



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

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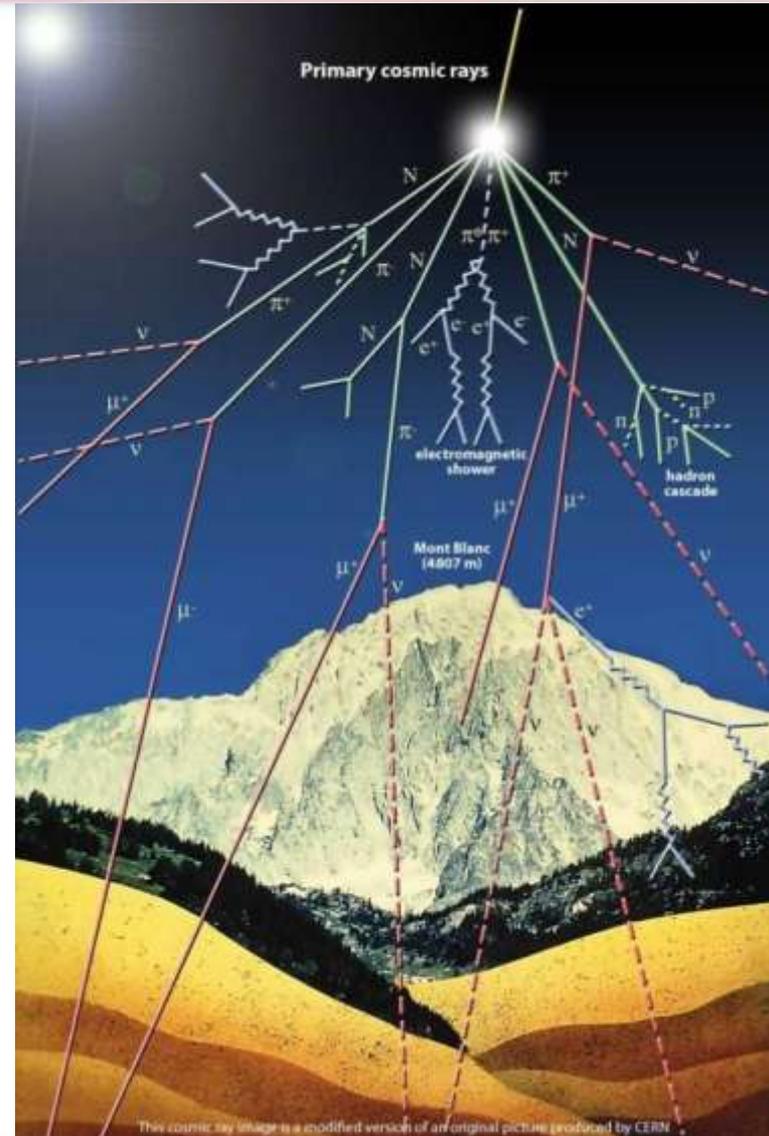
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory in part under Contract W-7405-Eng-48 and in part under Contract DE-AC52-07NA27344.

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)

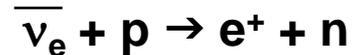
Primary Focus: Aboveground

- 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 5×10^5 events per day (~ 6 Hz) 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)

