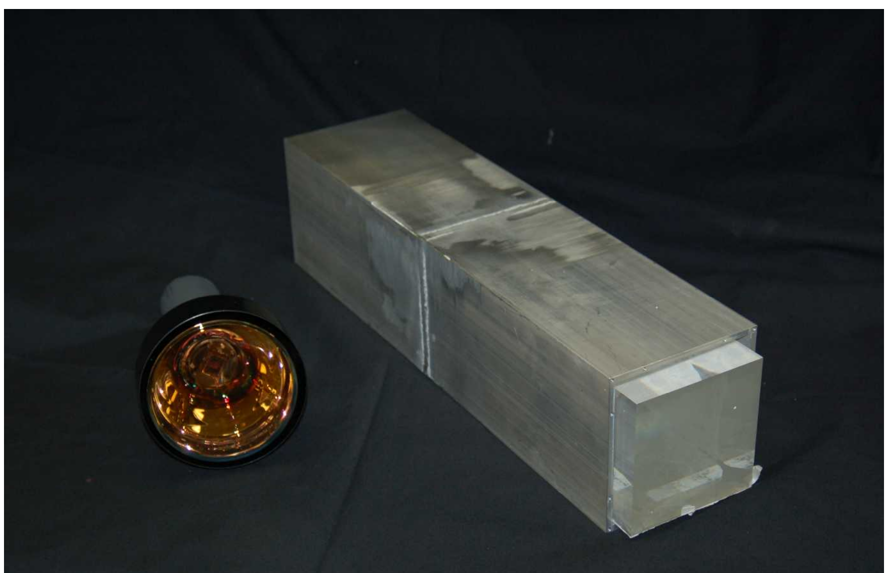
- **Positron**
  - Immediate
  - 1- 8 MeV (incl 511 keV γs)
- **Neutron**
  - Delayed (τ = 28 μs)
  - ~ 8 MeV gamma shower

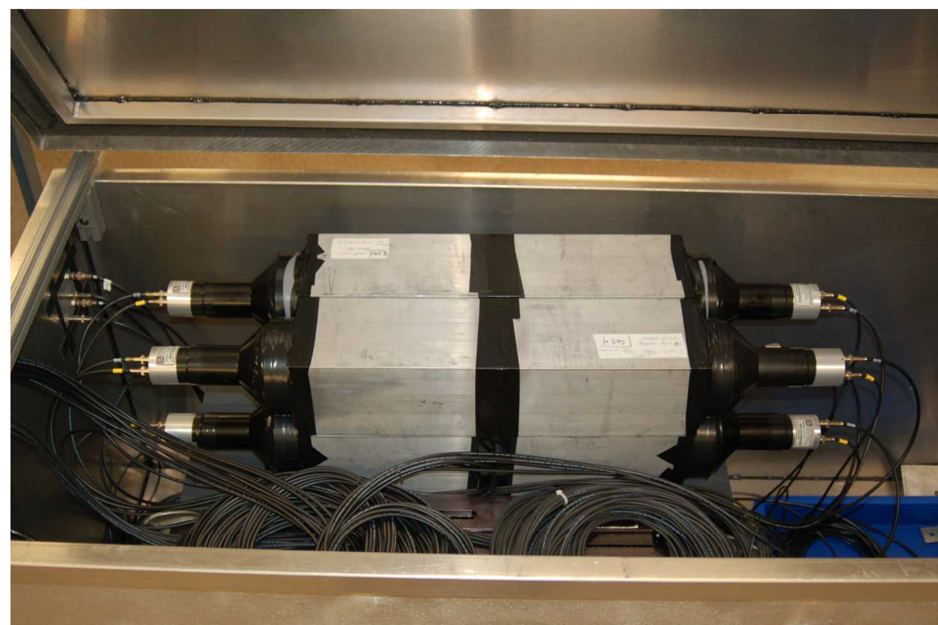
(200 μs and 2.2 MeV for KamLAND)

- Gadolinium yields poor detection efficiency for compact detectors…Li?

