Development and prototyping of a new highly-segmented neutron detector

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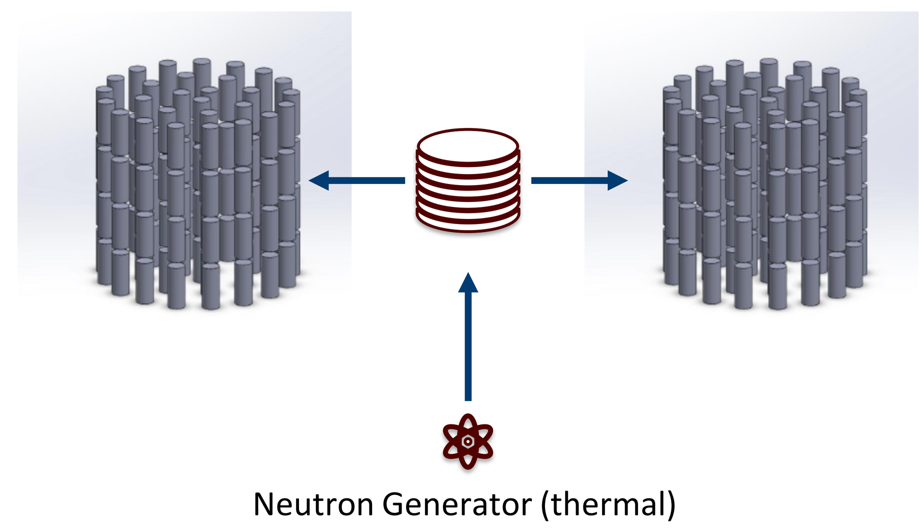
CENTER OF EXCELLENCE CENTAUR IN NUCLEAR TRAINING AND UNIVERSITY-BASED RESEARCH

NNSA National Nuclear Security Administration

Background and Motivation



Portal Monitor

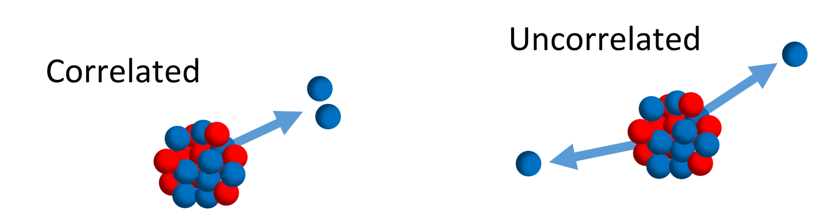
- Look for highly-enriched uranium using fast neutron scattering as an alternative to looking for γ-rays that can easily be shielded
- Double scattering technique to pinpoint neutron source
- Alternative to ^{3}He detectors that are only sensitive to thermal neutrons

Basic Nuclear Physics

- Invariant mass spectroscopy with focus on 2n emission and p+n decay channels
- Missing mass experiments w/ neutron ejectiles – (d,n) or (^{3}He,n)

These reactions are important in nuclear astrophysics and the structure of nuclei away from stability.

Two-Neutron Decay



(above) The opening angle between emitted neutrons provides information on whether the neutrons are emitted simultaneously or sequentially, and whether they interact as they leave the nucleus.

To benefit both basic science and applications, the goal is to build an array that has:

- Good efficiency – ~10's of percent for 1- to 30-MeV neutrons
- Improved resolution & sensitivity relative to existing devices
- Fast timing
- Low thresholds
- n/γ pulse-shape discrimination (PSD)
- ~1 cm position resolution

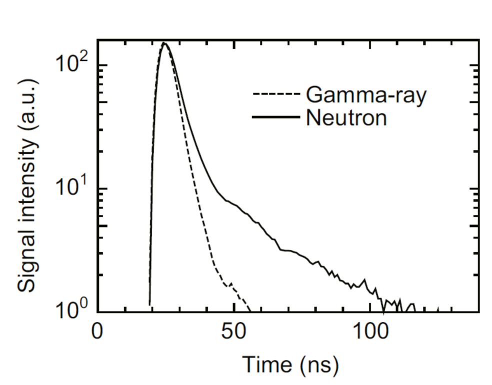
p-Terphenyl Multi-Cube Prototype

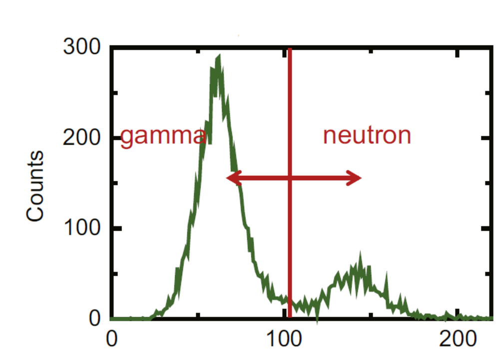
p-Terphenyl ($C_{18}H_{14}$) selected as the scintillator material because it has the following characteristics:

- Fast – 3.7-ns decay time
- Bright – 27,000 photons/MeVee
- Excellent PSD

Downsides of selecting p-Terphenyl:

- Expensive
- Difficult to grow / obtain in large sizes





(upper) Decay time for p-Terphenyl for a ^{252}Cf neutron source and a ^{60}Co γ-ray source.