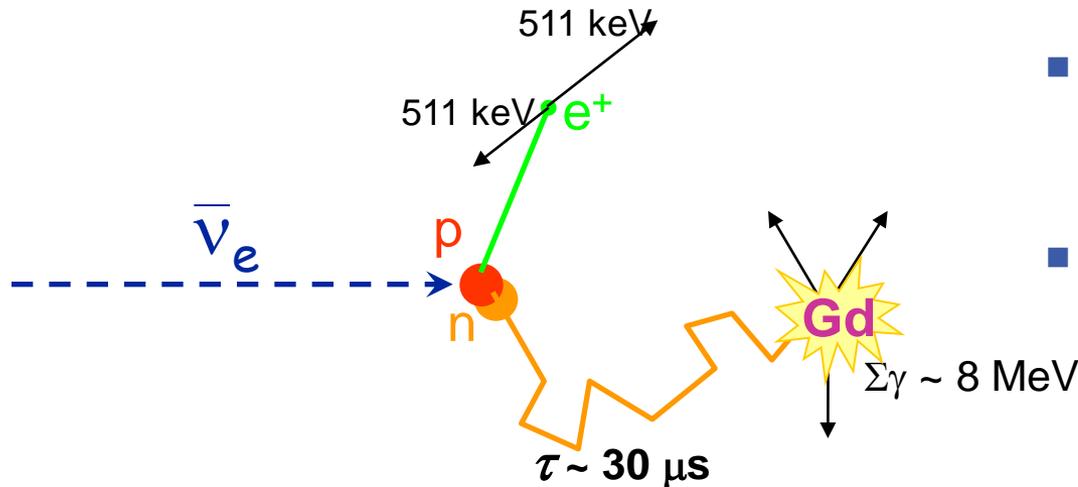


Standard Detection of Inverse Beta-decay

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



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



prompt signal + n capture on Gd

- **Positron**

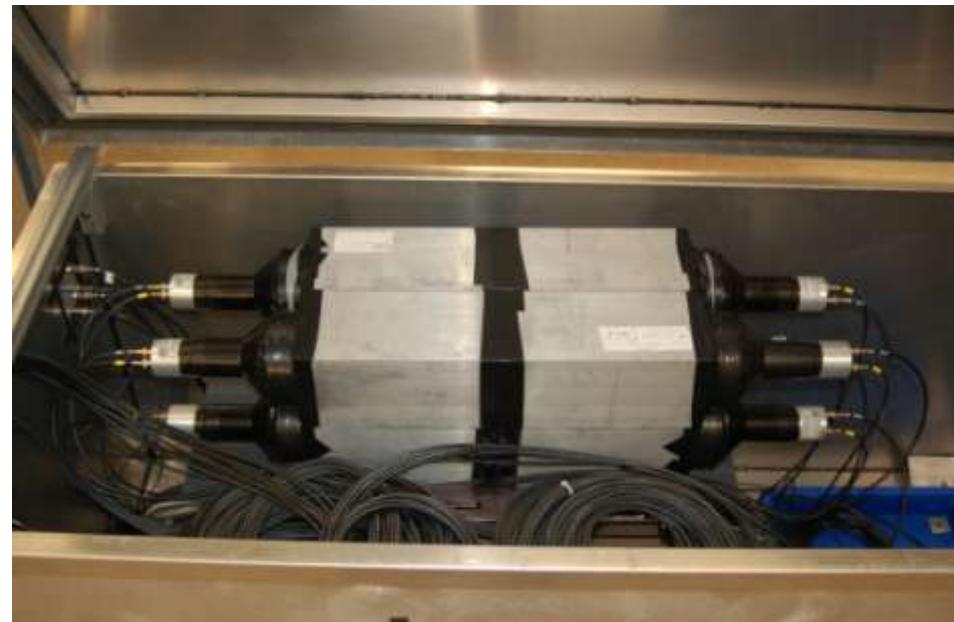
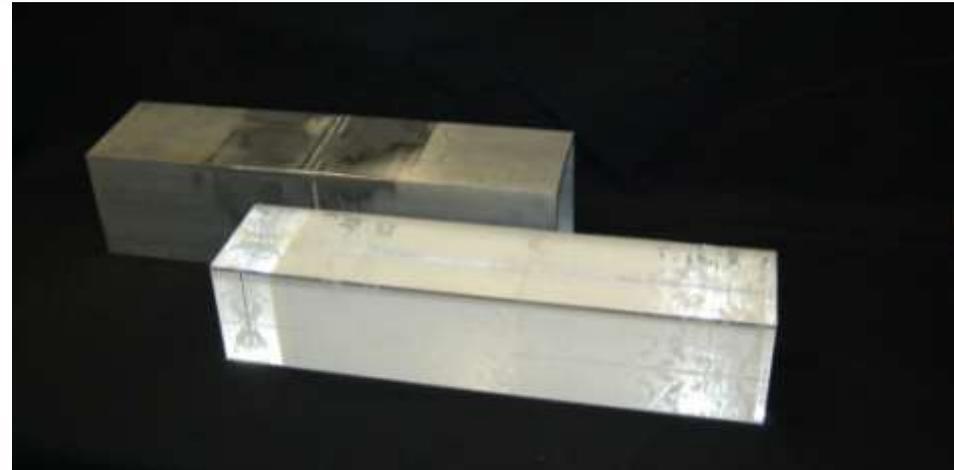
- Immediate
- 1- 8 MeV (incl 511 keV γ s)

- **Neutron**

- Delayed ($\tau = 28 \mu\text{s}$)
- ~ 8 MeV gamma shower (200 μs and 2.2 MeV for KamLAND)

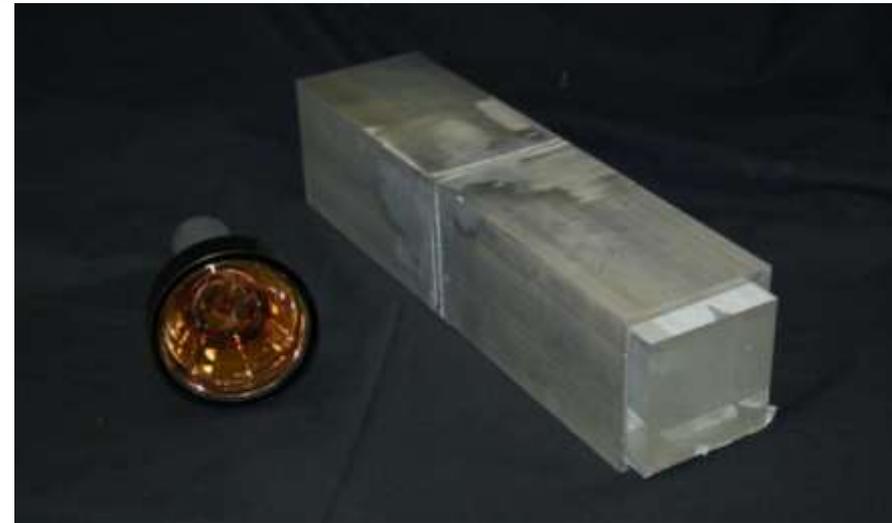
- Gadolinium yields poor detection efficiency for compact detectors...Li?

