Demonstration of Time-Correlated Pulse Height-based Confirmation Measurements

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Outline

- Motivation – Treaty Verification
- Methods – Template based approach
- Signature – Correlated neutrons and gammas
- Results – Passive Plutonium and Active HEU
  - Dismanntlement Confirmations
  - Item Confirmation

Motivation

Timing as a Unique Signature

- Application
  - Treaty verification (e.g. New START)
- Requirements
  - Portability
  - The primary variables are mass, density, morphology of nuclear material and presence of shielding and moderators
- Method
  - Time-correlated particles are a unique signature of the fission process and therefore the nuclear material content
  - SNM, by definition, exhibit these unique properties

Trust, Information Barriers and Templates

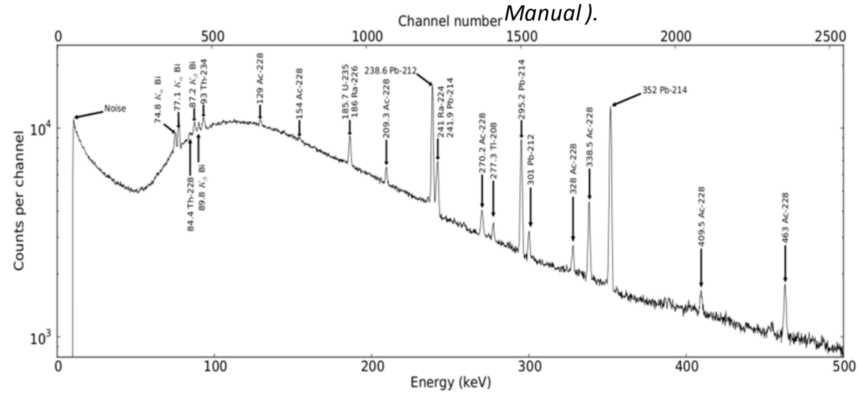
- Sensitive method that can reliably catch cheaters
- Signature that is unique to the test object
- Method can not reveal too much information about test object
- Template approach lends itself to application of information barriers
  - Cryptography
  - Zero knowledge protocol

Current Methods

Measurable Unique Signatures of Fissile Material

1. Gamma spectrum
   – Isotopic content
2. Total neutron rate
   – Assay of the contents of specific materials
3. Correlated counts
   – Multiplicity analysis (singles, doubles, triples): fission rate, multiplication, (α, n) component
   – Relative multiplication:
     - Rossi-alpha distribution
     - Feynman variance technique

Plutonium Scrap Multiplicity Counter, used for accurate assays of plutonium metal, oxide, mixed oxide, or scrap *(LANL PANDA Manual).*



Current Methods
Drawbacks and Limitations

1. Gamma spectrum
   - Attenuation and self-shielding
2. Total neutron rate
   - Requires administrative controls
   - Spontaneous & induced fission and (α,n) sources are indistinguishable
3. Correlated counts
   - Requires high efficiency, necessitates large detection system
   - Efficiency has to be well known
   - Detector die-away time of 10-30 μs ("superfission concept")
   - Neutron energy information is lost due to moderation

→ He-3 based technologies

Fast Correlation Discrimination Capable Organic Scintillators

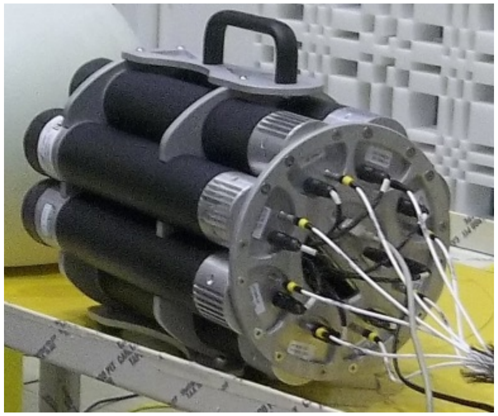
New Approach

System advantages:

1. Can be low efficiency
2. Efficiency can be ignored in calculations
3. Detection systems can be portable
4. Neutron energy information is preserved
5. Timing is within the resolution time of a fission chain

Potential:

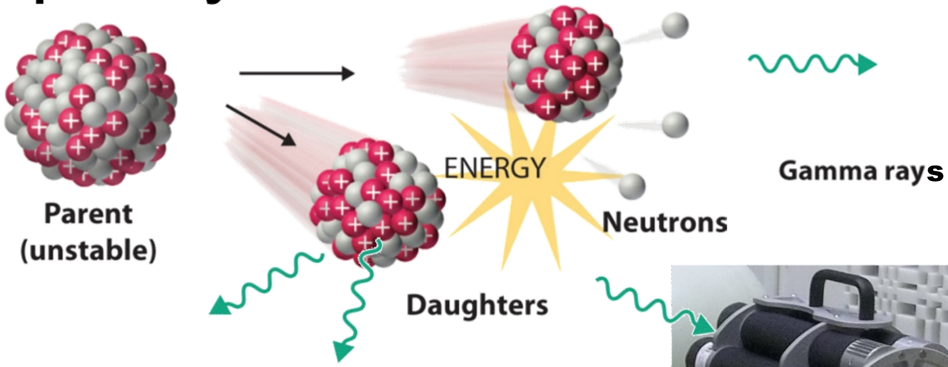
1. Differentiate contributions from spontaneous fission, induced fission (fission chains), and (α, n) sources
2. Simultaneously solve for mass, multiplication, and shielding

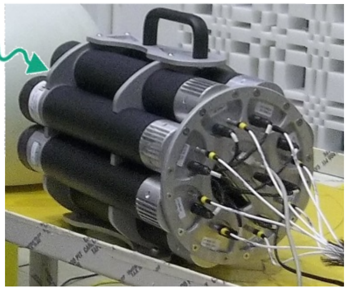


"The 8-shooter"
Array of Stillbene crystal scintillator

✓ PSD Capable
✓ Fast Timing

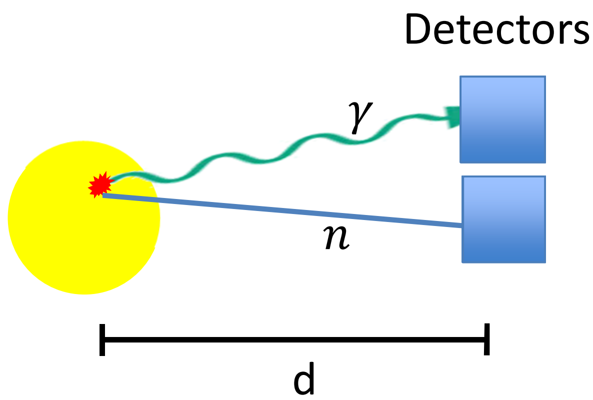
Multiplicity 2 correlation





- Neutrons and gamma-rays are emitted nearly simultaneously during the fission process.
- Minimum multiplicity equals two:
  1. Gamma-gamma: great for timing, but a lot of detector cross talk and uncorrelated background.
  2. Neutron-neutron: without event by event energy, expected correlated timing is spread on the order of the spread in fission chain dynamics.
  3. Gamma-neutron: gamma starts precise clock, neutron creates certainty that fission has taken place (also more penetrating).

Neutron-Gamma Correlation



$$\Delta t_{n-\gamma} = \left(R_n \sqrt{\frac{m}{2E_{n0}}} - \frac{R_\gamma}{c} \right) + \Delta T_{f_1,f_2}$$

Time of arrival difference between γ and neutron	Time-of-flight difference between γ and neutron	Time difference between fissions in a chain
Measured	Estimated	Signature

Observed:

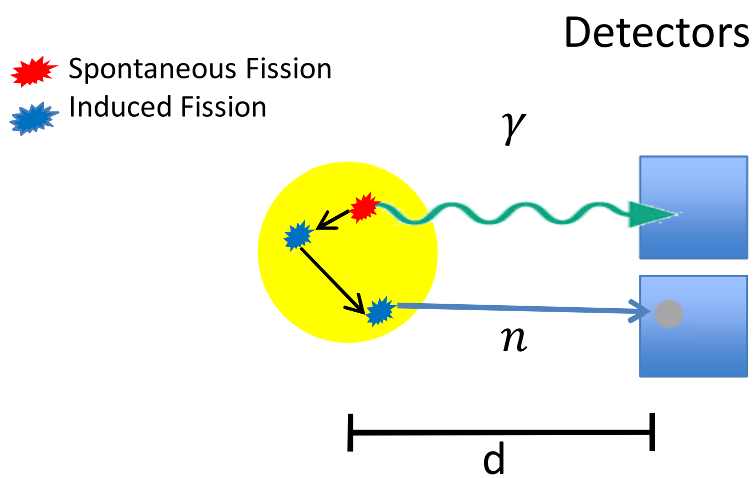
$$E_p \leq E_n$$

proton recoil

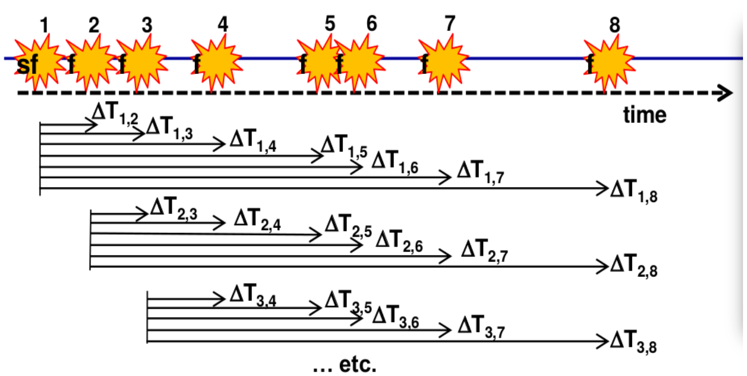
$$\Delta t_{n,\gamma} - d\left(\sqrt{\frac{m}{2E_p}} - \frac{1}{c} \right) \leq \Delta T_{f_1,f_2}$$

$$\Delta t_{n,\gamma} - \Delta \mathrm{t_p} \leq \Delta T_{f_1,f_2}$$

Neutron-Gamma Correlation – Fission Chain



Distribution of times between fission events in a chain



Time difference between fission events in a chain

$$\Delta t_{n-\gamma} - \Delta t_p \leq \Delta T_{f_1,f_2}$$

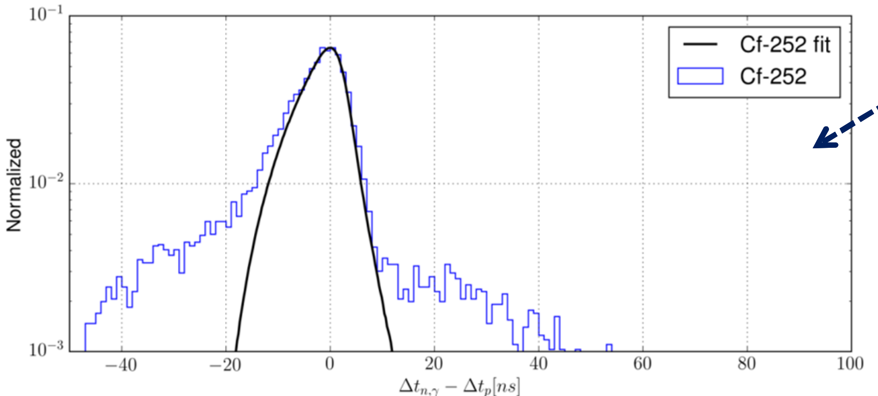
Measured time difference between neutron and nearest γ

Estimated travel time difference between neutron and gamma

$$\Delta T_{f_1,f_2} > 0 \text{ if } f_1 = \gamma \;\&\; f_2 = n$$

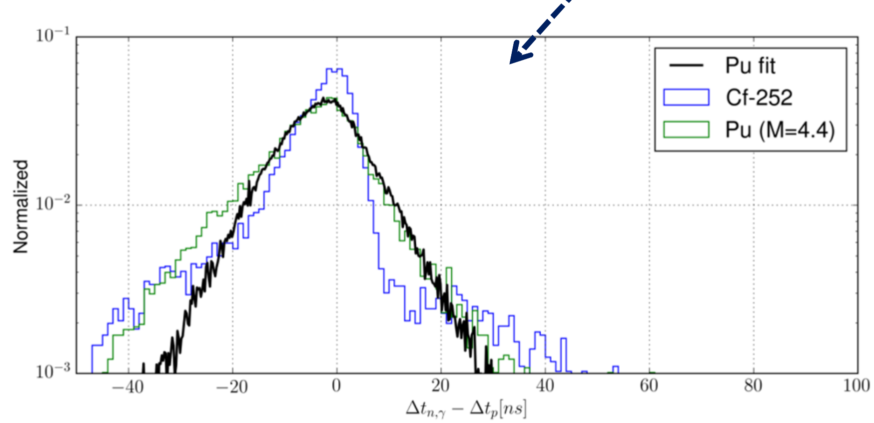
$$\Delta T_{f_1,f_2} < 0 \text{ if } f_1 = n \;\&\; f_2 = \gamma$$