Our New Segmented Scintillator Detector

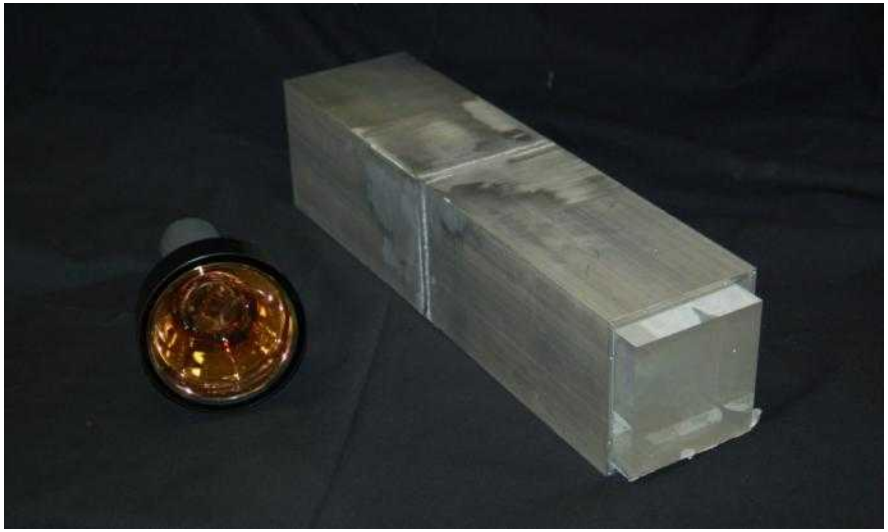


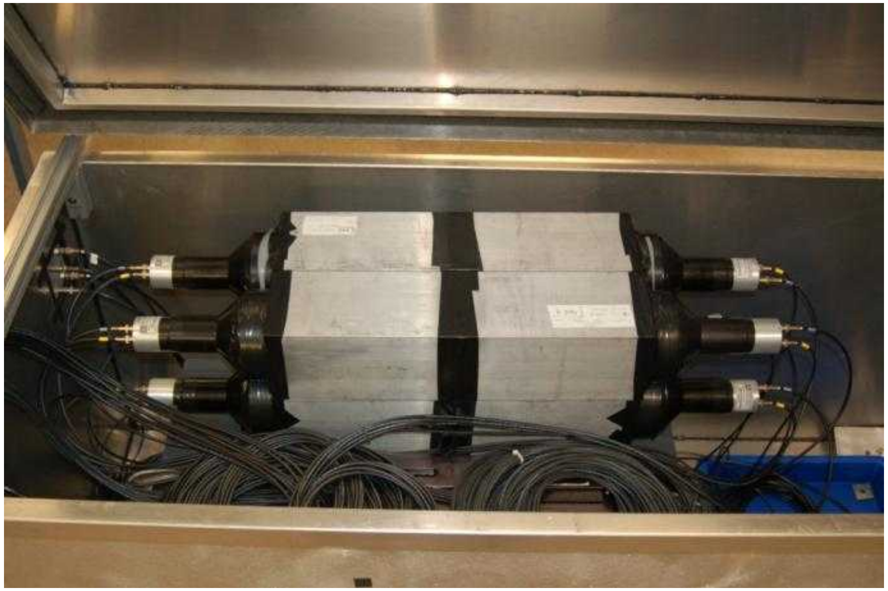




PID with Segmented Scintillator Detector

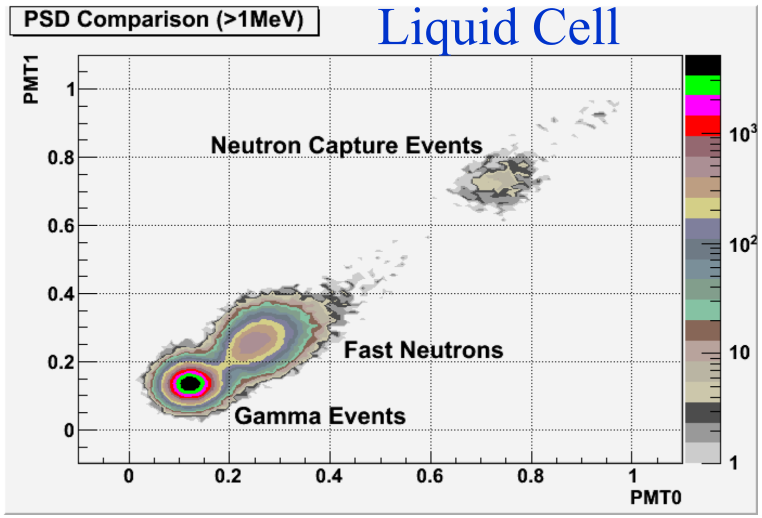
- Individual Segments contain organic scintillator with ZnS:Ag/^{6}LiF screens on outer surface
  - 3 cells with Plastic scintillator
  - 1 cell with Liquid scintillator
- Use of ZnS:Ag with ^{6}LiF allows identification of neutron capture
  - ZnS:Ag is sensitive to alpha from n-capture on Li
  - Very 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

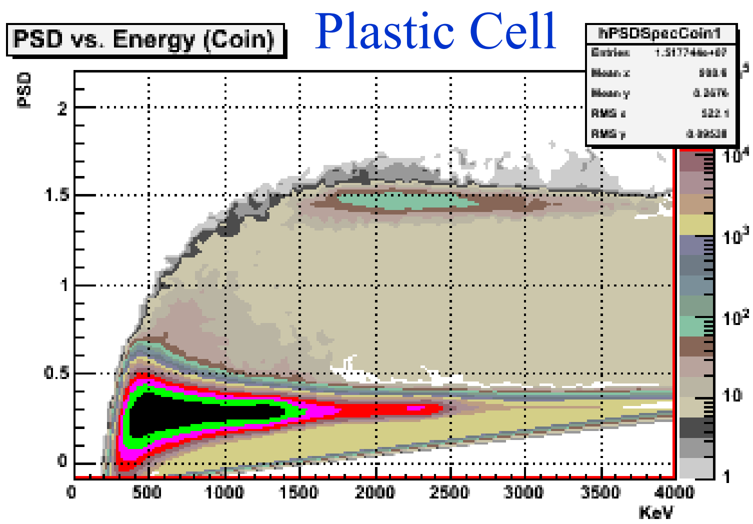




Particle Identification (PID)