Our New Segmented Scintillator Detector



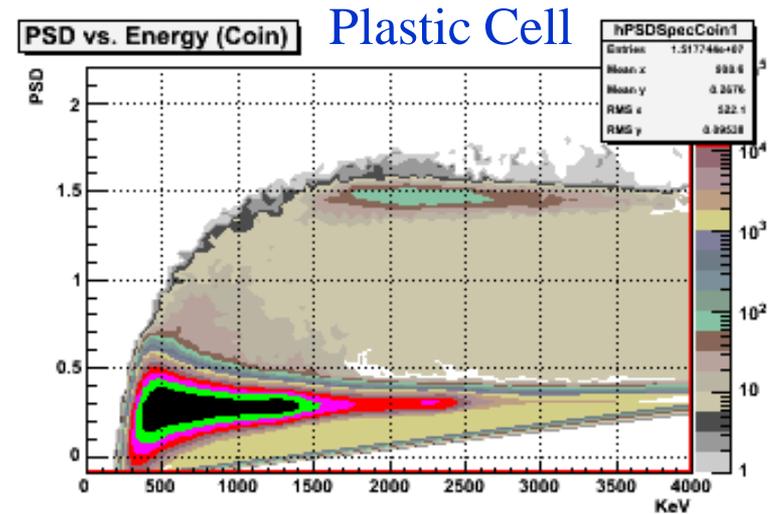
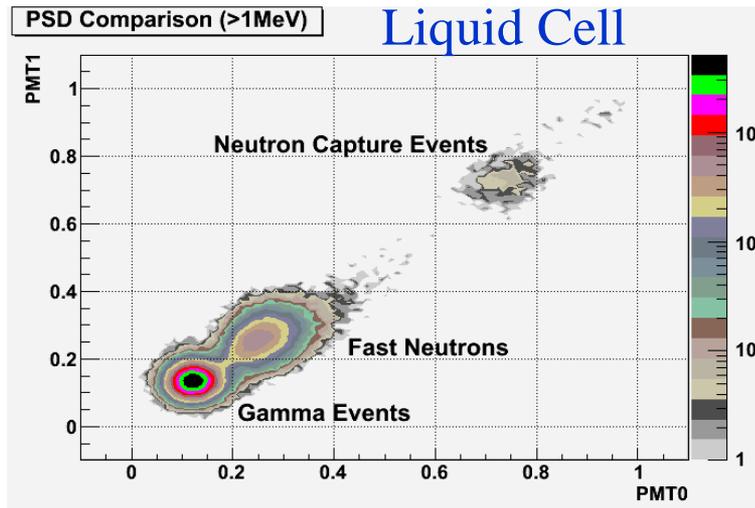
PID with Segmented Scintillator Detector

- Individual Segments contain organic scintillator with ZnS:Ag/⁶LiF screens on outer surface
 - 3 cells with Plastic scintillator
 - 1 cell with Liquid scintillator
- Use of ZnS:Ag with ⁶LiF 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



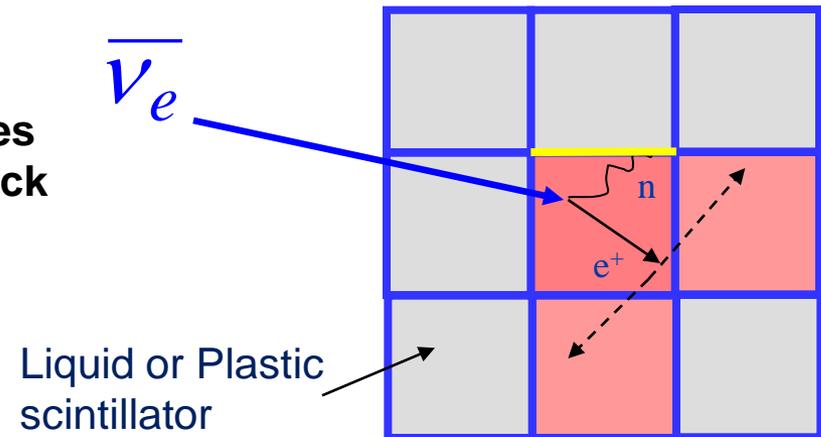
Particle Identification (PID)