Measured $(\Delta t_{n-\gamma} - \Delta t_p)$ Distributions



Non-fissile fission source

Fissile material
(BeRP ball, M = 4.4)

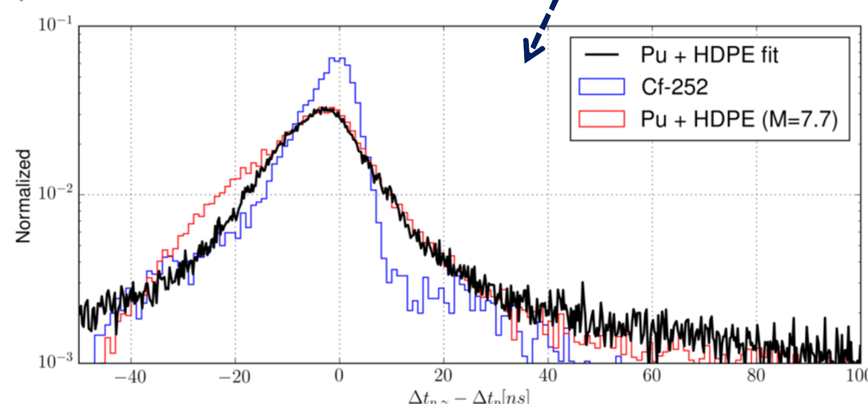


Moderated Fissile material
(BeRP ball, M = 7.7)

$\Delta T_{f_1,f_2}$ can discriminate:

1. Fissile vs. fissionable
2. Fissile, different multiplications
3. Moderated vs. reflected or bare

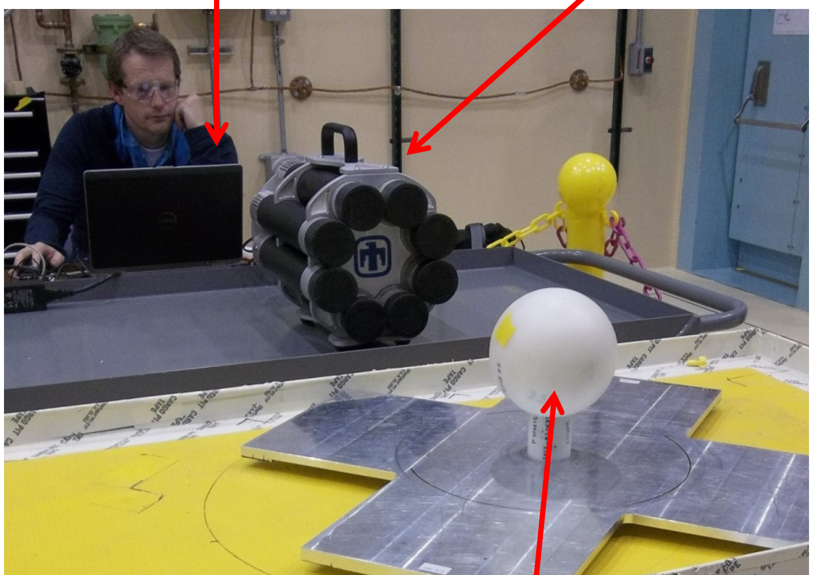
Simple fission chain models fit the distribution well!