(lower) PSD histogram for slow / fast time windows of 30-150ns / 20-30ns based on the upper plot, showing the separation.

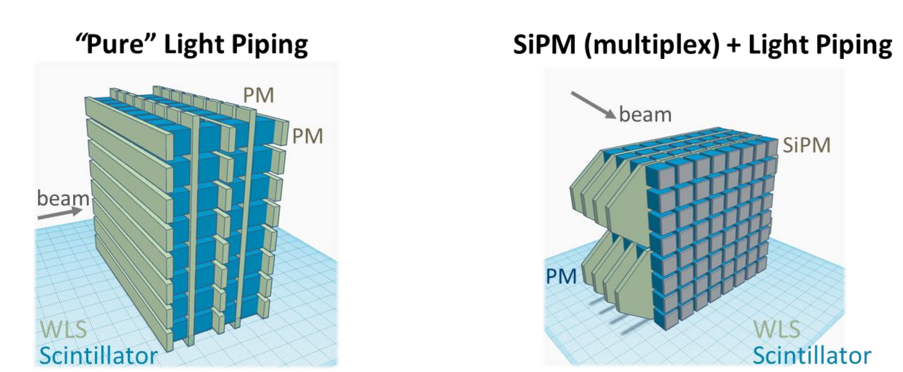
Figures from Yanagida *et al.*, NIM A **784**, 111 (2015).

Downsides mitigated by "thinking small" and building detector of many ~1 cm^3 cubes.

Potential Array Designs

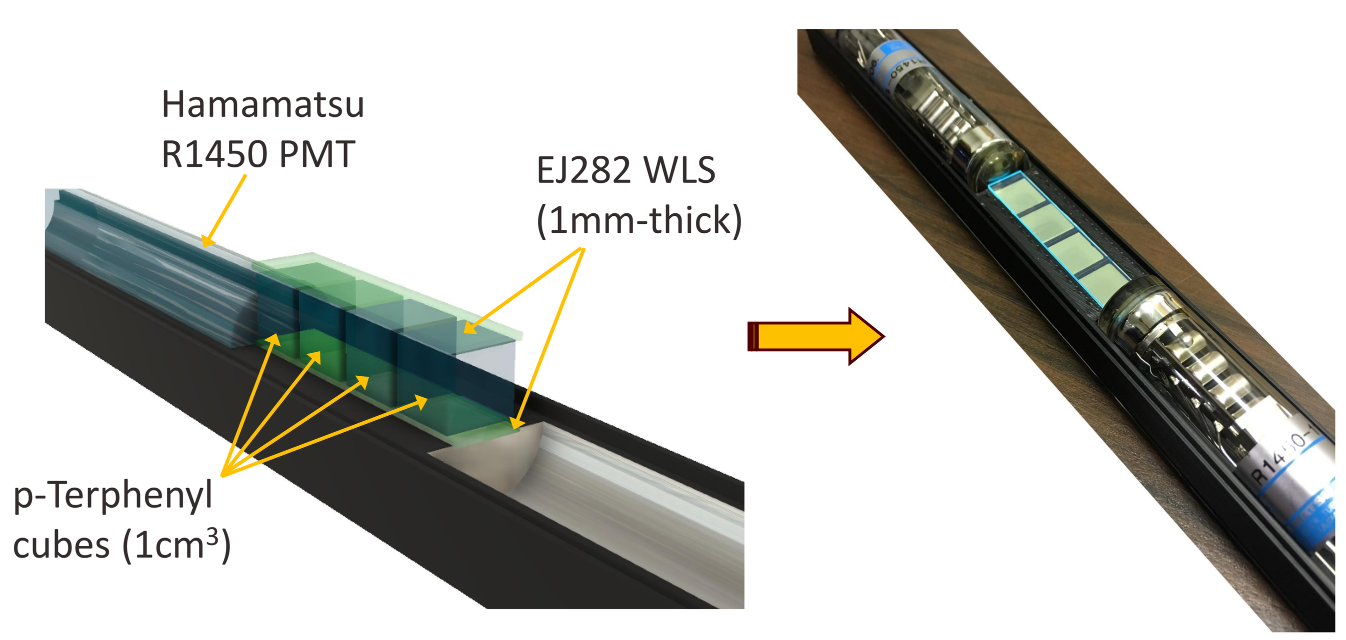
Challenging, coupled issues with designing an array:

- Necessary detector geometry / performance – driven by Physics requirements
- Readout scheme w/ cube-of-interaction (COI) sensitivity – use of SiPMs vs. PMTs as both have benefits and trade-offs



(above) CAD drawings of potential multi-cube array designs.
(left) Layers of wavelength shifter (WLS) strips are alternated with scintillators, and PMs are coupled at the ends of the WLS.
(right) Similar alternating layers, but the WLS material is "fishtailed" to PMs along one axis and SiPMs (without WLS) on the other. Note that designs could include a combination of both SiPMs and traditional PMTs.

Initial Multi-Cube Prototype



(left) CAD drawing of lower portion of the prototype detector housing; second PMT and cube slots have been removed for clarity.
(right) Photo of cubes, WLS piece, and PMTs in 3D printed holder; not pictured is the top of the housing.

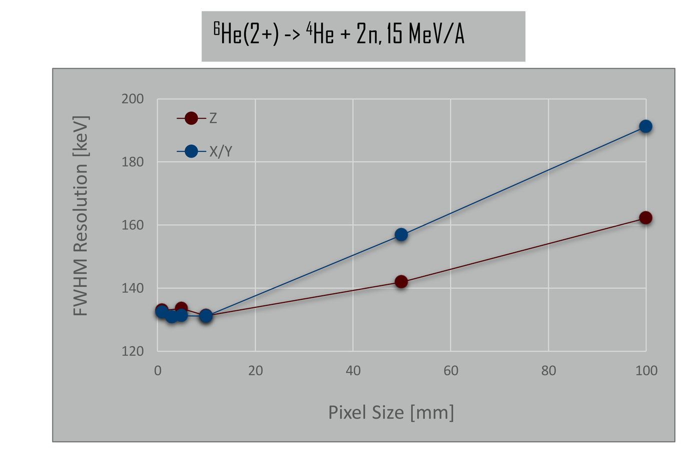
- Prototype of four 1-cm^3 cubes sandwiched between WLS pieces coupled to PMTs, oriented 180° apart, currently under construction
- Run plan is to test response with ^{207}Bi and ^{137}Cs sources and then optimize n/γ PSD with ^{252}Cf source
- Compare data with a single crystal (with and without WLS) tested in the same two-PMT geometry

Parallel Efforts

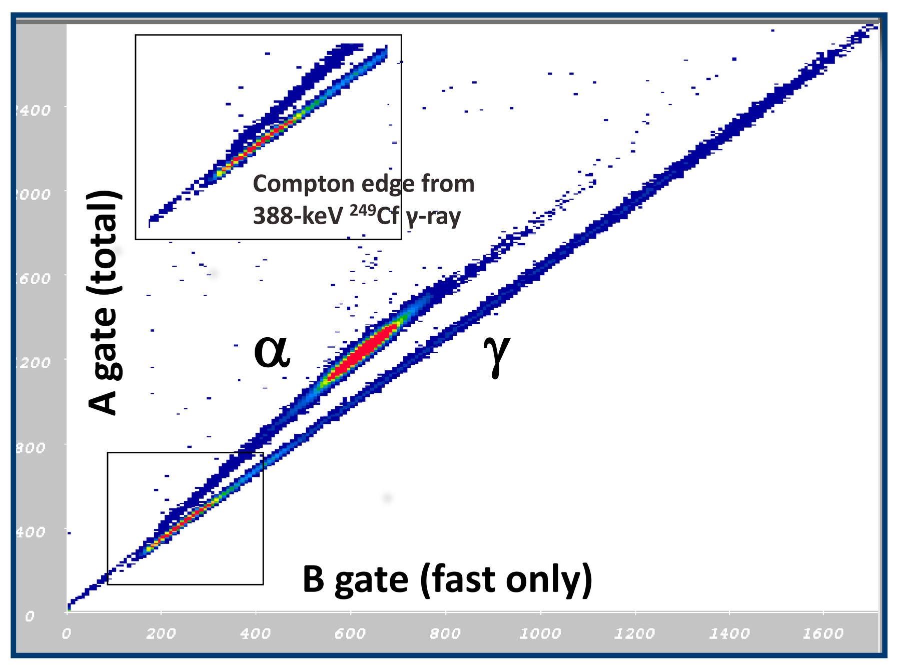
Simulations to Inform Cube Size

Simulation (GEANT4) work to inform detector design for various physics experiments:

- 2n decay of ^{6}He$^{(2+)}$ [TAMU]
- 2n decay of ^{26}O$^{(gs)}$ [NSCL/FRIB]
- Photo-disintegration of ^{3}H [TUNL]



(above) Back-of-the envelope simulation for ^{6}He decay indicates cubes of ~1 cm^3 would provide the desired resolution.