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

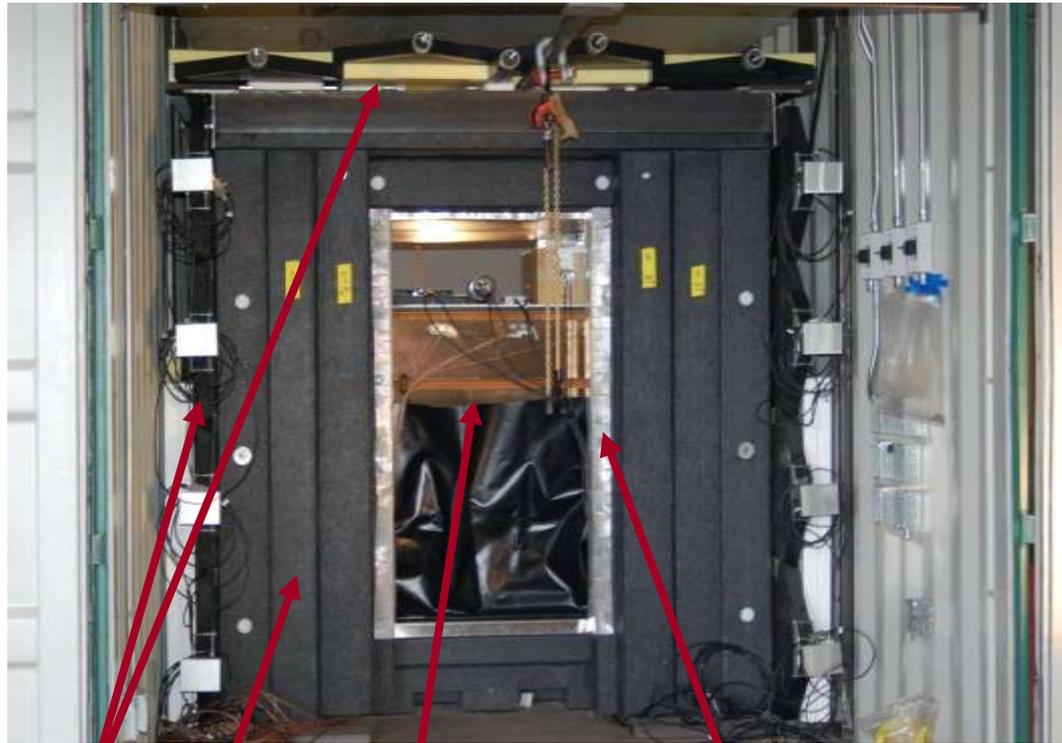


Containerized Shield for Aboveground Deployment

December 2009



February 2010



2" Plastic Scintillator Muon Veto

45 cm HDPE Neutron Shield

**1" Borated Poly with
Mu-metal Liner**

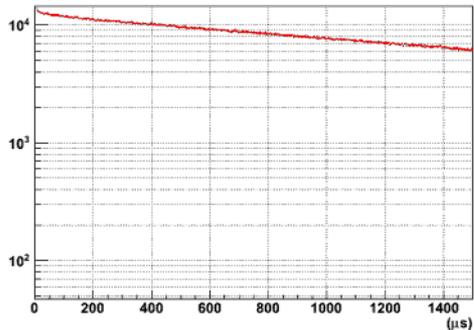
**Central Detector
+ secondary containment**