Experiments

Computer/digitizer

Stilbene array

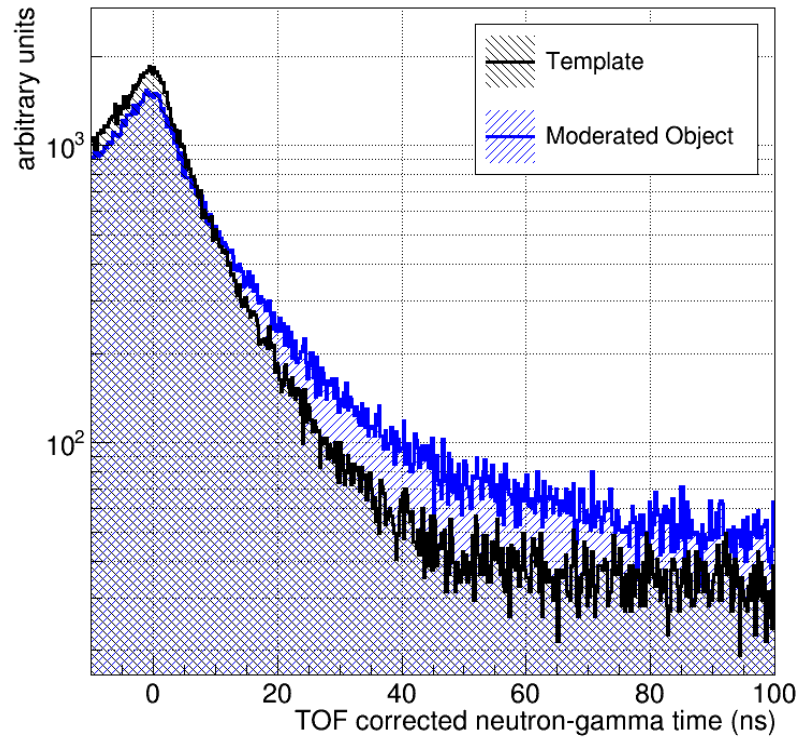


Beryllium Reflected Plutonium (BeRP) ball in a 1” shell of High Density Polyethylene

Source	Distance (cm)	Total Time (minutes)	Rate of gamma-Neutron Pairs (Bq)
BeRP	34	59	55.6
BeRP + 1 in HDPE	34	589	77.8
HEU	34	55	0.068
HEU + 0.6 in Lucite	34	80	0.077
Hemi	46	499	0.096
Cf-252	36	31	10

Data Analysis Methodology

- Align peak to zero
  - Source-to-detector distance
- Subtract background (-1500-500 ns)
- Compare measurement to template
  - Threshold on log-likelihood
- Determine match
  - Pass/Fail

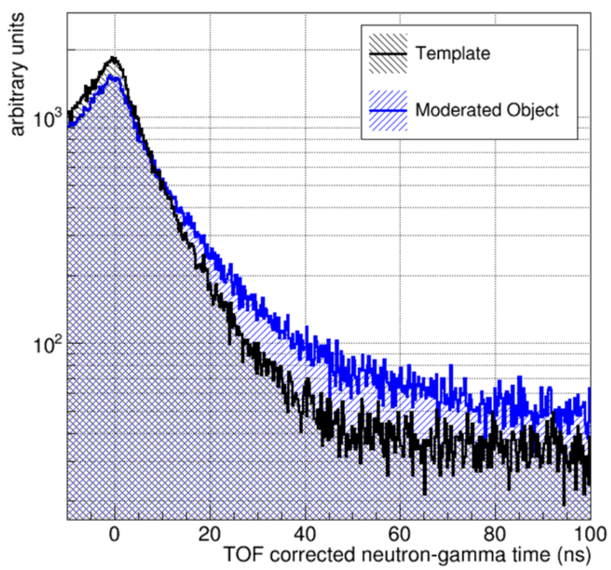


$$L = \sum_{i=0}^{n} -\log(P(x_i|\mu_i))$$

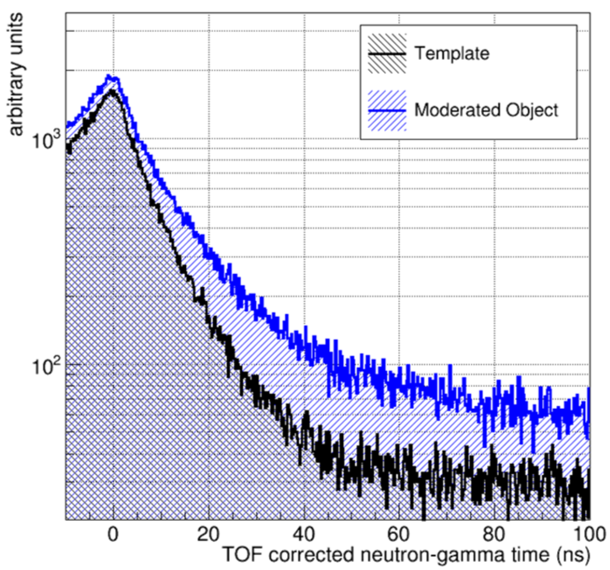
Data Analysis - Normalization

- Gamma-neutron rate provide more discriminating matric than shape alone
- Comparisons normalize to both counts and rate to demonstrate the effect