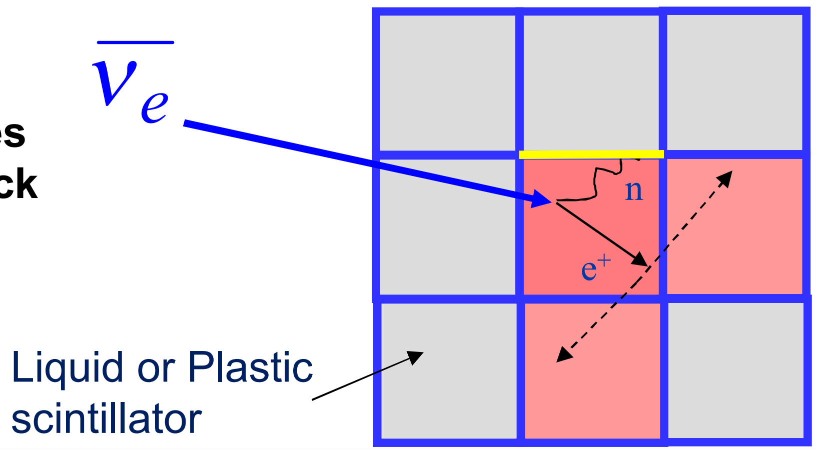
Neutron identification through Pulse Shape Discrimination (PSD)





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



Containerized Shield for Aboveground Deployment

December 2009

February 2010

2" Plastic Scintillator Muon Veto

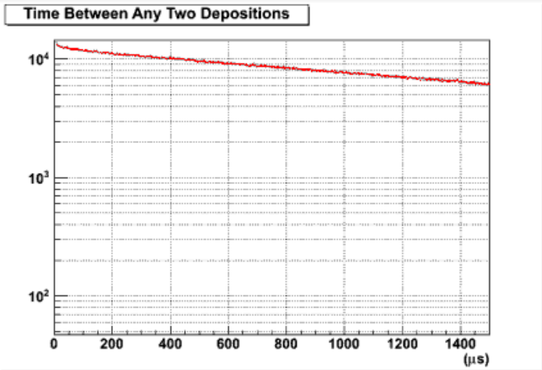
1" Borated Poly with Mu-metal Liner

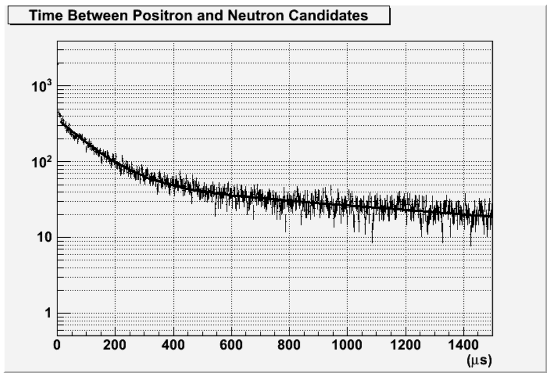
45 cm HDPE Neutron Shield

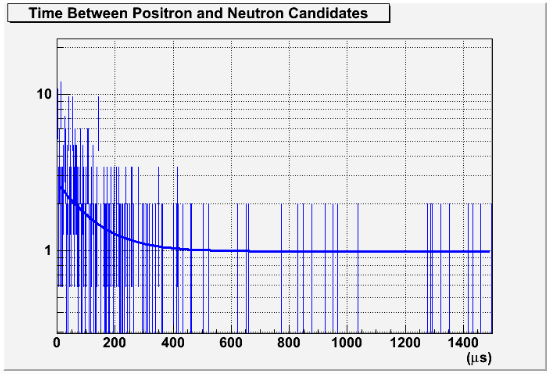
Central Detector
+ secondary containment