Final Deployment at SONGS



First Analysis of Reactor Off Data

Time Between Any Two Depositions



No PID
225,200 ev/day

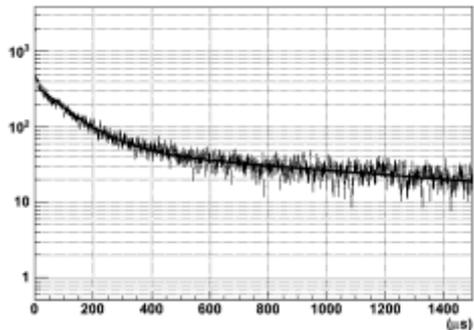


Only Neutron PID
1,830 ev/day

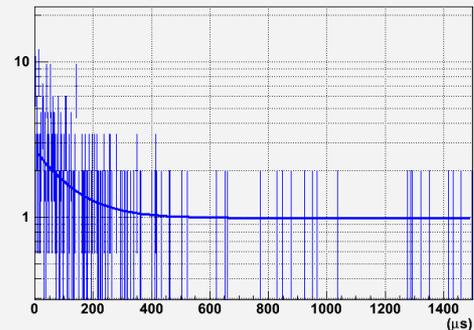


Max PID info
23 ev/day

Time Between Positron and Neutron Candidates



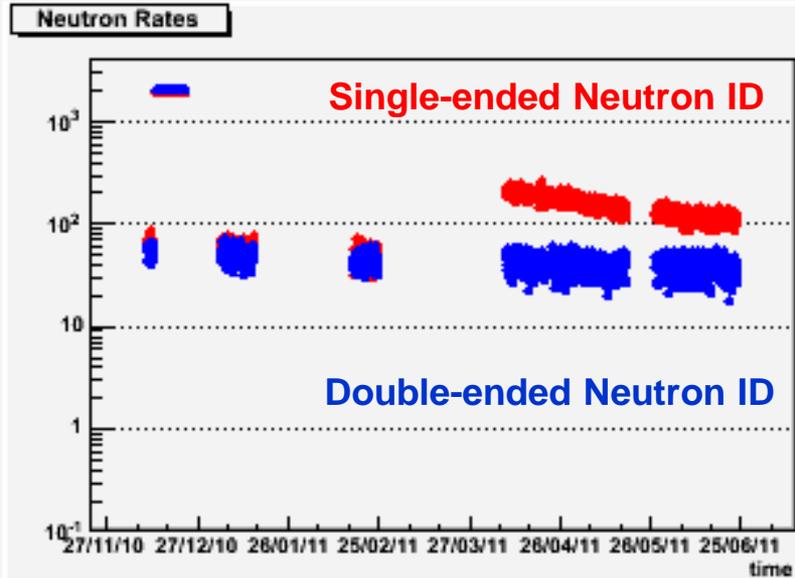
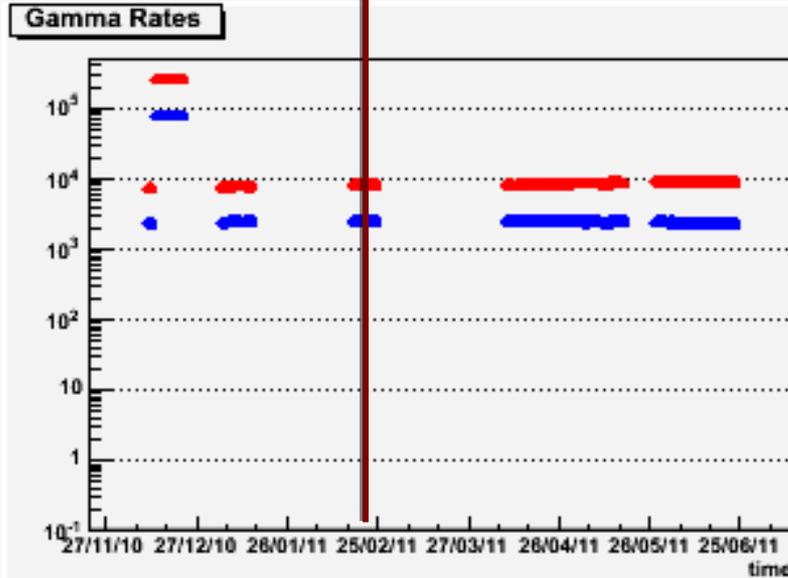
Time Between Positron and Neutron Candidates



- **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 $\bar{\nu}_e$ signal, expect 3 sigma detection in 4 – 6 weeks**
 - Expect 1 – 37 ev/day
- **Very encouraged by technology performance**

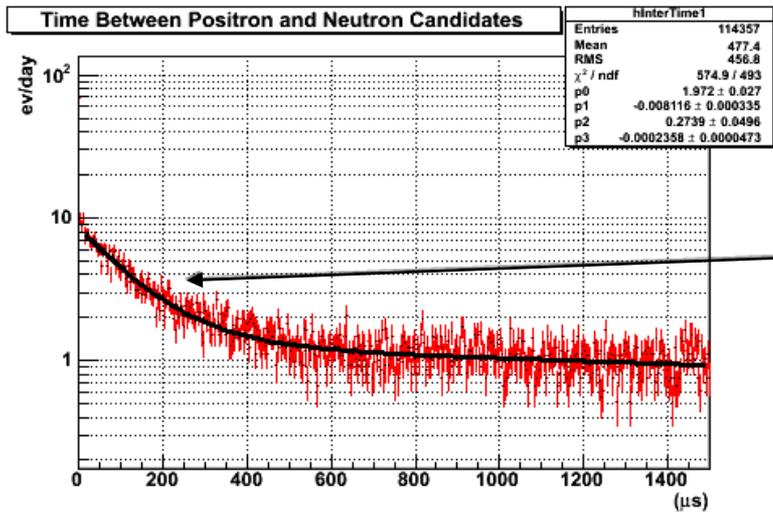
Challenging Operation Environment

Reactor Turn-on



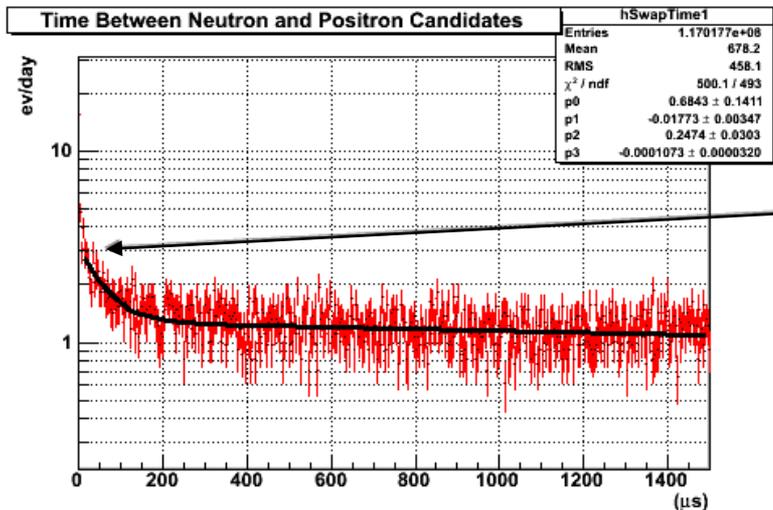
- **Multiple Hardware failures**
 - Replaced UPS twice
 - Loss of electrical power
 - HV spikes caused failure of PMT Bases
- **After Change of HV, significant response change to detector**
 - Neutron detection efficiency down by ~30%
 - Gamma detection efficiency is stable to < 4%
 - Contamination by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