Count Normalized

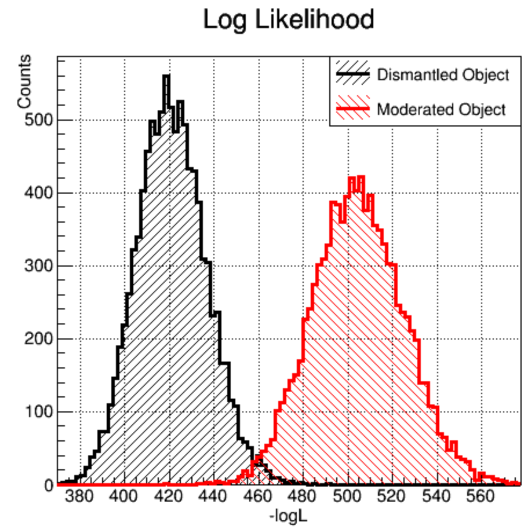


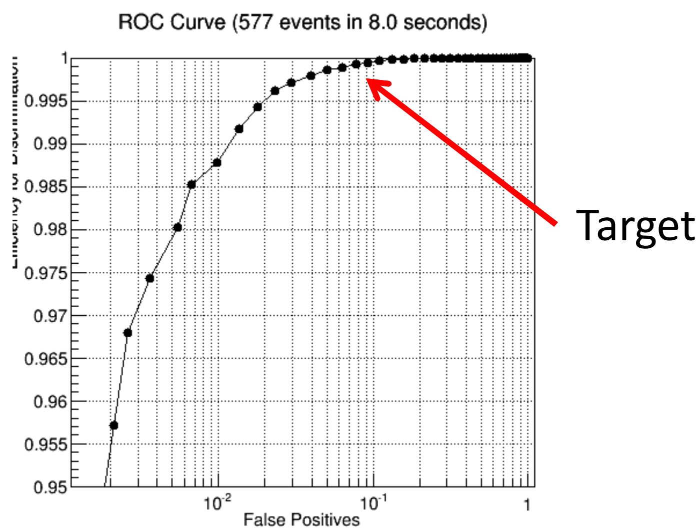
Rate Normalized



Determine Threshold

- Target:
  - 99% True Positive (TP) rate
  - <1% False Positive (FP) rate
- For specific *dwell time* throw 10,000 random trails
- Calculate ROC curve
- Increase dwell time until target is met