Final Deployment at SONGS

First Analysis of Reactor Off Data







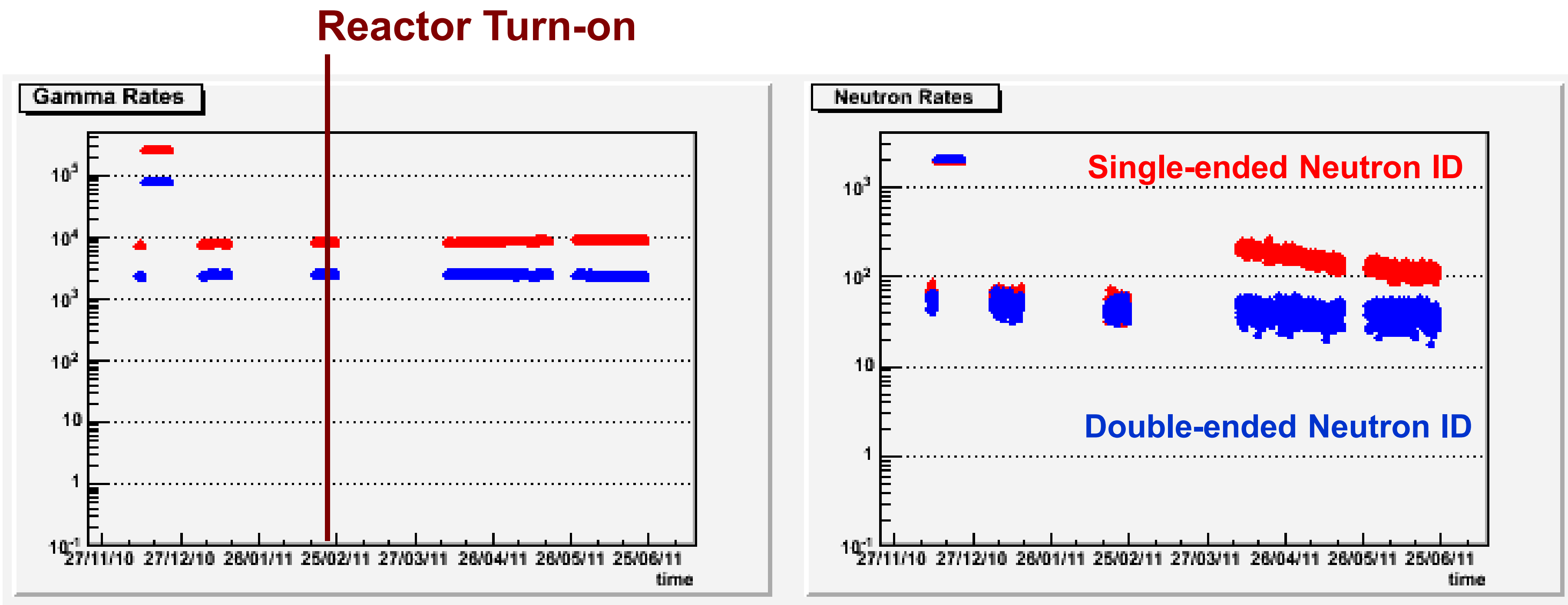
No PID
225,200 ev/day

Only Neutron PID
1,830 ev/day

Max PID info
23 ev/day

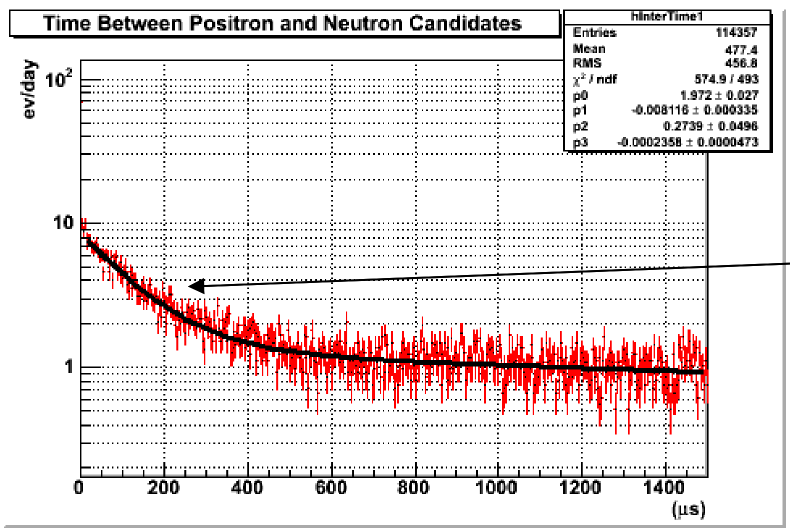
- **Detector Performance looks stable**
  - **Detector efficiencies look reasonable**
    - **N-capture efficiency of 18%**
    - **Positron efficiency 2—87%**
- **Background rates are reasonable for a possible observation of reactor transition**
  - **2 – 4 orders of magnitude rejection**
  - **2 methods of analysis agree**
- **Based on expected $\overline{\nu}_e$ signal, expect 3 sigma detection in 4 – 6 weeks**
  - **Expect 1 – 37 ev/day**
- **Very encouraged by technology performance**