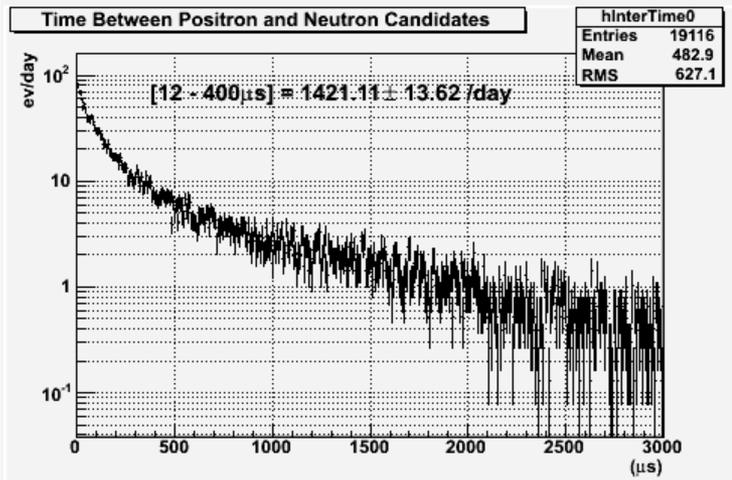
Unexpected exponential (time constant ~30us)

matches Gd capture in Water detector

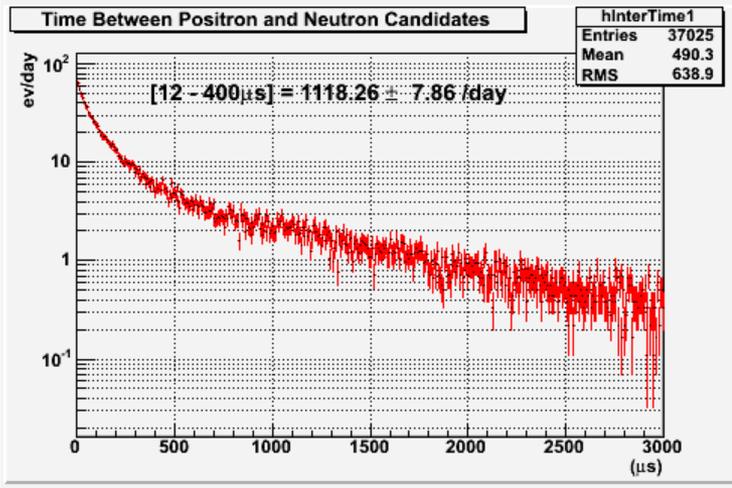
Events in Water contribute 30% of correlated events in the segmented detector!!!

Fully Corrected/Calibrated Data (using only neutron PID)

Signal

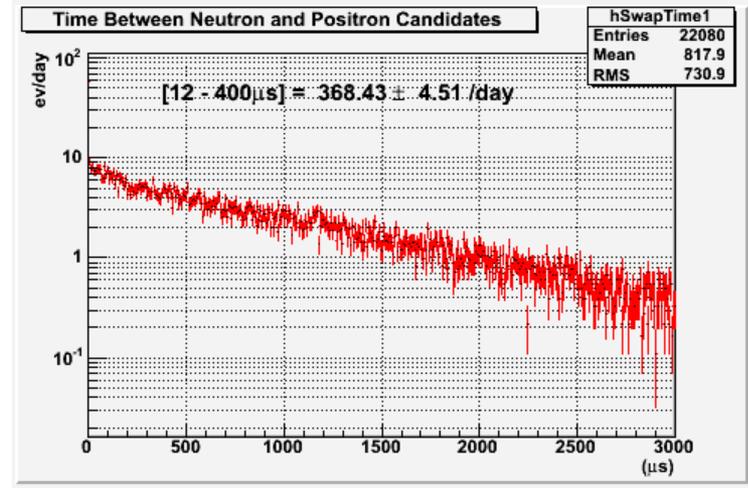
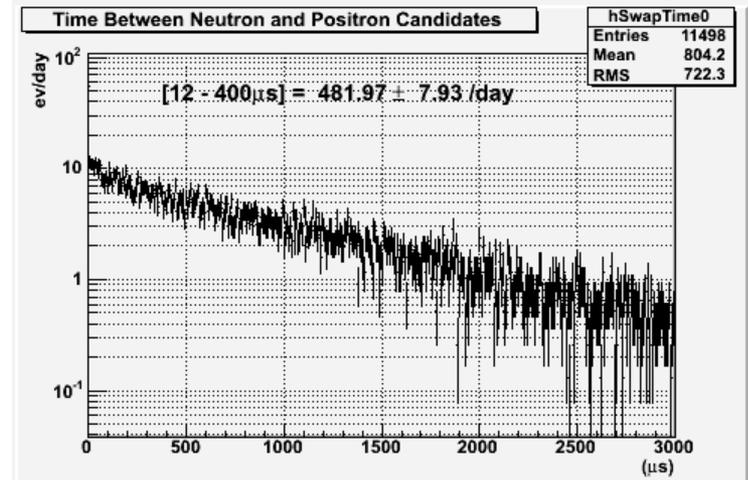