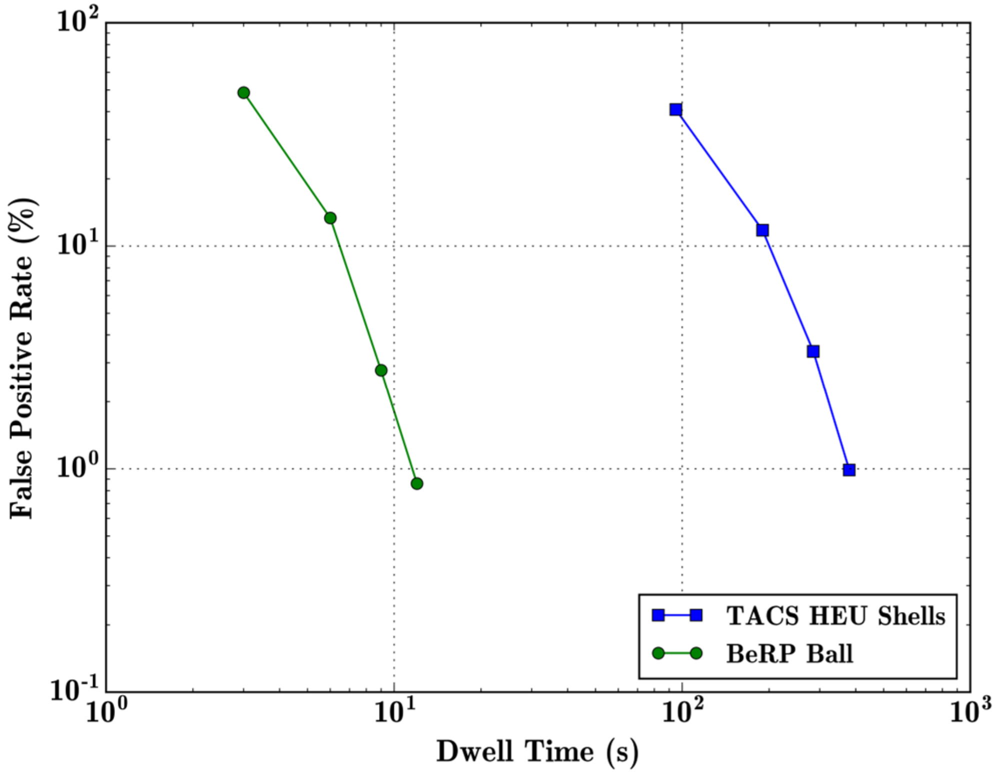




Results – Dismantlement Confirmation

- Template: Bare (non-moderated) object

Object	Count normalized (s)	Rate normalized (s)
BeRP ball	12	3.6
TACS HEU	380	590

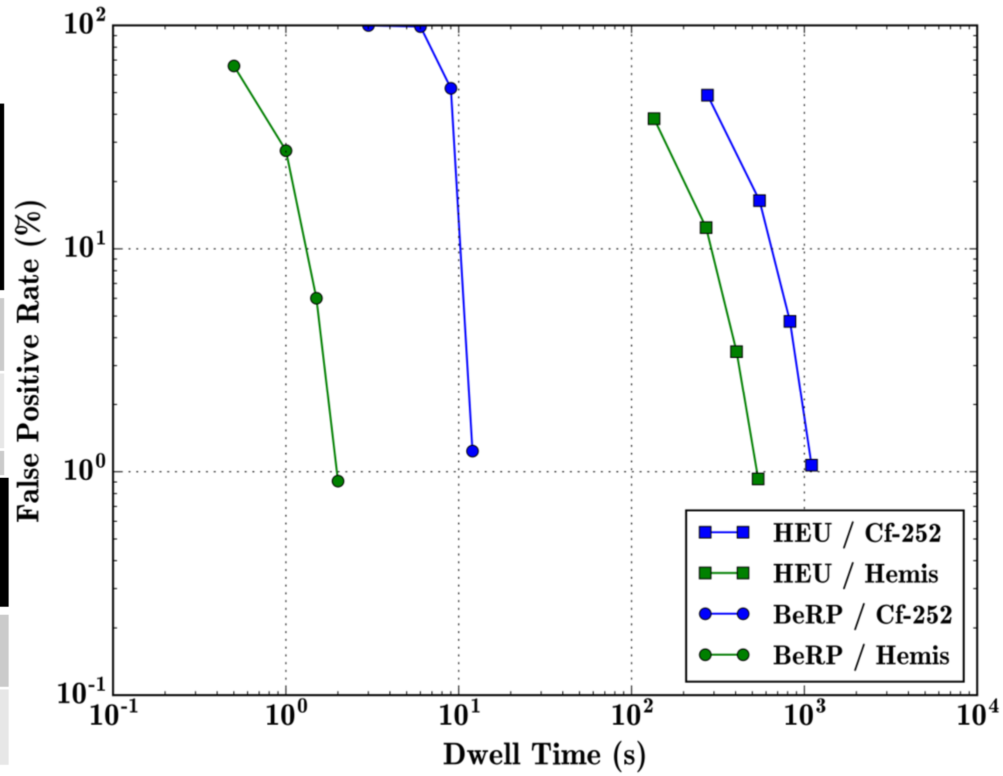


Results – Item Confirmation

- Templates: Non-multiplying Cf-252 and Hemi Shells (Pu Oxide)

Template	Count normalized (s)	Rate normalized (s)
Cf-252	12	6
Hemi Shells	2	6

Template	Count normalized (s)	Rate normalized (s)
Cf-252	1100	80
Hemi Shell	540	960



Conclusions

- Demonstrated a unique signature derived from previously studied TCPH distribution
- Applied signature with template-based approach to determine dismantlement and item confirmation
- Target threshold of 99% TP and <1% FP
- BeRP ball (Pu) confirmation was established within sever seconds
- TACS HEU shells required hundreds of seconds of dwell time and an external source (Am-Li)