Challenging Operation Environment



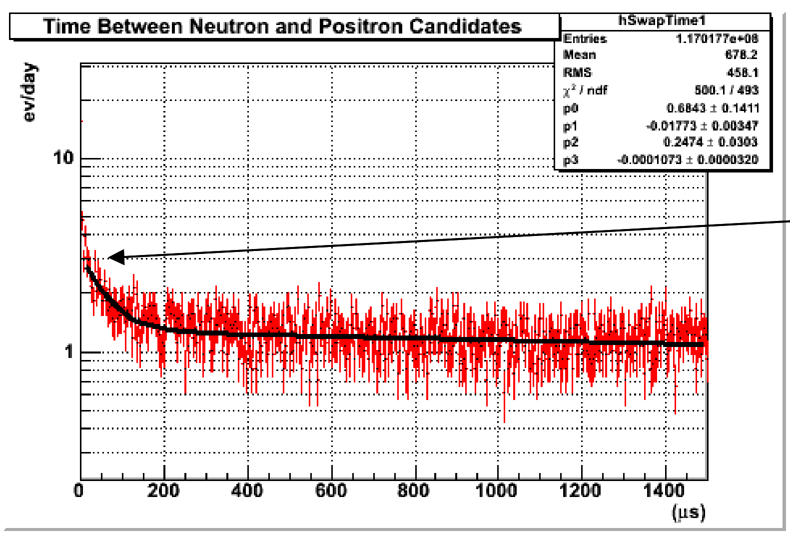
- **Multiple Hardware failures**
  - **Replaced UPS twice**
  - **Loss of electrical power**
  - **HV spikes caused failure of PMT Bases**
- **After Change of HV, significant response change to detector**
  - **Neutron detection efficiency down by ~30%**
  - **Gamma detection efficiency is stable to < 4%**
  - **Contamination by re-triggering in some cells**

The Power of Particle ID



Standard Inter-event Time distribution allows for correlated event extraction

Exponential matches expected Li Capture time constant ~100us



“Swapped” Time distribution allows for independent extraction of un-correlated backgrounds

Unexpected exponential (time constant ~30us)

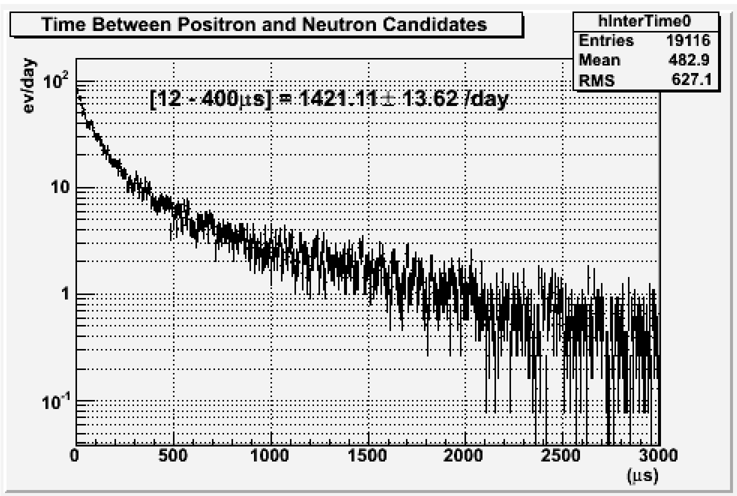
matches Gd capture in Water detector

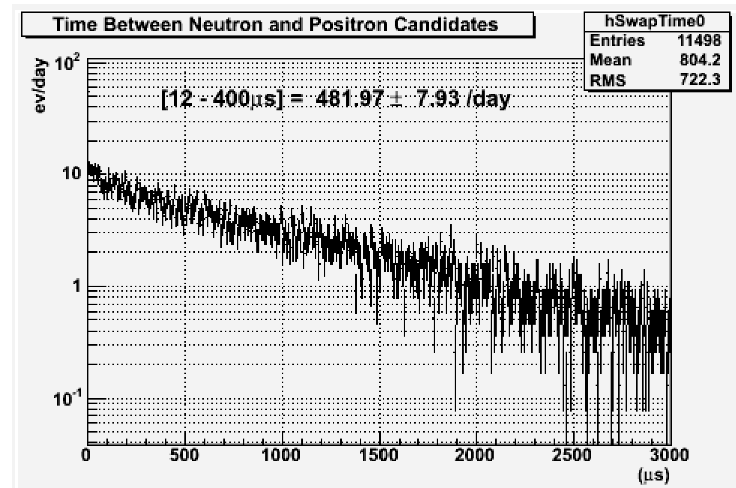
Events in Water contribute 30% of correlated events in the segmented detector!!!

Fully Corrected/Calibrated Data (using only neutron PID)