Reactor
Off



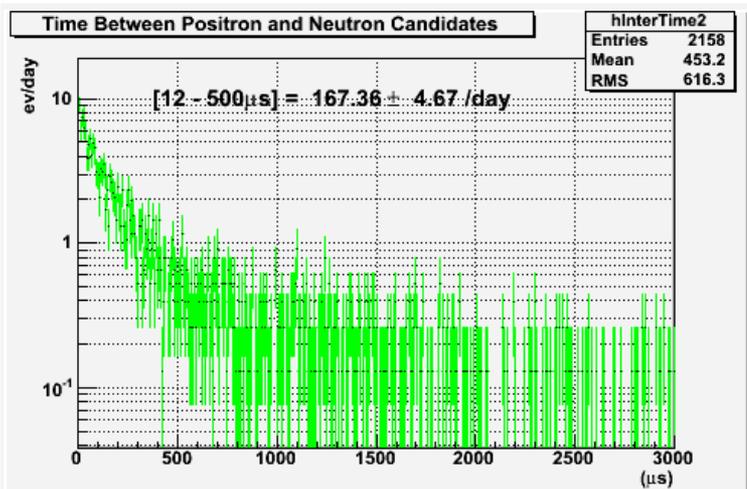
Reactor
On

Background

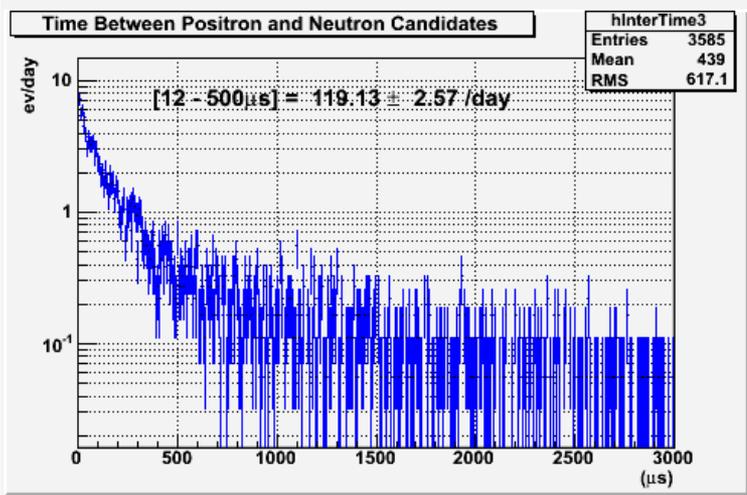


Fully Corrected/Calibrated Data (using both neutron and positron PID)

Signal

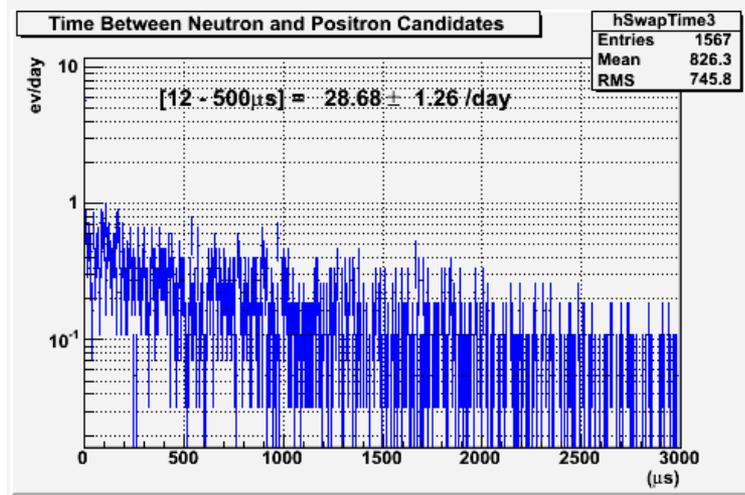
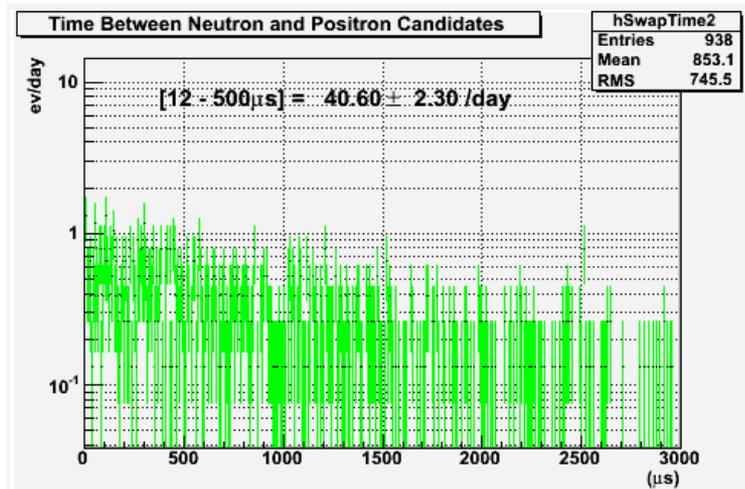