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Neutron Sources in Nuclear Fuel Cycle

- Spontaneous Fission
  - Pu-238/240/242, Cf-252
  - Energy spectrum is Maxwellian (~2 MeV mean):
    - Sqrt(E) exp(-E/1.43)
- Induced Fission
  - U-233/235, Pu-239
  - Spectrum depend on the energy of incident neutron
- (alpha, n) reactions
  - Alpha + O-18 → Ne-21 + n
  - Alpha + F-19 → Na-22 + n
  - Spectrum depends on target isotope to second order alpha energy

Pulse Shape Discrimination

Pulse Shape Dependence on Interacting Particle

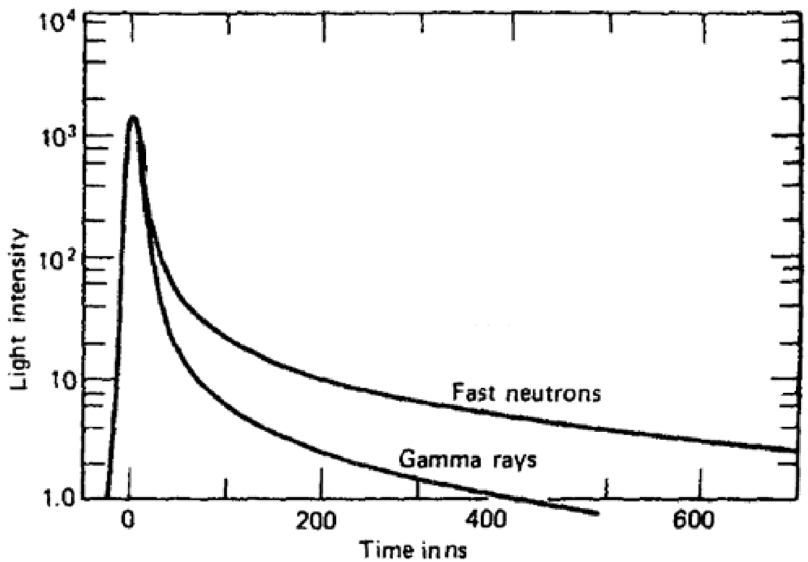
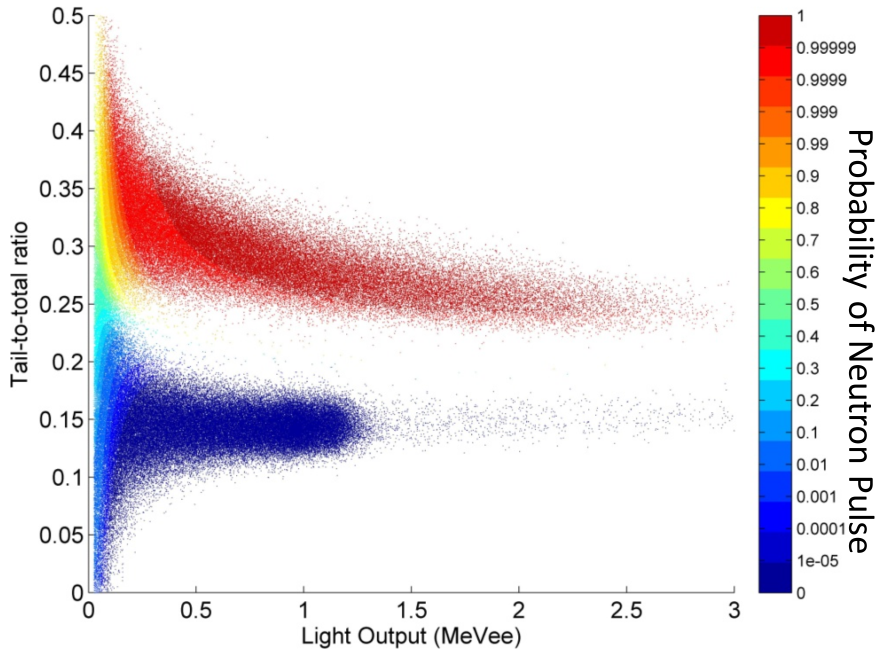


Figure from Glenn Knoll *Radiation Detection & Measurement 3rd Edition*

Bayesian Probability Map



Measured Quantities from Organic Scintillators