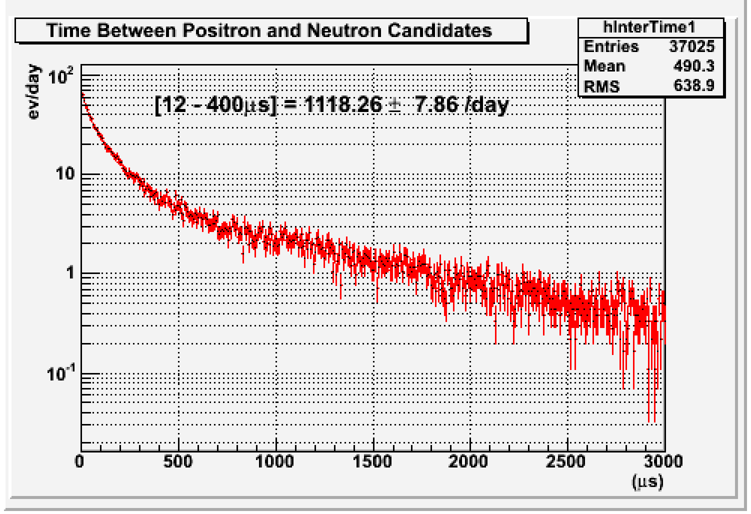
Signal | **Background**

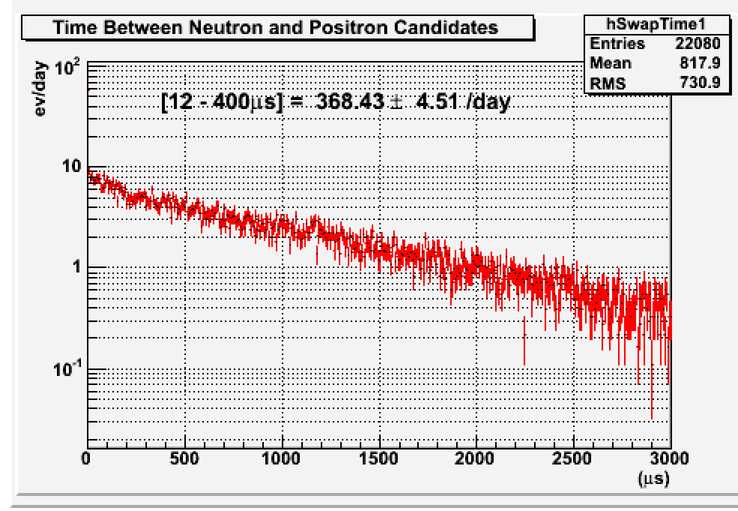
Reactor Off





Reactor On

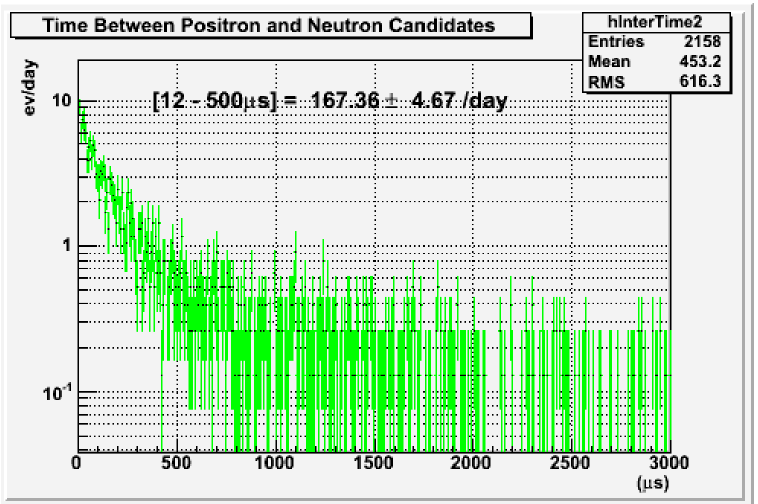


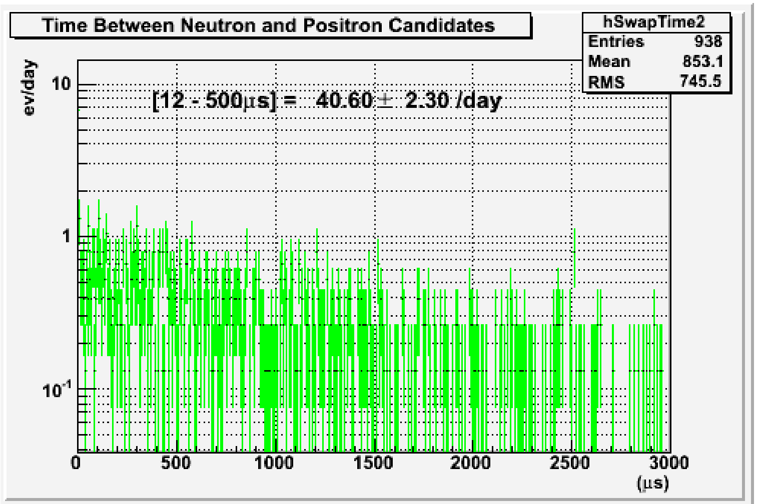


Fully Corrected/Calibrated Data (using both neutron and positron PID)