Reactor
Off



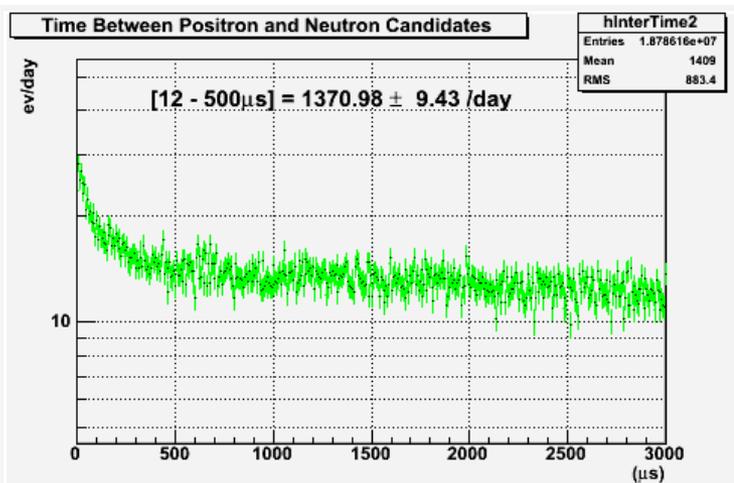
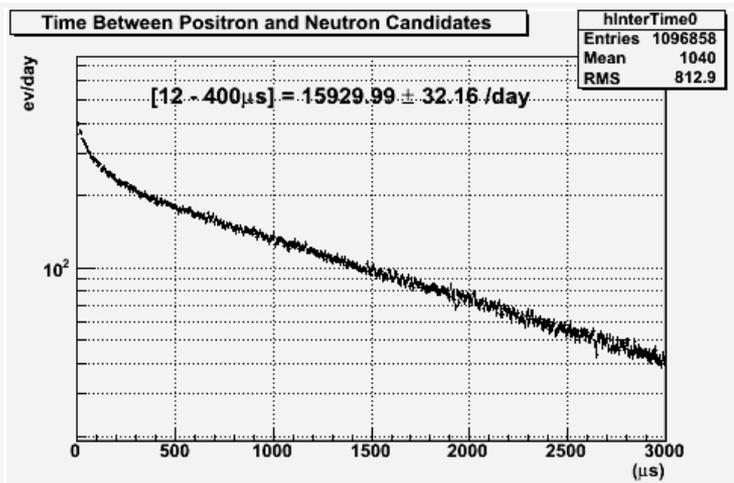
Reactor
On

Background



Operation Outside of Shield

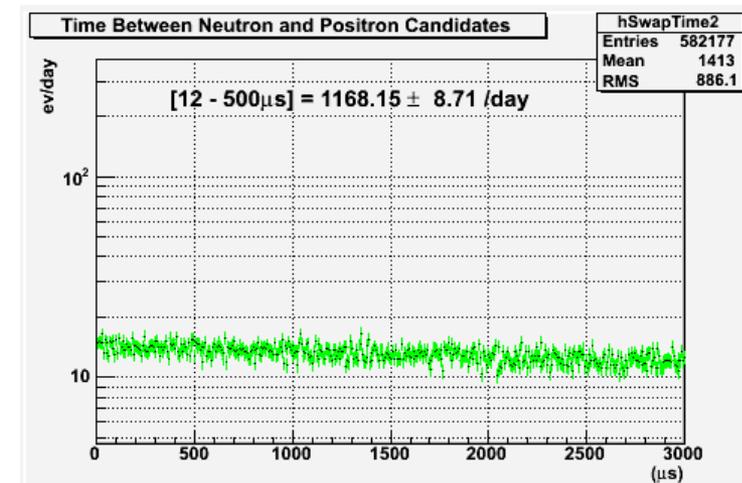
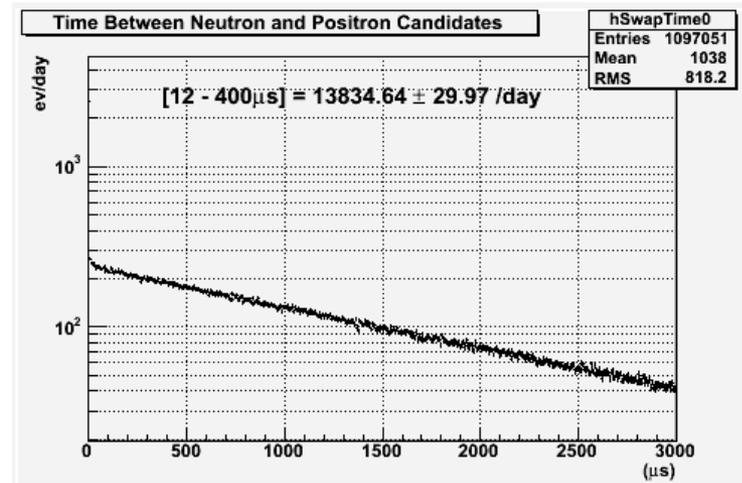
Signal



Only
Neutron PID

Neutron
and
Positron
PID

Background



Data Comparisons (events/day)

Event Definition	Reactor Off			Reactor On		
	Correlated	Un-correlated	Subtracted Signal	Correlated	Un-correlated	Subtracted Signal
1) Using only neutron PID	1421 ± 14	482 ± 8	939 ± 16	1118 ± 8	368 ± 5	750 ± 9
2) Neutron + positron PID	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 \cong 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/\sqrt{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