(above) PSD for α-particles and γ-rays using the ^{249}Cf(αγ) and ^{60}Co source; (insert) zoom-in of lower left corner, highlighting the Compton edge of the 388-keV γ-ray from ^{249}Cf, located at 155 keV.

SiPM Readout Scheme Testing

Efforts to characterize PSD using SiPMs with different amplifier and chip configurations underway

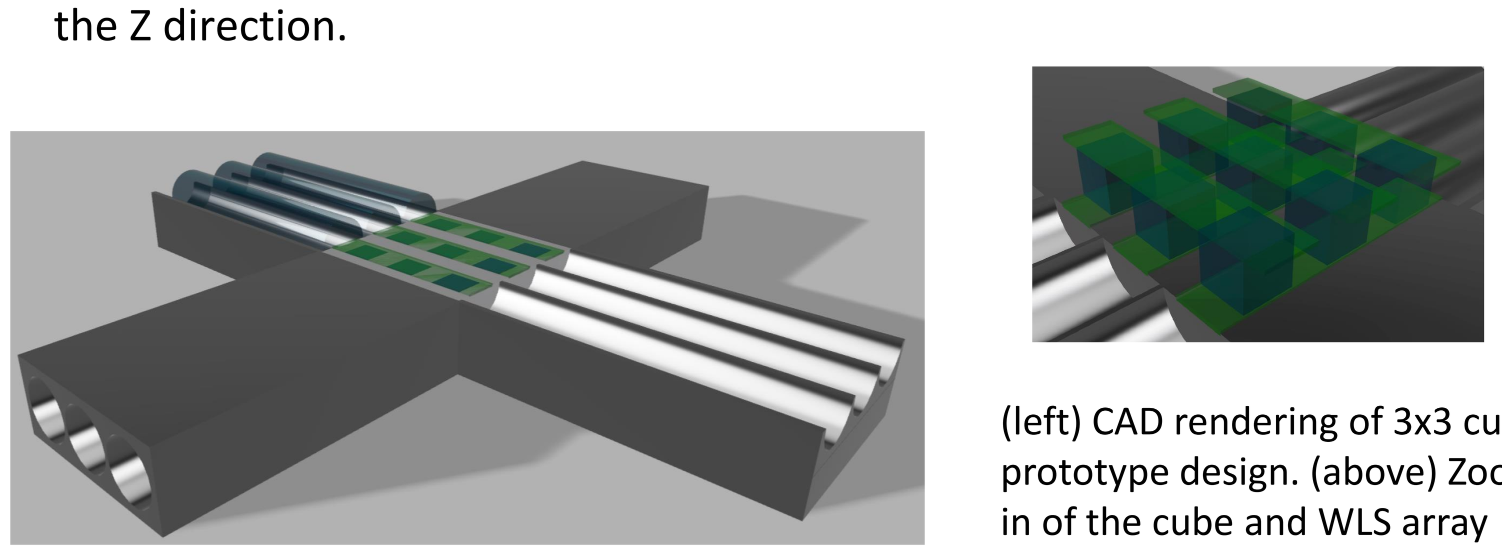
^{249}Cf(αγ) and ^{60}Co source with the following gating:

- A gate: total 400ns wide
- B gate: Fast 100ns wide
- Gates precede signal by 40ns

First success of PSD with SiPMs in nuclear physics!

Expanded Multi-Cube Prototypes

The next step in prototype designs includes an array of nine 1-cm^3 cubes with PMTs coupled to WLS pieces in both the X and Y directions. The design is modular to build additional layers to ultimately include the Z direction.



(left) CAD rendering of 3x3 cube prototype design. (above) Zoom-in of the cube and WLS array with frame removed for clarity.

Acknowledgements

We would like to thank W. Seward and B. Hyman for their assistance in this project. This work is supported in part by the U.S. Department of Energy (National Nuclear Security Administration) through grant number DE-NA0003841.