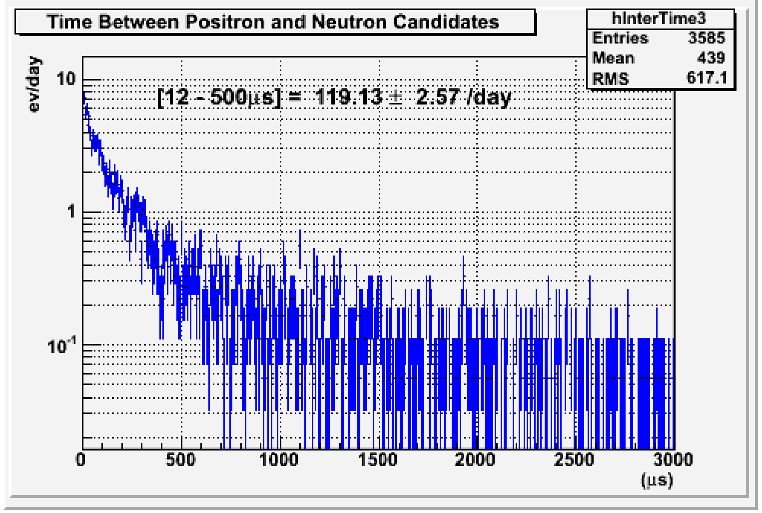
Signal | **Background**

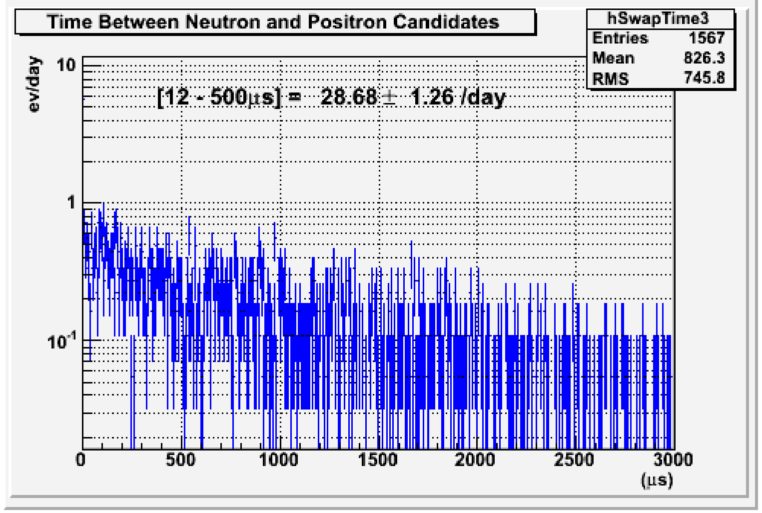
Reactor Off





Reactor On

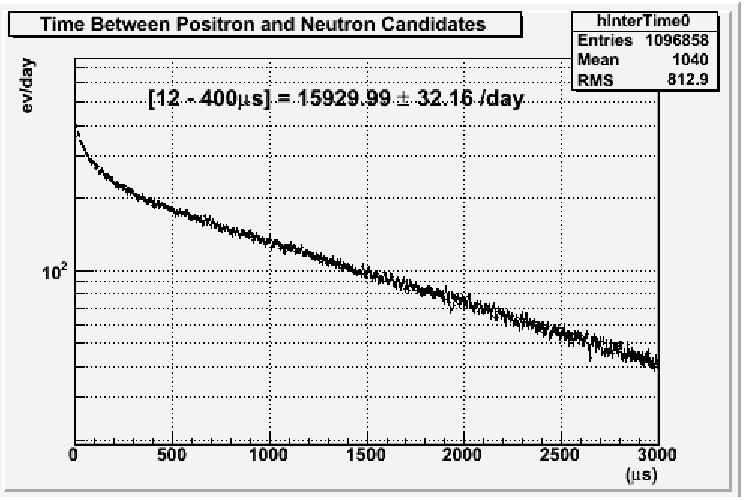


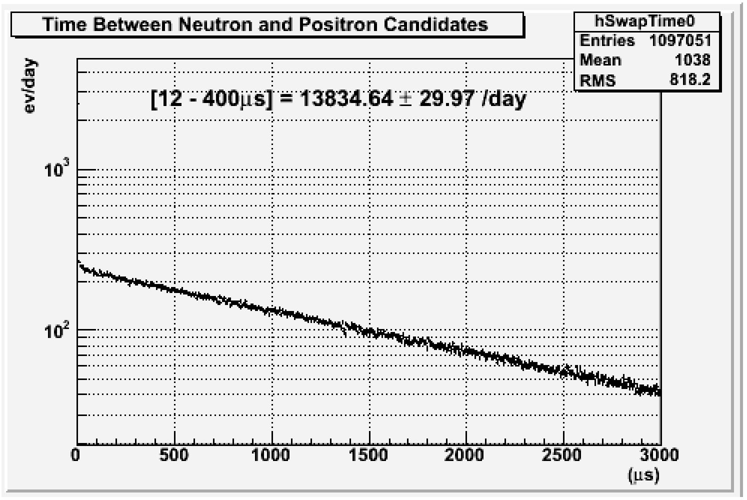


Operation Outside of Shield

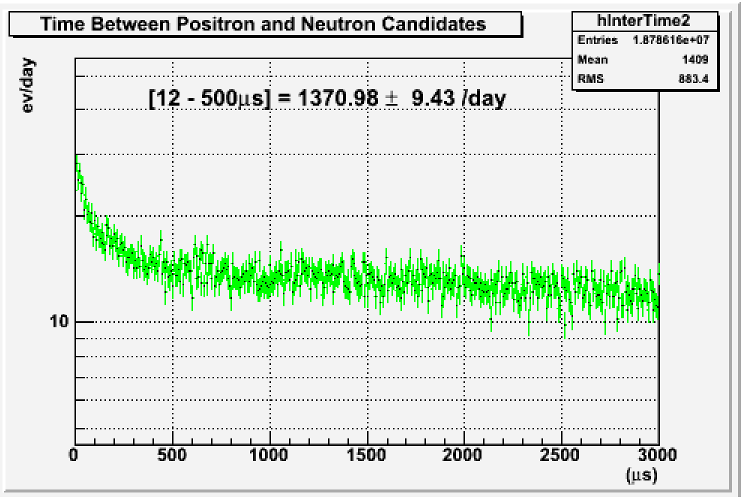
Signal | **Background**

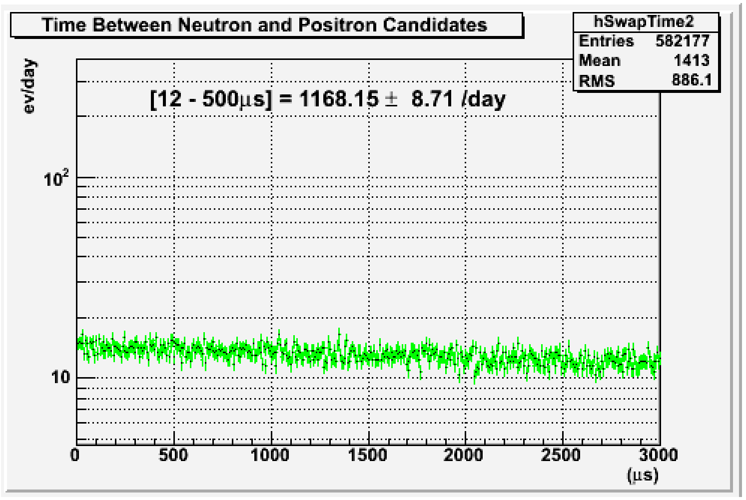
Only Neutron PID





Neutron and Positron PID





Data Comparisons (events/day)

Event Def.	Reactor Off			Reactor On		
	Correlated	Un-correlated	Subtracted Signal	Correlated	Un-correlated	Subtracted Signal
1)	1421 ± 14	482 ± 8	939 ± 16	1118 ± 8	368 ± 5	750 ± 9
2)	167.4 ± 4.7	40.6 ± 2.3	126.8 ± 5.2	119.1 ± 2.6	28.7 ± 1.3	90.4 ± 2.9

- Measured Errors on Subtracted Signal are already below expected antineutrino signal
  - Dominated by limited 8-day Reactor Off data
  - Prototype 4-Cell array is still highly inefficient
- Unshielded Operation Shows Promise
  - Uncorrelated rates increase by x 40
  - Correlated only goes up by x 2—3
  - Even 3-week unshielded operation of this small prototype has errors that are ≅ expected rate
- True comparison of Reactor On/Off data is impossible due to significant hardware changes
  - A suggestive hint is possible by scaling Reactor Off data by the ratio of uncorrelated rates
  - Consistent with changes in detection of ambient neutron and gamma rates

Event Def.	Unshielded Operation		
	Correlated	Un-correlated	Subtracted Signal
1)	15930 ± 32	13835 ± 30	2095 ± 44
2)	1371 ± 9	1168 ± 9	203 ± 13

Event Def.	Antineutrino Rate Expectation from MC
1)	37
2)	12.7

Next Step for Segmented Scintillator

	16-Cell Array		64-Cell Array	
	Increase for Event Def. 1	Increase for Event Def. 2	Increase for Event Def. 1	Increase for Event Def. 2
Increase in Mass	x 4	x 4	x 16	x 16
Neutron Capture Efficiency	x 2	x 2	x 2.5	x 2.5
Positron Detection Efficiency	no change	x 1.8	no change	x 2
Total Signal Increase	x 8	x 14	x 40	x 80
Total Background Increase	x 4	x 4	x 16	x 16
Improvement in S/√B	x 4	x 7	x 10	x 20

- We believe that a larger version of this detector would demonstrate reactor antineutrino sensitivity
  - Especially below ground
  - Possibly even without a shield
- This compact detector system can fit inside of a single sealed rack
  - 4-cell prototype mounted vertically
  - Single VME crate of electronics
- Scheduled to deploy this small setup to the SONGS Unit-2 Tendon Gallery later this year

Conclusion

- Very encouraged by performance of Segmented Scintillator prototype
  - Reasonable efficiencies have been achieved even with a small 4-cell detector
  - Increase to a 16 or 64 cell system would show marked improvement
- Demonstrated rejection of backgrounds
  - 3+ orders of magnitude even without an external shield
  - Ability to use PID improves understanding of background components
- Components are very robust and easy to handle
  - Looking forward to unshielded test belowground